UAV Autonomous Navigation in a GPS-limited Urban Environment

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retour sur innovation

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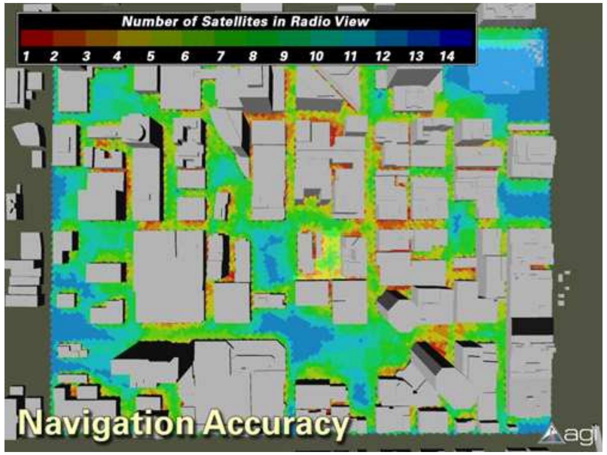
❖ Global objective

Development of a UAV onboard system to maintain flight security and navigation & guidance capability for urban operation

❖ GPS signal occlusion

- Alternative GPS-independent navigation system
  - Stabilization
  - GN&C functions → { Mission continuation, Automatic return-to-base, etc. }
- Path planning with GPS signal occlusion map
  - Safe path plan w.r.t. localization uncertainty
  - Sensor availabilities



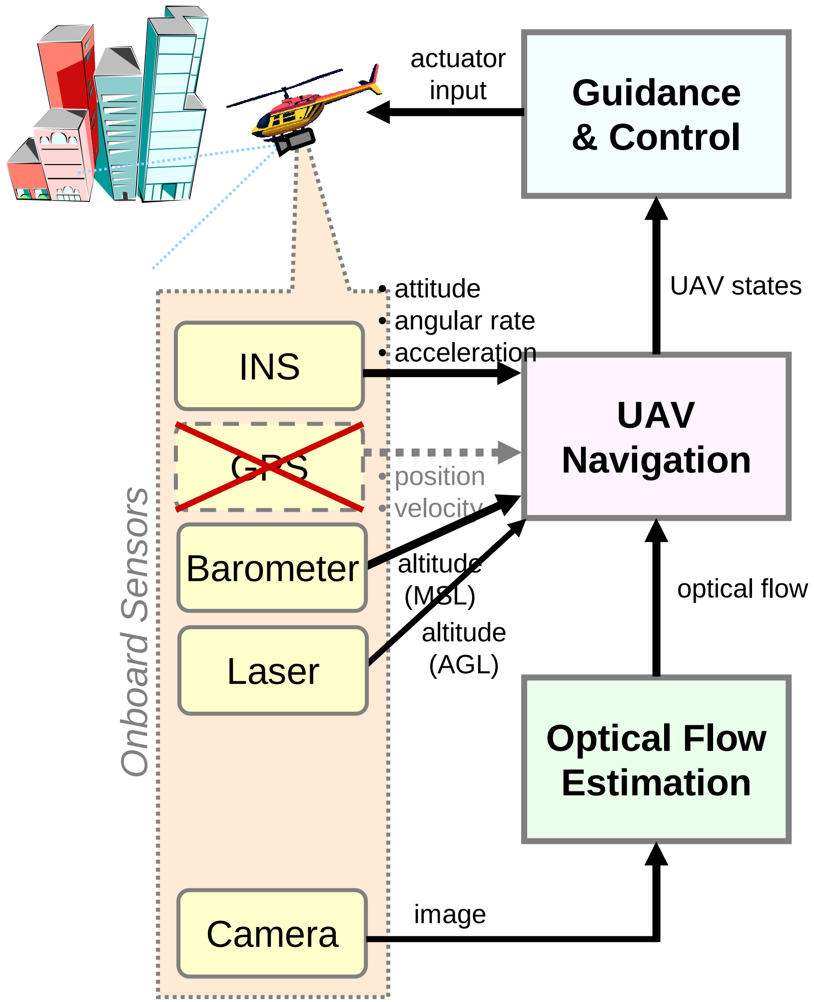
A. Gorski «Understanding GPS performance in urban environments»
http://blogs.agi.com/agi/2011/01/04/understanding-gps-performance-in-urban-environments/

❖ Objective

- Development of alternative back-up navigation system which estimates UAV absolute state by using onboard sensors other than GPS, given the last GPS-updated state
    - No dedicated sensors
    - No knowledge on environment
    - Low computation
    - Robustness
- In-flight validation on outdoor UAV helicopter
    - Onboard system integration with
        - flight avionics
        - onboard sensors
    - Closed-loop flight using existing GN&C functions with GPS signal cut-off

Vision-aided inertial navigation

- ❖ Stereo vs Monocular visions
- ❖ Pure vision vs INS-fusion
- ❖ Visual odometry vs Visual SLAM
- ❖ Filter vs Optimization (BA)



Vision-aided inertial navigation

❖ Visual odometry

- Stereo vision
- Monocular vision (motion stereo)

[Kelly 2007], [Kendoul 2009] and many others.

☺ Low computation
☹ Estimation drift due to absence of absolute measurement

❖ Visual SLAM

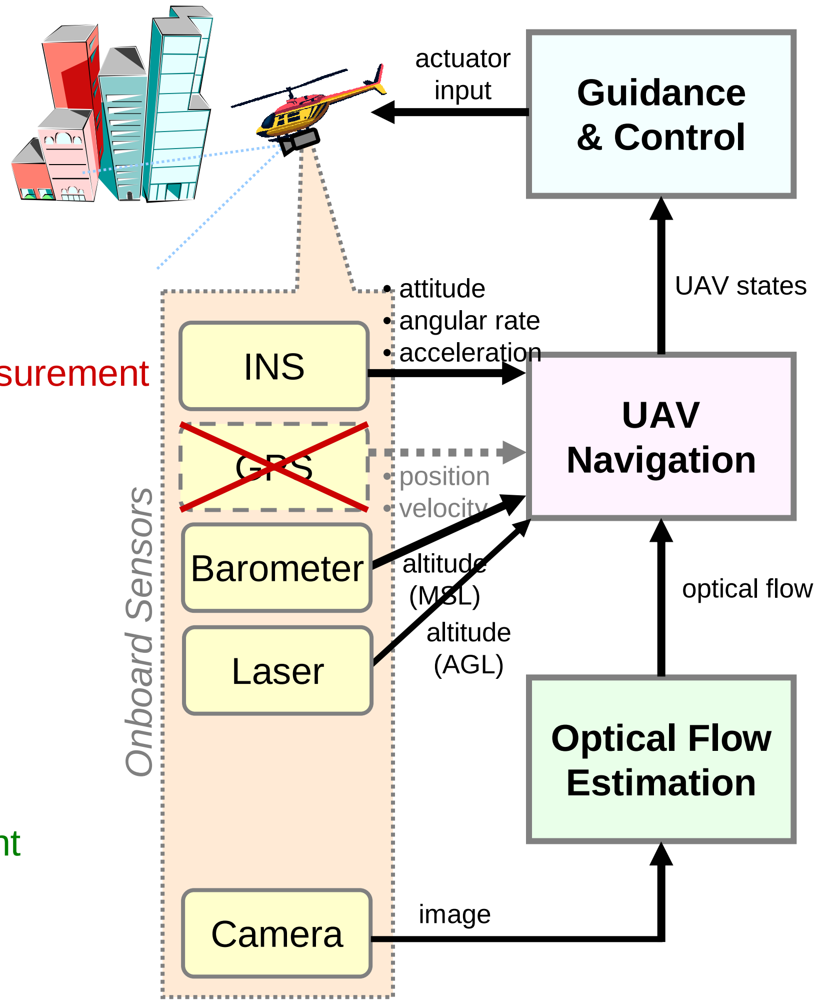
- Loop-closure (memorization of feature points)

[Weiss 2012], [Chaudhar 2013] and many others.

☺ High computation + memory-use
☹ Estimation correction with absolute measurement

- Keyframe-based SLAM

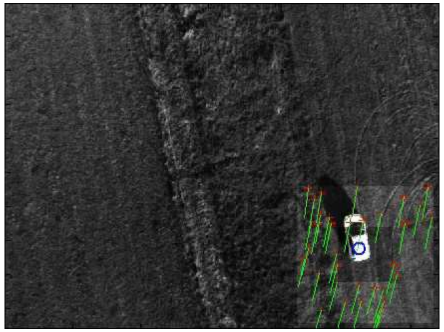
[Klein 2007] and many others.



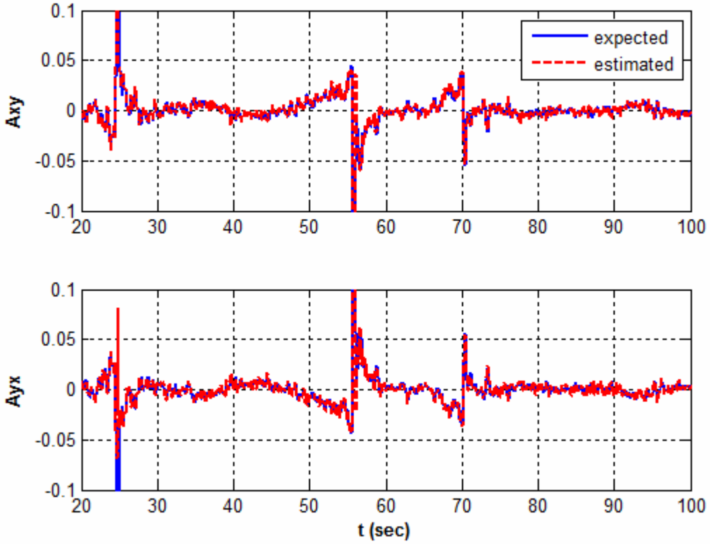
Robust estimation of Affine model optical flow field (DTIM)

- Feature point matching on a small window
- RANSAC approximation
- ~10Hz

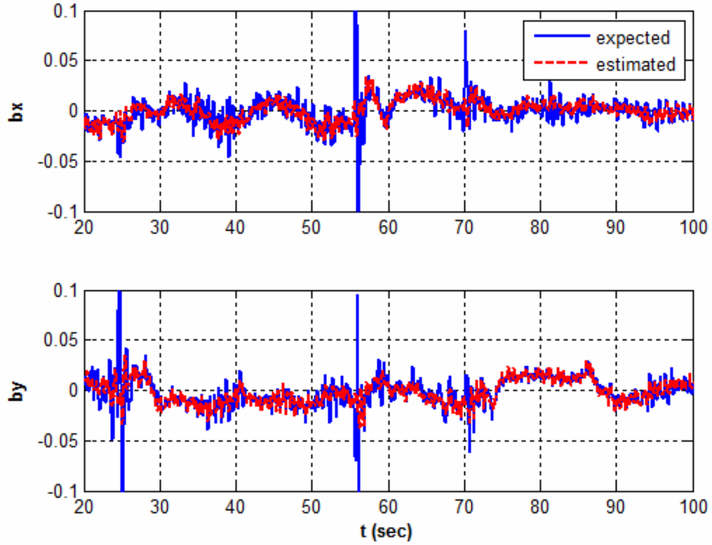
$$¢\, x_{p_k} = A_k x_{p_k} + b_k$$



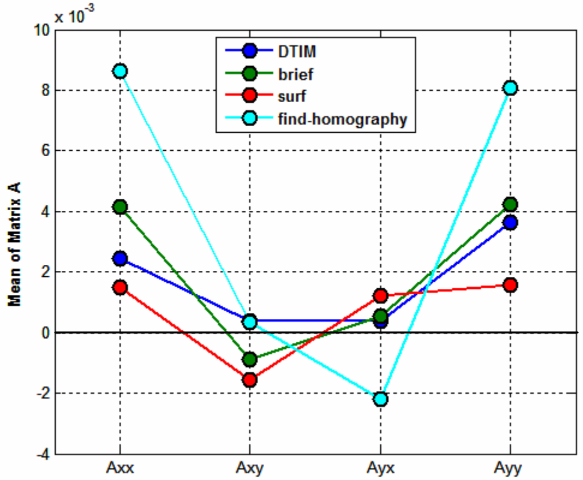
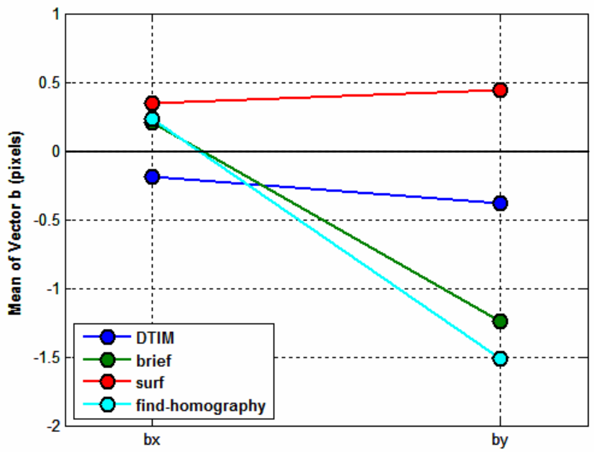
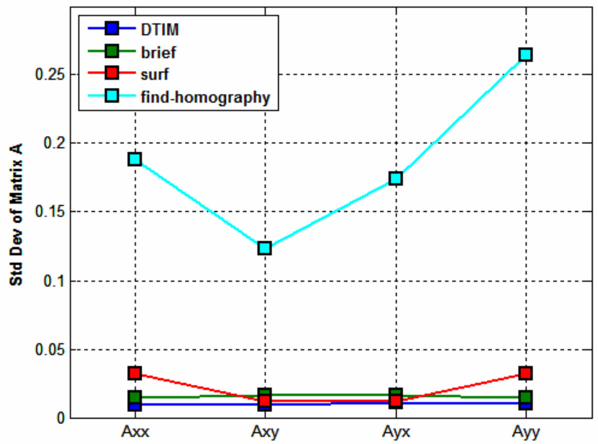
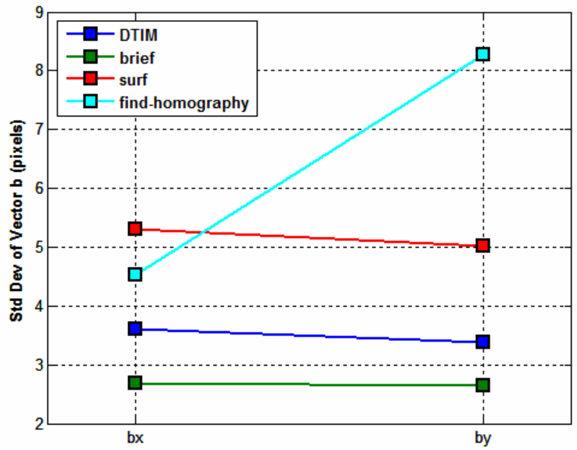
Rotational flow



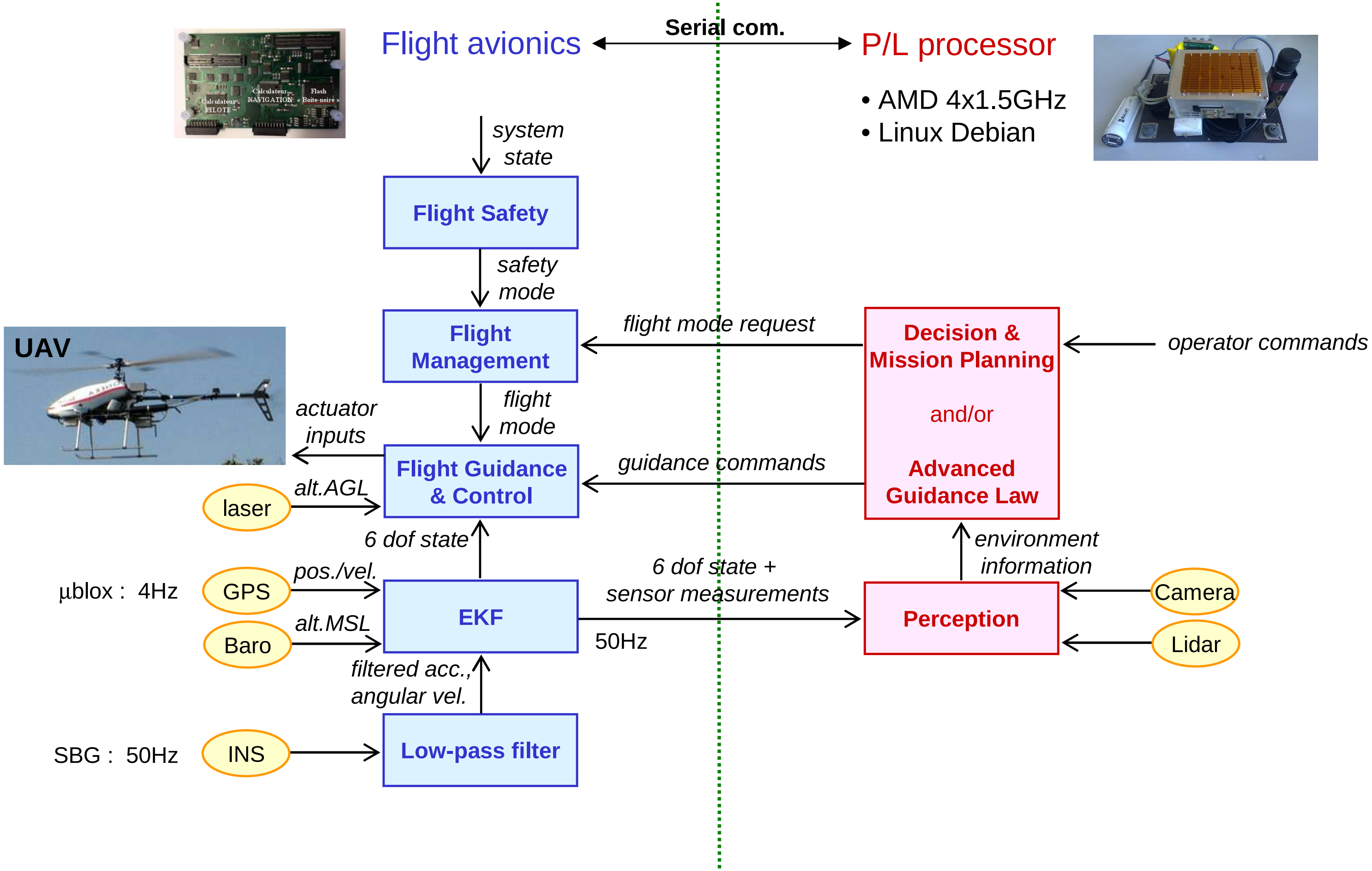
Translational flow



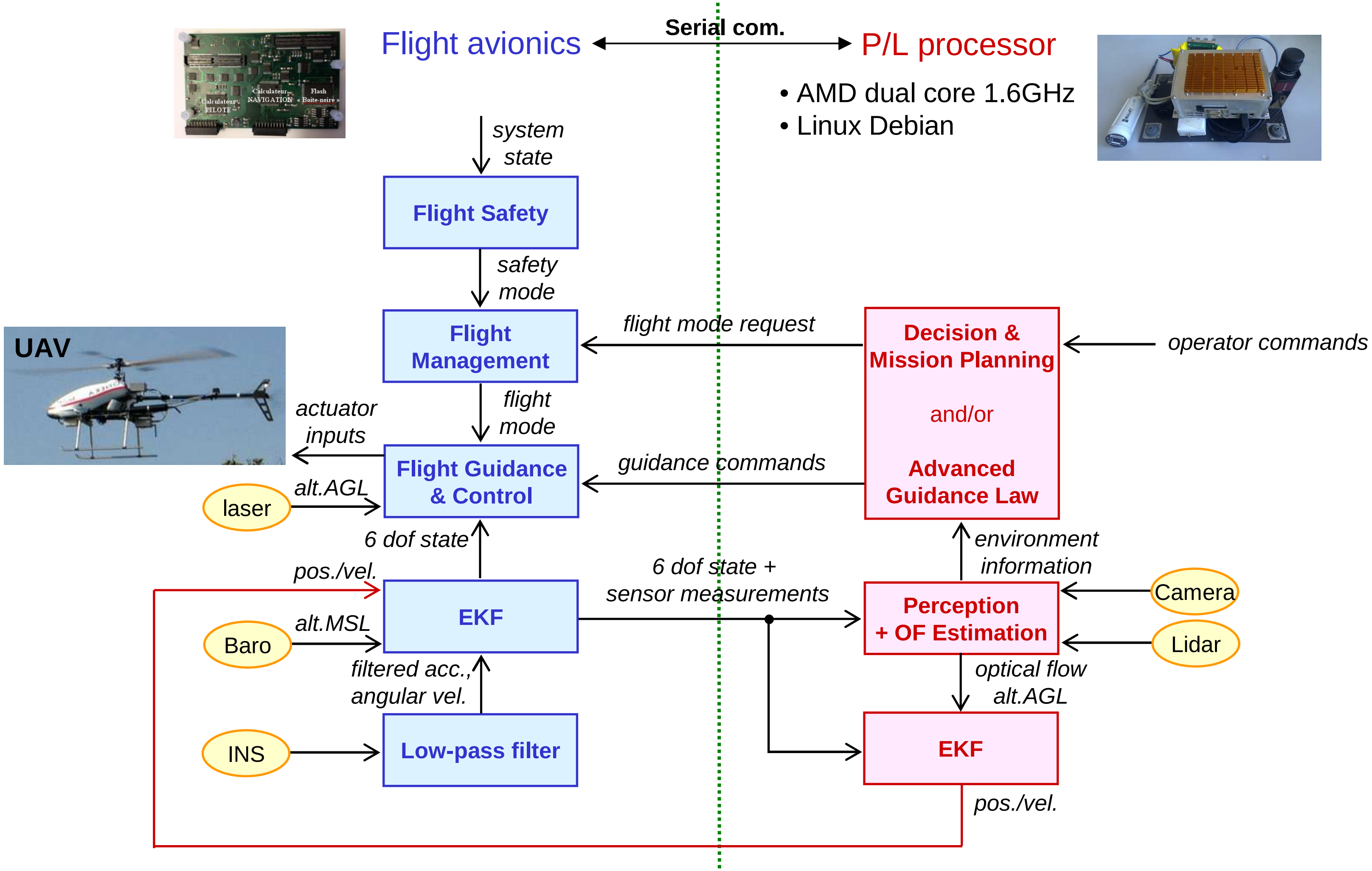
❖ vs. OpenCV

	Matrix A ~ Rotation	**Vector b ~ Translation**
Mean of Estimation Error ~ **Bias**		
Std. Deviation of Estimation Error ~ **Noise**		

Onboard system architecture

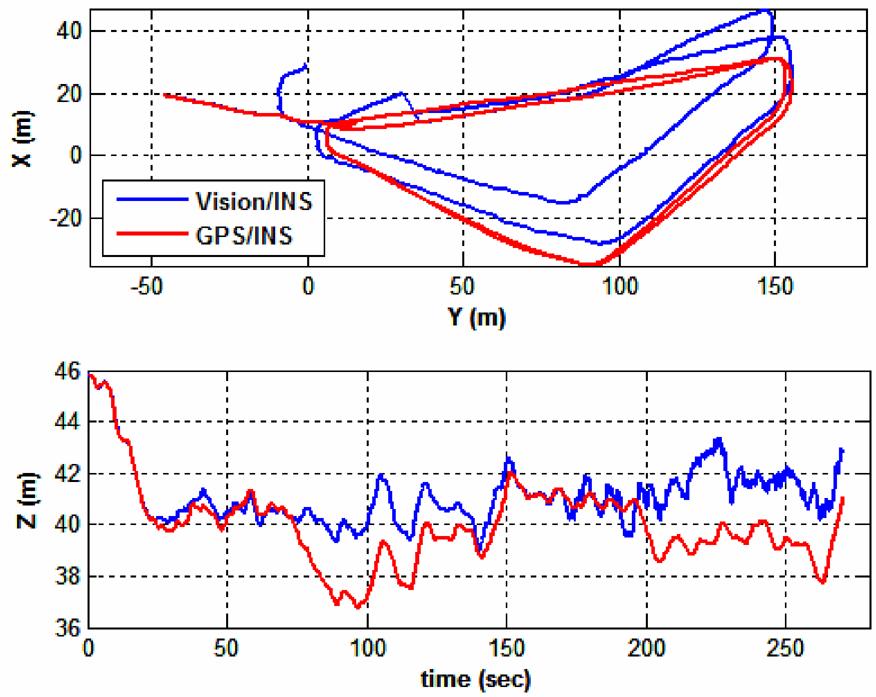


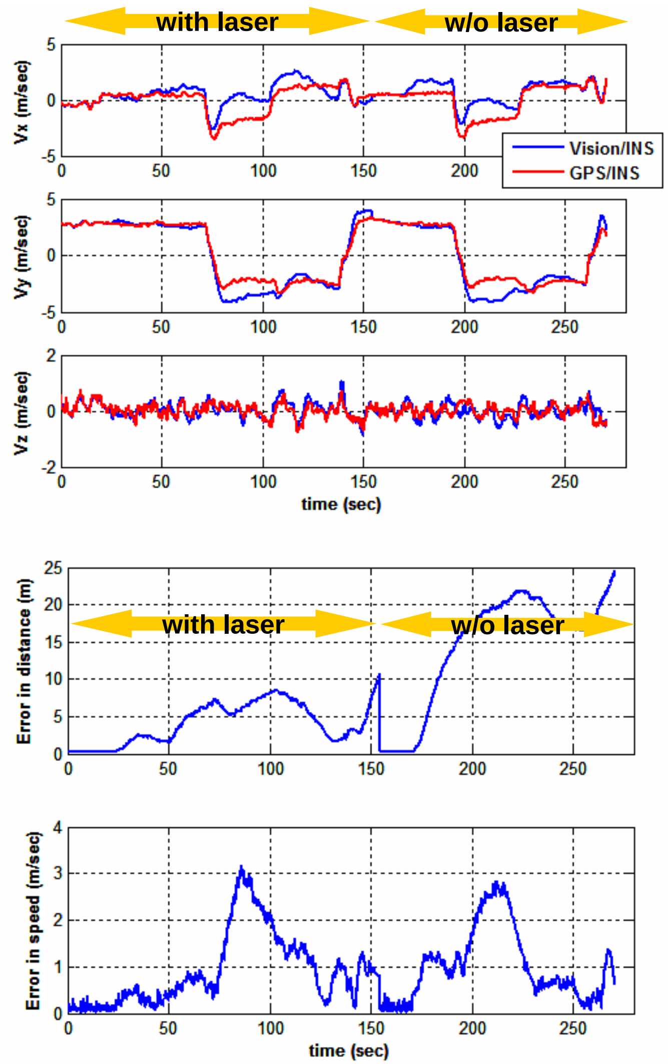
Onboard system architecture with GPS-independent navigation



Open-loop flight test results

- OF + INS + Barometer
  - with or w/o laser (alt. AGL)
  - over a slope





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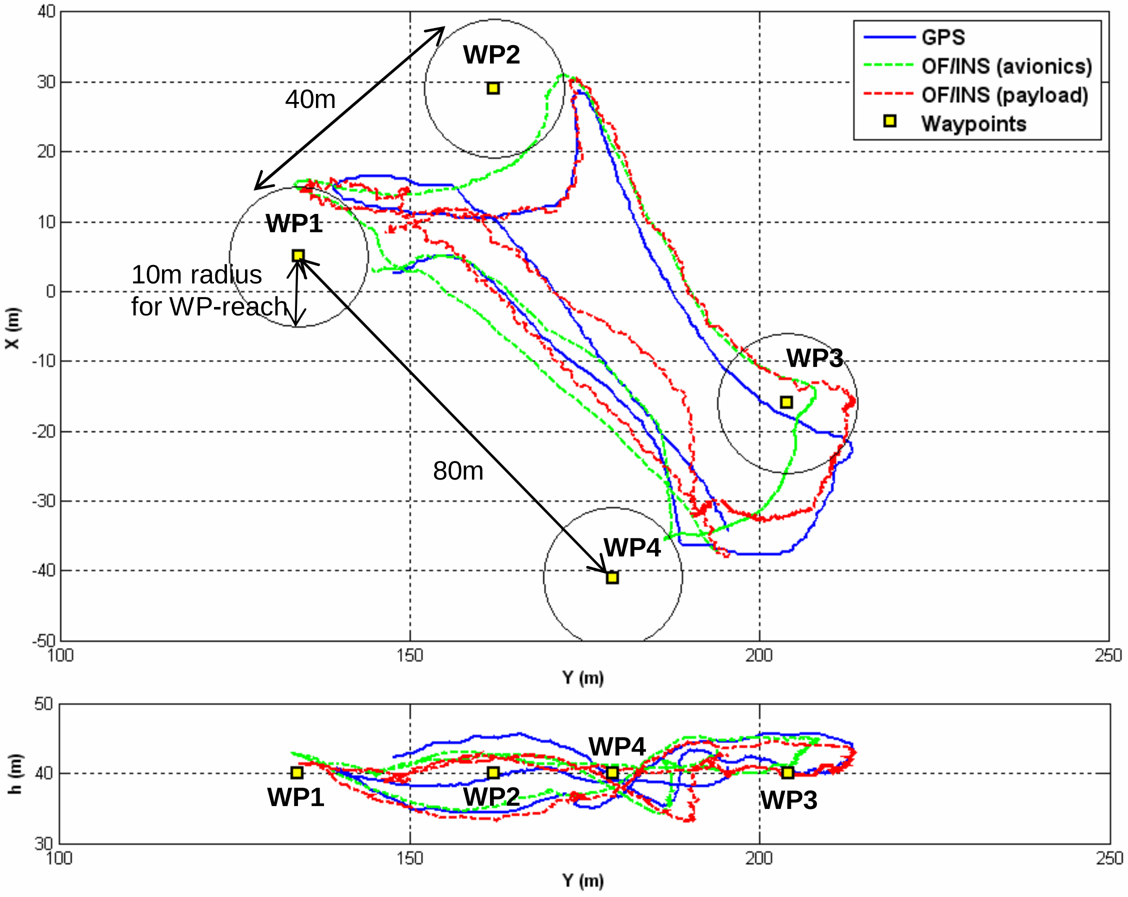
Closed-loop flight test results

❖ GPS cut-off during WP tracking mission

- Rectangle trajectory
  40 x 80 (m)
- Constant heading
  into wind NW

- 10m of WP-reach criteria

- Flight distance (w/o GPS)
  ~ 320 (m)
- Flight time (w/o GPS)
  ~ 130 (sec)



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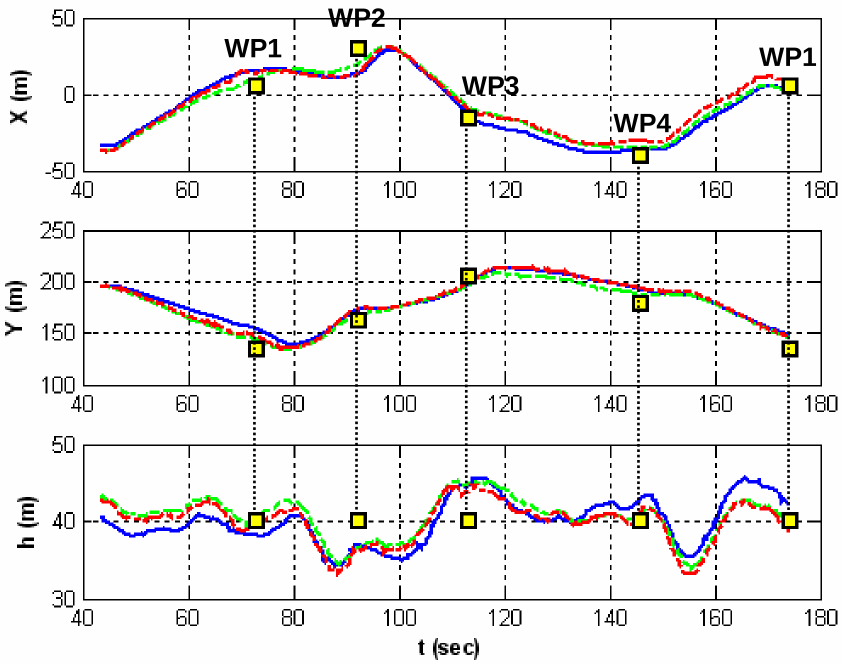
Closed-loop flight test results

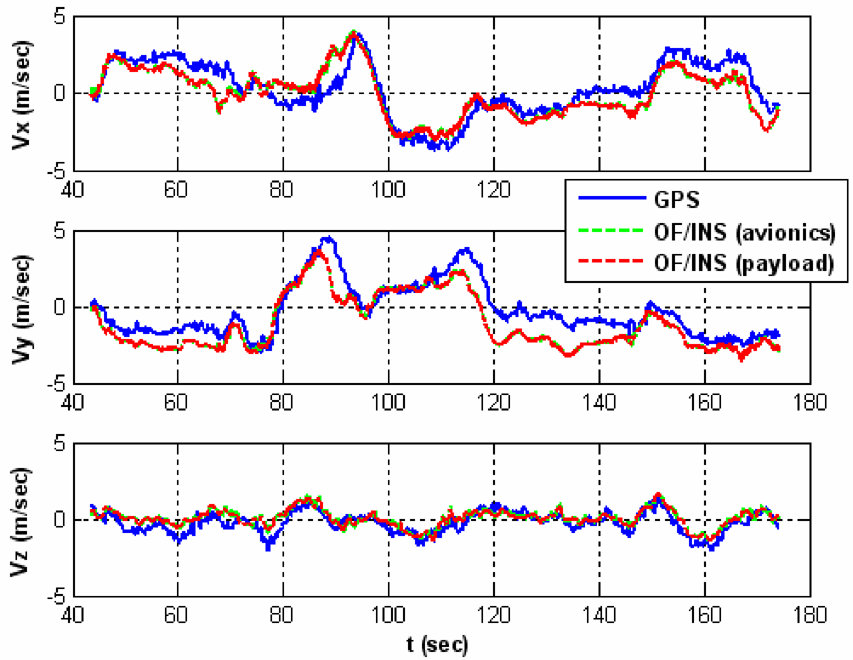
❖ OF-estimated vs. GPS-estimated position and velocity

- Position estimation error < 12m
- Stable altitude estimation by barometer + laser
- WP miss distance < 12m

Position



Velocity



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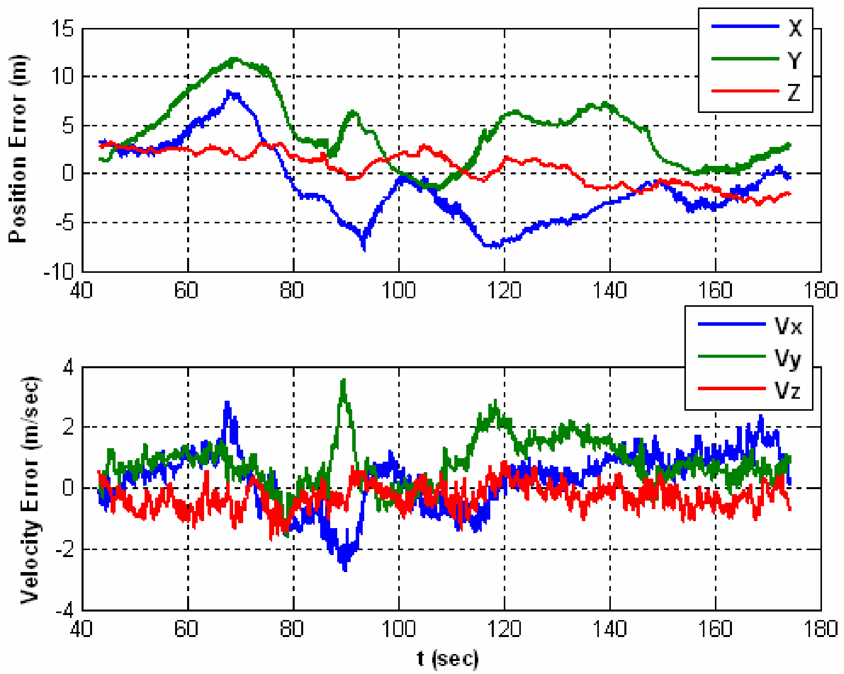
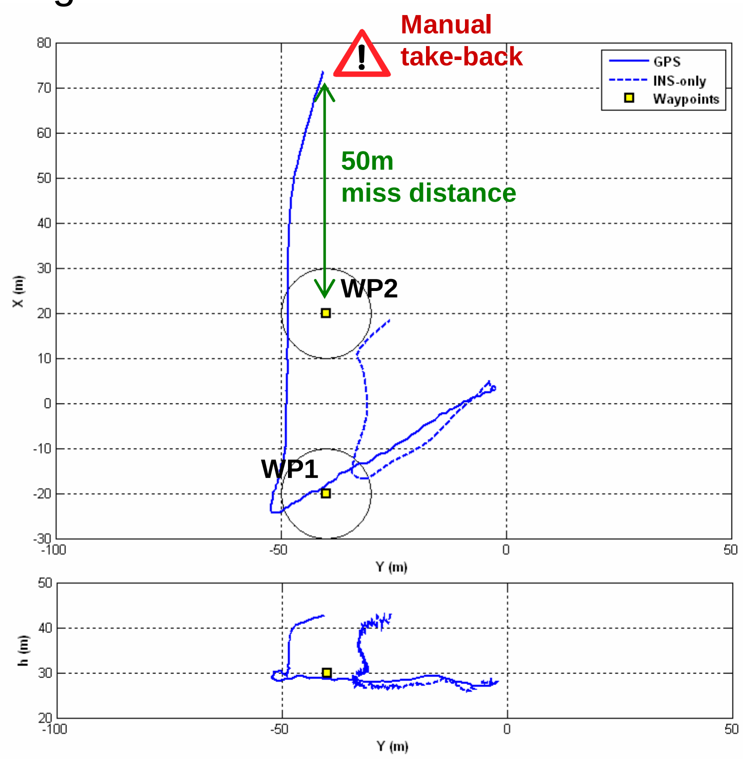
Closed-loop flight test results (3/3)

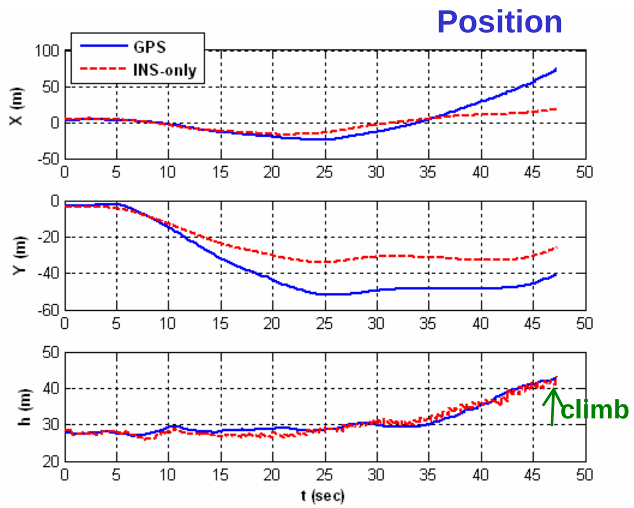
❖ Position and velocity estimation errors

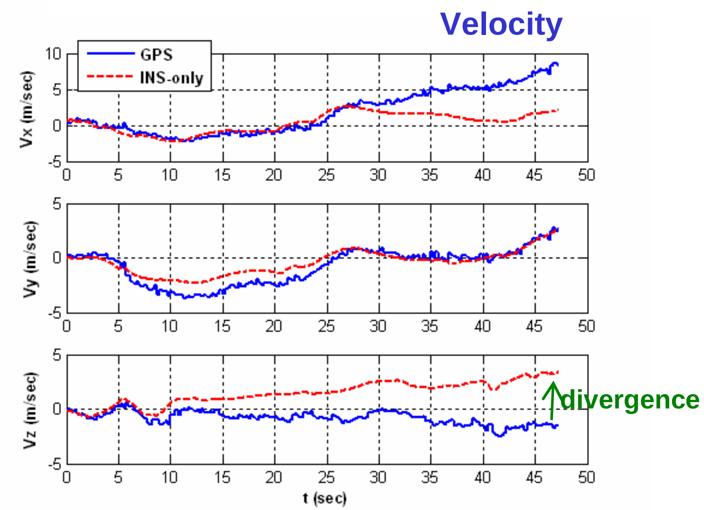


Closed-loop flight test results with INS-only navigation

- Position and velocity estimation errors
  - Stabilization
  - 50 m of drift after 45 sec
  - Divergence in altitude control due to Vz estimation

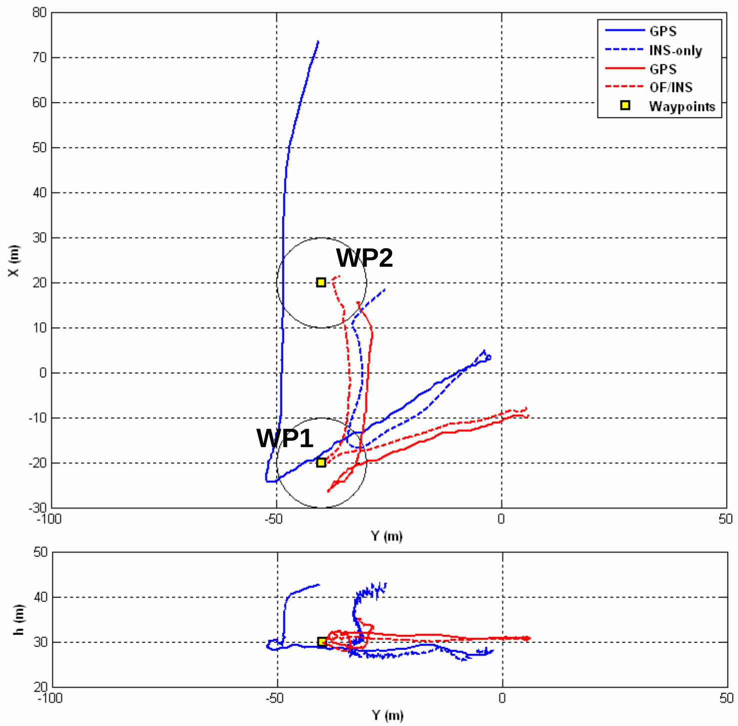






Closed-loop flight test results with INS-only navigation

❖ Position and velocity estimation errors



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Summary for GPS-independent navigation system

❖ Summary

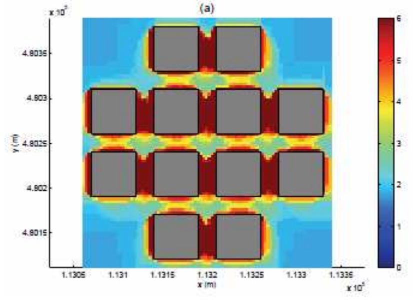
- Development and in-flight validation of optical flow-based inertial navigation system
- WP tracking mission continuation with GPS cut-off (switch navigation modes)

❖ Perspectives

- Performance improvement
  - Different OF estimation algorithms
  - Different VINS algorithms
- Demonstration of automatic return-to-base w/o GPS
  - Return-to-base by VO
  - Automatic landing with vision-based control
- Reconfigurable navigation system
  - Sensor failure
  - GPS accuracy

Path planning with GPS signal occlusion map

F. Kleijer et al. «Prediction of GNSS availability and accuracy in urban environments»



❖ Motivation

- Prediction of PDOP (Positional Dilution of Precision) of GPS at a certain time & location, from 3D obstacle map

UAV safe operation planning

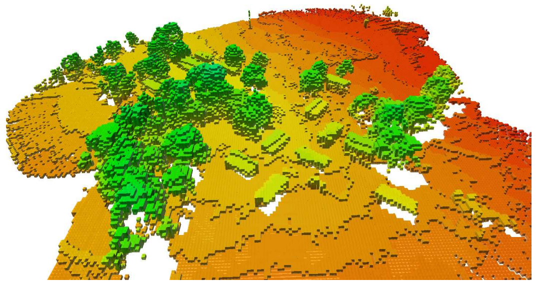
- Avoid zones at high risk of GPS signal loss, if no degraded navigation mode is available
  - → Use sensor availability map in path planning task
  - → Choice of the best navigation mode
- Take more safety margin when using degraded navigation mode
  - → Obstacle collision risk w.r.t. localization uncertainty

3D safe path planning problem

❖ Objective = find a *safe & short* path from A to B

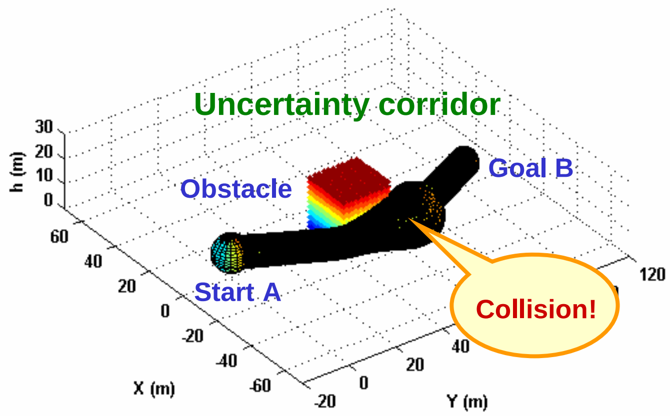
❖ Given :

- Environment model = 3D voxel occupancy map



- *N* different UAV localization modes
  - Positional availability
  - Error propagation model

- Collision criteria
  - Minimum safety distance = ds
  - Uncertainty corridor = (2σ+ds)-ellipsoid evolution
  - Safe path = no interception between the corridor and occupied voxels



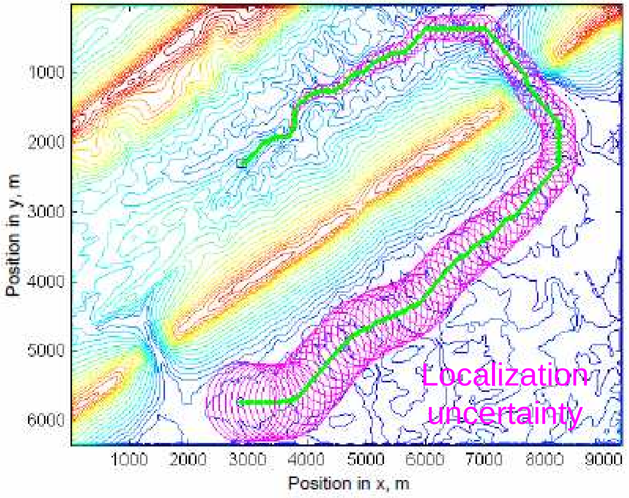
- Minimizing function =
  Volume of the uncertainty corridor
  - Path length
  - Integrated localization uncertainty

❖ Path planning with localization uncertainty

- Ground mobile robot navigation with
  - Dead-reckoning
  - Landmark detection

- Collision risk-free minimum distance path
  - A* : [Alami 1994], [Lambert 2003], [Gonzales 2005] etc.
  - Sampling-based (PRM, RRT) : [Peppy 2006], [Luders 2013], [Bopardikar 2014] etc.
  - POMDP : [Candido 2010] etc.

The localization mode is imposed



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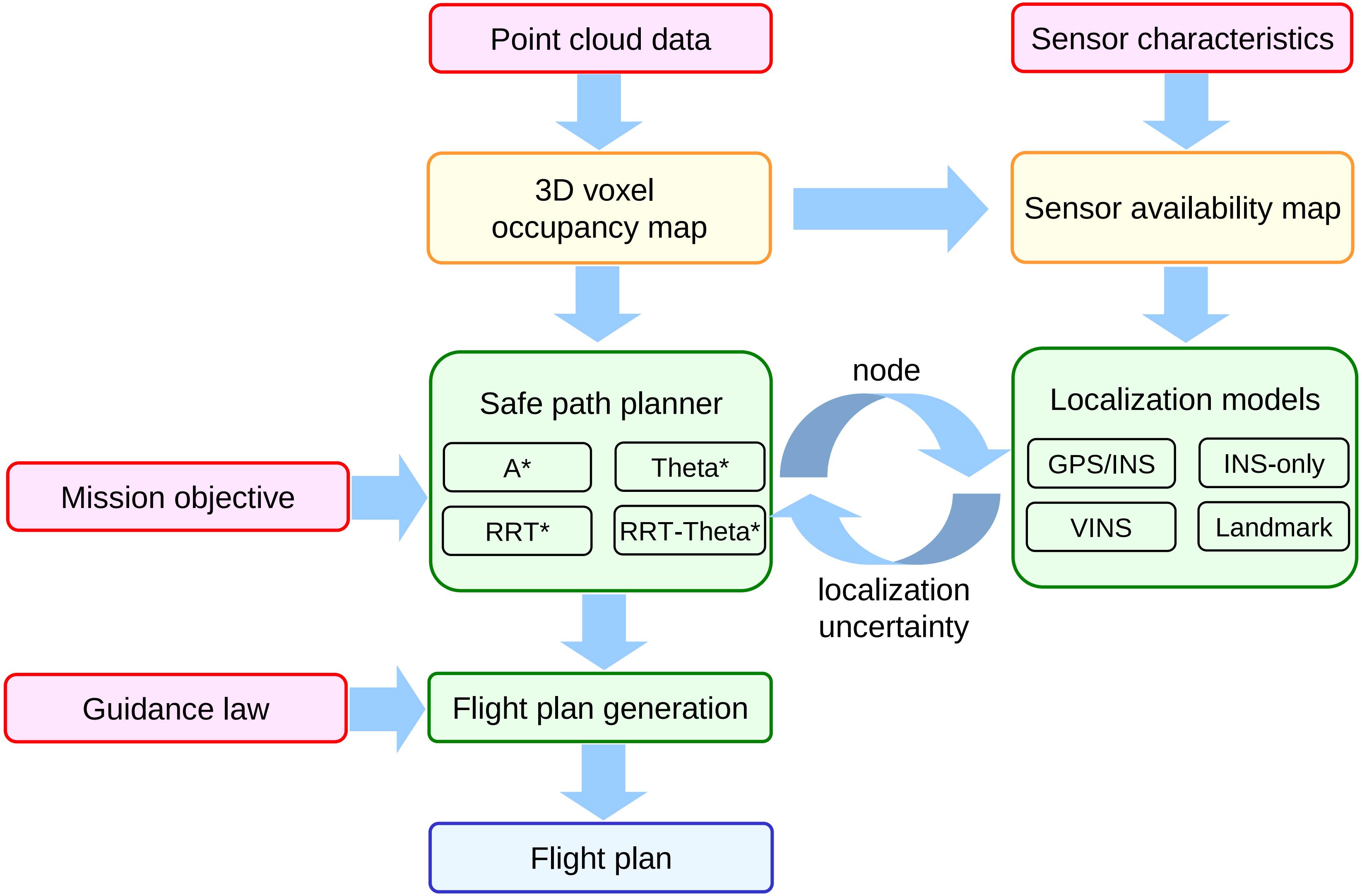
Related Work (2/2)

❖ Path and <u>observation strategy</u> planning

A. Yamashita, K. Fujita and K. Kaneko, "Path and viewpoint planning of mobile robots with multiple observation strategies," IROS 2004.

- Ground mobile robot navigation with
  - Dead-reckoning
  - Landmark detection
    - 1 landmark by stereo
    - 2 landmarks
    - 3 landmarks
- Two-stage planning
  - Search for all collision risk-free paths with maximum allowable localization uncertainty
  - Viewpoint (and localization mode) planning on each path

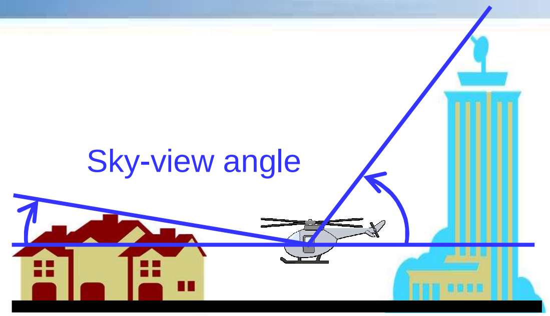
3D safe path planner architecture

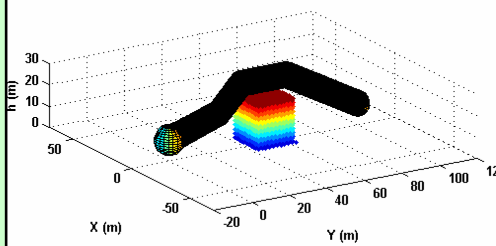
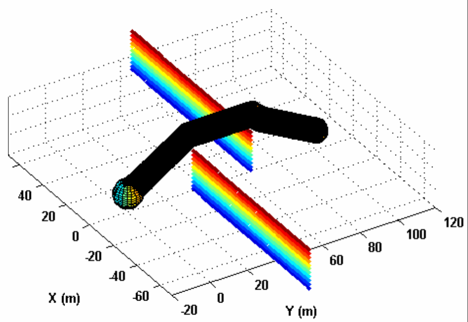
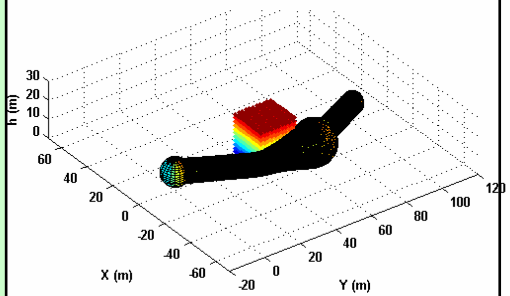
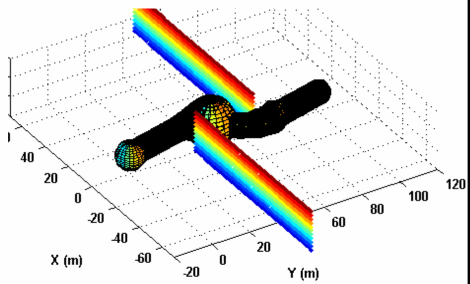


Example 1 : No VINS

❖ Path planning with GPS availability map

- No vision-aided navigation mode available onboard



	Cube	Wall Baffle
Safe path planner		
Shortest path planner		

→ fly over the obstacles to avoid no GPS zones

→ collisions due to divergence in localization error covariance

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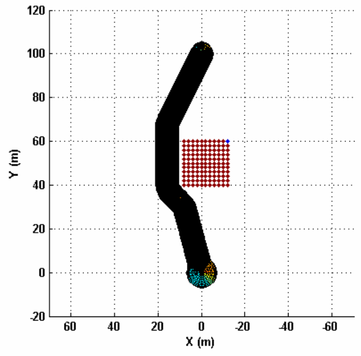
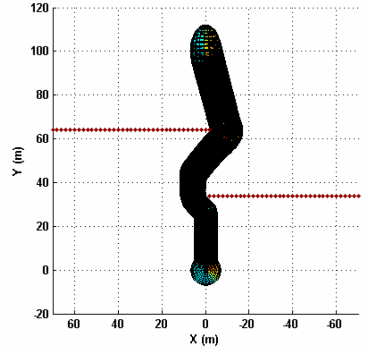
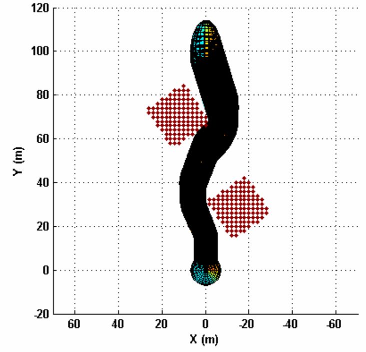
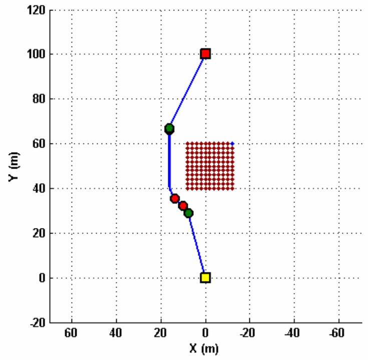
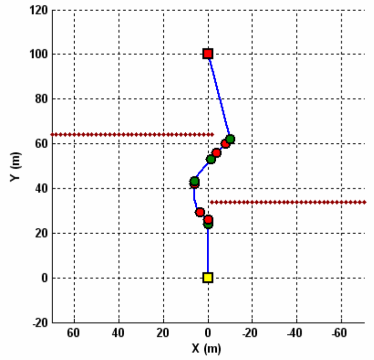
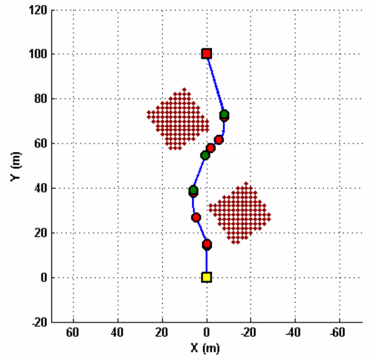
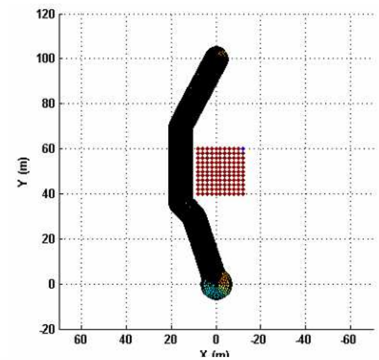
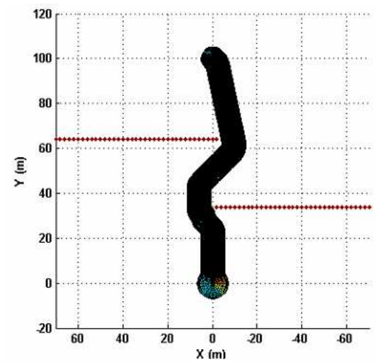
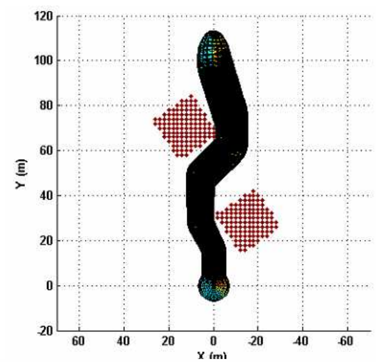
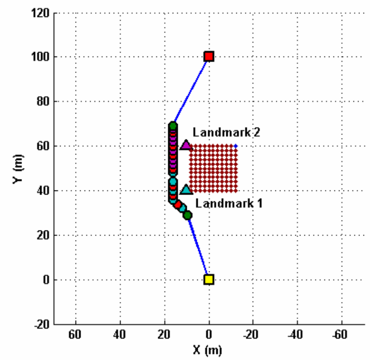
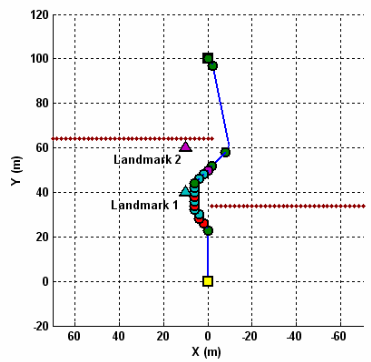
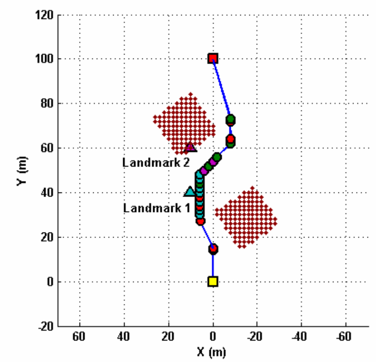
Example 2 : with VINS

	Cube	Wall Baffle	Cube Baffle
Uncertainty corridor			
Flight plan ● **INS-only** ● **GPS / INS** ● **VINS**			

Remark : Dependence on optical flow measurement noise

Example 3 : with VINS + Landmarks

	Cube	Wall Baffle	Cube Baffle
Uncertainty corridor			
Flight plan ● INS-only ● GPS / INS ● Vision / INS ○ Landmark1 ○ Landmark2			

Remark : Alternate use of VINS and Landmarks → Fusion

Summary for 3D safe path planning

❖ 3D safe path planner

- Under uncertainty with multiple localization modes
- Simulation studies with UAV obstacle field navigation benchmark
- Preliminary flight test to validate onboard mapping and planning

❖ Future work

- Dynamic path re-planning using sampling-based graph search (RRT*)
  - online mapping
  - supervision on real sensor availability and localization performance

- Path planning with different guidance strategies
  - visual servoing (e.g. wall following etc.)