Virtual Distinguished Lecturer Program

Principles and Cooperative Techniques for Multi-drone Systems and Swarms

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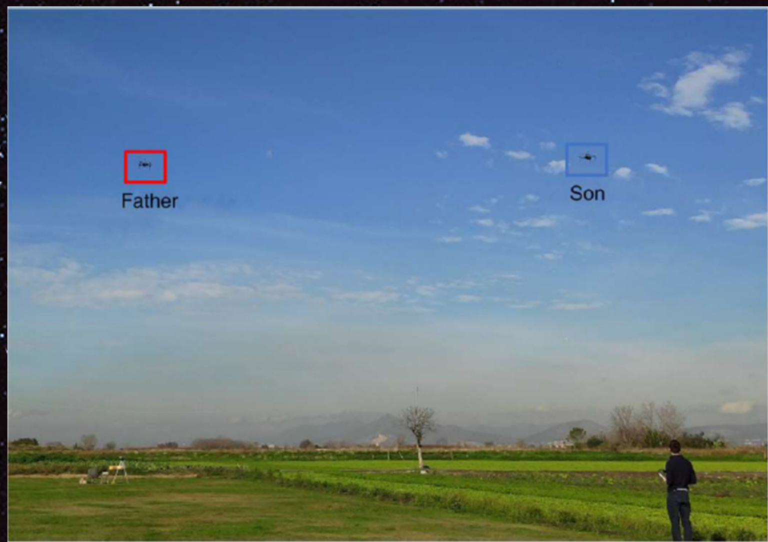
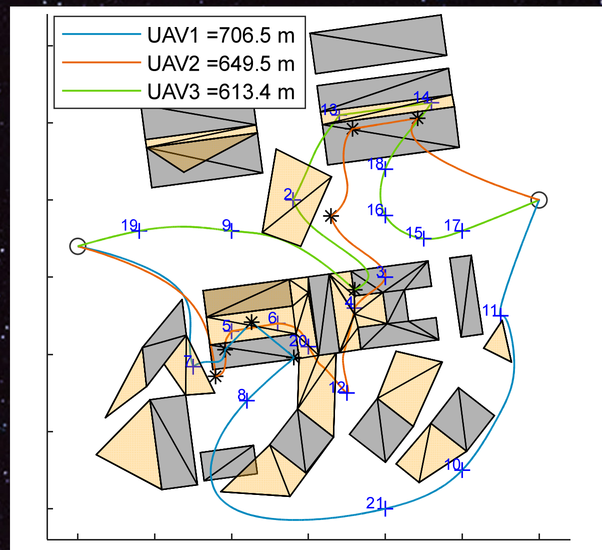




AESS Virtual Distinguished Lecture, September 17, 2024

Outline

- Introduction
- Motivations and Application Scenarios
- Taxonomies
- Key elements and research areas
- Multi-drone Research @ UniNa
- Perspectives and conclusion

Introduction

- Multi-drone systems and swarms: key elements within the evolution of UAS technology
- Increasing impact in military and civilian applications, as well as in the regulatory evolution, tightly linked with improvements in UAS autonomy
- A way to scale up operations and overcome technological limits of single vehicle architectures, for different classes of UAS
- Lecture objective
  - Introduce motivations and principles
  - Address enabling technologies and recent research efforts
  - Discuss perspectives

(UniNa multi-drone flight tests)

Introduction - terminology

- Level of coordination and technological requirements may change greatly – «swarming» terminology used regardless of collective behaviour nature

- Within the research community, «swarming» has been linked to coordinated guidance and relative motion control

- Within regulations and in the users community, «swarming» is used to emphasize the 1-to-N remote control paradigm

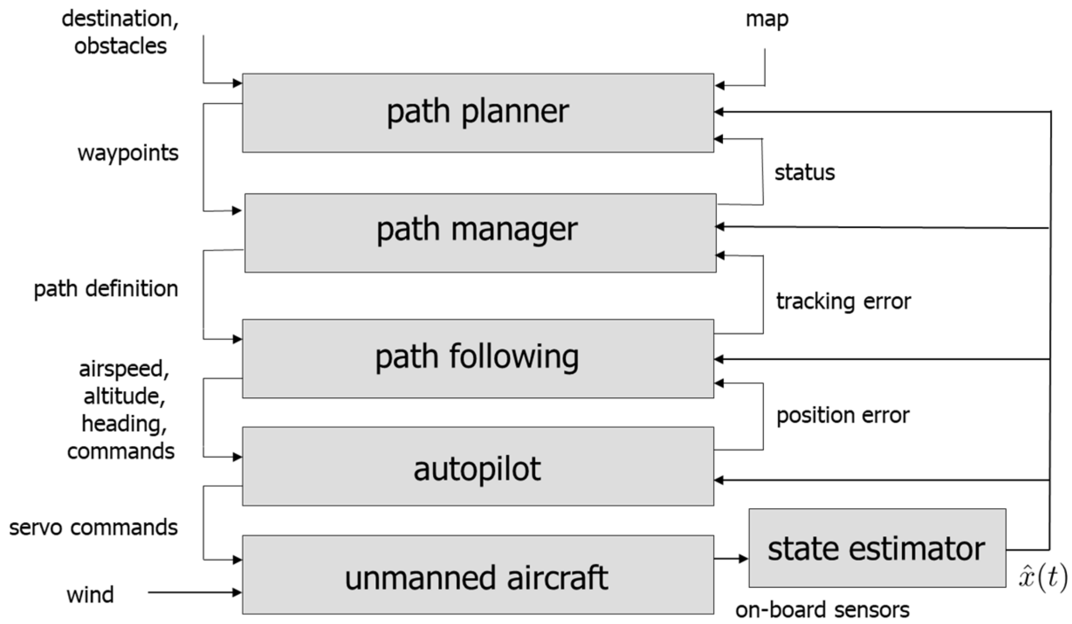
- In general, multi-drone systems include a number of drones who work synergistically towards a common mission goal

(https://www.darpa.mil/news-events/2021-12-09)

(https://uavcoach.com/teal-drones-4-ship/)

- Typical potential advantages:
  - Time efficiency
  - Cost
  - Simultaneous actions
  - Complementarity
  - Fault tolerance
  - Flexibility
  - Performance
- Multi-drone blocks as higher layers that can be interfaced with planning/guidance at different levels
- Coordination and cooperation
- Communications and networking
- From 1-to-1 to 1-to-N and M-to-N paradigm
- Human-swarm control and interaction

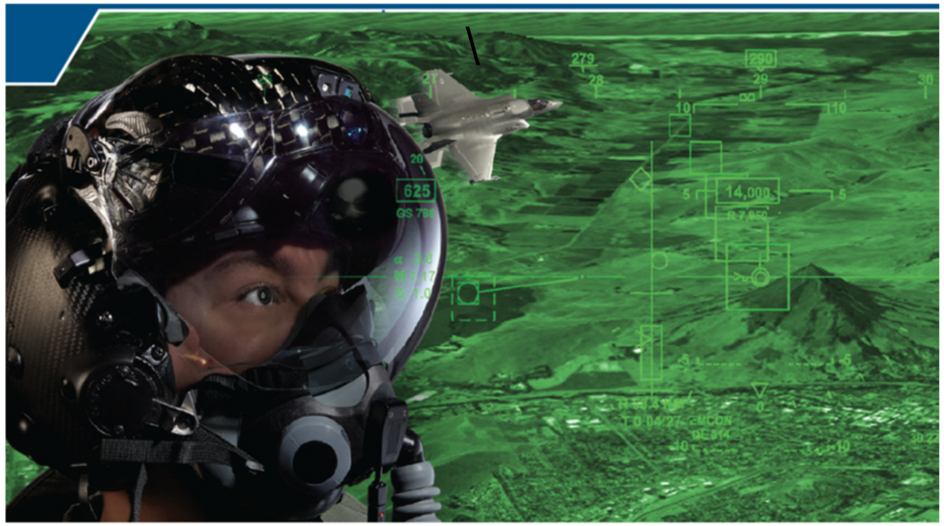
Multi-drone Algorithms



(Beard and McLain, Small Unmanned Aircraft Theory and Practice, 2012)

- In the military field, swarms are in general considered as «force multipliers»
- Key areas/applications
  - Multi-vehicle attack or defense – attritable systems
  - Distributed sensing for enhanced situational awareness, cooperative target detection and tracking (information superiority)
  - Enhanced mission performance and resilience thanks to multi-drone planning, guidance, navigation, and control logics
- Swarming and counter-swarm technologies
- Strong link with manned/unmanned teaming and optionally piloted aircraft systems, as well as with mission autonomy concepts (human-autonomy and human-swarm interaction)
- Multi-vehicle fusion as natural evolution of advanced pilot situational awareness

(https://www.darpa.mil/program/gremlins)



Improved pilot awareness (5° generation fighter)
(https://www.flightglobal.com/f-35-programme-receives-first-rockwell-collins-gen-3-helmet/117935.article)

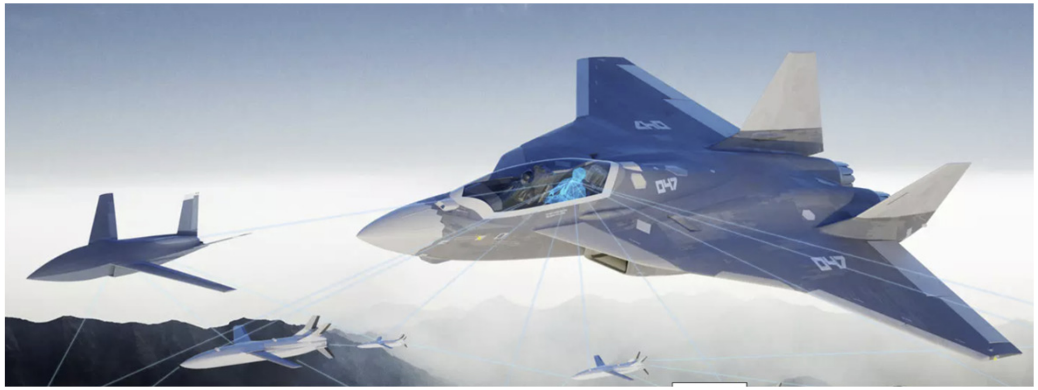
Military Applications - Swarming and Manned-Unmanned Teaming

- Mission control with different levels of interoperability (LOI), 1 to 5
- Cooperative Mission Execution
- Integrated Human Machine Interfaces to reduce crew workload
- Many recent flight demonstrations (mainly with rotorcraft)

- Swarming and MUM-T as foundational concepts in the technological evolution towards 6° generation fighters

Live feed from drone

(https://theaviationist.com/2020/10/20/aw159-wildcat-helicopter-remotely-controls-a-uav-in-uks-first-manned-unmanned-teaming-mumt-trials/)

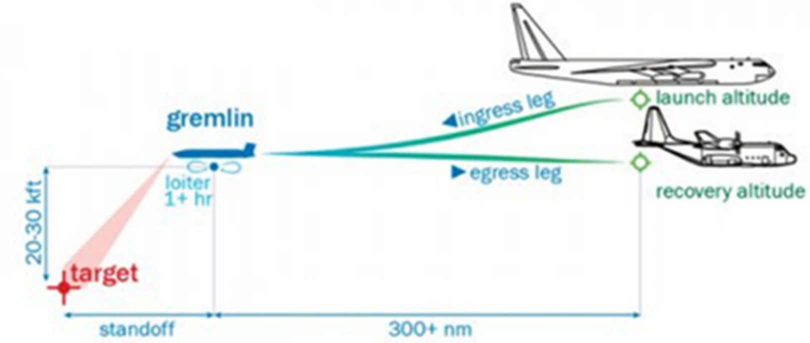


(https://www.airbus.com/en/products-services/defence/uas/uas-solutions/manned-unmanned-teaming-mum-t)

(https://www.youtube.com/watch?v=mrvZWaB7_1E)

Military Applications: Air-launched Swarms and Multi-scale Swarming

- Several running projects, e.g.
  - DARPA project GREMLINS focuses on airborne deployment and recovery of UAV swarms
  - Airbus recently demonstrated 4-drones control from a tanker



(https://www.darpa.mil/program/gremlins)

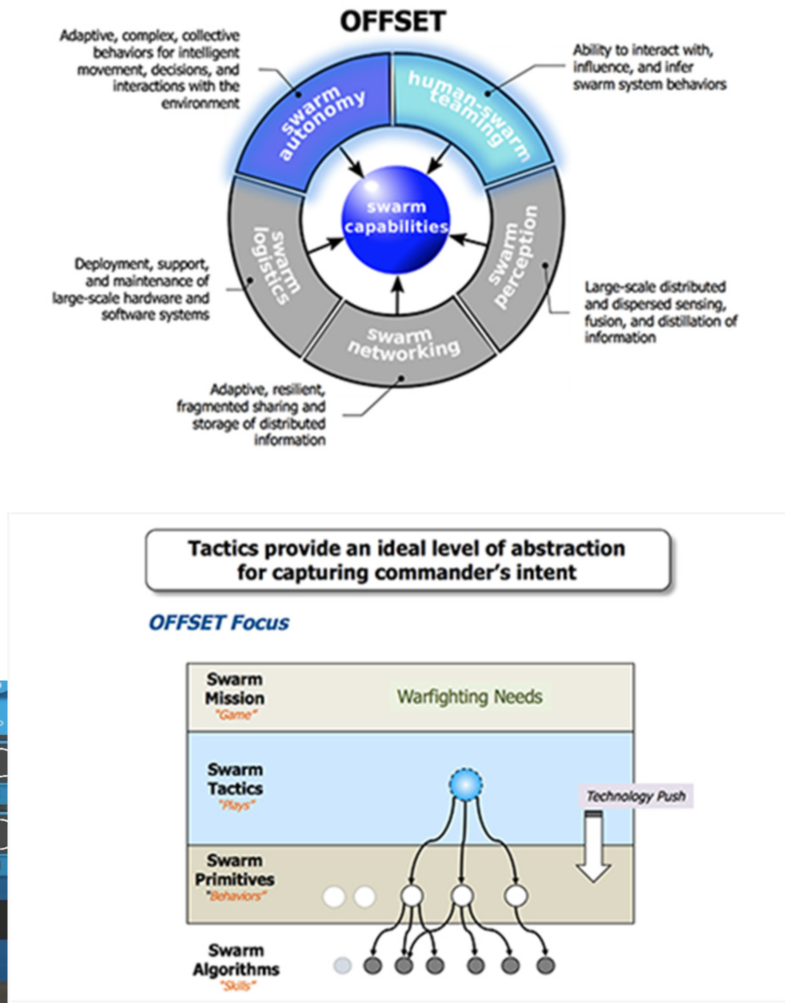
- Multi-scale swarming

(https://www.aero-mag.com/xq-58a-valkyrie-swarming-drones-09042021/)

(https://www.airbus.com/en/newsroom/news/2022-02-future-combat-air-system-a400m-clears-the-first-hurdle-as-a-remote-carrier)

- R&D programs
  - DARPA program OFFSET
    - aimed at developing swarm tactics and adaptive high level control concepts with a focus set on small unmanned aircraft
  - AFRL Skyborg - Low cost attritable flight demonstration program
  - Boeing Airpower Teaming System
  - Other known developments in many countries

- In the field of small UAS, defense-oriented multi-drone systems which can be controlled in a centralized way have appeared on the market



(https://www.darpa.mil/program/offensive-swarm-enabled-tactics)

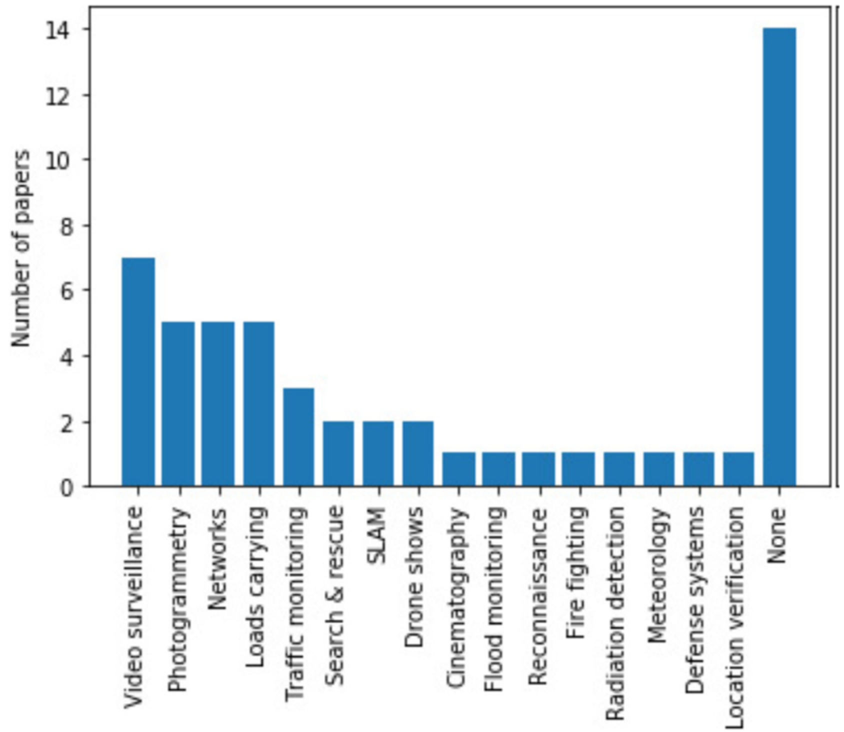
(https://uavcoach.com/teal-drones-4-ship/)

Civilian Applications

- Multi-drone systems and swarms offer great potential also in a variety of civilian scenarios

- Applications include
  - Precision agriculture
  - Cinematography
  - Civilian ISR
  - Mapping and infrastructure inspection
  - Package delivery
  - Joint load transportation
  - Communication networks
  - Search and rescue

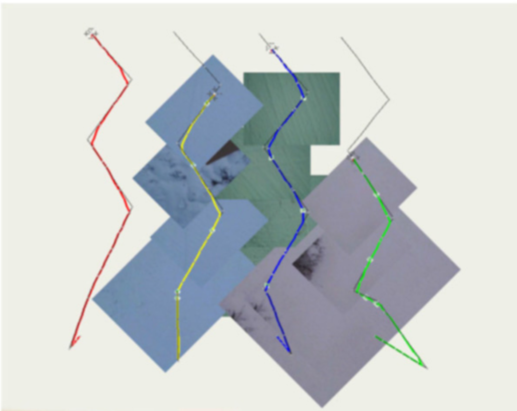
- Similar to military applications, key advantages are linked to
  - Scalability: e.g., coverage per unit time
  - Enhanced mission performance
    - Distributed sensing
    - GNC advantages, e.g. flight in challenging environments



G. Skorobogatov et al., Multiple UAV Systems: A Survey, Unmanned Systems, Vol. 8, No. 2 (2020) 149–169

Search and Rescue

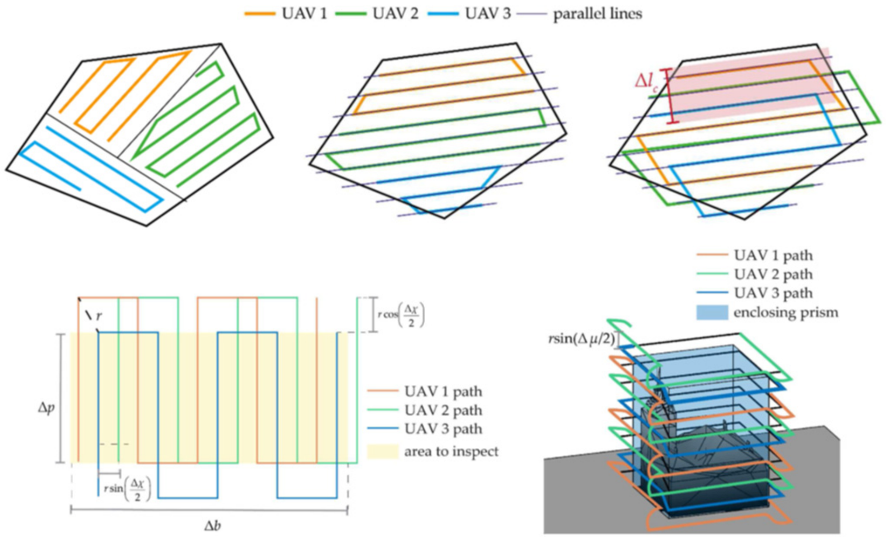
(https://eng.vt.edu/magazine/stories/fall-2021/drone-swarms.html)



(Scherer et al, An Autonomous Multi-UAV System for Search and Rescue, Proceedings of the First Workshop on Micro Aerial Vehicle Networks, Systems, and Applications for Civilian Use, 2015)

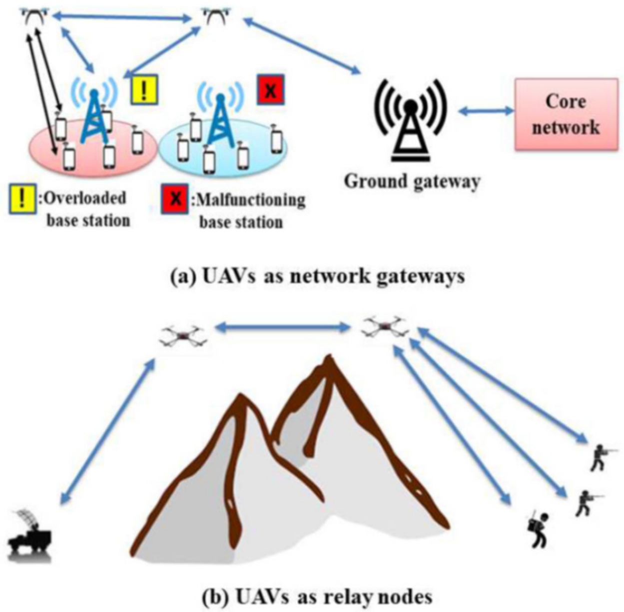
Mapping / Area monitoring

(Balampanis et al, Area Partition for Coastal Regions with Multiple UAS, JINT 2017)



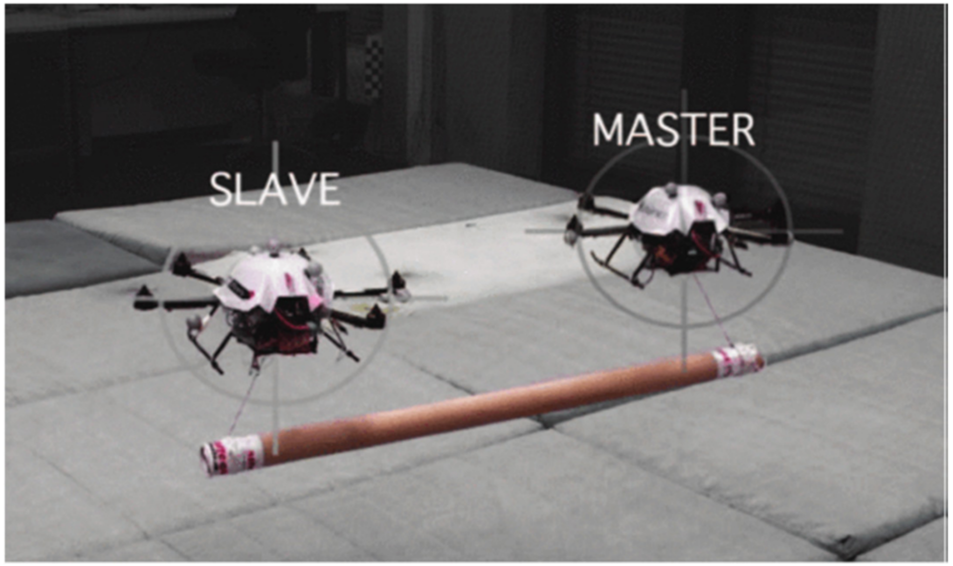
(Causa et al, Multi-Drone Cooperation for Improved LiDAR-Based Mapping, Sensors 2024)

Communication Networks



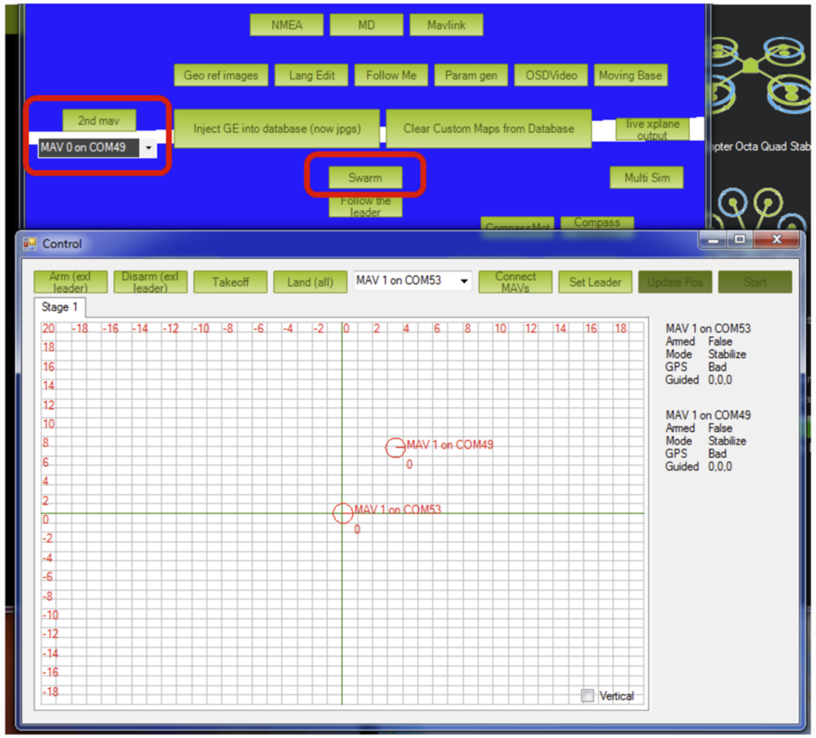
Shakhatreh, H., Sawalmeh, A. H., Al-Fuqaha, A., Dou, Z., Almaita, E., Khalil, I., Othman, N. S., Khreishah, A., and Guizani, M., "Unmanned Aerial Vehicles (UAVs): A Survey on Civil Applications and Key Research Challenges," *IEEE Access*, vol. 7, 2019, pp. 48572–48634

Joint Load Transportation



Tagliabue, A., Kamel, M., Verling, S., Siegwart, R., and Nieto, J., "Collaborative transportation using MAVs via passive force control," 2017 IEEE International Conference on Robotics and Automation (ICRA), 2017, pp. 5766-5773

- 1-to-N monitoring and control capabilities offered by open source GCS software tools (e.g. Mission Planner, Mavproxy)



https://ardupilot.org/planner/docs/swarming.html

- «Swarms» have appeared in the regulations (FAA, EASA) as centralized systems – operations requiring risk assessment
- Multi-drone operations with 1-to-N remote control paradigm are being authorized
- Link with BVLOS operations and their safety concepts and risk mitigation strategies
- Clear trend towards 1-to-N and M-to-N paradigm

FAA approves agri-drones for BVLOS, swarming and night flights

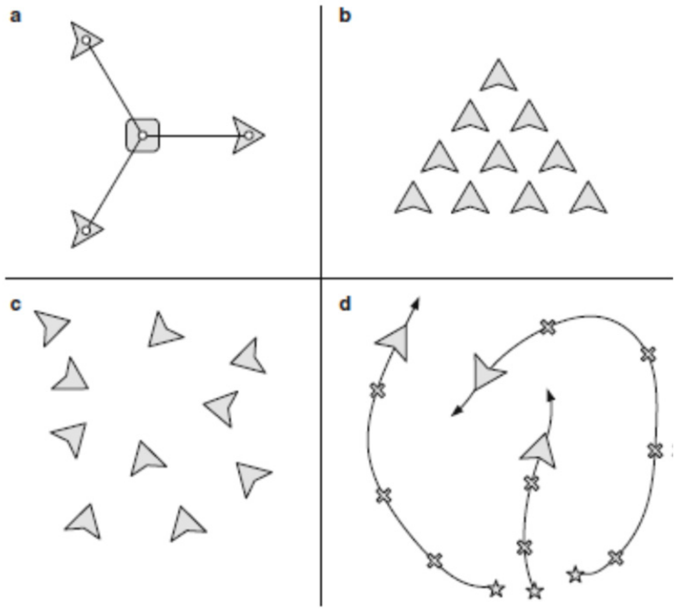
July 5, 2024 UAS traffic management news

https://www.unmannedairspace.info/latest-news-and-information/faa-approves-agri-drones-for-bvlos-swarming-and-night-flights/

FAA awards first approval for drone swarm testing

https://www.llnl.gov/article/51291/faa-awards-first-approval-drone-swarm-testing

- Maza et al. (2015) proposed a classification as follows:
  - *Physical coupling*. In this case, the UAVs are connected by physical links and then their motions are constrained by forces that depend on the motion of other UAVs.
  - *Formations*. The vehicles are not physically coupled, but their relative motions are strongly constrained to keep the formation.
  - *Swarms*. They are homogeneous teams of many vehicles which interactions generate emerging collective behaviors.
  - *Intentional cooperation*. The UAVs of the team move according to trajectories defined by individual tasks that should be allocated to perform a global mission



(I. Maza et al, Classification of Multi-UAV Architectures, Handbook of Unmanned Aerial Vehicles, 2015)

- Other more recent approaches focus on the number of UAVs (e.g., teams, formations or swarms)
- or consider different classifications logics based on various aspects

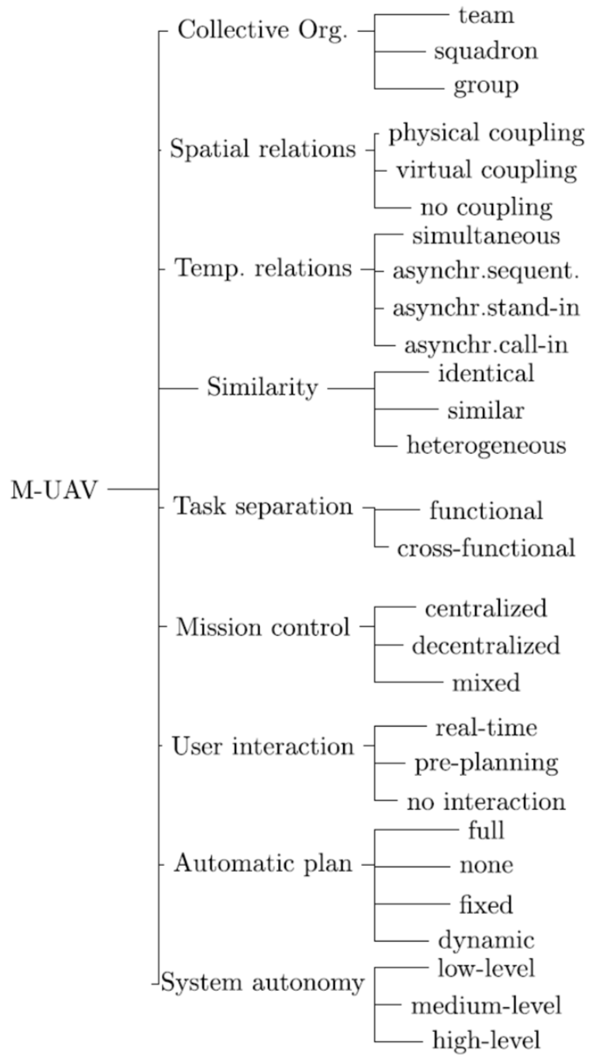
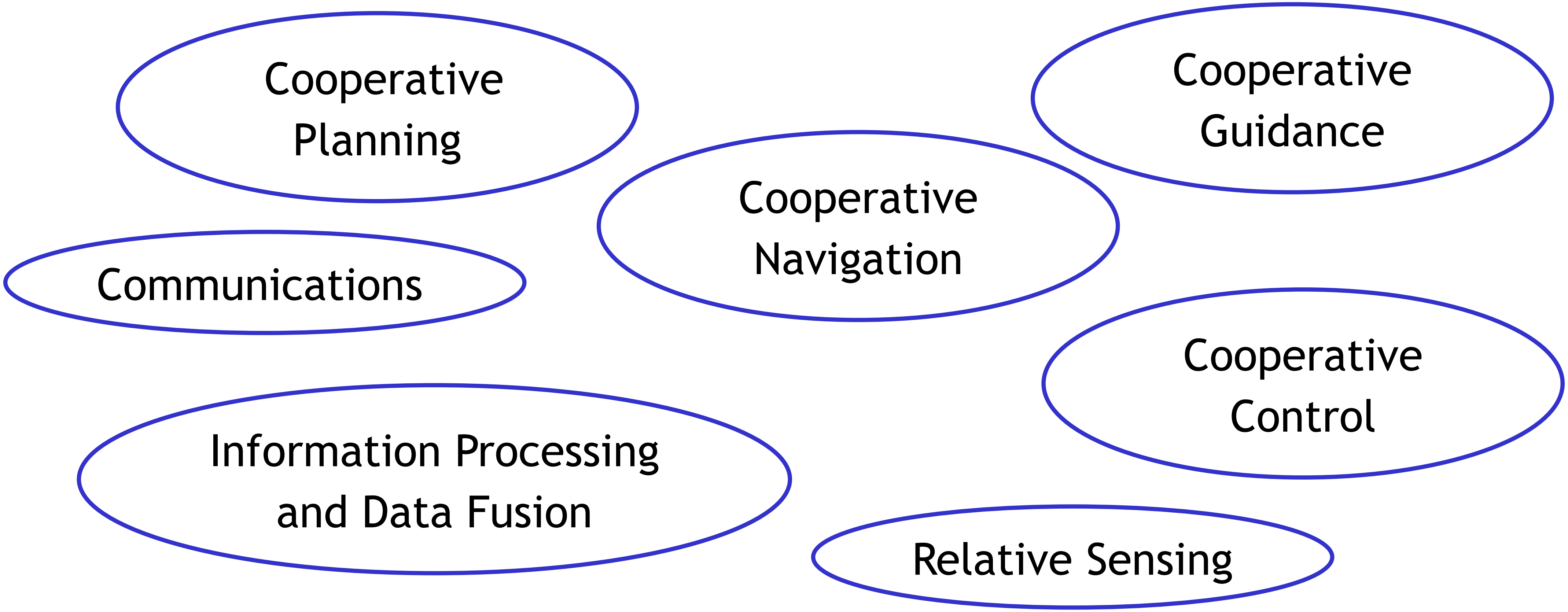


Fig. 3. Proposed taxonomy for multiple UAV systems.

(G. Skorobogatov et al., Multiple UAV Systems: A Survey, Unmanned Systems, Vol. 8, No. 2 (2020) 149–169)

Key elements for multi-drone systems

- Several areas are involved in the design and operation of multi-drone systems
- Different applications may be mapped towards these areas, involving some of them and/or their interaction



Multi-drone Research @ UniNa

- Cooperative planning, guidance, and navigation to overcome single vehicle limits in small UAS / low altitude applications

- Focus on outdoor missions

- Integrated approach, several (interconnected) research paths:
  - Cooperative navigation: potential linked with redundancy, spatial diversity, information sharing
    - Improvement of navigation performance under GNSS coverage
      - Attitude
      - Inertial biases
      - Magnetic biases
    - Improvement of navigation performance in GNSS challenging environments
    - Integrity augmentation
    - Scalable decentralized cooperative navigation
  - Cooperative guidance
  - Relative sensing
  - Multi-drone path planning
    - Heterogeneous mission environments
    - Routing and task assignment for homogeneous / heterogeneous fleets

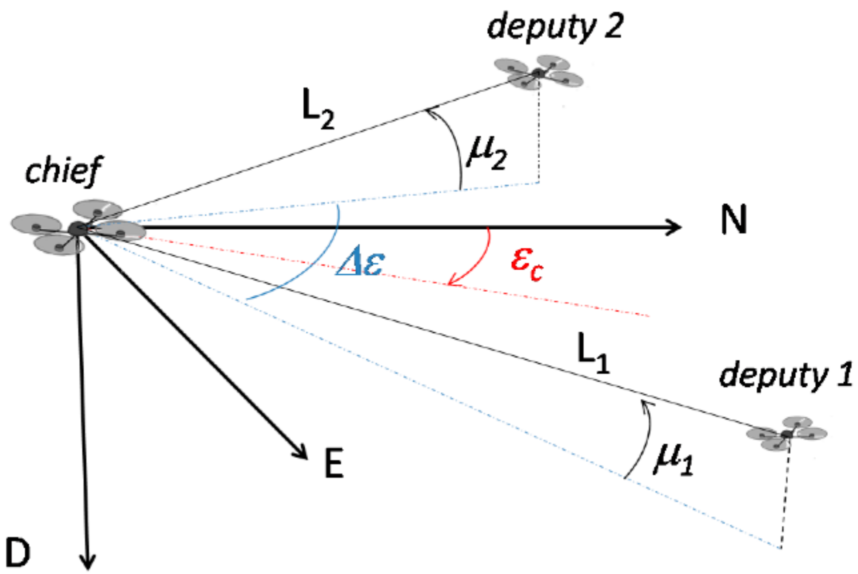
- Research directions

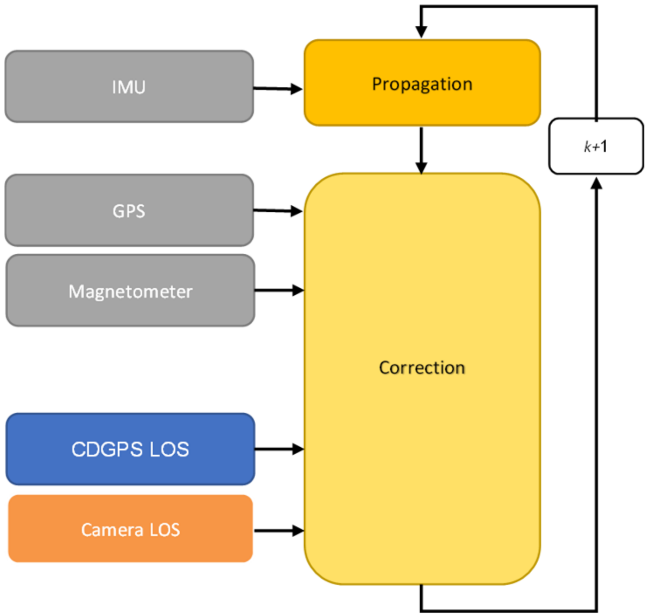
IDEA: Define a more accurate attitude of a «chief» UAV measuring the Line of Sight w.r.t. «deputies»

- In CRF → BRF with camera(s) and visual tracking algorithms
- In NED with GNSS measurements -(C)DGNSS baseline

Extends the GNSS multi-antenna concept to a multi-vehicle scenario

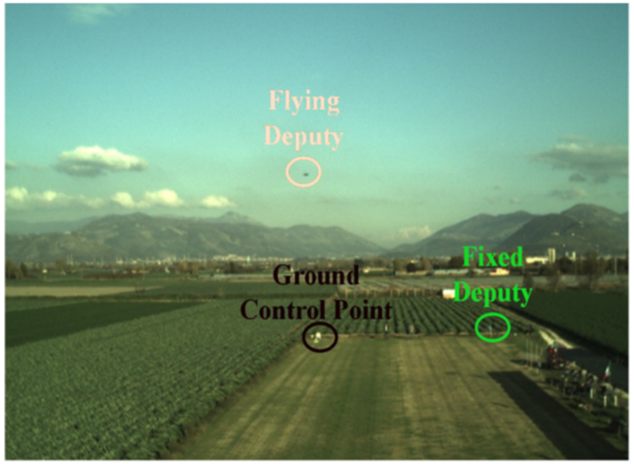
Example applications: geolocation, sensor fusion of data from multiple drones, 3D reconstruction

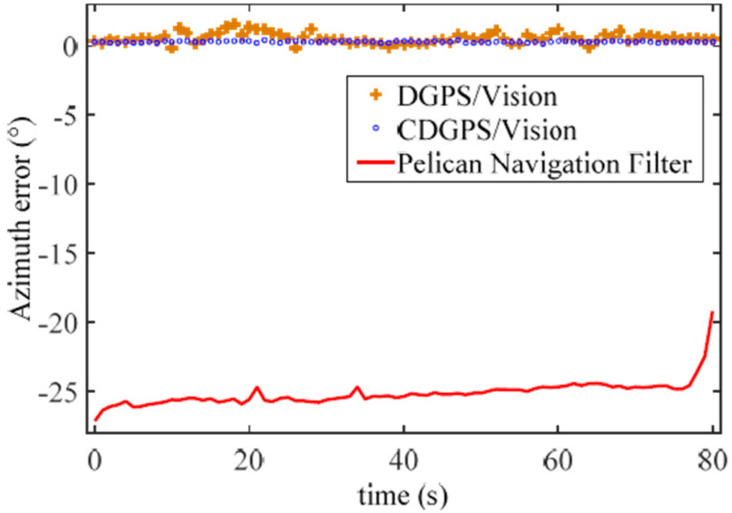




(Vetrella et al, Multi-UAV Carrier Phase Differential GPS and Vision-based Sensing for High Accuracy Attitude Estimation, 2018, Journal of Intelligent and Robotic Systems: Theory and Applications)

Performance: mapping-level attitude knowledge with COTS avionics

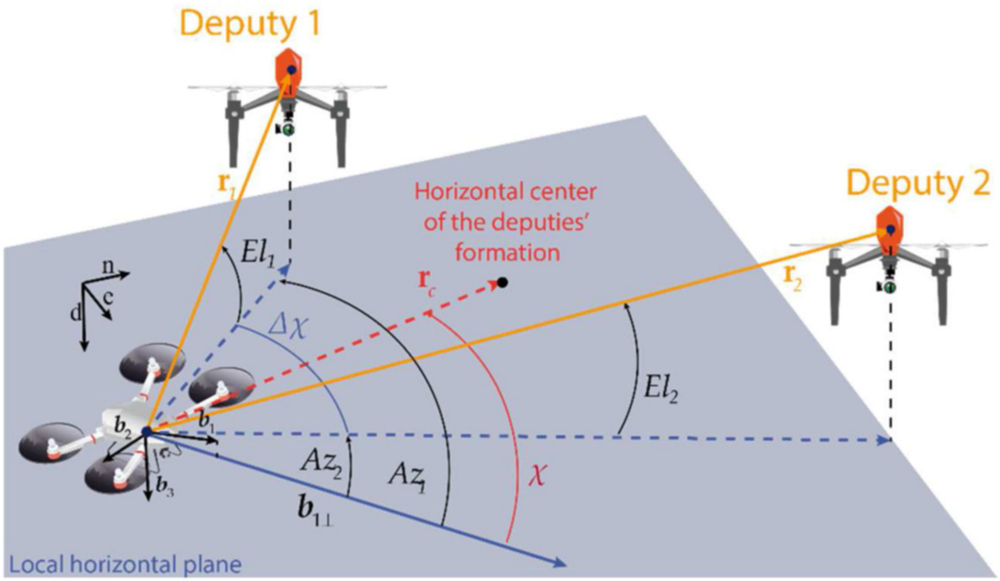


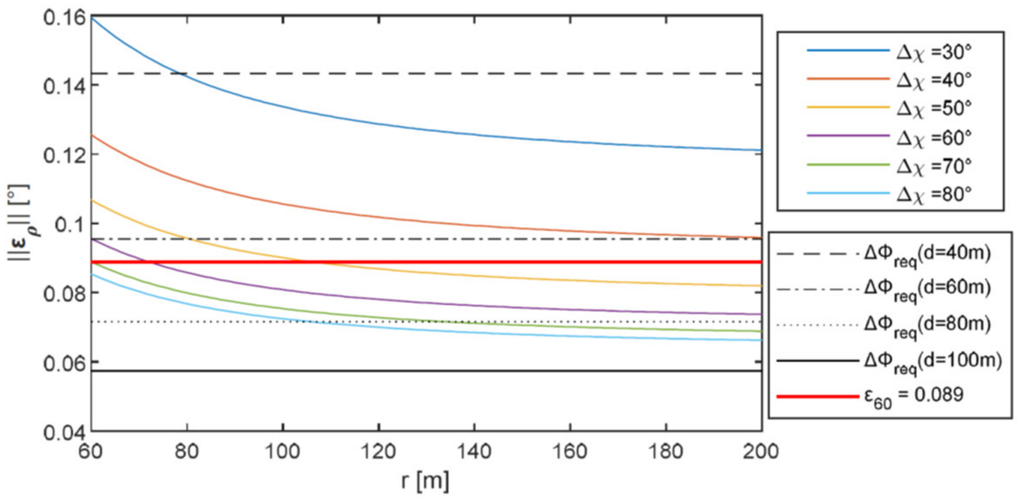


(Vetrella et al, Attitude estimation for cooperating UAVs based on tight integration of GNSS and vision measurements, 2019, Aerospace Science and Technology)

- Attitude error uncertainty can be predicted by analytical tools

- Increasing range to deputies and angular distance between them enables more accurate attitude estimation (trade-off with relative sensing challenges)

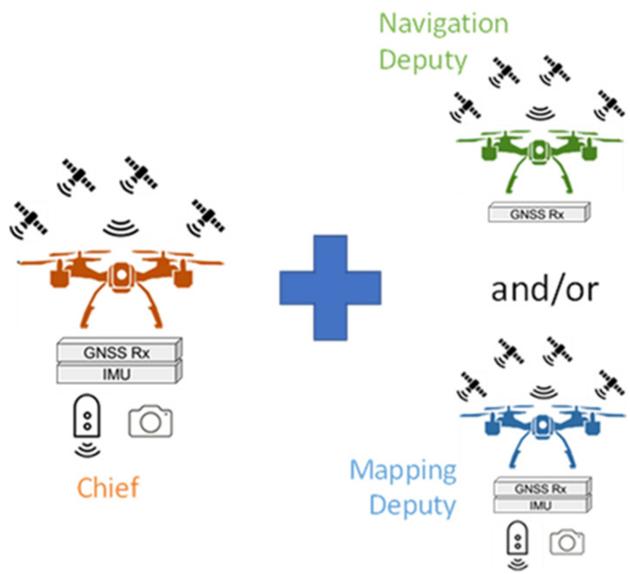


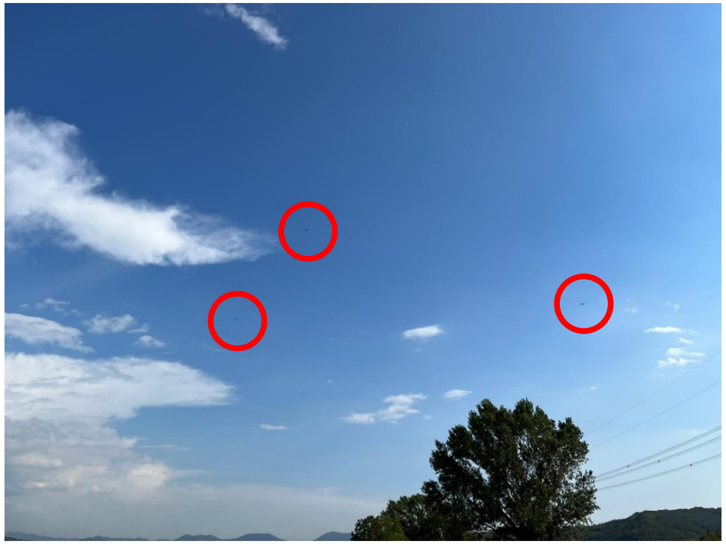


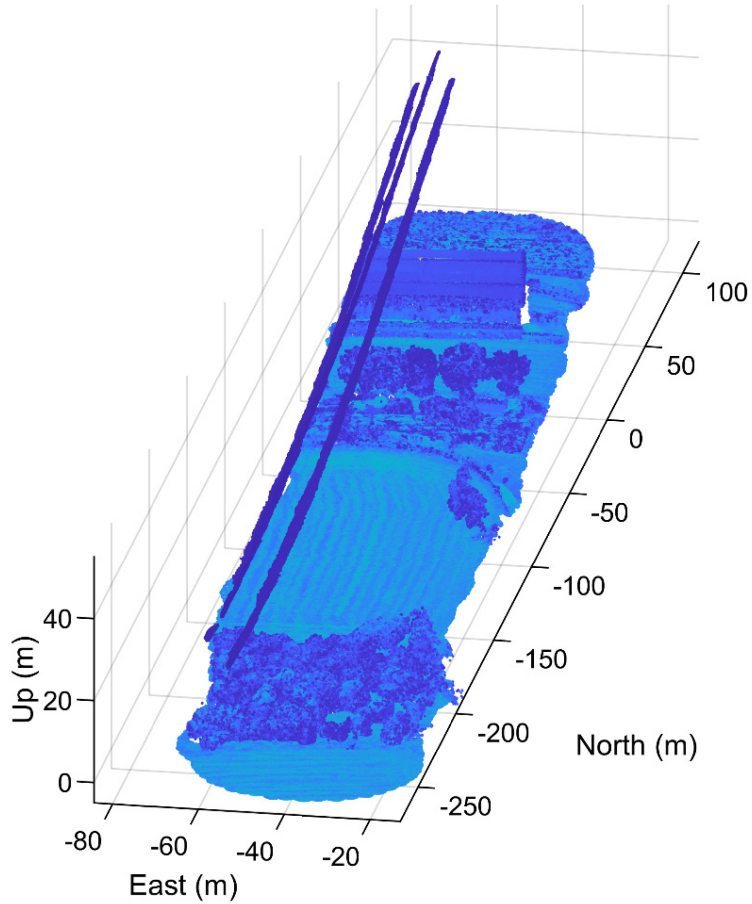
(Causa, F.; Opromolla, R.; Fasano, G. Multi-Drone Cooperation for Improved LiDAR-Based Mapping. Sensors 2024)

Recent developments

- Concept exploitation for Lidar-optical based powerline mapping
- AMPERE - Asset Mapping Platform for Emerging Countries Electrification (2020-2022) – funded by EUSPA (EU Agency for Space Programme - Horizon 2020 Programme)
- Cloud-based platform for electrical asset mapping and inspections, powered by field data acquired with small UAS
- Follow-on activities carried out within the national 4IPLAY project





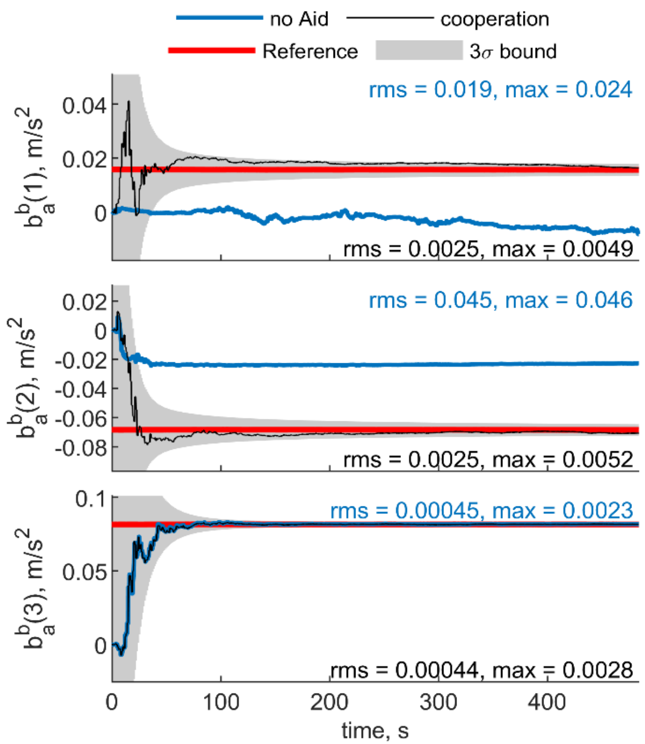


(Causa et al., Cooperation-Aided Accurate UAV-Based LiDAR Mapping: Experimental Assessment, ICUAS 2024)

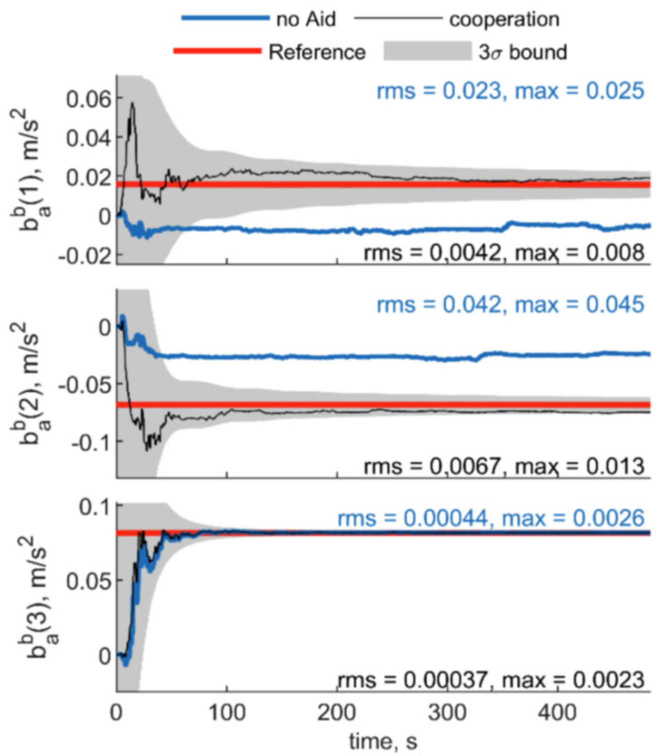
Cooperative navigation: inertial biases

- Cooperative navigation provides accurate and inertial/magnetic-independent attitude information → Potential for improved in-flight estimation of inertial sensors biases
- The concept has been demonstrated in simulations and flight experiments
- Single deputy architectures may tackle observability challenges by changing the relative geometry and thus providing spatial diversity to the measurements

Simulation results



Two deputies



Single deputy with geometry variation

(Causa and Fasano, Improved in-flight estimation of inertial biases through cdgnss/vision based cooperative navigation, Sensors 2021)

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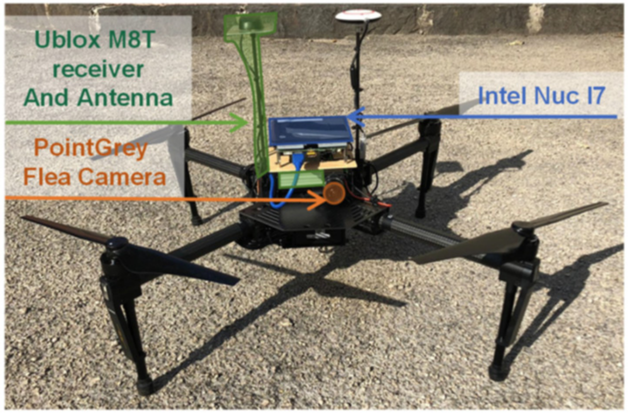
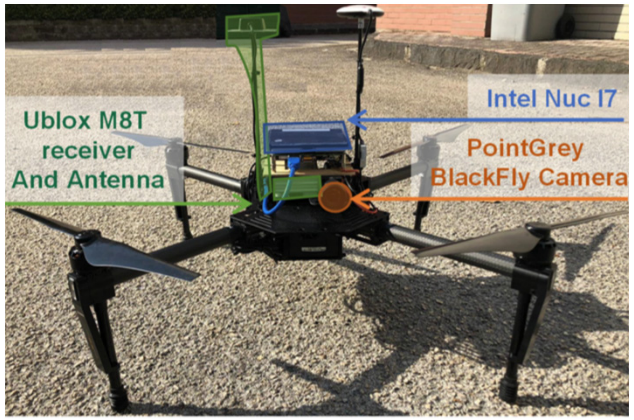
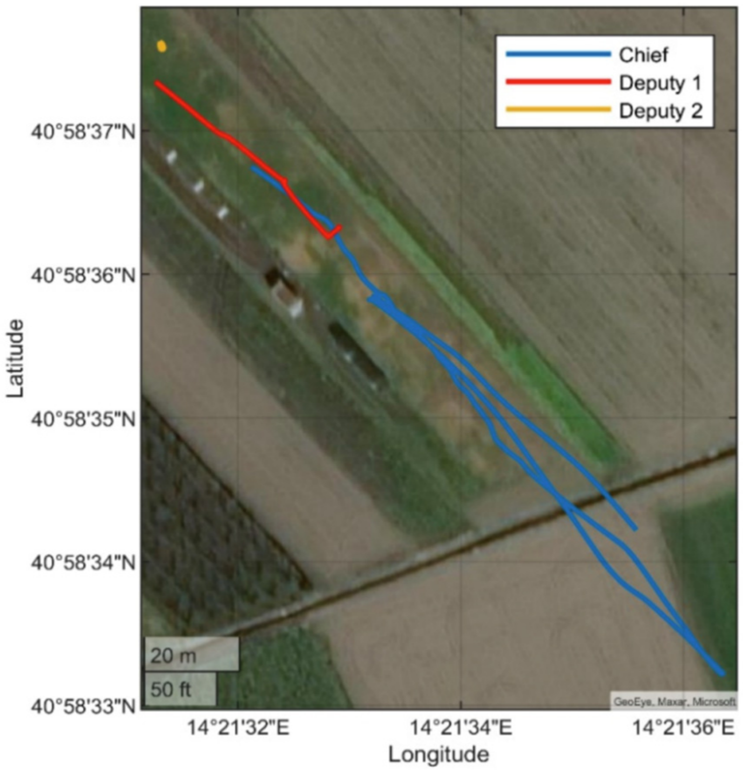
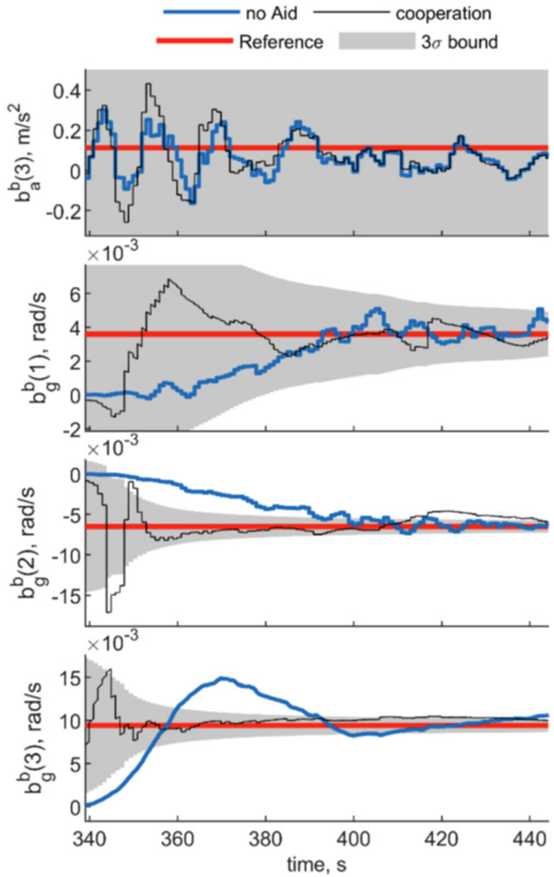




Flight results

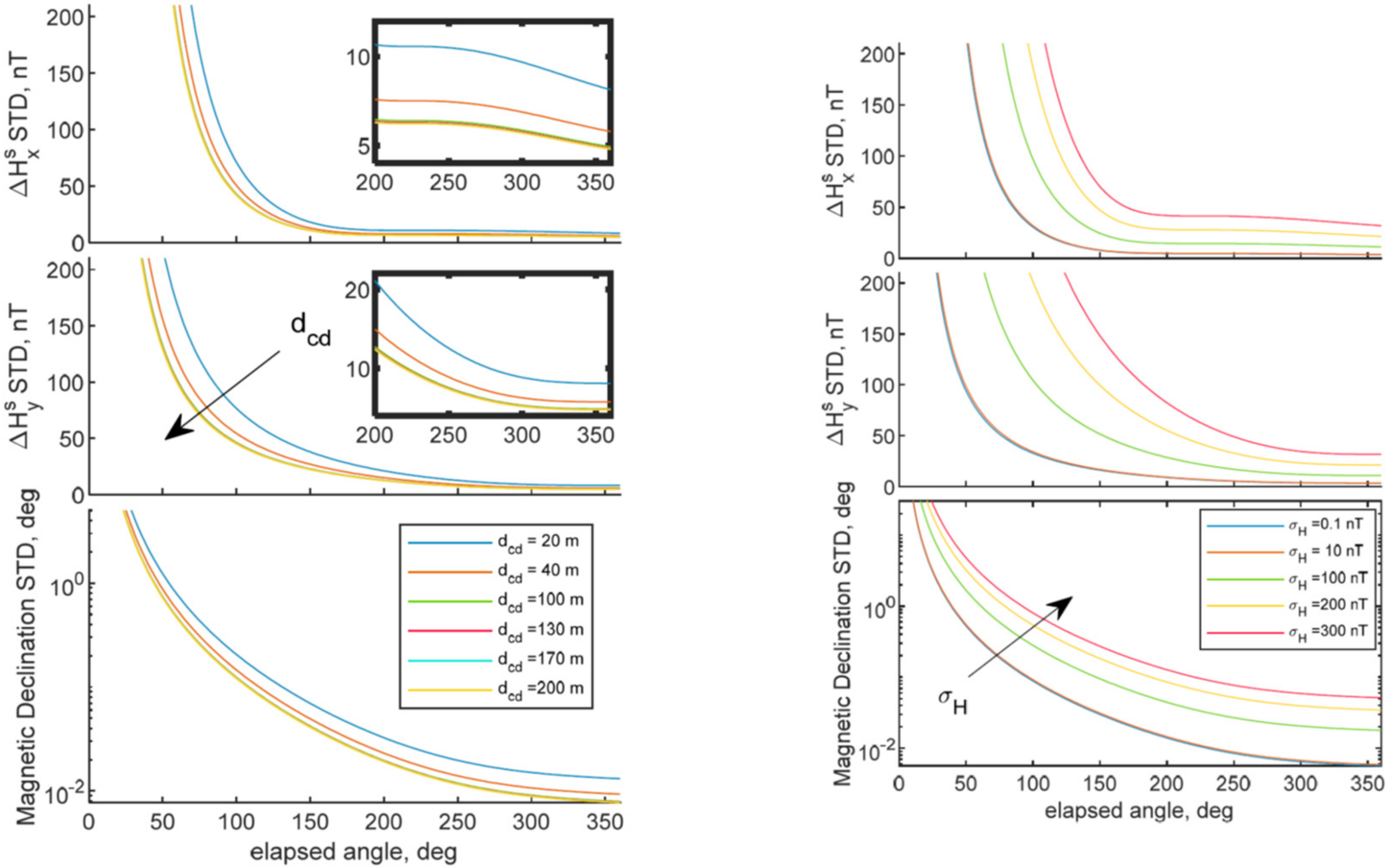




(Causa and Fasano, Improved in-flight estimation of inertial biases through cdgnss/vision based cooperative navigation, Sensors 2021)

- Cooperative navigation may provide magnetic-independent accurate heading estimate → integrated external/onboard magnetic biases evaluation

- The concept has been demonstrated in simulations and flight experiments



(Vitiello et al, Onboard and external magnetic bias estimation for uas through cdgnss/visual cooperative navigation, Sensors 2021)

Cooperative navigation: magnetic biases

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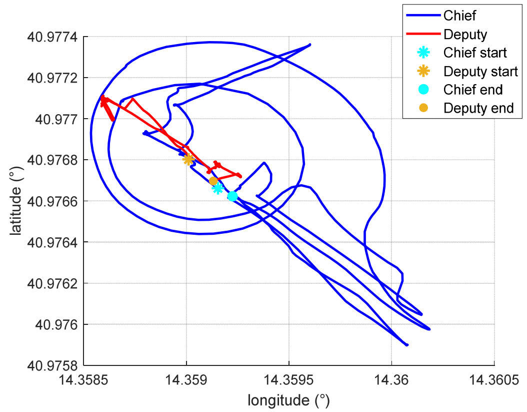
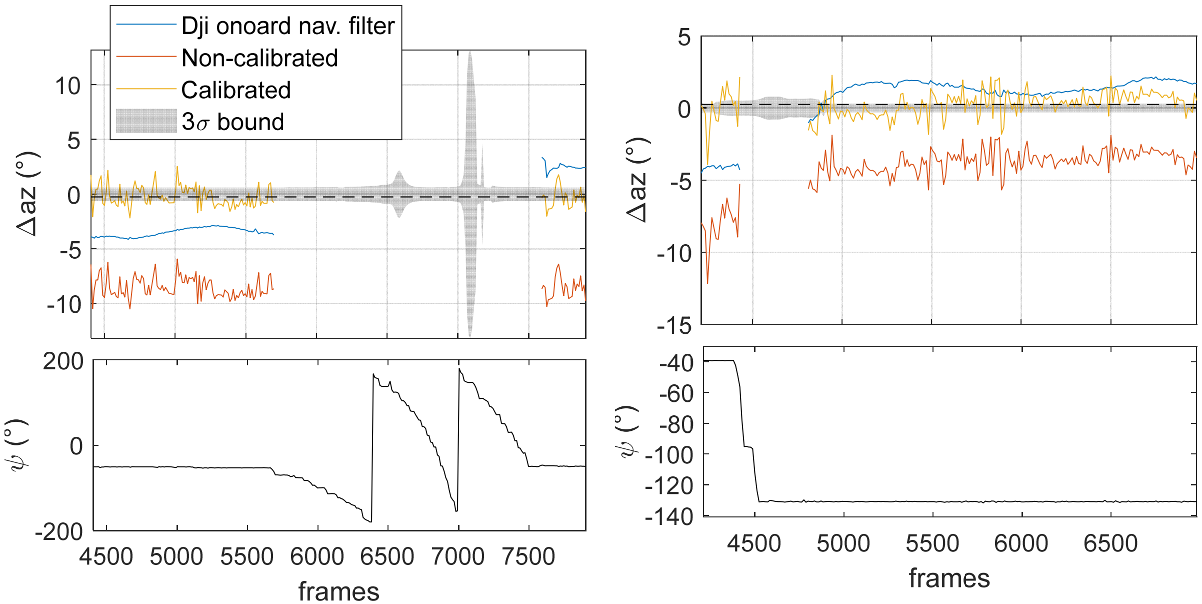
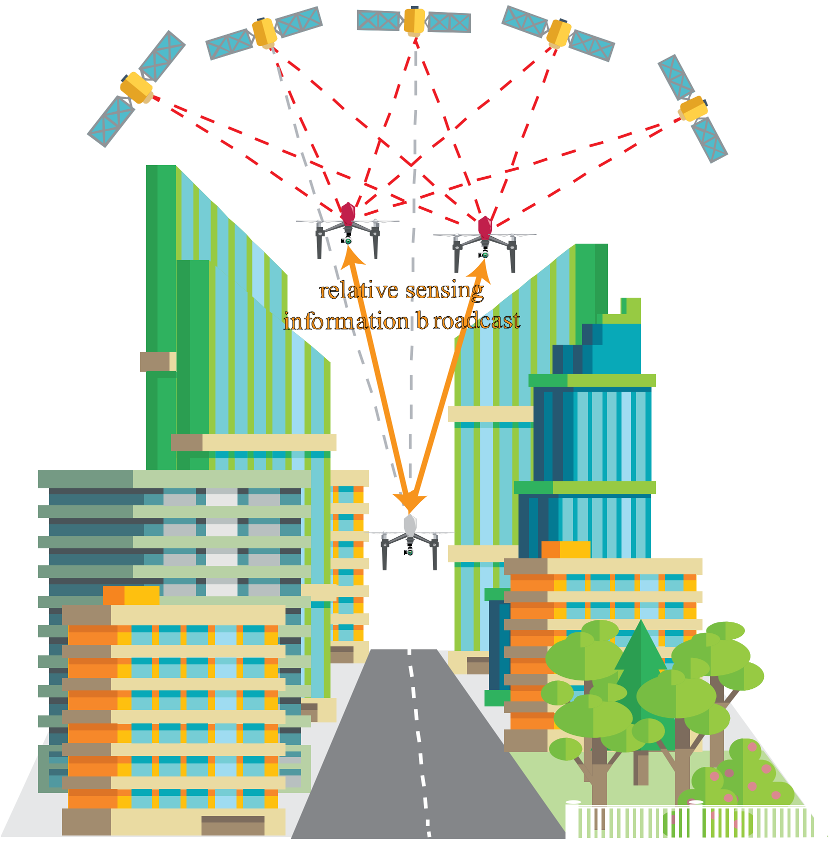




(Vitiello et al, Onboard and external magnetic bias estimation for uas through cdgnss/visual cooperative navigation, Sensors 2021)

Cooperative Navigation in GNSS-challenging environments

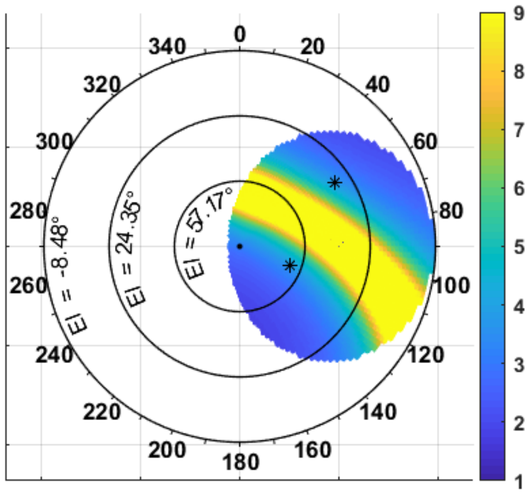
- Many applications require the unmanned aircraft to fly in GNSS challenging environments, at least in a part of the mission
- Navigation issues (no fix or bad dilution of precision conditions) affect flight autonomy
- Additional aiding information needed



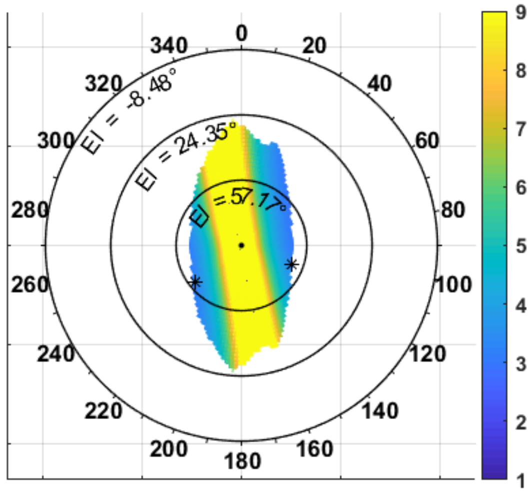
- **Approach:** exploit cooperation with one or more UAVs under "good" satellite coverage: father(s)/son scheme
  - Son UAV – inside the challenging area – low satellite number / high DOP (obstructed signal)
  - Father UAV is outside the challenging area and has a reliable estimate of its position with a GNSS/INS filter – becomes an additional source of information

Cooperative Navigation in GNSS-challenging environments

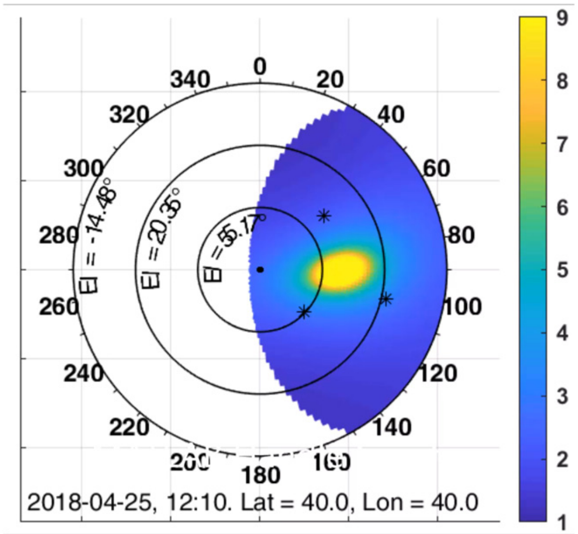
- Cooperation performance depends on
  - relative flight geometry
  - GNSS constellation(s) and 3d scenario geometry
  - Adopted sensors and processing strategies (RF ranging, camera)
- **generalized Dilution Of Precision** (geDOP) concept introduced to predict navigation performance of the Son and thus support planning/guidance
- It extends the GNSS-based DOP concept to multi-drone architectures exploiting cooperative navigation

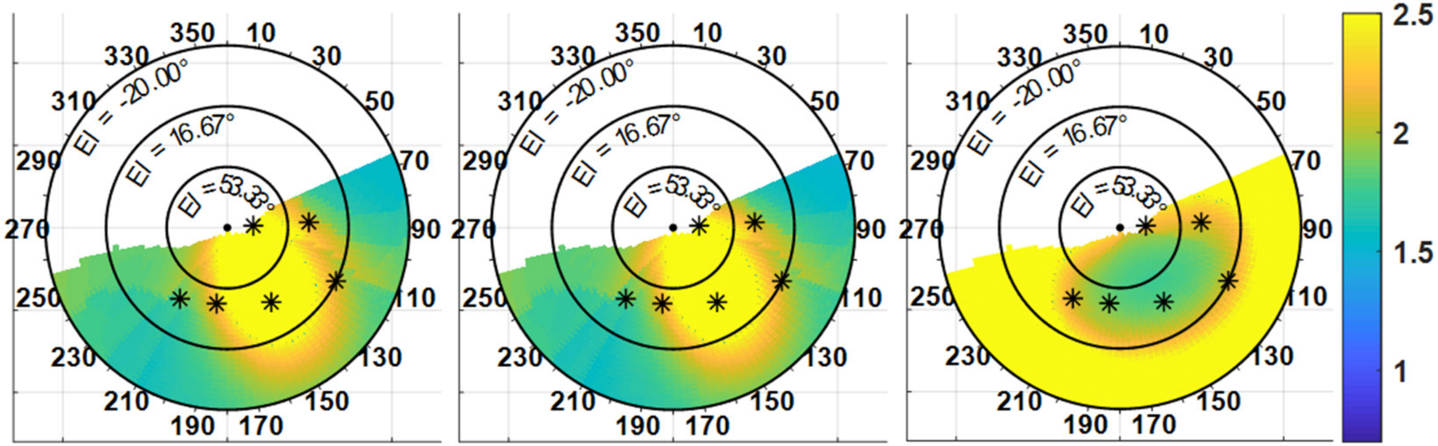


Building on the left



Canyon





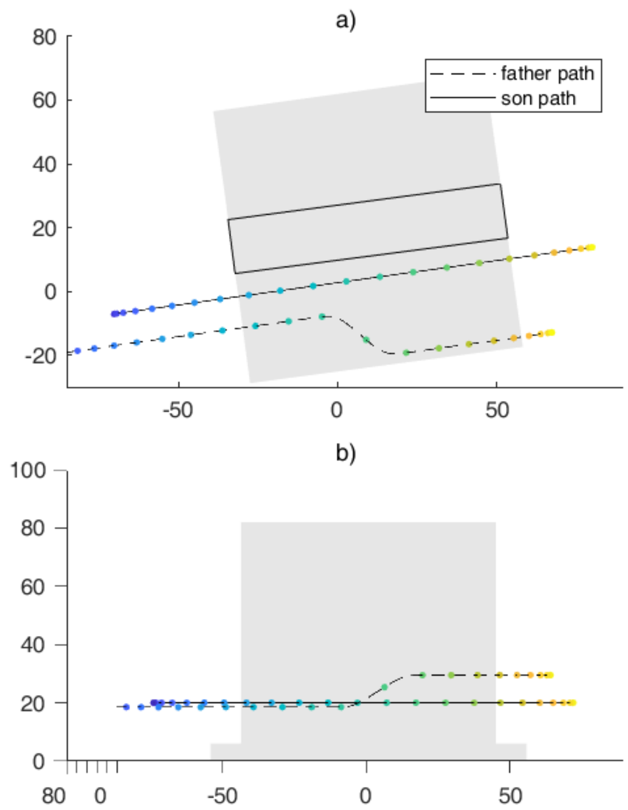
a) b) c)

Son to Father visual tracking | Father to Son visual tracking | RF ranging

(Causa and Fasano, Improving Navigation in GNSS-challenging Environments: Multi-UAS Cooperation and Generalized Dilution of Precision, 2020, IEEE Transactions on Aerospace and Electronic Systems)

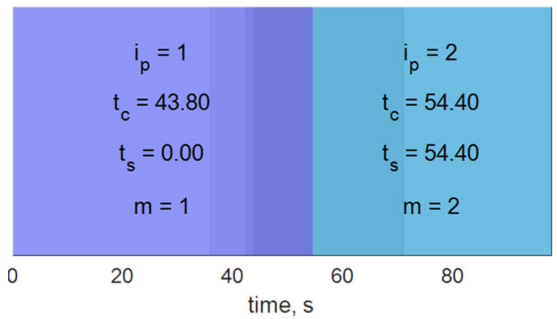
Cooperative Navigation in GNSS challenging environments

- Path planning technique of the father in a tandem formation been developed using geDOP

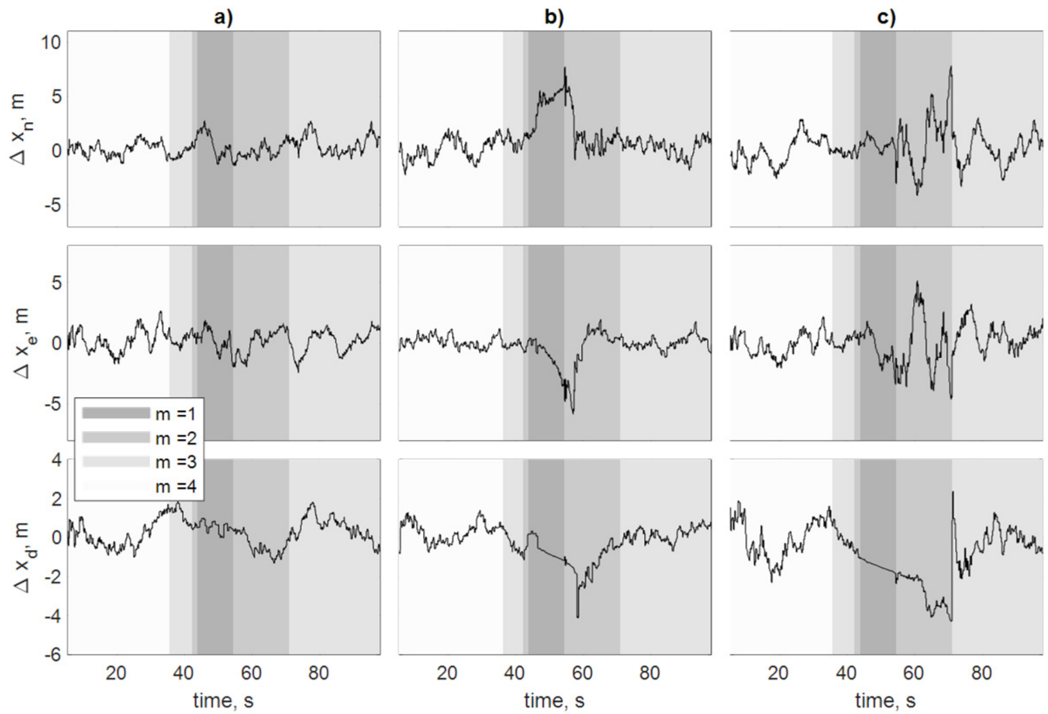


(Causa et al., Navigation aware planning for tandem UAV missions in GNSS challenging environments, AIAA Scitech 2019)

ETH Zürich
Autonomous Systems Lab



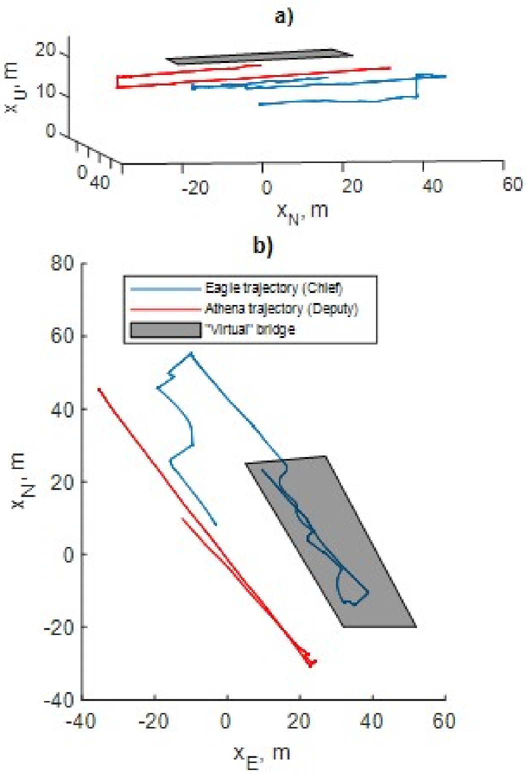
Parameter	i_p=1	i_p=2
Az_p	-124.59 °	-154.67°
El_p	-3.91 °	17.64°
r_p	22.20	31.18
$\lVert \breve{D} \rVert$	1.73	1.12

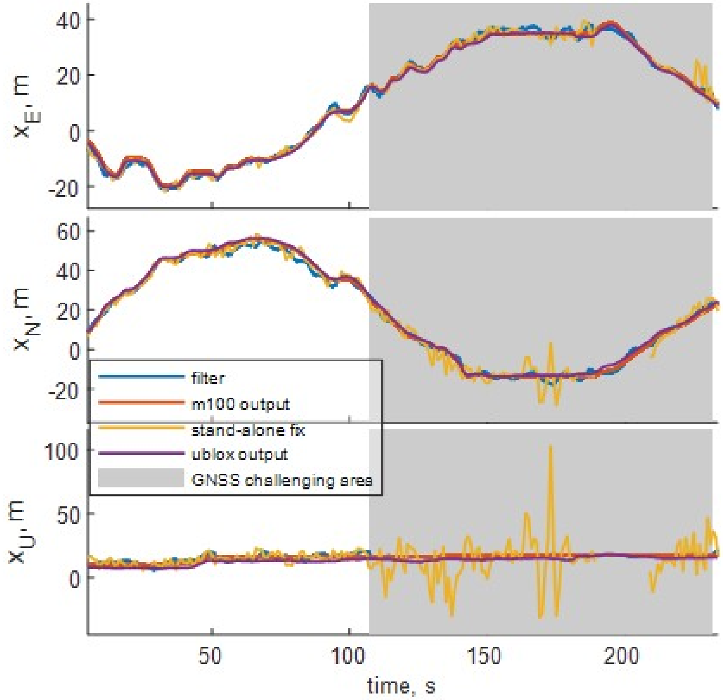


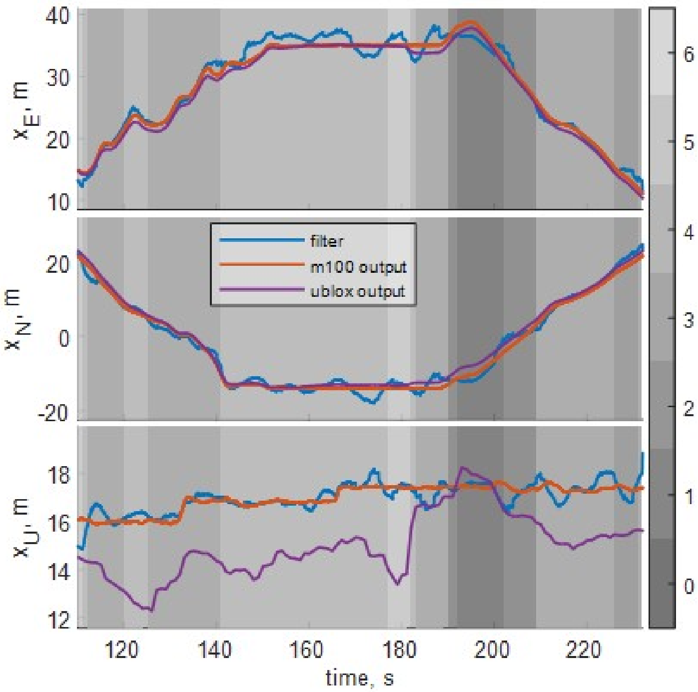
Error in son's navigation State

Cooperative Navigation in GNSS challenging environments

- «Hybrid» experiments (virtual 3d environment simulated to remove satellites)
- Bounded meter-level error in absence of reliable GNSS coverage, son-to-father visual tracking



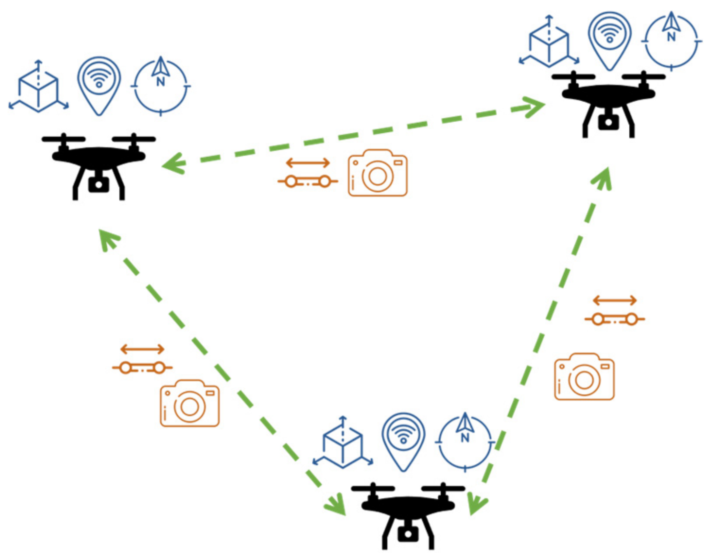




(Causa and Fasano, Improving Navigation in GNSS-challenging Environments: Multi-UAS Cooperation and Generalized Dilution of Precision, 2020, IEEE Transactions on Aerospace and Electronic Systems)

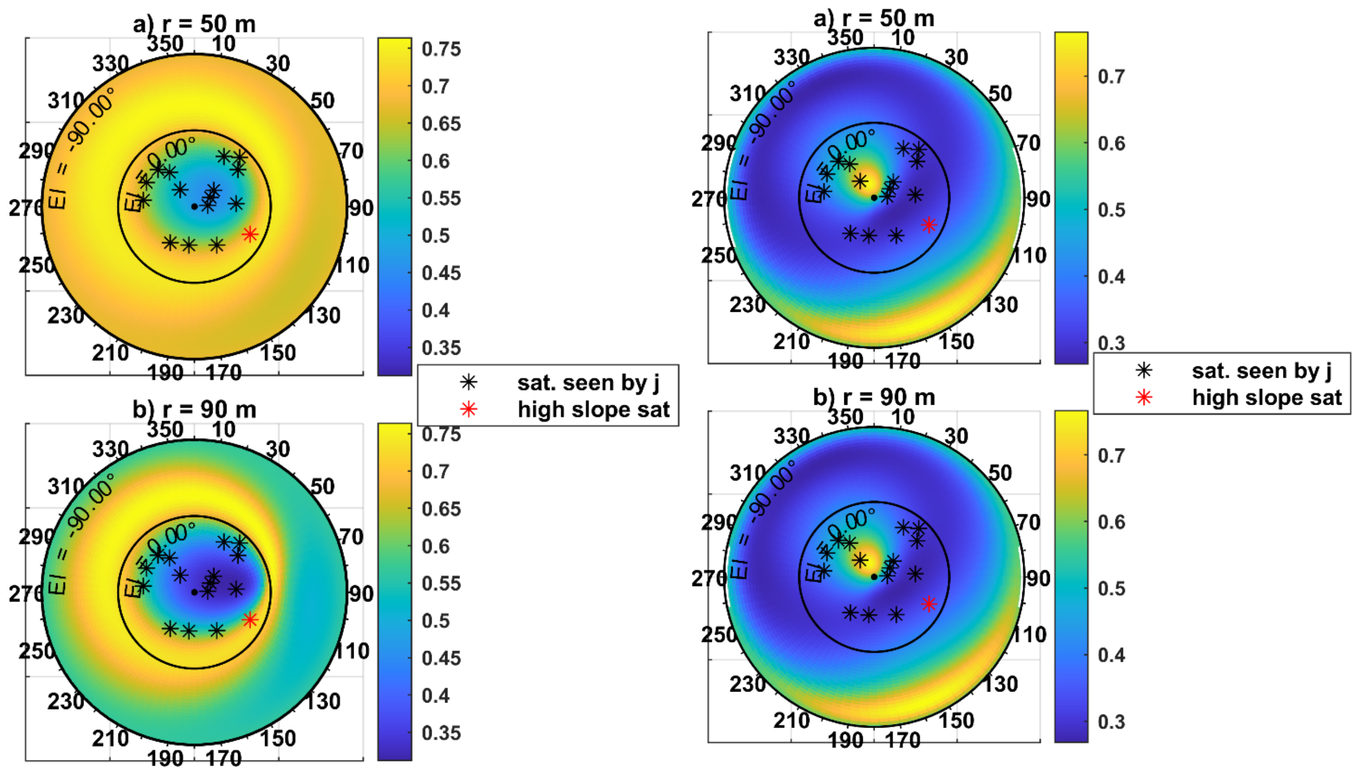
Cooperative navigation for integrity

- Idea: use information redundancy and spatial diversity to enhance protection against spoofing and multipath
- All the aircraft communicate to each other and exploit relative sensing (range and angles)
- Definition of a (satellite-dependant) metric to select the best formation geometry named **C-Slope**
  - Extends the "Slope" concept used in single vehicle navigation
  - Can be considered as the inverse of sensitivity/observability – low slope/C-slope values imply enhanced fault detection and exclusion capabilities
  - Cooperation reduces Slope – reduced vulnerability
  - System can be designed aiming to reduce max Slope values



Vehicle 1 C-slope: GPS + Glonass/ Two Vehicles formation

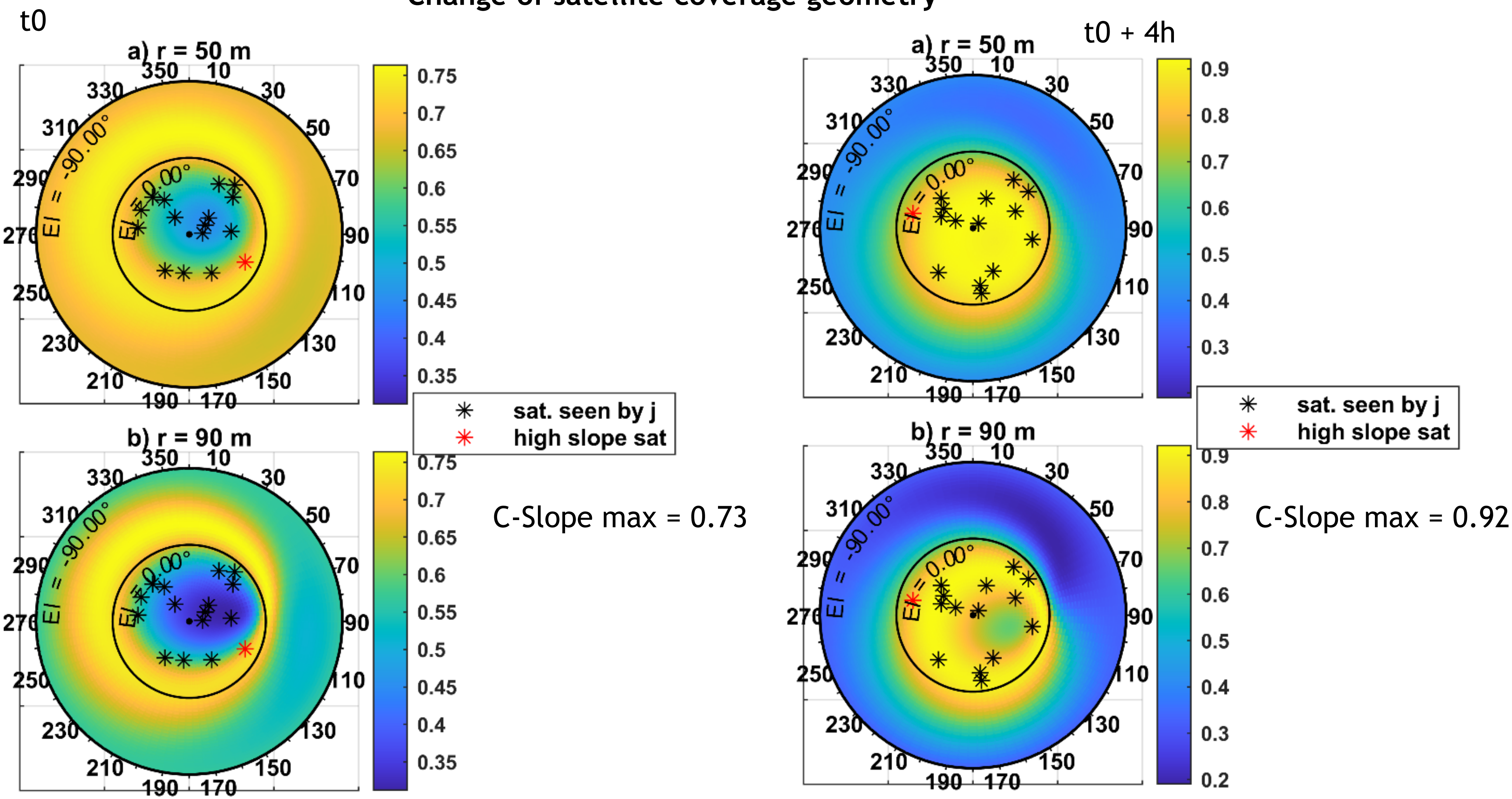
Ranging | Camera



(Causa and Fasano, Multi-drone cooperation to improve navigation integrity in low altitude urban environments, 2023 IEEE/ION PLANS)

Vehicle 1 C-slope: GPS + Glonass/ Two Vehicles formation – **Ranging Instrument**

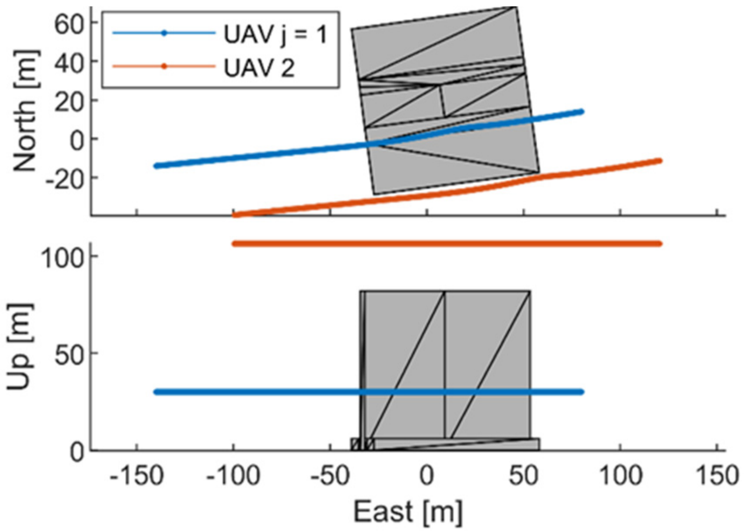
Change of satellite coverage geometry

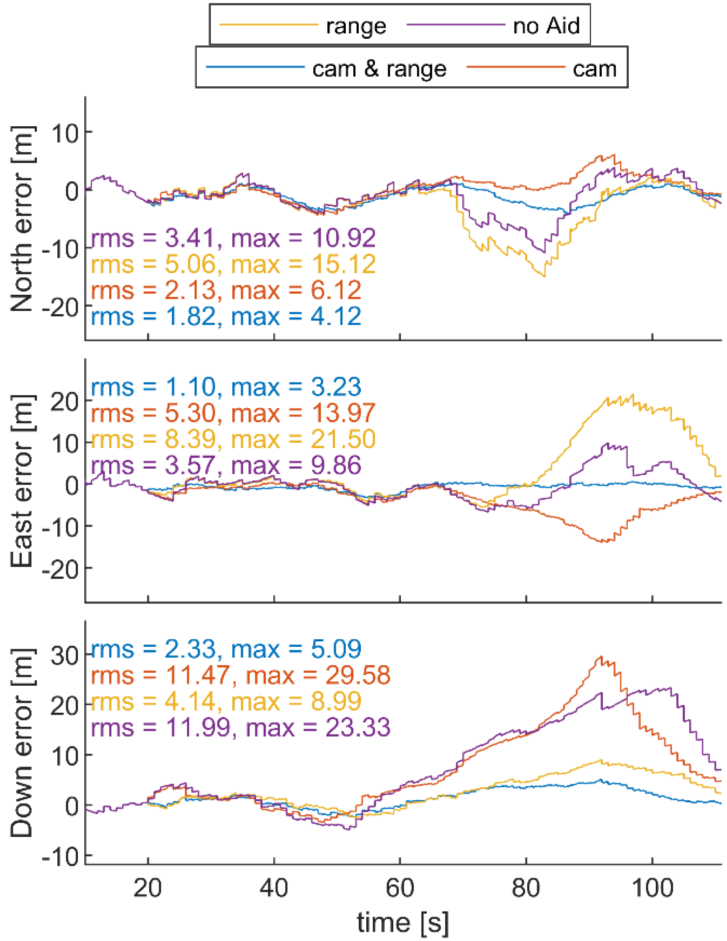


(Causa and Fasano, Multi-drone cooperation to improve navigation integrity in low altitude urban environments, 2023 IEEE/ION PLANS)

- Promising simulation results, to be validated in flight in real operational environments

Simulated performance with multipath

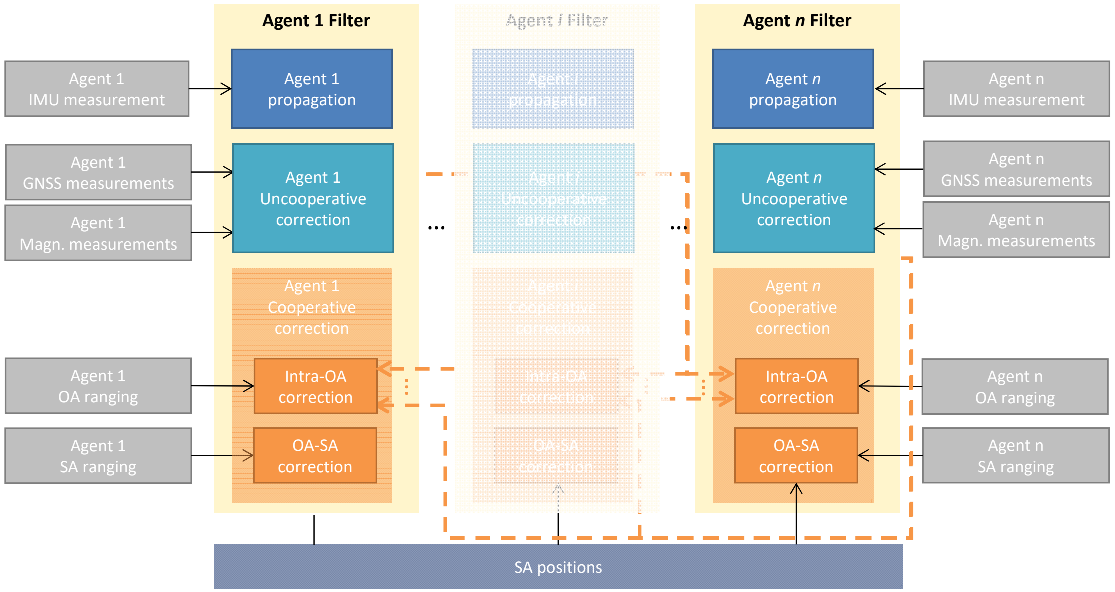


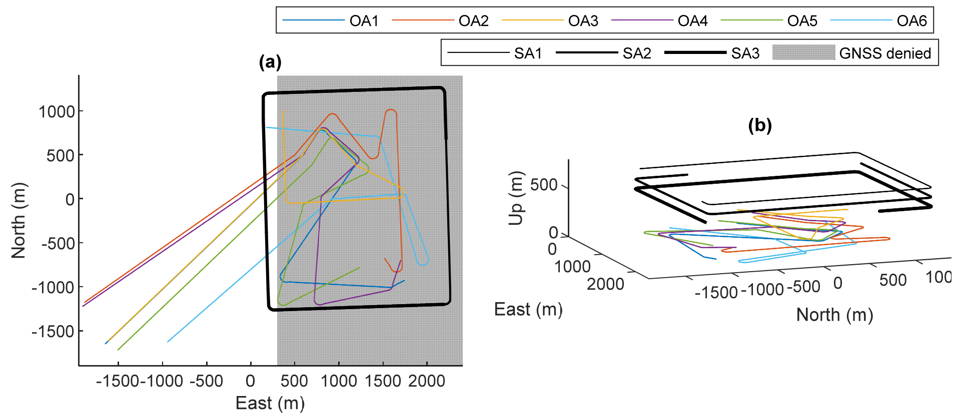


(Causa and Fasano, Multi-drone cooperation to improve navigation integrity in low altitude urban environments, 2023 IEEE/ION PLANS)

Decentralized cooperative navigation

- Research interest in cooperative navigation approaches which are
  - Scalable with respect to the number of aircraft and their operating conditions
  - Adaptive with respect to communication conditions
  - Redundant and resilient w.r.t. failures
- Decentralized approaches have been explored and customized
  - Operating and Supporting Agents
- Promising performance to be verified in flight experiments

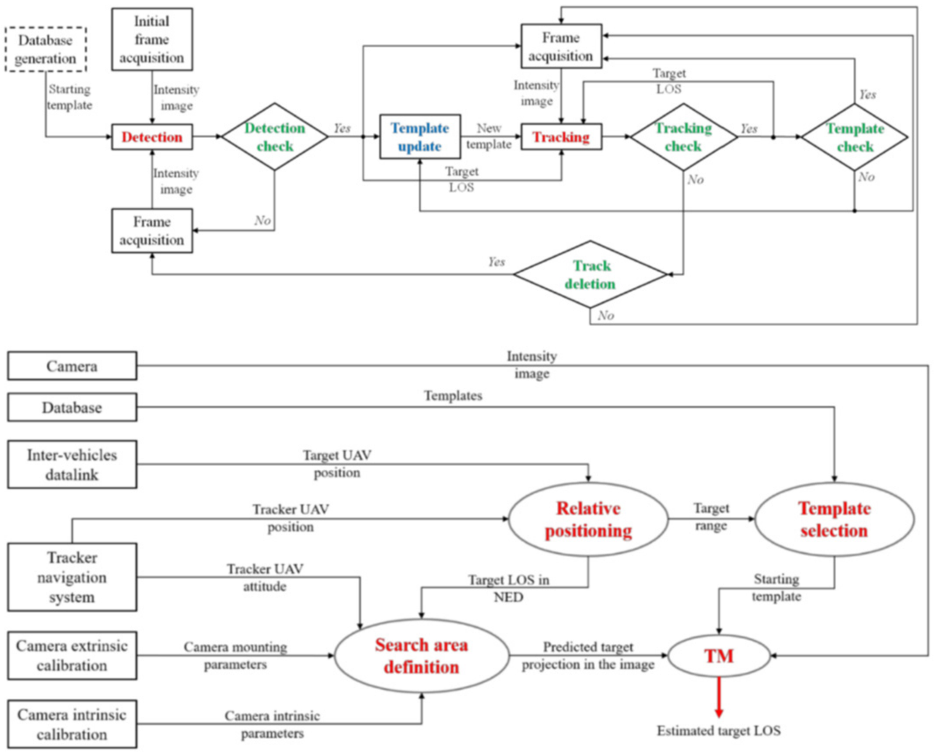




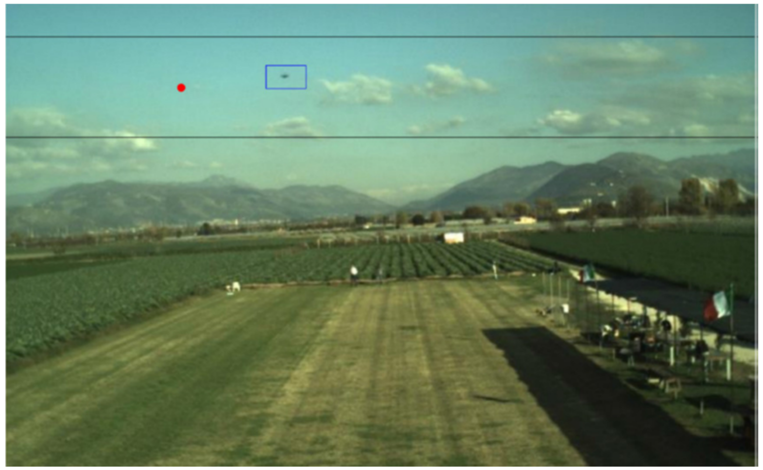
(Causa et al, Decentralized cooperative navigation solution for a swarm of UAVs operating in GNSS degraded environment, AIAA Scitech 2024)

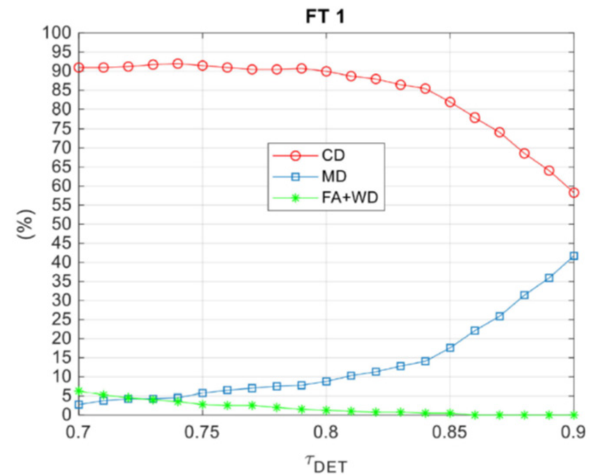
Relative Sensing: drone-to-drone visual tracking

- Relative sensing (and communications) as key elements for cooperation
- Visual tracking exploiting conventional techniques and/or AI, and sensor fusion with navigation sensors
- First visual tracking implementations using adaptive template matching and morphological filtering



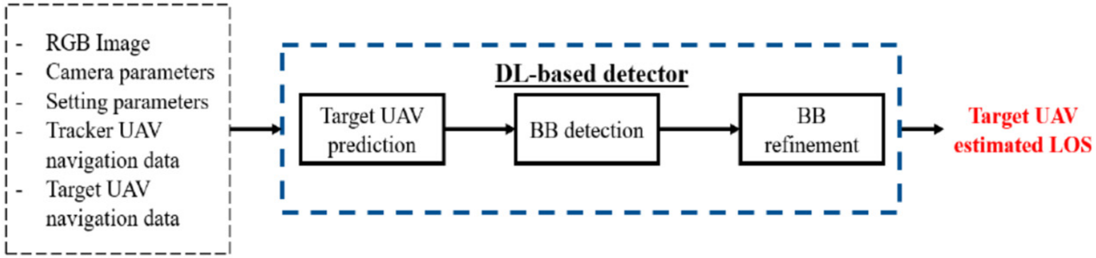
(Opromolla et al., A vision-based approach to uav detection and tracking in cooperative applications , Sensors 2018)

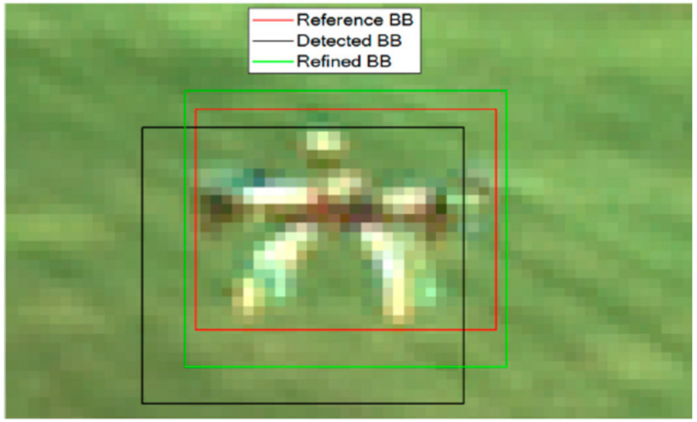




Relative Sensing: drone-to-drone visual tracking

- Then, deep learning-based detection concepts augmented with bounding box refinement have been selected
- Again, detection/tracking architecture also exploits navigation sensors measurements

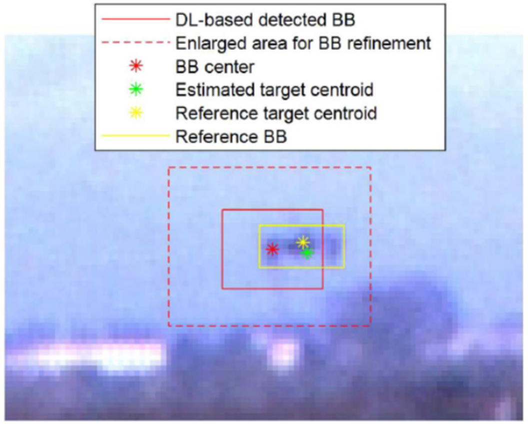


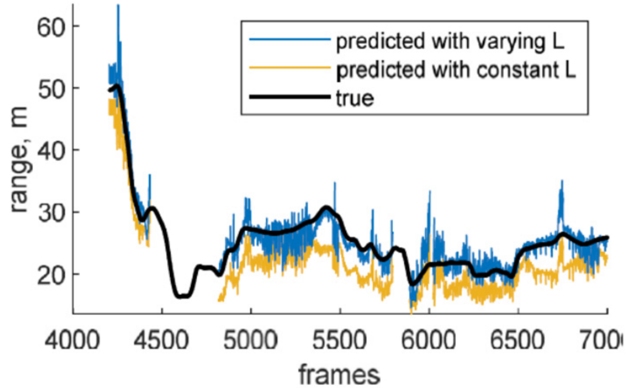


(Opromolla et al., Airborne visual detection and tracking of cooperative UAVs exploiting deep learning, Sensors 2019)

Relative Sensing: drone-to-drone visual tracking

- Recent research introducing shape-based ranging techniques – meter-level range uncertainty up to medium (few tens of m) distances for the considered drones
- The added value of passive ranging depends on the scenario and the geometry
- Closed-loop integration with cooperative navigation algorithms for GNSS-challenging environments





Case 1: LOS + shape-based ranging

Case 2: LOS-only

RMS error on the position in the challenging areas.

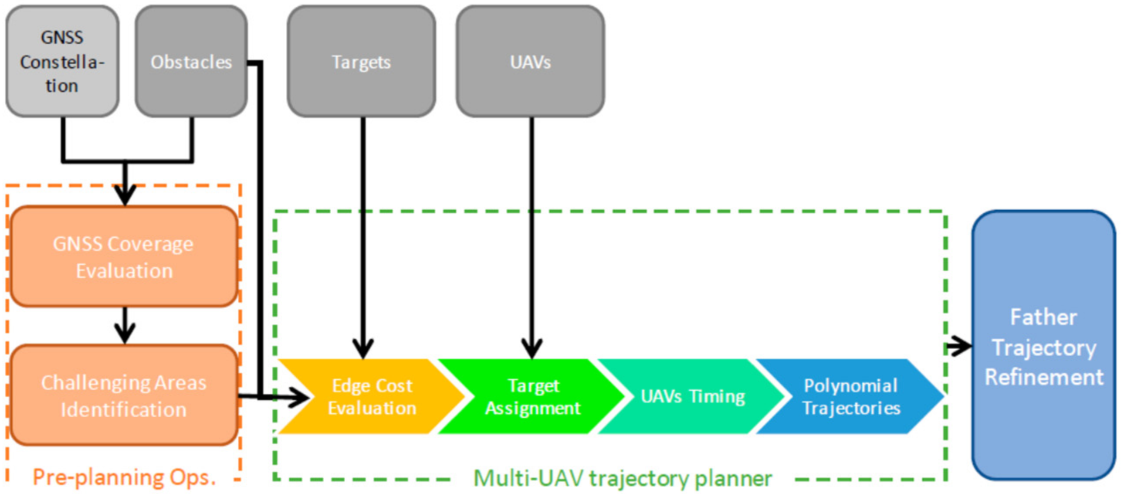
Scenario	RMS norm, m		Gain
	Case 1	*Case 2*	
Bridge	1.83	2.08	0.13
Building	1.99	3.41	0.42
Canyon	2.40	2.88	0.17

(Causa et al., Closed loop integration of air-to-air visual measurements for cooperative UAV navigation in GNSS challenging environments, Aerospace Science and Technology, 2022)

✓Environments with mixed GNSS coverage conditions

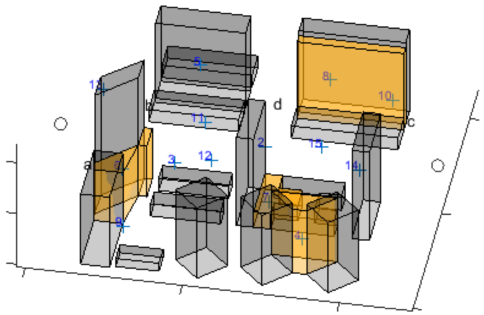
✓Resources optimization

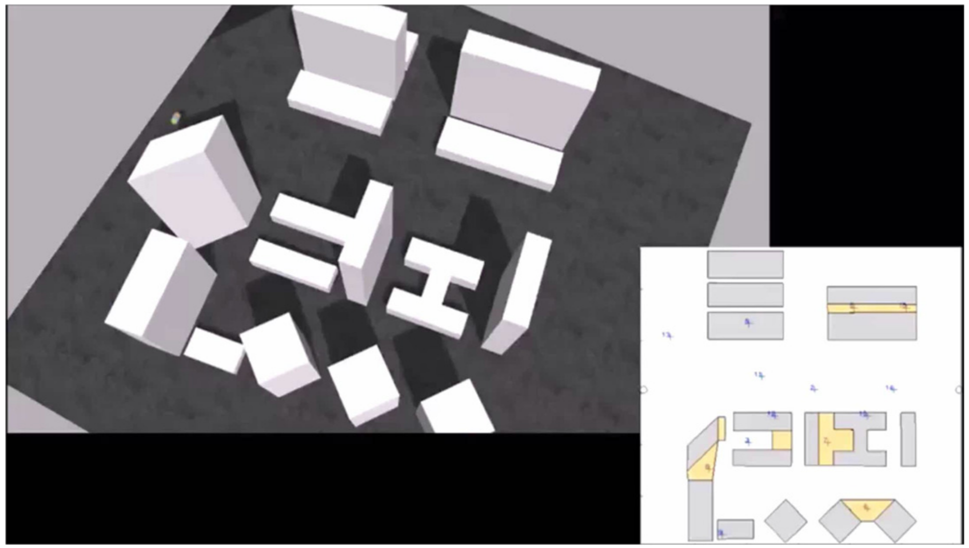
✓Cooperative navigation where and when needed



Coarse 3d model

Synthetic scenario with GNSS-challenging zones





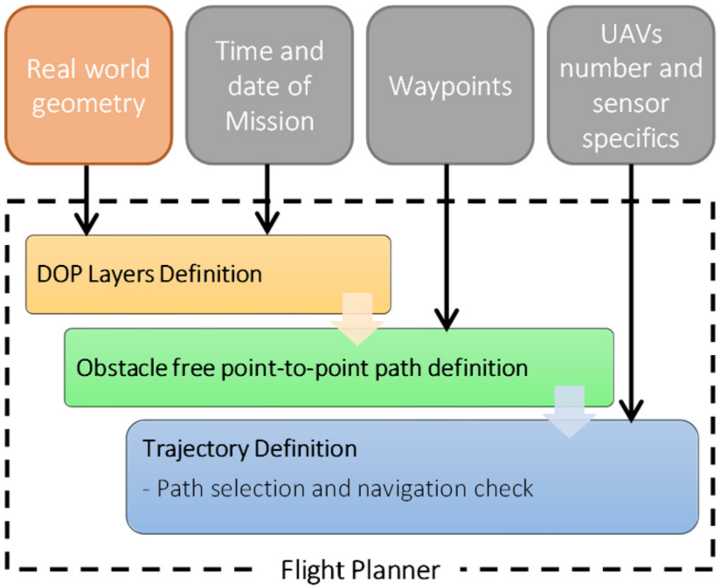
(Causa et al., Multi-UAV path planning for autonomous missions in mixed GNSS coverage scenarios , Sensors 2018)

Multi-drone path planning - 2

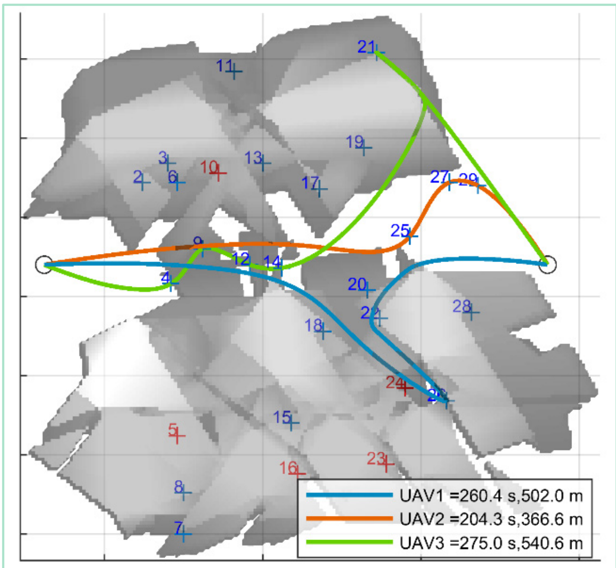
- Vehicle Routing Problem scenario with multiple drones and no in-flight cooperation

- Navigation-aware cooperative planning: «better equipped better planned» paradigm

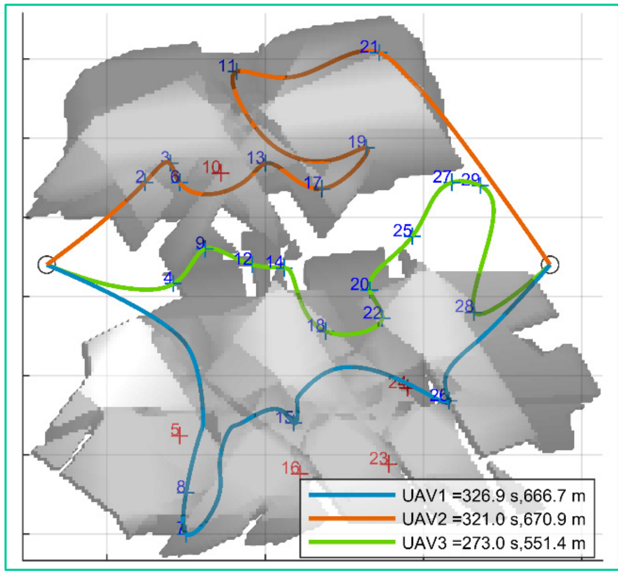
- Concepts extendable to centralized planning in U-Space/UAM



All UAVs with type A IMU



All UAVs with type B IMU



(Causa and Fasano, Multiple UAVs trajectory generation and waypoint assignment in urban environment based on DOP maps, Aerospace Science and Technology, 2020)

Research directions

- Technology demonstration in operational environments
  - Bridge inspection
  - Flight in complex urban environments

- Real time implementation

- End-to-end integrated implementations including online cooperative guidance

- Integration of new GNSS signals / services (e.g., Galileo HAS and OS-NMA)

- Integration of other sensing architectures

- Interaction with other research paths
  - Low altitude surveillance and navigation
  - High density airspace operations

Perspectives

- Significant progress in multi-drone systems, but their potential is yet to be fully unleashed

- Scalability and impact

- Resiliency, cyber-security, autonomy

- Solutions and technologies are heavily application-dependant

Perspectives

- Multi-drone evolution in phase with BVLOS operations
  - Enhanced connectivity
  - Routine operations may be foreseen in near term, at least for some applications

- Significant links with other research and development areas, e.g.
  - Sensing for surveillance and navigation
  - Fleet Management
  - Management of high density airspace scenarios

- Evolution poses multi-disciplinary problems requiring an integrated approach
  - Air/ground-based solutions and their interaction

Conclusion

- Multi-drone systems as natural evolution of drone technology, maximizing performance and efficiency

- Their development is pushed by technological progress, e.g. in communications and computing power

- Within the civilian framework, the impact will be maximized as more flights are demonstrated in operational environments, proving safety

- This lecture tried to briefly introduce main concepts and research areas, and hopefully to stimulate ideas and developments

Contact information

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