The AZUR project

Development of autonomous navigation software for urban operation of VTOL-type UAV

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ONERA

THE FRENCH AEROSPACE LAB

retour sur innovation

MAVRC – Garden Workshop

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Context

❖ Needs

- Increasing demands of operational UAVs for missions in a complex environment
  - Infrastructure inspection (railway, pipeline, dam, etc.)
  - Scientific mapping (archaeology, agriculture, etc.)
  - Disaster relief and recovery
  - Reconnaissance and surveillance …
- UAV flight safety for such operations
- Limited skills and workload for UAV operator

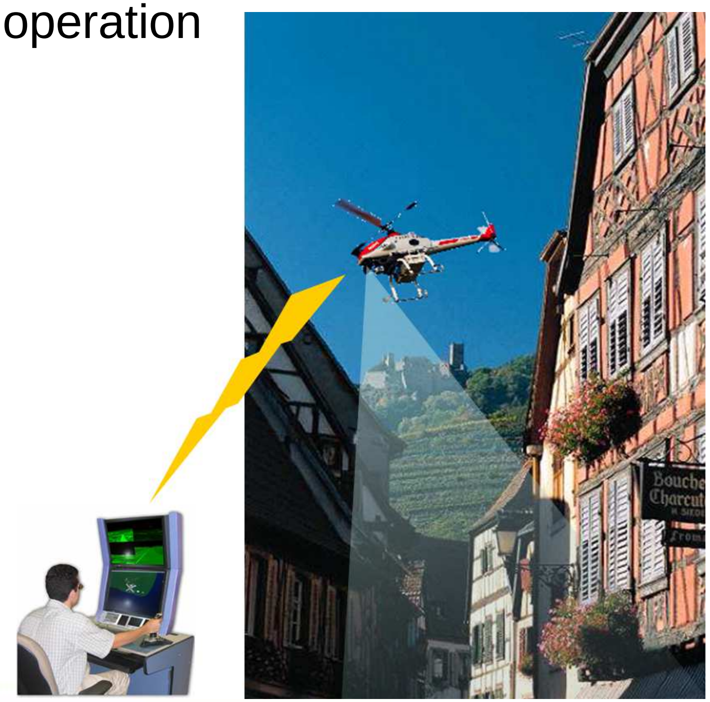
Autonomous navigation system for UAV operations in a complex environment (obstacles, wind gust etc.) with onboard perception capability

PR AZUR (2011-2014)

❖ AZUR (Autonomie en Zone URbaine)

❖ Objectives

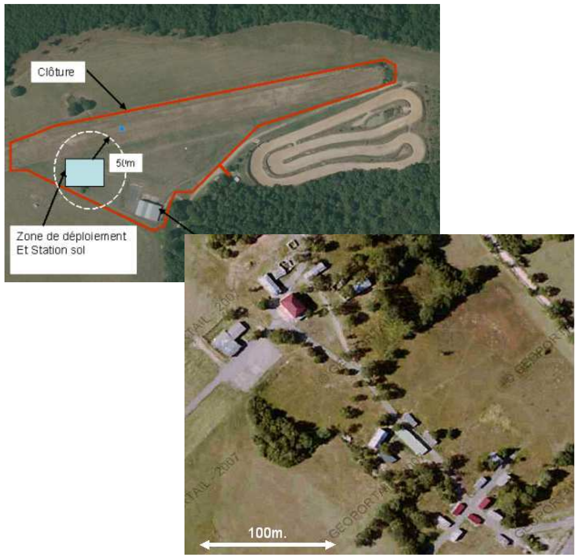
- Development of onboard navigation software kit for “rurban” operation of VTOL-type UAVs
- Flight experiments and validation of each developed navigation function
- Realization of autonomous mission operation

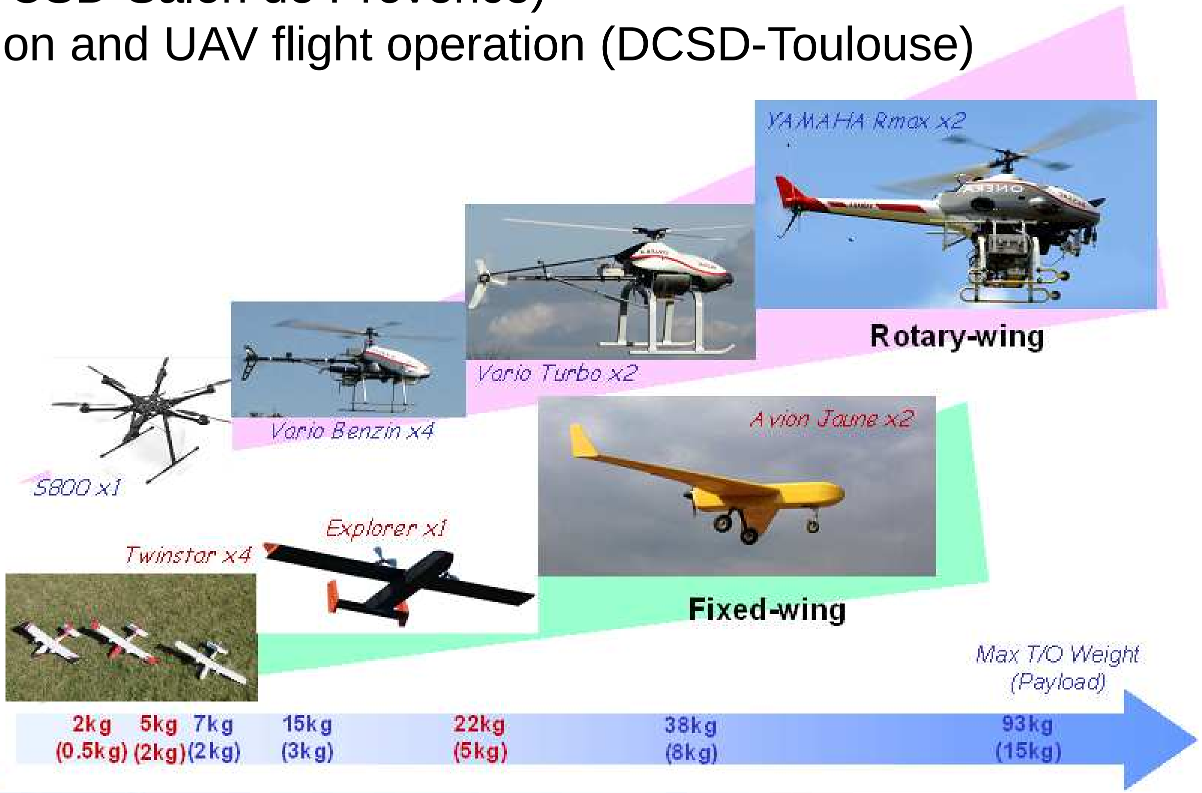


PR AZUR (2011-2014)

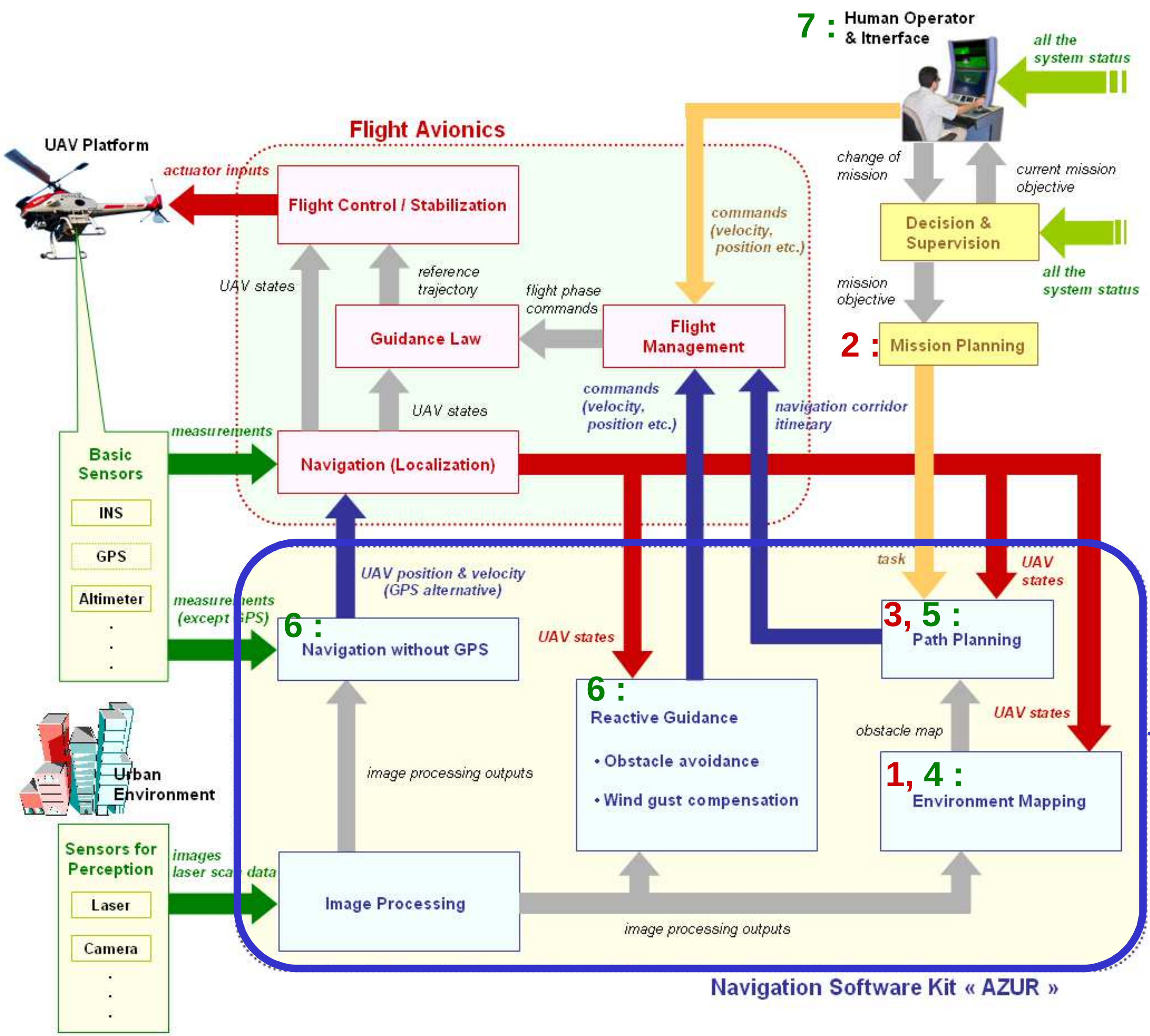
❖ Capitalization of different competences of ONERA-TIS

- UAV guidance, navigation and control (DCSD-Toulouse, DCPS-Palaiseau)
- Onboard perception, image processing (DTIM-Palaiseau)
- Mission and path planning (DCSD-Toulouse)
- Operator interface (DCSD-Salon de Provence)
- System implementation and UAV flight operation (DCSD-Toulouse)





Navigation functions in the AZUR software



Mission Scenario

❖ Preparation phase

- Data acquisition from high altitude
- Data processing on ground

1. Environment mapping
2. Mission planning
   → *PEA Action, etc.*
3. Flight path planning

❖ Execution phase

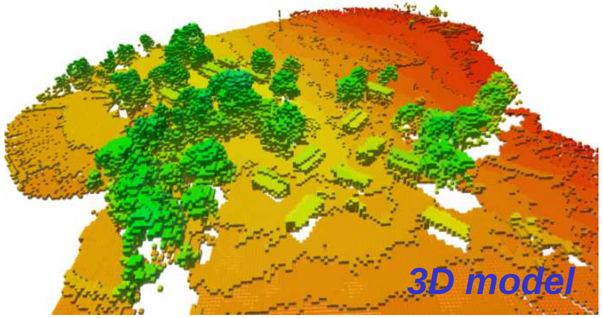
- Mission operation at low altitude close to obstacles

4. Onboard mapping
5. Adaptation of current flight plan
6. Safe flight under GPS occlusion risk, wind gust...
7. Operator intervention

1. Environment mapping

❖ Geometric 3D modeling with high precision

- LiDAR + Vision-aided trajectography [1]
  - Refinement of GPS/INS-estimated trajectory by bundle adjustment
  - LiDAR data projection with the refined trajectory



[1] *M. Sanfourche, J. Delaune, J. Israel, G. le Besnerais, H. de Plinval, P. Cornic, A. Treil, Y. Watanabe and A. Plyer, "Perception for UAV : Vision-based navigation and environment modeling", ONERA Aerospace Lab Journal, 2012.*

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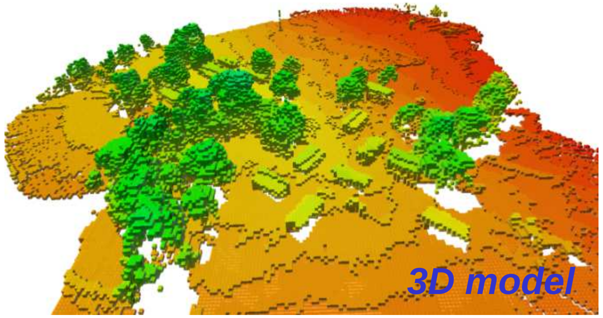
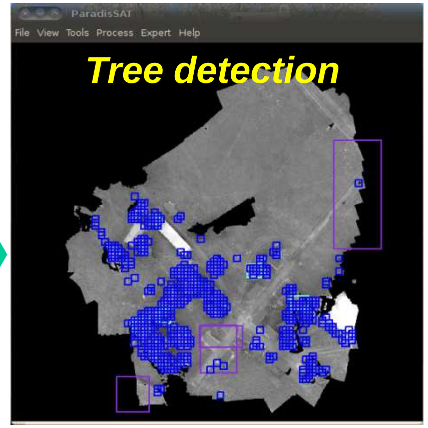


❖ Semantic scene interpretation

- Terrain type classification (e.g. tree/building) [2]
  - Interactive learning on orthomosaïc images
  - Online domain adaptation on onboard image sequence



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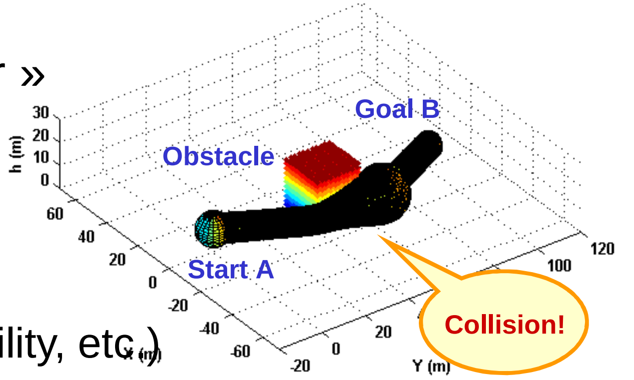
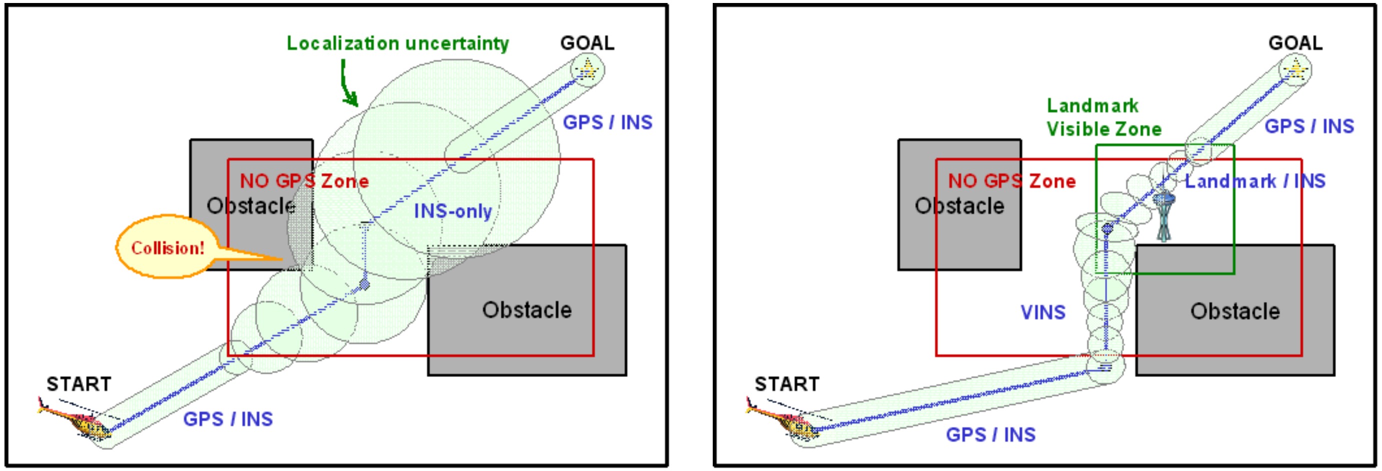
[2] *B. Le Saux and M. Sanfourche, "Rapid Semantic Mapping: Learn Environment Classifiers on the Fly," IEEE/RSJ IROS, 2013.*

3. Safe flight path planning

❖ Path planning under localization uncertainty [3]

- Collision risk evaluation with « uncertainty corridor »
  → Search for a safe flight path
- Taking into account different localization modes (GPS, INS-only, visual odometry, landmark…) and their availabilities (GPS occlusion, landmark visibility, etc.)





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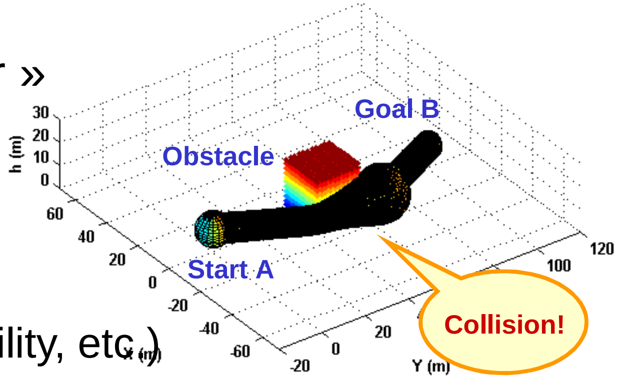
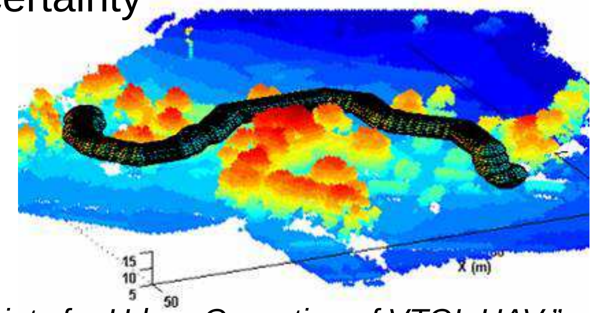


- Taking into account different localization modes (GPS, INS-only, visual odometry, landmark…) and their availabilities (GPS occlusion, landmark visibility, etc.)

- Navigation strategy planning
  - Graph search in 4D space (3D space + localization mode)
    ← *deterministic search algorithms (A*, Theta*)*
  - Minimization of flight distance as well as localization uncertainty

Cost function = Volume of the uncertainty corridor



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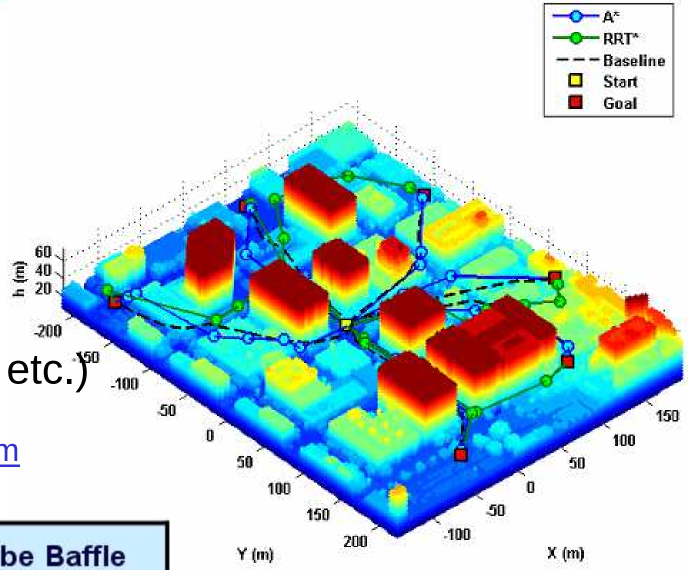
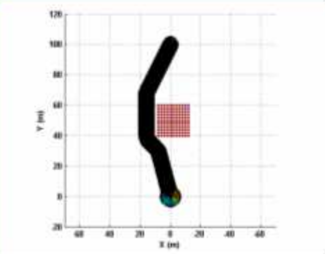
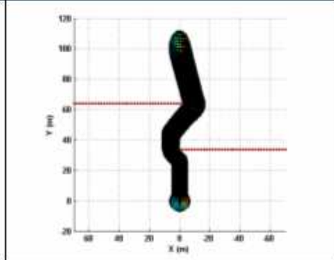
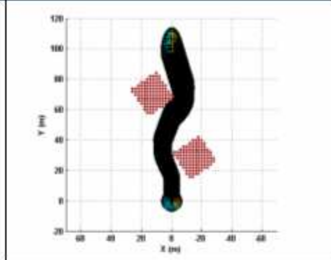
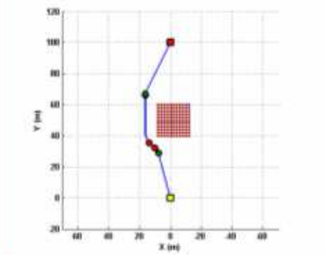
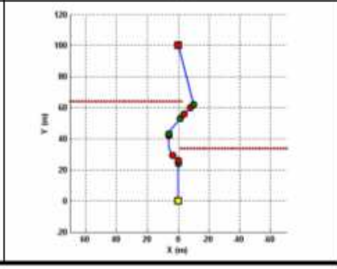
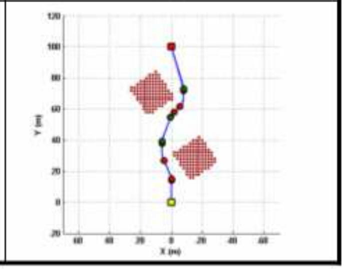
3. Safe flight path planning

❖ Path planning under localization uncertainty

- Evaluation with the VTOL UAV Obstacle Field Navigation (OFN) benchmark*
  - Participation and contribution to the benchmarking working-group (US Army, UMN, DLR, CMU, GaTech, etc.)*



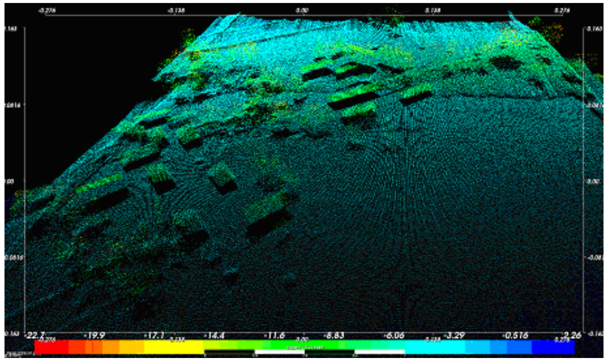
* http://www.aem.umn.edu/people/mettler/projects/AFDD/AFFDwebpage.htm

	BM4 : Cube	BM5 : Wall Baffle	BM6 : Cube Baffle
Uncertainty corridor			
Flight plan ● INS-only ● GPS / INS ● Vision / INS			

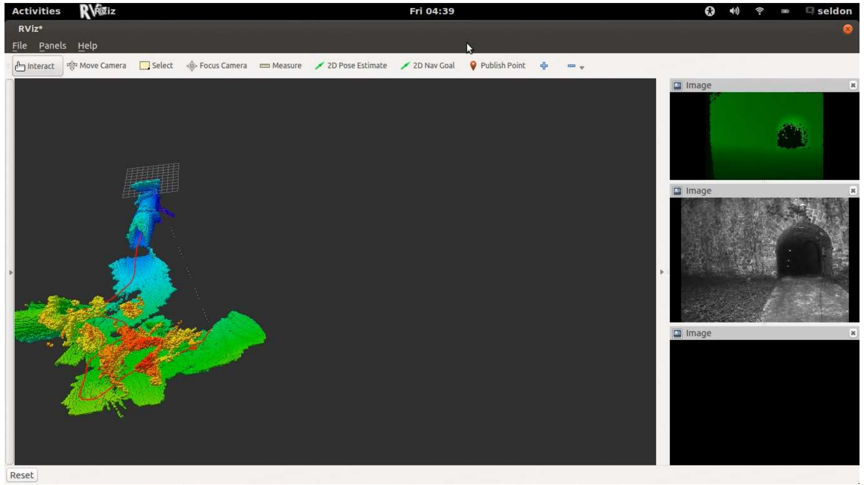
4. Onboard mapping

❖ 3D geometric modeling

- LiDAR
  - Data projection by using GPS/INS-estimated trajectory (w/o refinement)
  - Data fusion through ICP (iterative closest point)



- Stereo visual SLAM + Kinect [4]
  - Keyframe-based real-time visual SLAM (simultaneous localization and mapping
  - Combined with Kinect sensor in case of having poor visibility condition (mixed outdoor-indoor flight)



[4] *M. Sanfourche, V. Vittori and G. Le Besnerais, "Evo: A realtime embedded stereo odometry for MAV applications," IEEE/RSJ IROS, 2013.*

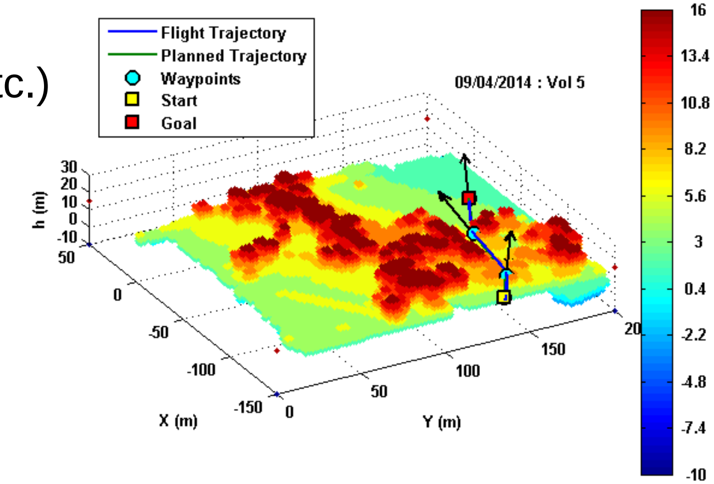
5. Onboard flight trajectory adaptation

❖ Flight path replanning

- Supervision
  - Feasibility of execution of current flight plan
  - Possibility of performance improvement (= cost reduction)

  ← Position, localization uncertainty, environment map

- Replanning
  - Sampling-based search (RRT*/# algorithms etc.) to obtain *sub-optimal* solution in real-time
  - Search tree initialization with an executable part of the current path

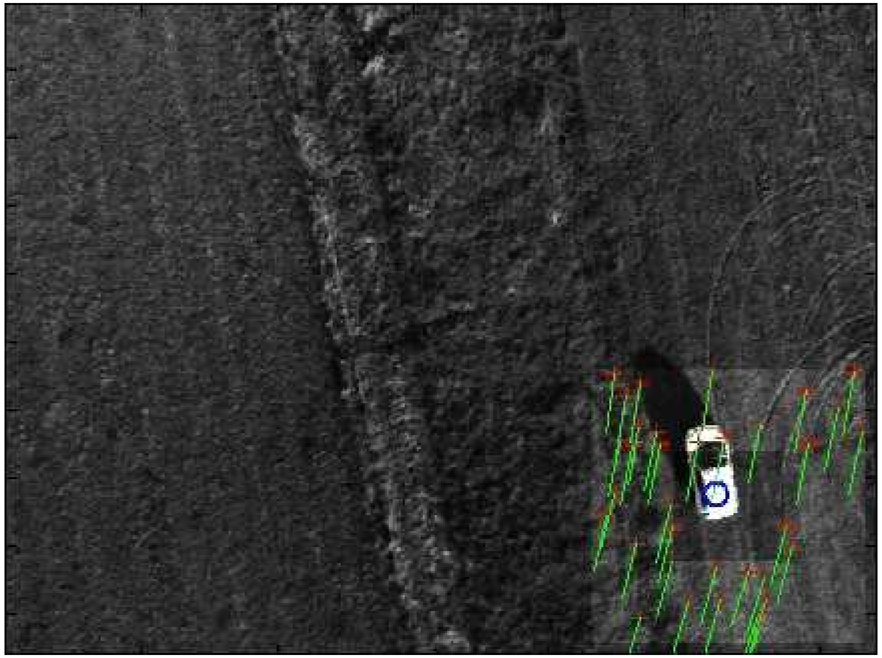


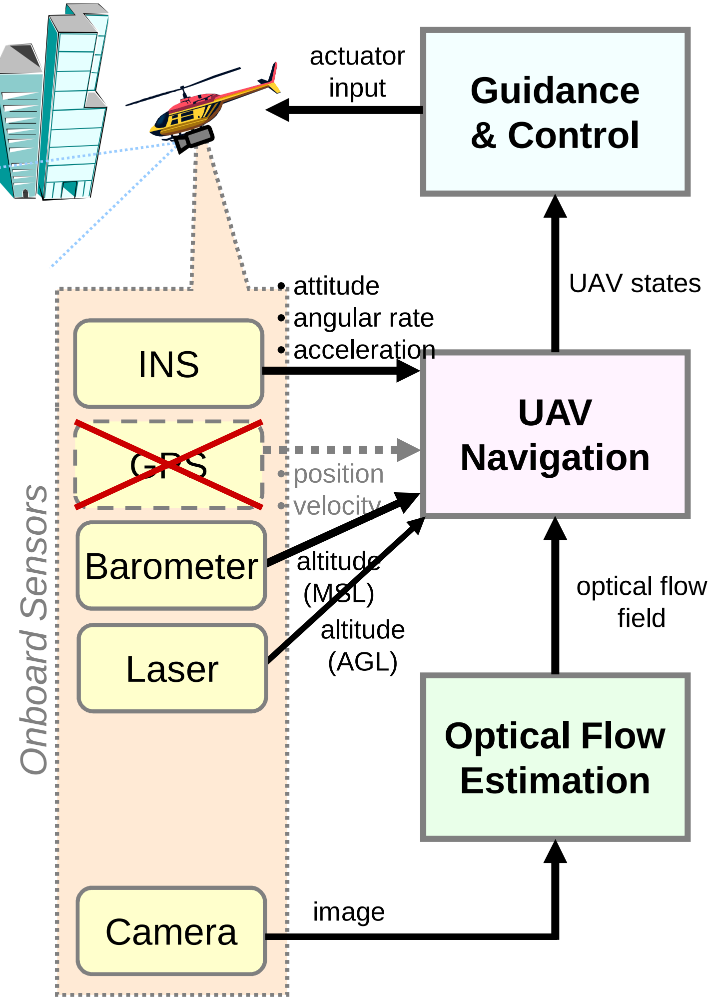
❖ Reactive obstacle avoidance

- V(elocity)-obstacle aooroach
- Analysis of vehicle stability when switching modes (mission → avoidance) hybrid system modeling

❖ Optical flow-based visual odometry [5]

- Optical flow + ground altitude
  → Reconstruction of 3D velocity information
- Data fusion through Extended Kalman Filter





[5] *Y. Watanabe, A. Piquereau, P. Chavent, R. Mampey, P. Fabiani and M. Sanfourche,*
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6. Navigation without GPS

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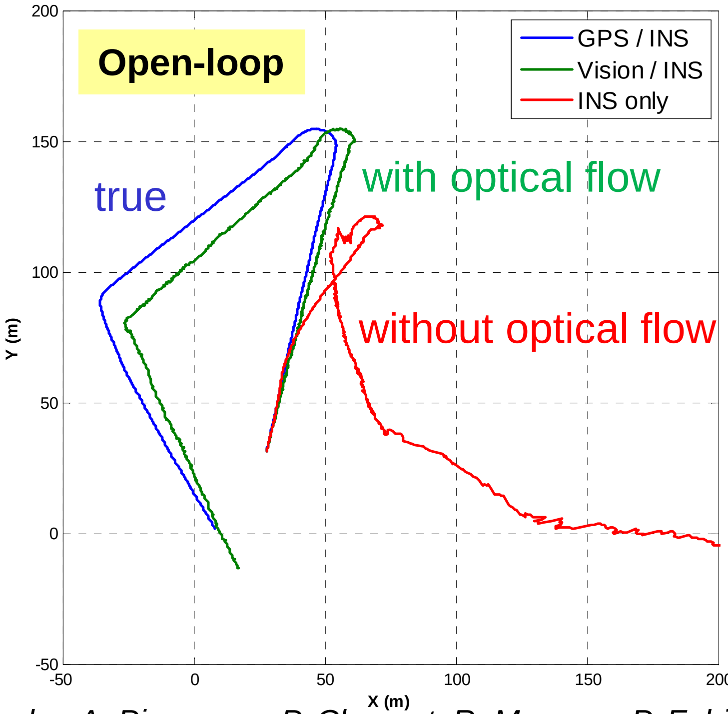

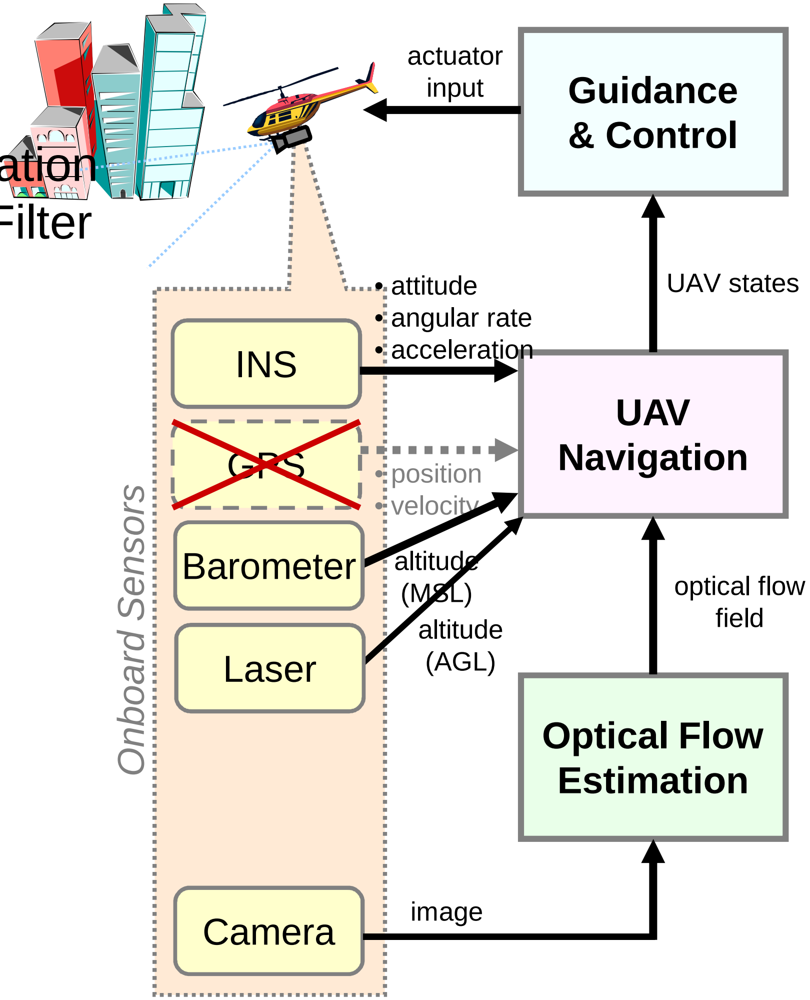

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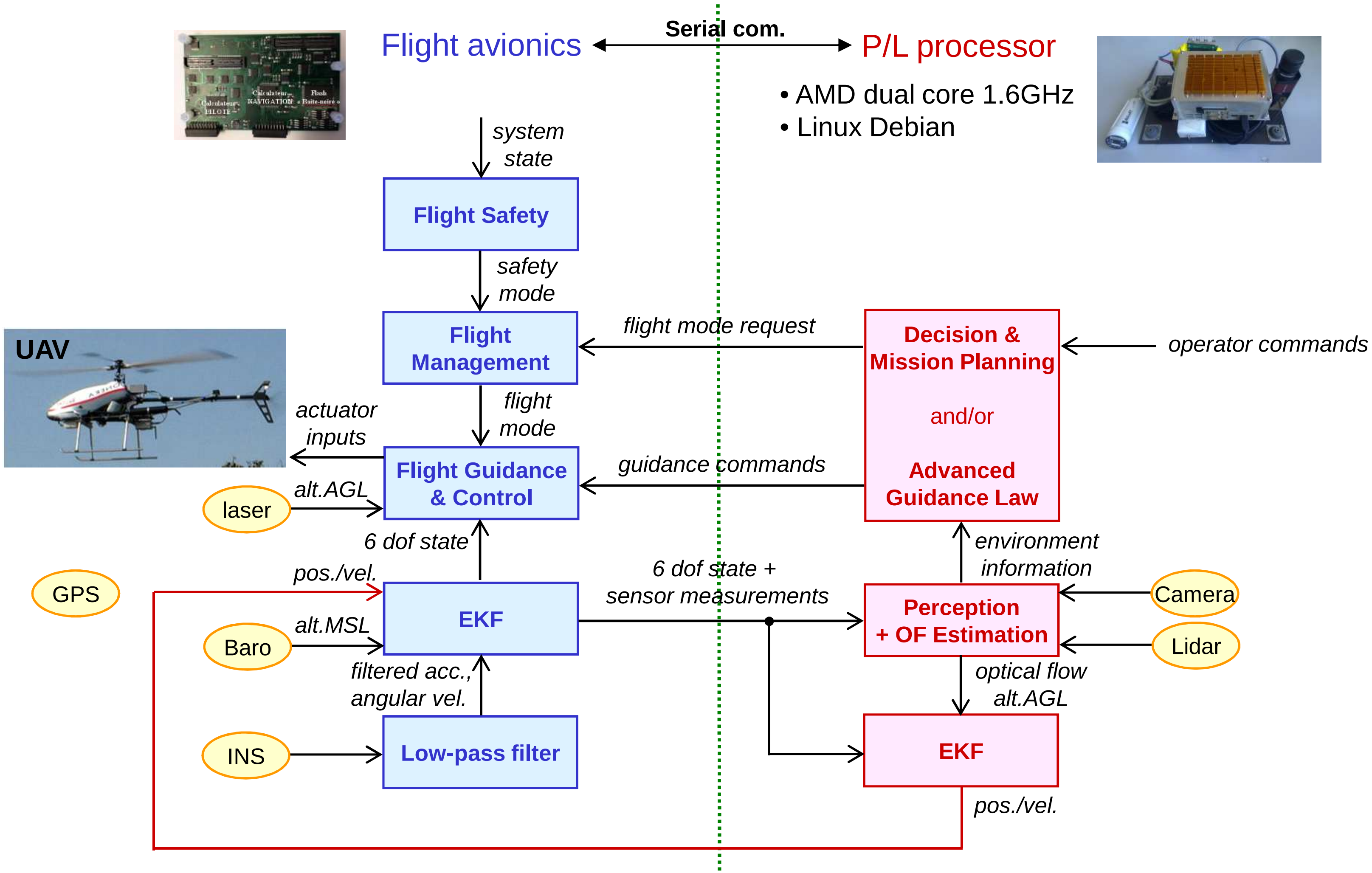
6. Navigation without GPS

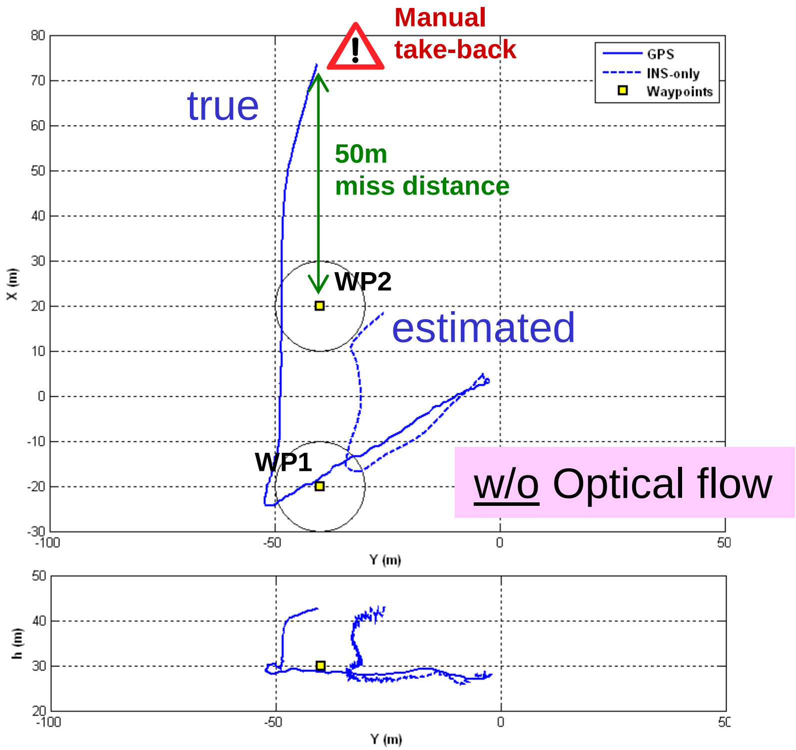


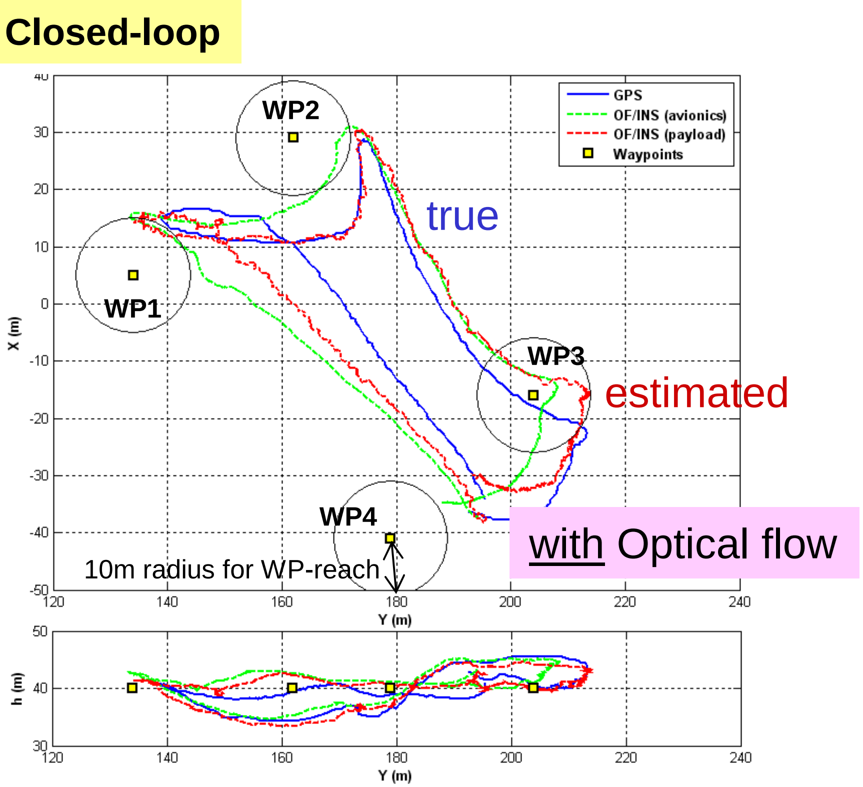
6. Navigation without GPS

❖ Optical flow-based visual odometry

- Automatic waypoint tracking flight with GPS cut-off
- 10 m of drift after 2 min. of GPS signal loss

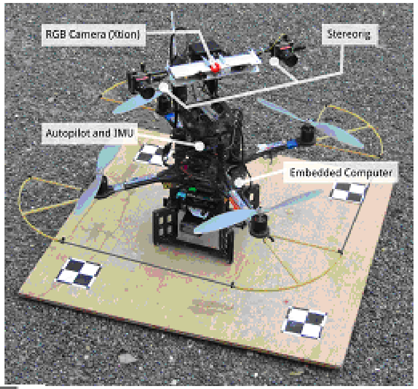
DCSD-Ressac Vario





6. Navigation without GPS

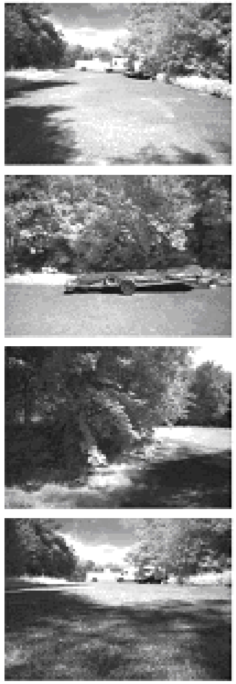
DTIM-Pelican

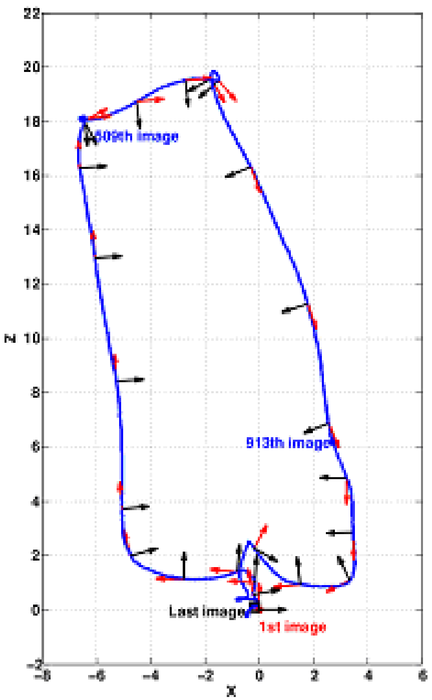


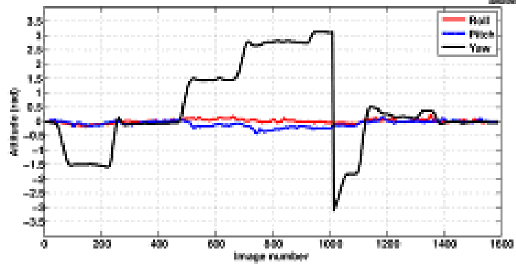
❖ Stereo visual SLAM [4]

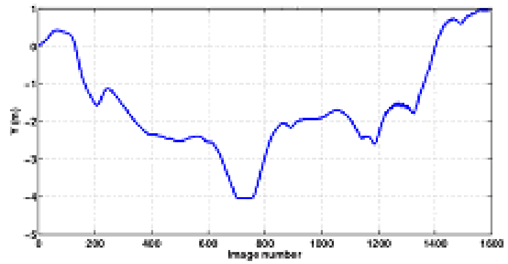
- 6D camera pose estimation by image matching
- Feature points tracking ~ absolute measurement
- High estimation precision
  - → 1st on the KITTI benchmark* in 2013

* www.cvlibs.net/datasets/kitti/









[4] *M. Sanfourche, V. Vittori and G. Le Besnerais, "Evo: A realtime embedded stereo odometry for MAV applications," IEEE/RSJ IROS, 2013.*

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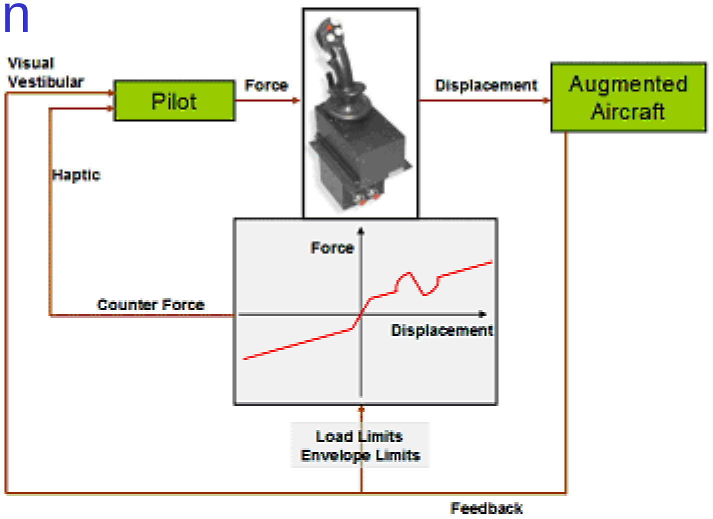
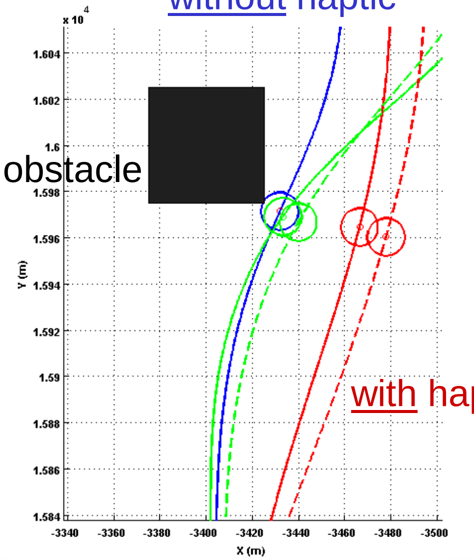
7. Operator intervention

❖ Haptic interface for obstacle field navigation

- Inform an operator with obstacle proximity by using force-feedback [6]

- Evaluation using LabSIM cockpit / flight simulator (DCSD-Salon de Provence)

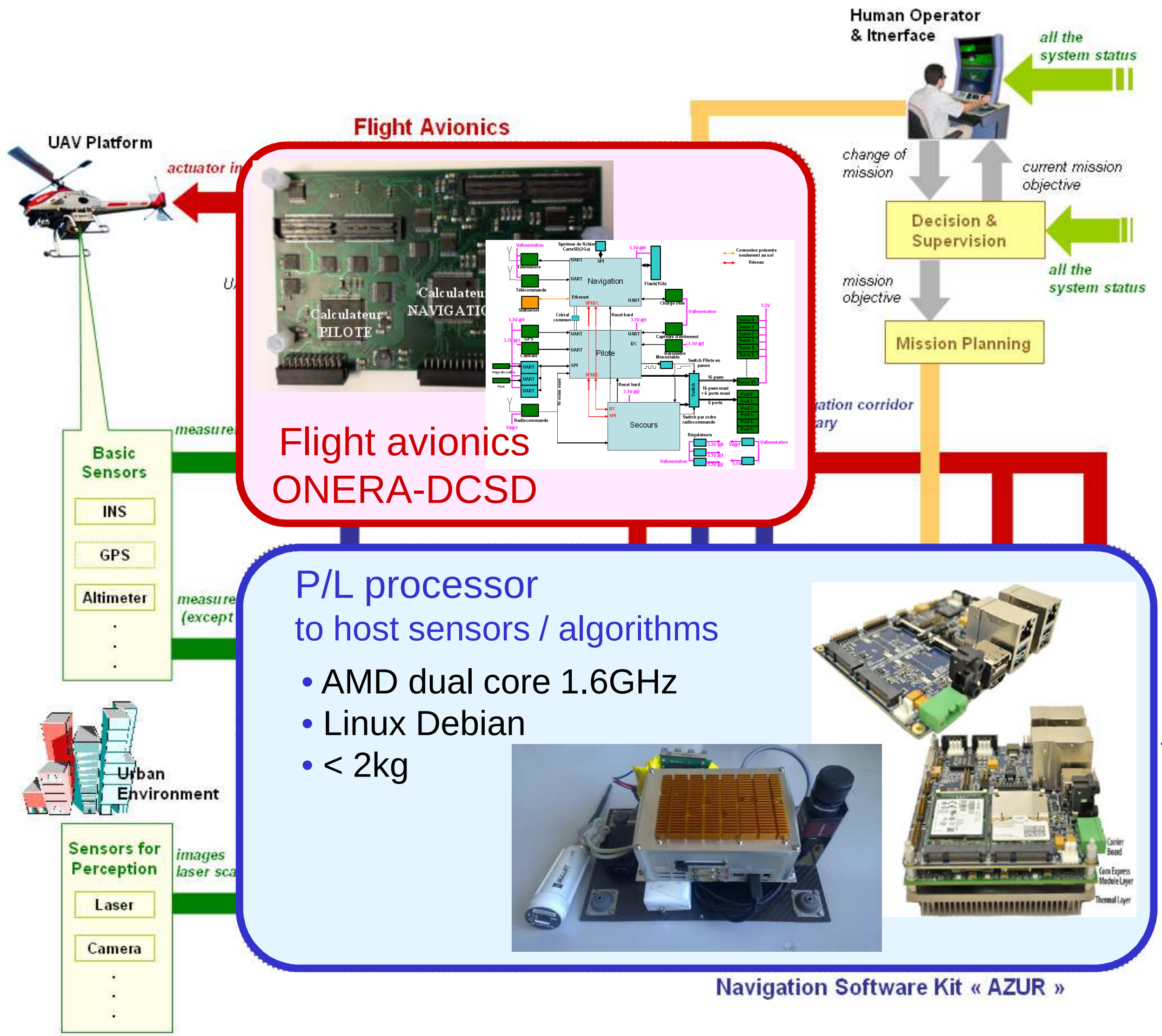




DCSD - LabSIM

[6] *L. Binet and T. Rakotomamonjy, "Using haptic feedbacks for obstacle avoidance in helicopter flight," European Conference for Aeronautics and Sapce Sciences, 2015.*

System integration



Interface with

- ❖ Sensors
  - Camera
  - Lidar …etc.
- ❖ Avionics
  - Communication at 50 Hz
  - Clock synchronization by using GPS PPS signal
- ❖ Ground station
  - P/L operation

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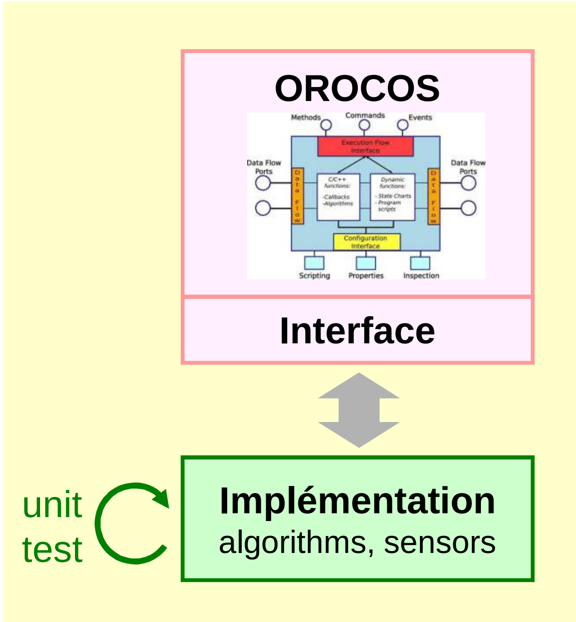
System integration

❖ Onboard software architecture

- OROCOS (Open RObot Control Software)
  - Component-based architecture
  - Real-Time Toolkit

- « Interface - Implementation » pattern
  - Easy to perform unit-test of an implementation
  - Interchangeability of
    - components
    - deployment modes (flight, simulation, data replay)
    - runtime frameworks



- Implementation of developped navigation functions
  - Environment mapping and path planning
  - Navigation without GPS
  - Visual servoing
  - Target detection and tracking…etc.

Prototype of onboard software architecture to host different algorithms/sensors

Conclusion and Perspectives

❖ Conclusion

- Development and flight validation of different « Onboard navigation functions »
    - Environment mapping and safe path planning
    - Vision-aided navigation (visual odometry, visual SLAM)
    - Visual servoing for relative navigation without GPS
    - Obstacle avoidance guidance…
- Development of onboard software architecture on the P/L processor
    - Interface and synchronization with flight avionics
    - « Interface-Implementation » pattern for interchangeability
- No demonstration of autonomous operation of a complete mission with an "integrated" navigation software kit ☹

Conclusion and Perspectives

❖ Perspectives

- Demonstration of autonomous operation of a complete mission with an “integrated” navigation software kit
    - PRI SNCF (2015-2019) : Infrastructure inspection

- Evolution of the onboard navigation functions
    - Navigation and guidance strategy planning
      → Joint research ONERA/DLR (2015-)
    - Vision-based navigation / guidance / control
        - Automatic indoor/outdoor flight
        - See & Avoid …
    - System reconfiguration in case of anomaly
      → PRF DROPTER (2016-2019)
    - Integration of haptic interface into GCS
      → PR CONTAHCT (2016-2018)

- Utilization, Evaluation and Evolution of the onboard software architecture

Thank you & Questions?