Autonomous navigation in industrial cluttered environments using embedded stereo-vision

Julien Marzat
ONERA Palaiseau

Aerial Robotics workshop, Paris, 8-9 March 2017

ONERA
THE FRENCH AEROSPACE LAB

retour sur innovation

Copernic Lab (ONERA Palaiseau)

❑ Research topics

- Vision-based localization, state estimation and mapping
- Guidance and control (including multiple vehicles)
- Safety, fault diagnosis and reconfiguration
- Embedded algorithms for autonomous navigation

Main application: Autonomous navigation of robots in indoor cluttered environments

❑ On-going projects

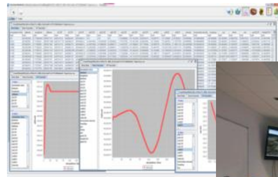
- ONERA / SNCF Research Partnership (DROSOFILES)
- FP7 EuRoC (European Robotics Challenges)

http://w3.onera.fr/copernic

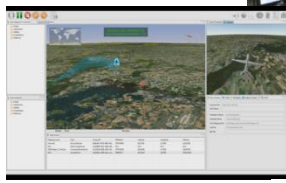
ONERA / SNCF Research Partnership

PRI DROSOFILES

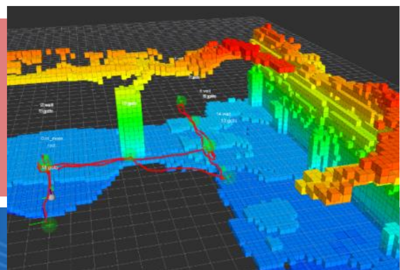
- **UAVs for SNCF (French Railways)**
  - Topics: indoor inspection, outdoor line or structure inspection
  - From corrective maintenance to predictive maintenance
  - Cost reduction



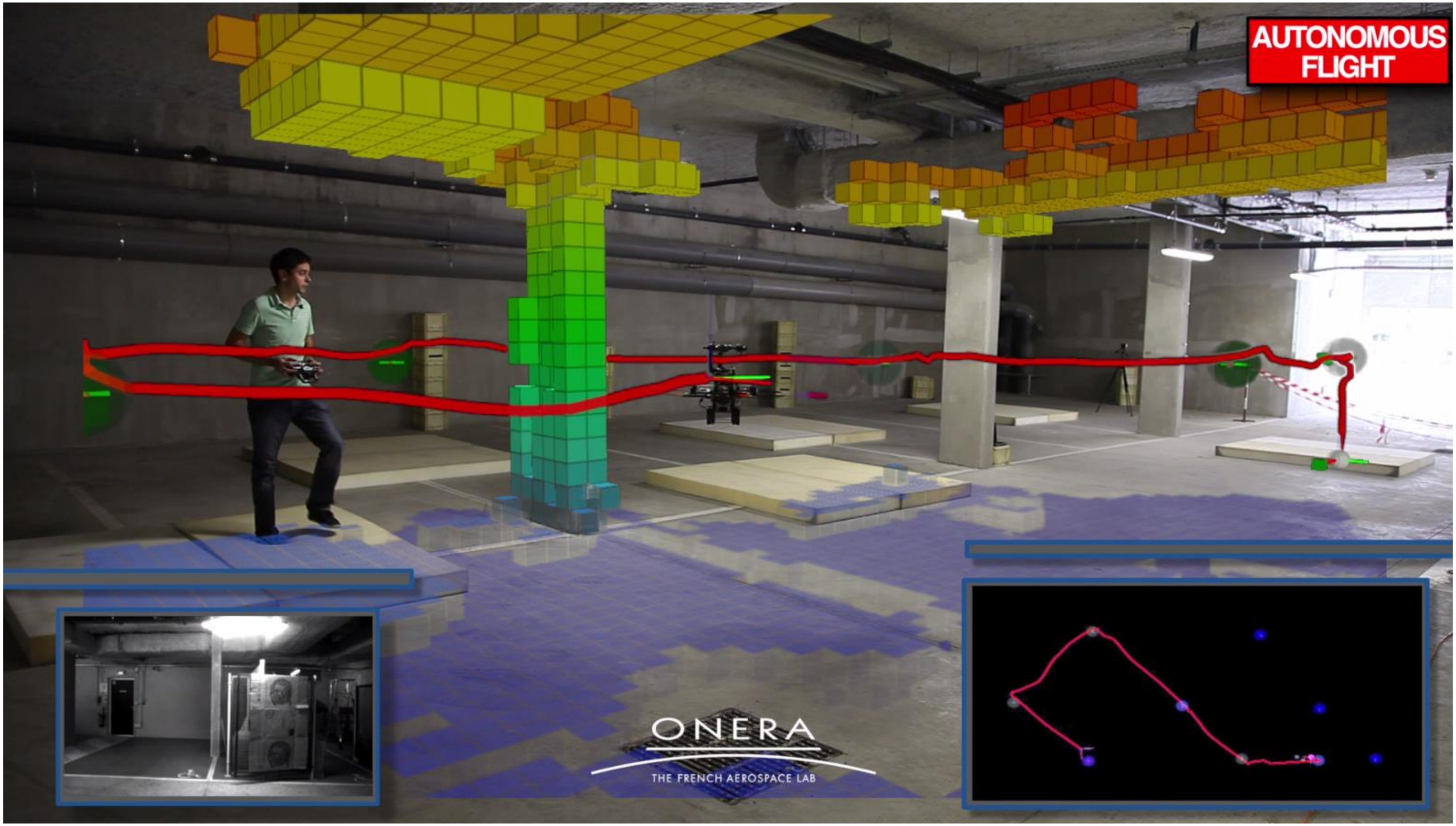
- **Multi-disciplinary ONERA expertise**
  - System Analysis, conception and simulation validation (SimulationLab)
  - Reglementation, safety and certification
  - Aerial Robotics (autonomous navigation)
  - Embedded sensors (IR, camera, radar)
  - Ground Station
  - Data processing and interpretation



Flight demonstration



First demonstration (June 2015)
Waypoint navigation using vision-based localization and mapping



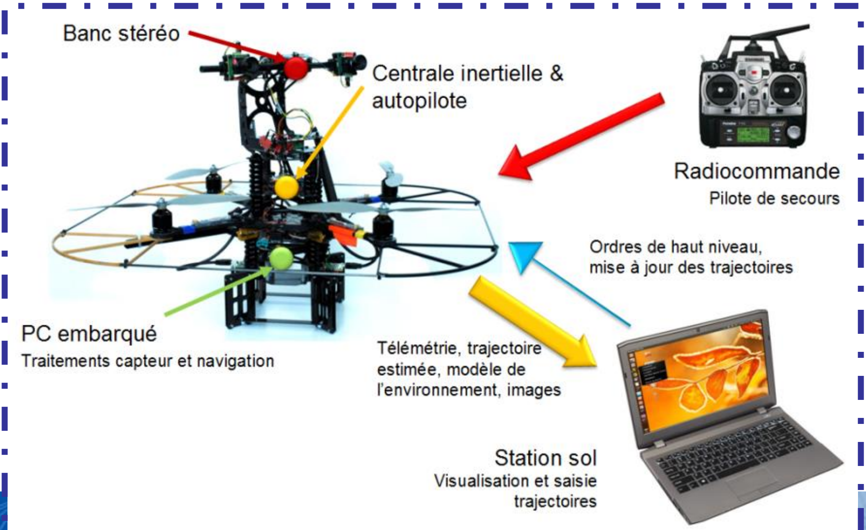
On-board sensor fusion (IMU/vision) for localization, octomap mapping, PID control

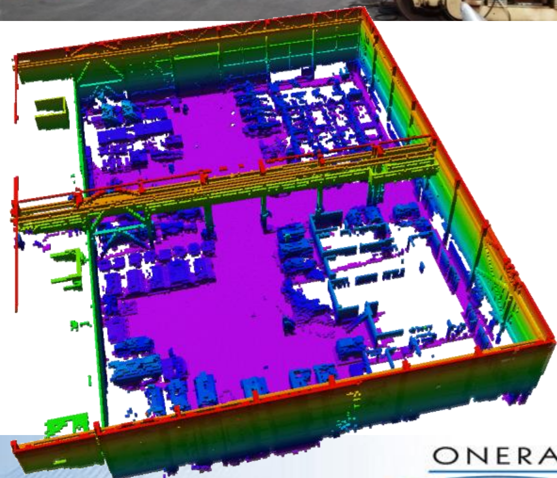
Demonstrations in industrial environment (2016)

❑ New functionalities

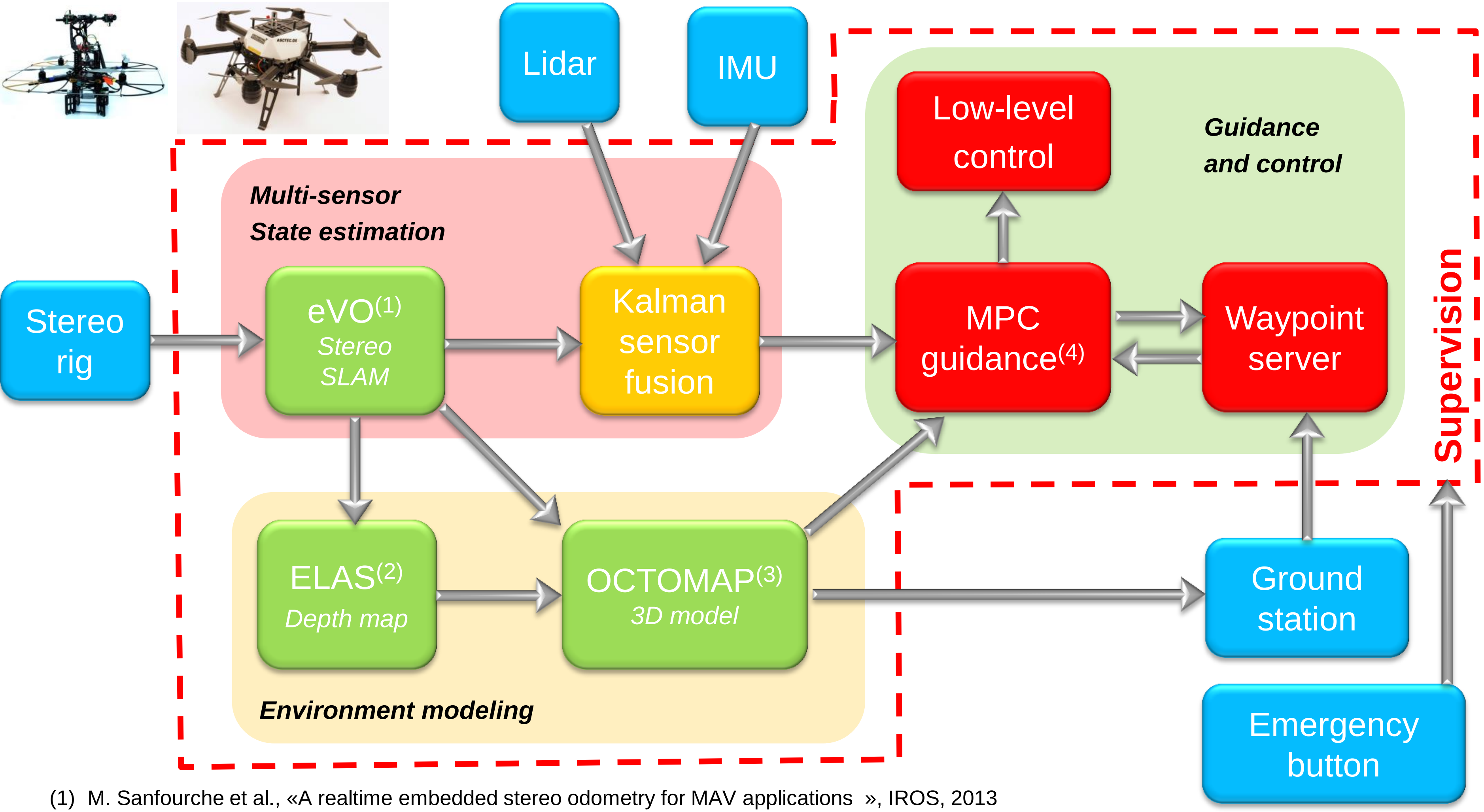
- Automatic take-off and landing using laser telemeter
- Yaw control from 3D coordinates
- Trajectory tracking
- Obstacle detection and avoidance

❑ Asctec Pelican platform





Embedded perception and control loop



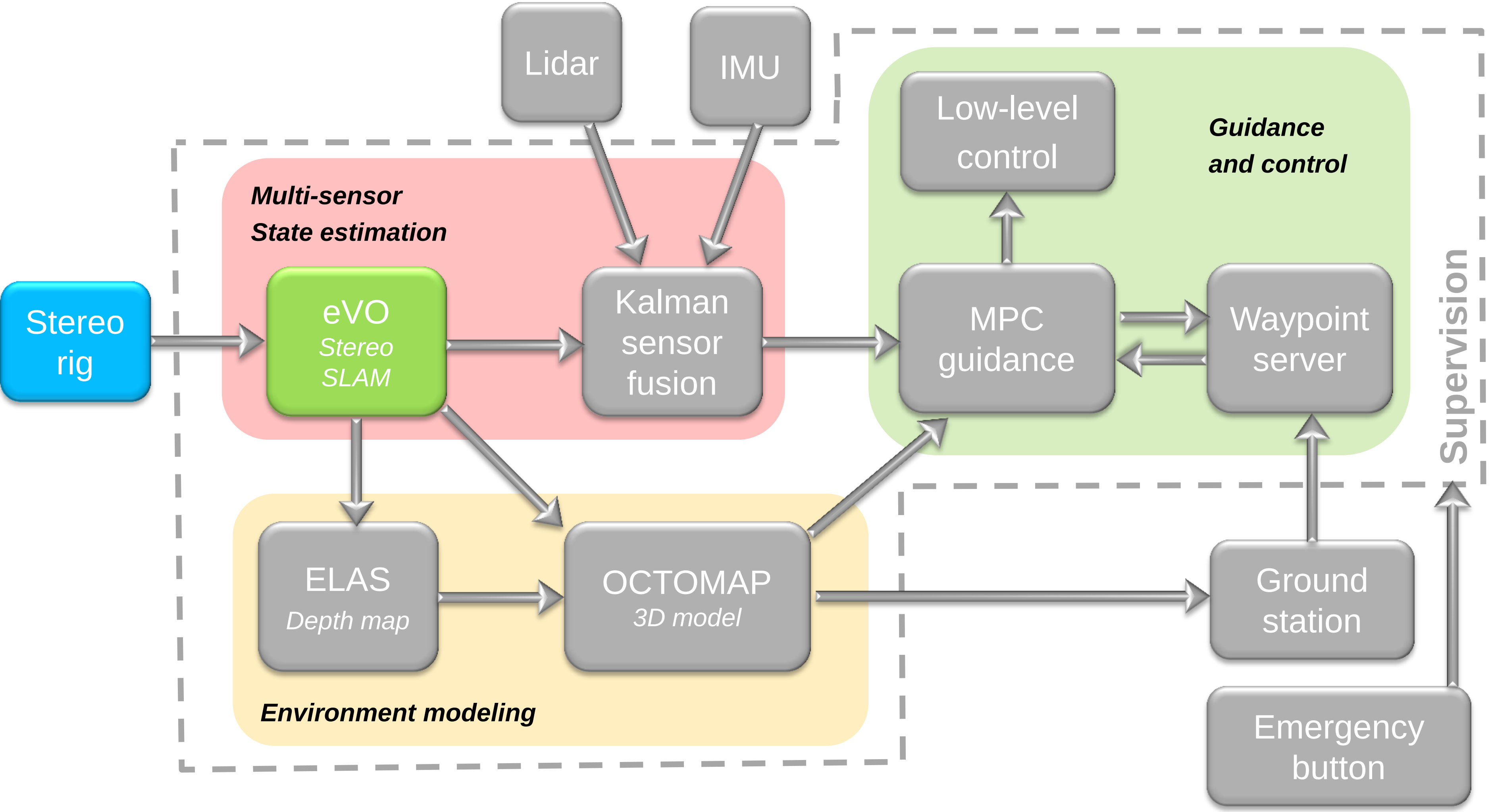
(1) M. Sanfourche et al., «A realtime embedded stereo odometry for MAV applications », IROS, 2013

(2) A. Geiger et al. , « Efficient Large-Scale Stereo Matching », ACCV, 2010

(3) A. Wurm et al., « Octomap: an efficient probabilistic 3D Mapping Framework based on octrees », Autonomous Robots, 2013

(4) S. Bertrand et al. « MPC Strategies for Cooperative Guidance of Autonomous Vehicles », AerospaceLab Journal, 2014

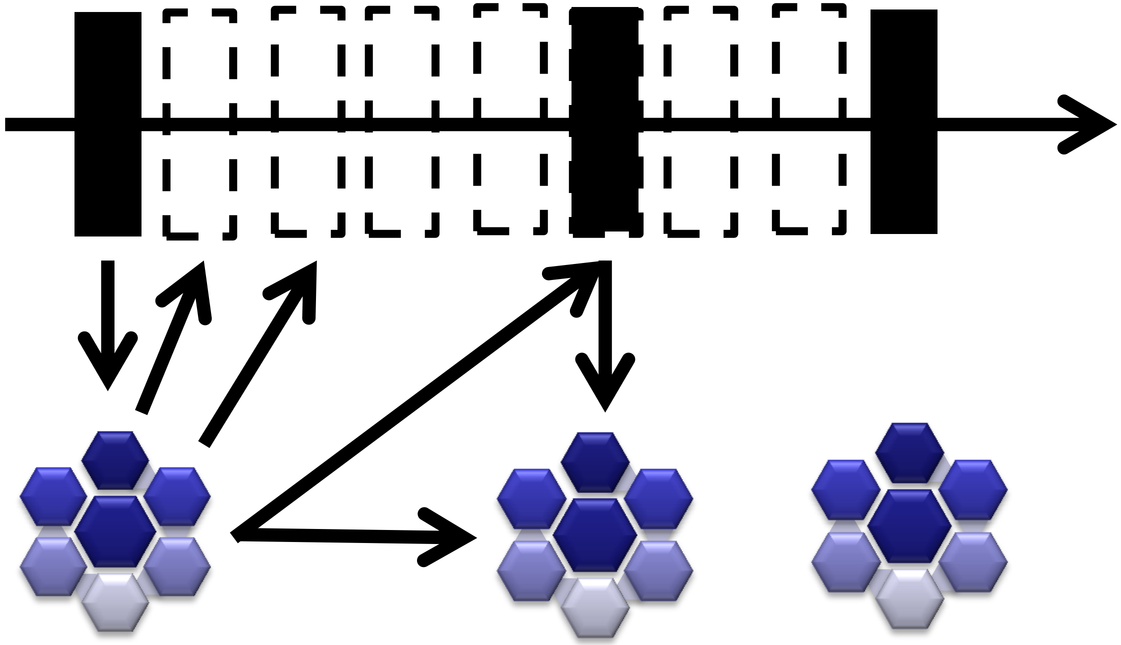
Vision-based localization: eVO



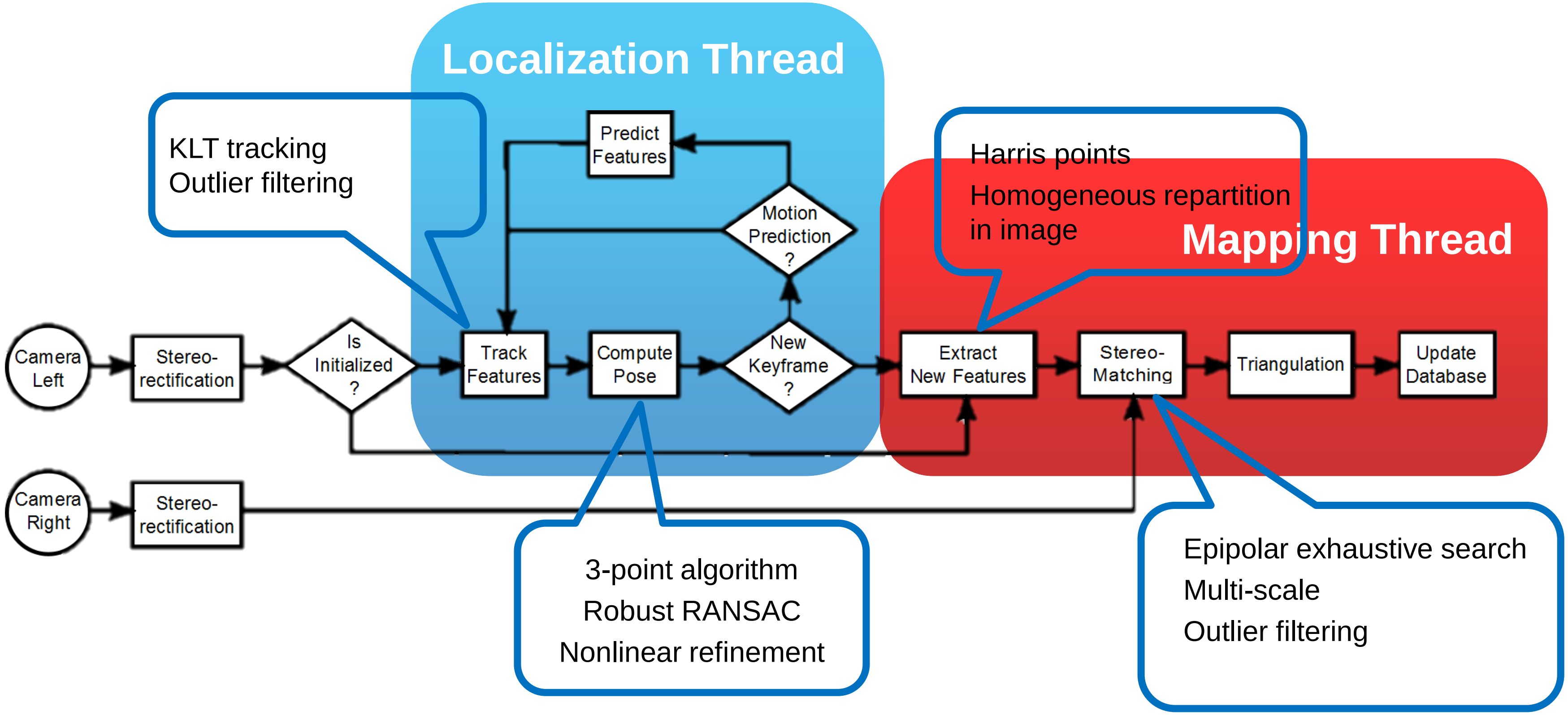
Vision-based localization: eVO

- Computes position and attitude using 3D sensors (stereo rig or RGB-D)
  20 Hz on a usual embedded CPU (Core2duo, i5, i7)
  Many flight hours in the last 4 years

- Operating principles
  - Map of 3D landmarks built on-line + localization in image => position and attitude
  - Key-frame scheme to limit complexity (update on number of visible landmarks)

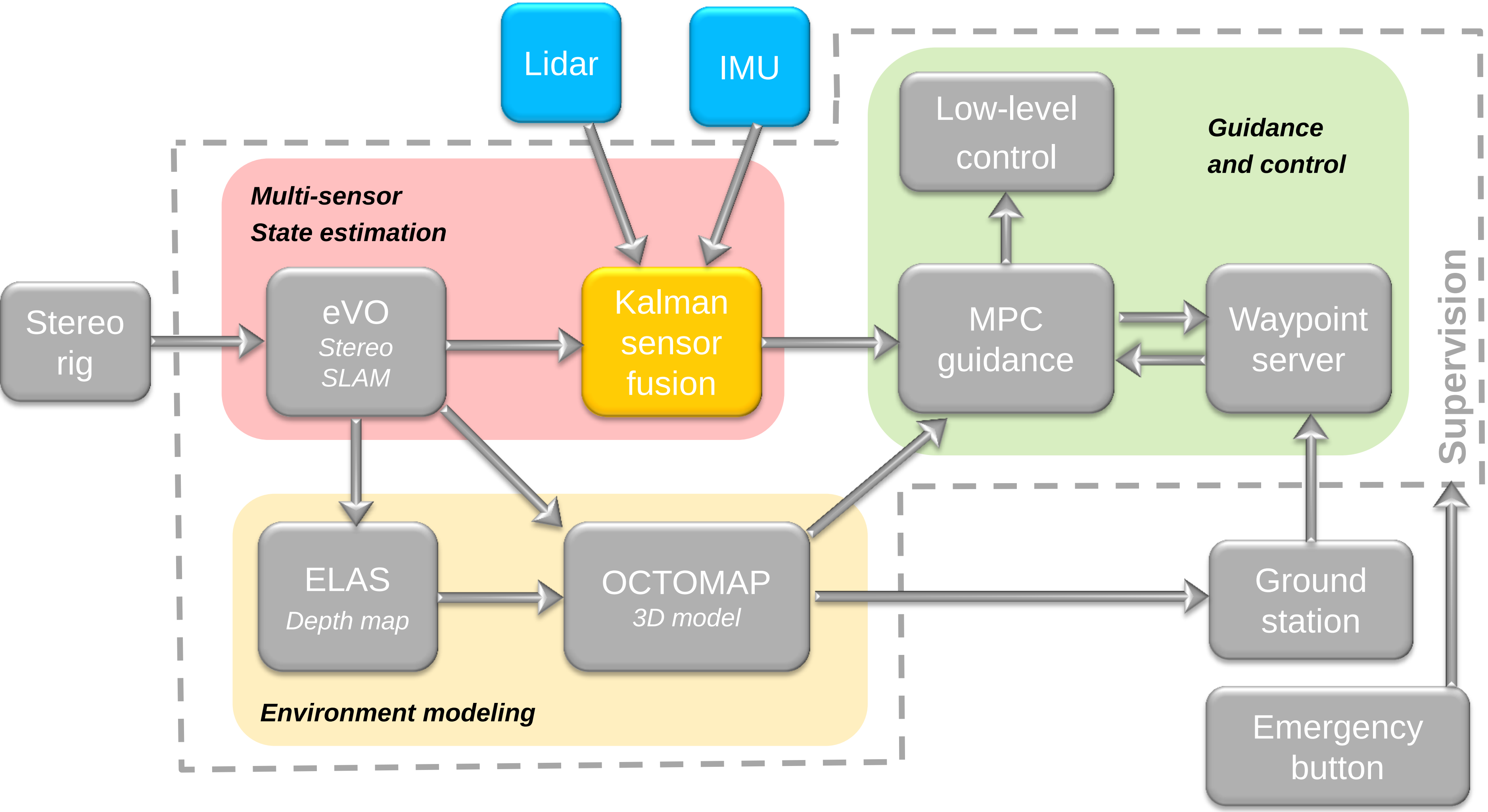


Vision-based localization: eVO



- **Other features**
  - Handles large fields of view using distortion models
  - RANSAC management of 3D landmarks

Multi-sensor state estimation

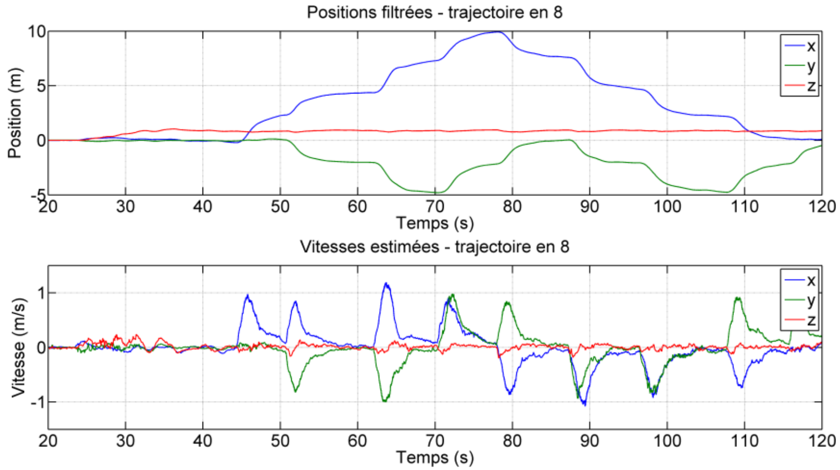


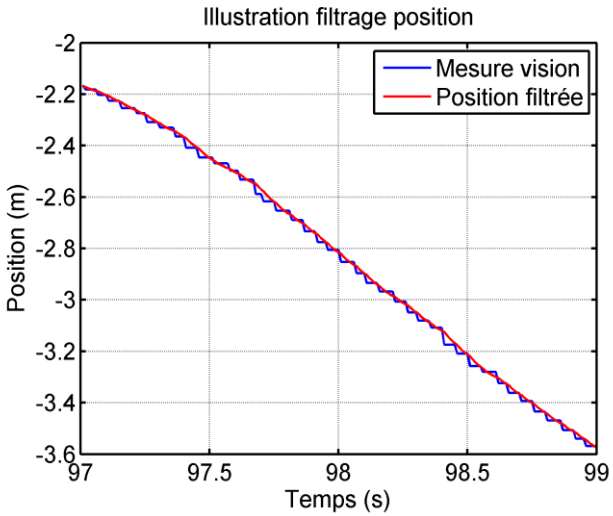
Multi-sensor state estimation (Kalman filter)

- Prediction of position and velocity using IMU measurements [accelerometers at 100 Hz]
- Filtered orientation provided by Asctec IMU [100 Hz]

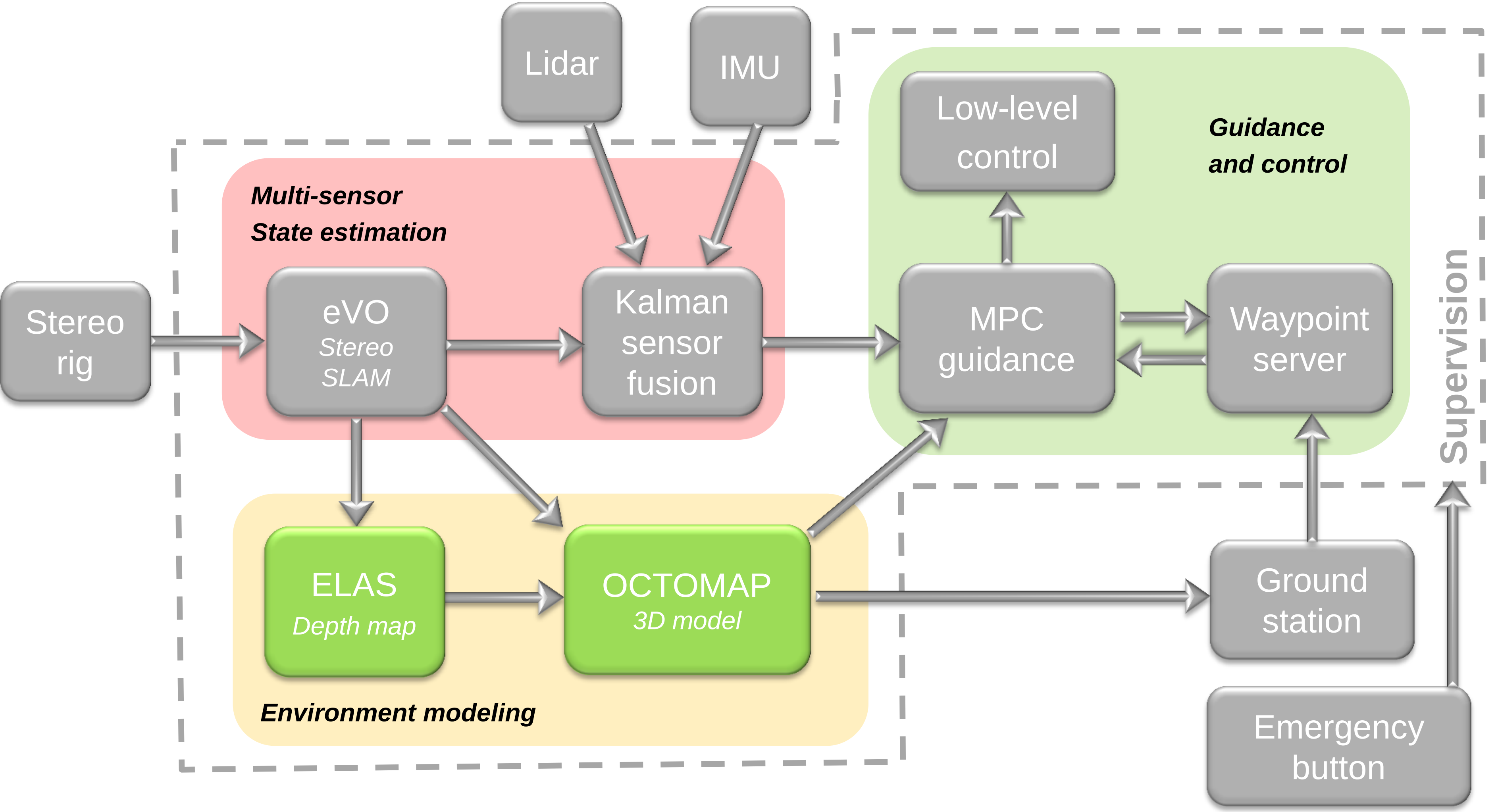
$$\begin{cases} \widehat{\boldsymbol{P}}(k+1) = \widehat{\boldsymbol{P}}(k) + \widehat{\boldsymbol{v}}(k)\ \delta\mathrm{t} \\ \widehat{\boldsymbol{v}}(k+1) = \widehat{\boldsymbol{v}}(k) + \big(R\big(\boldsymbol{\theta}(k)\big)\boldsymbol{a}_{\boldsymbol{IMU}} + \boldsymbol{g}\big)\ \delta\mathrm{t} \\ \boldsymbol{\theta}(k+1) = \boldsymbol{\theta}_{\boldsymbol{IMU}} \end{cases}$$

- Correction using eVO position measurements [20 Hz]



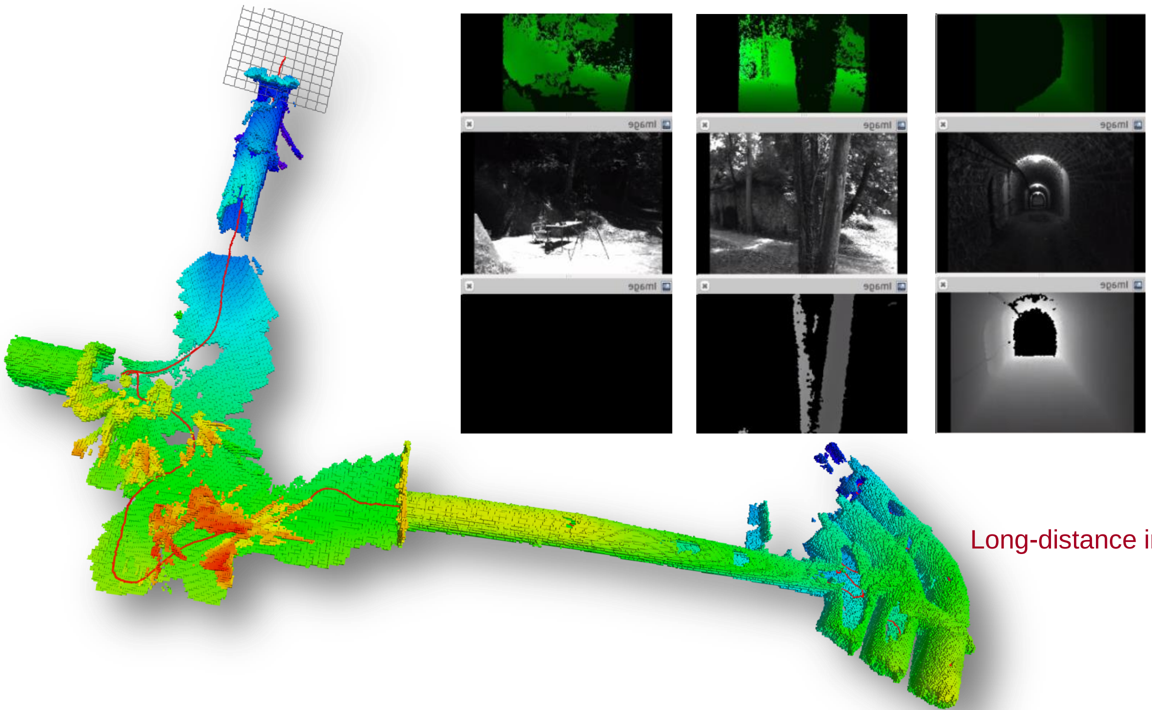


Environment modeling for safe navigation



3D environment modeling for safe navigation

- Discretized 3D voxel model (Octomap)
- Integration of depth maps (vision-based or sensor-based) in association with vehicle estimated position and attitude
- Probabilistic multi-scale representation of free/occupied/unexplored cells
- 1-2 Hz on embedded CPU

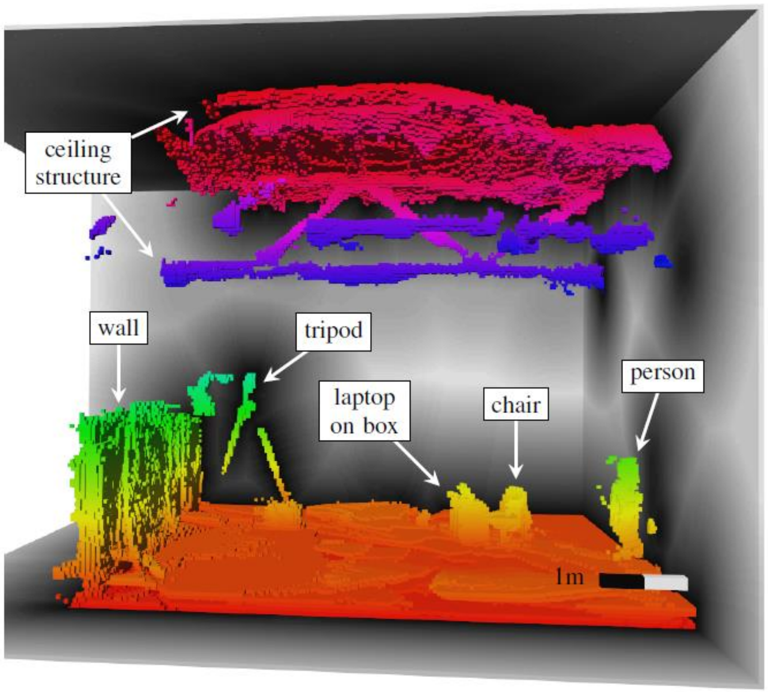


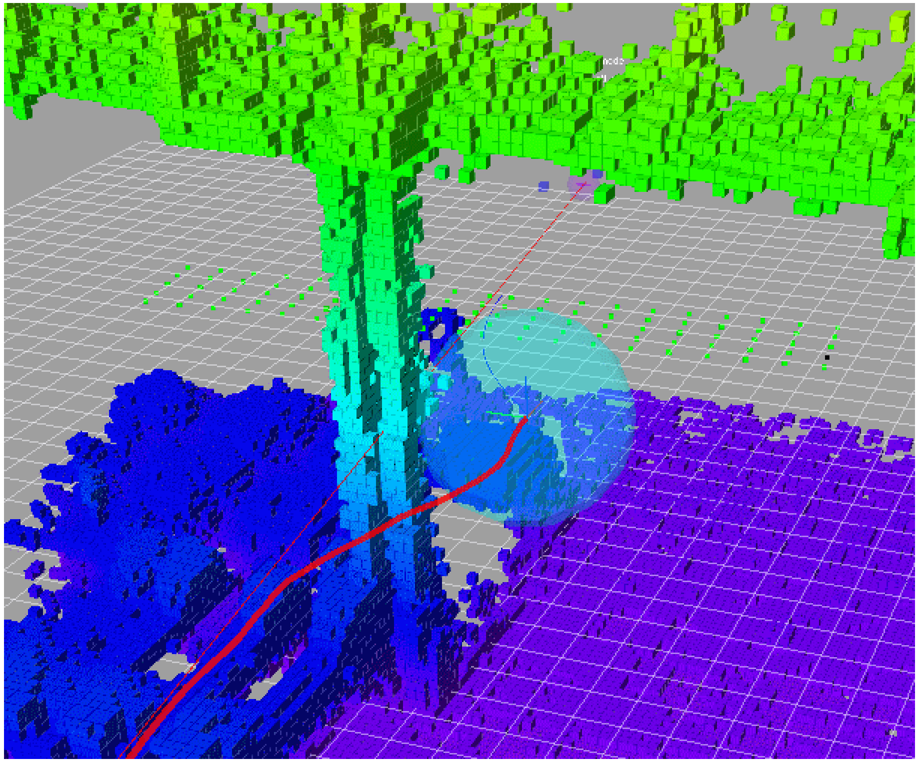
Long-distance indoor/outdoor 3D reconstruction
M. Sanfourche *et al.* 2014

(a) A. Wurm et al., « Octomap: an efficient probabilistic 3D Mapping Framework based on octrees », Autonomous Robots, 2013

3D environment modeling for safe navigation

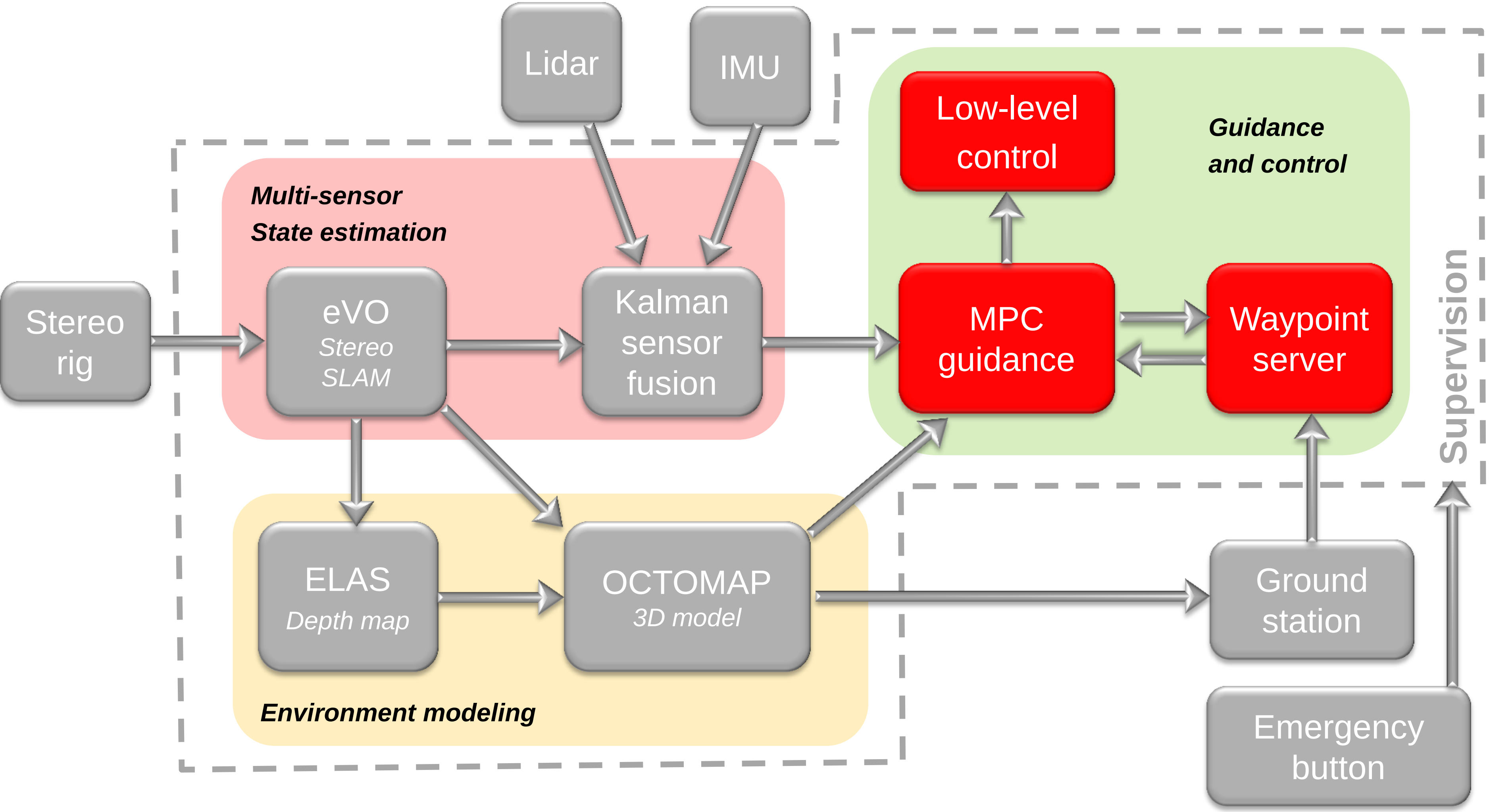
- Computation of an obstacle distance map from the voxel Octomap
  - Incremental Euclidean Distance Transform[b]
  - Efficient for collision checking: single call per position





(b) B. Lau et al., « Efficient grid-based spatial representations for robot navigation in dynamic environments », Robotics and Autonomous Systems, 2013

Guidance for autonomous navigation



Guidance for autonomous navigation

- **Control of translational dynamics**
  - Waypoint stabilisation, trajectory tracking, obstacle avoidance
  - Double integrator discretized model, acceleration control input

- **Model Predictive Control**

  Find optimal control input sequence minimizing a multi-criterion cost

$$U_k^* = \mathrm{Arg} \underset{U_k \in \mathcal{U}^{H_c}}{\mathrm{Min}} J\left(x_k, U_k, \overline{X}_k\right)$$

Sequence of H_c control inputs: $U_k = \left\{u_k, u_{k+1}, \ldots, u_{k+H_c-1}\right\}$

Predicted states on H_p (>H_c) steps $\overline{X}_k = \left\{\overline{x}_{k+1}, \overline{x}_{k+2}, \ldots, \overline{x}_{k+H_p}\right\}$

  - Takes into account future behaviour and environment
  - Handle constraints on control inputs
  - Optimization required => computation time should be limited

Guidance for autonomous navigation

- Multi-criterion cost function to be minimized

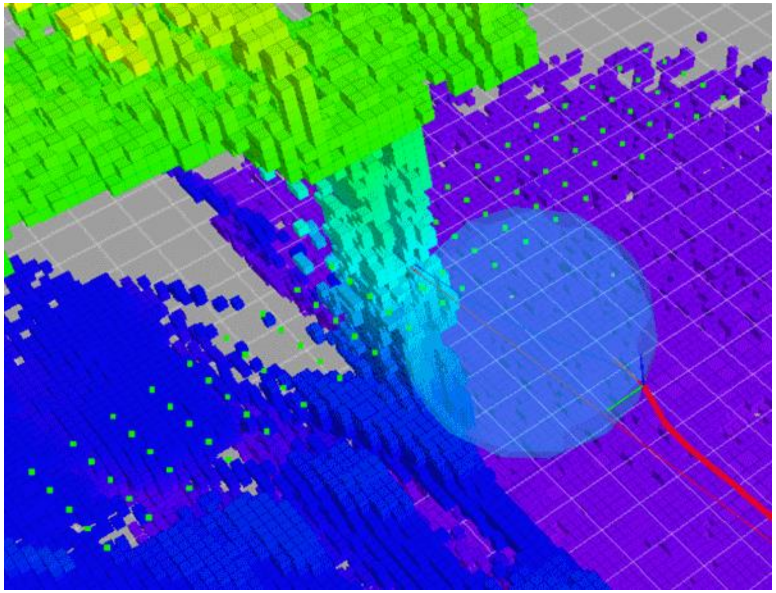
$$J = w_u.J_u + w_{nav}.J_{nav} + w_{obs}.J_{obs}$$

High-amplitude control inputs

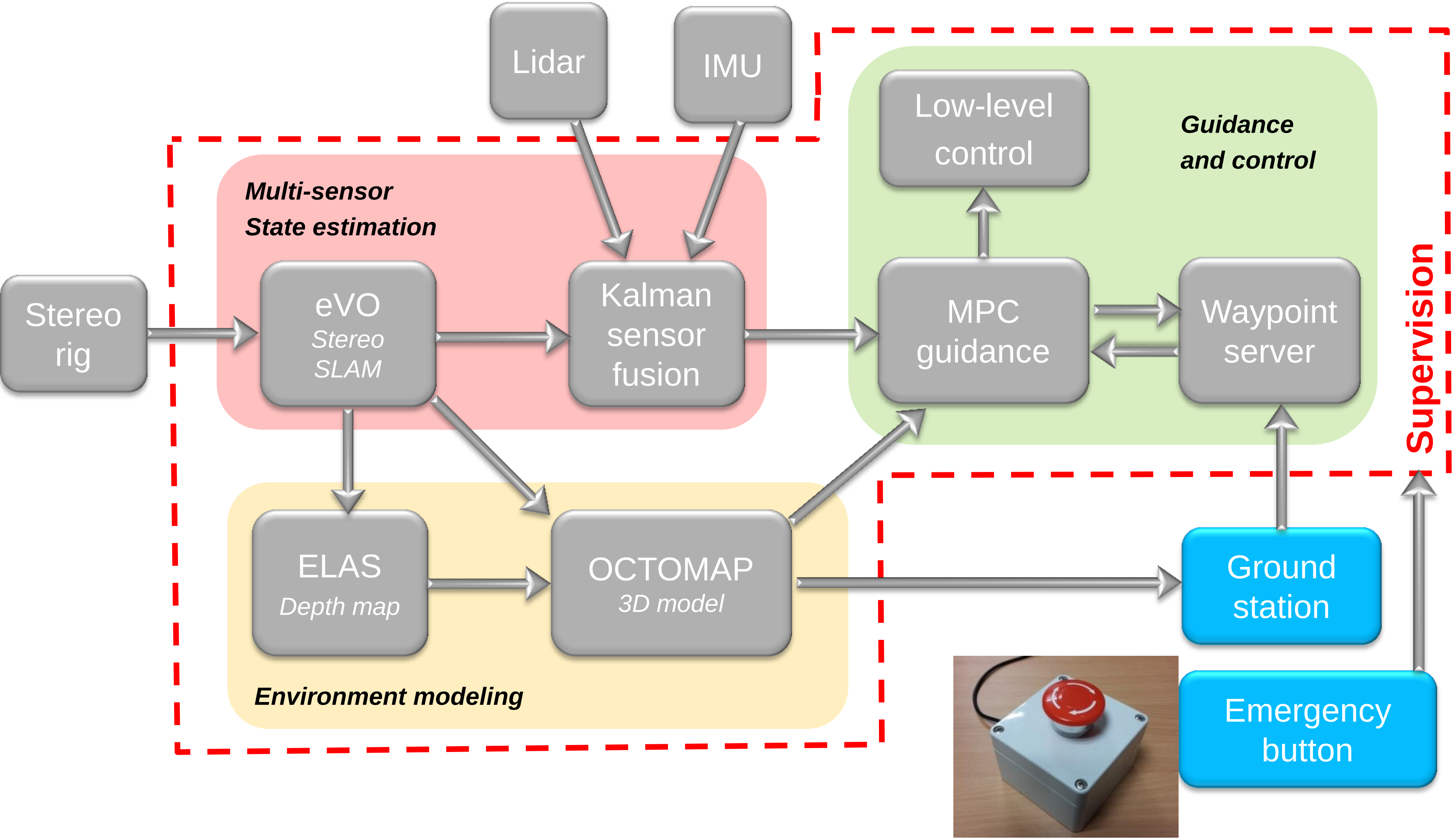
Deviation from reference trajectory

Distance to obstacles on predicted trajectories

- Search for sub-optimal solution in pre-discretized space
  - Limits and bounds computational cost
  - Successive avoidance planes tested



Supervision



Supervision – state machine for flight phases

Landed

Human pilot activates autopilot
Thrust stick at takeoff value

Taking-off

Nominal thrust reached

Calibrated

First waypoint validated

Mission

MAV is above landing position
OR
Emergency landing required

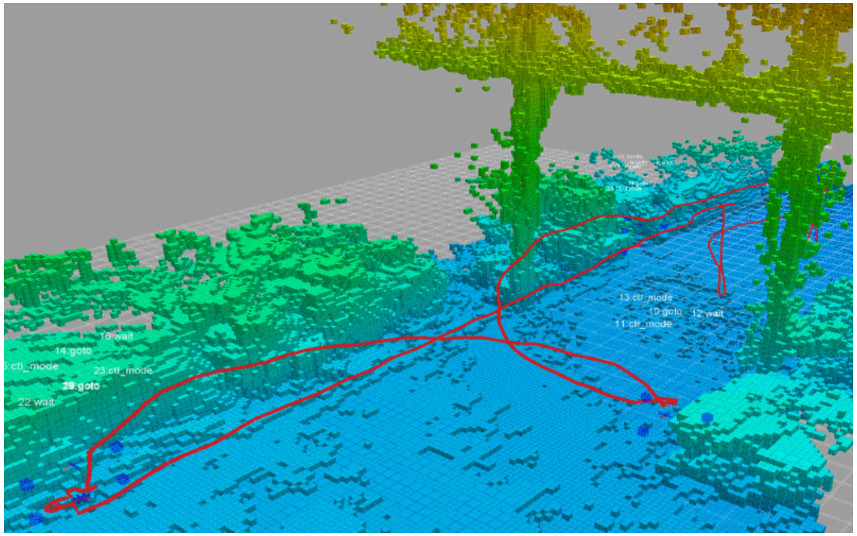
Landing

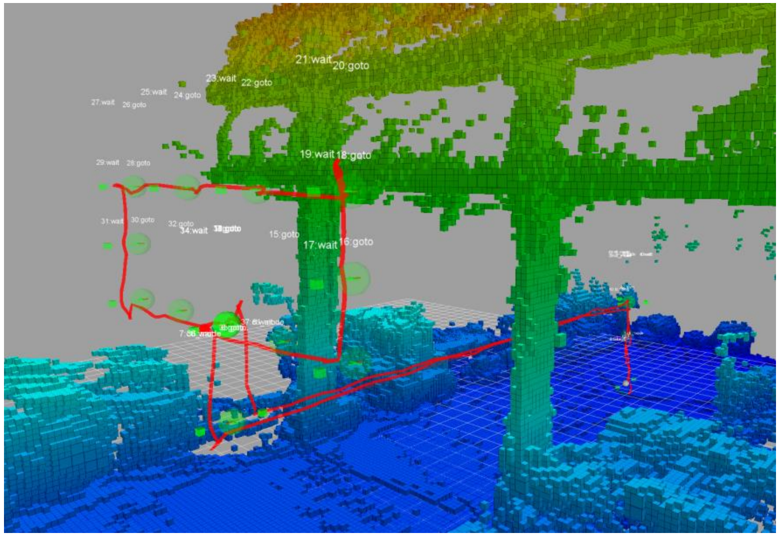
Human pilot puts thrust back to zero

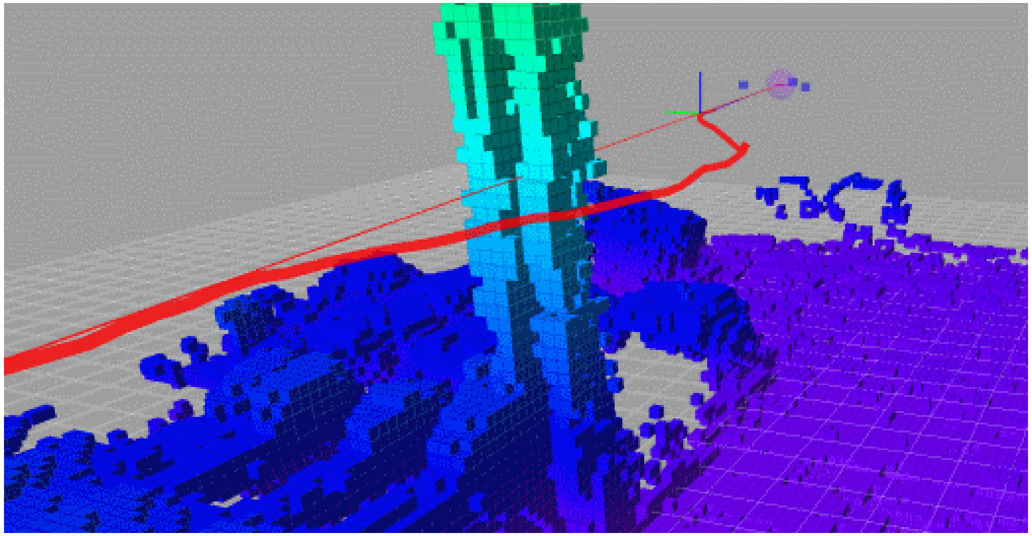
EMERGENCY

- Stay in place with remaining healthy sensors
- Emergency landing can be activated from ground station
- In last resort, control is given back to safety pilot

Experimental Results in SNCF warehouse







Autonomous damage inspection in power substation

ONERA THE FRENCH AEROSPACE LAB

UPMC SORBONNE UNIVERSITÉS

Rte

Vision-based autonomous exploration and mapping

Freestyle (August 2016)

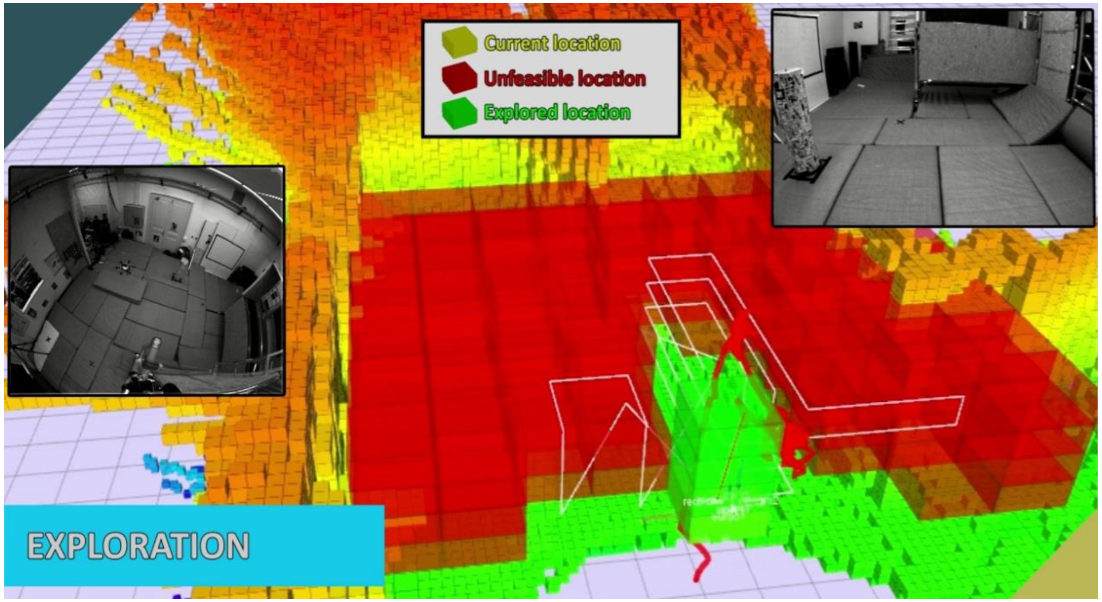
1. Autonomous exploration in GPS-denied environment
2. Dynamic non-cooperative obstacle avoidance

Showcase (March 2017)

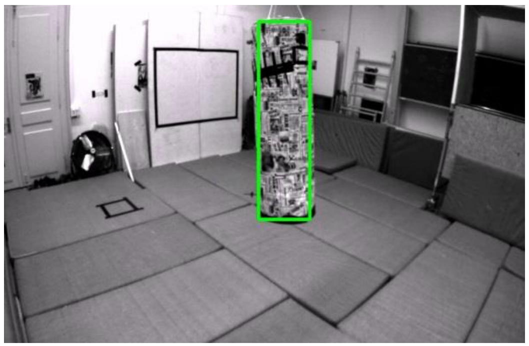
3. Many thin, hollow and linear structures
4. Variable illumination conditions (reduced light)

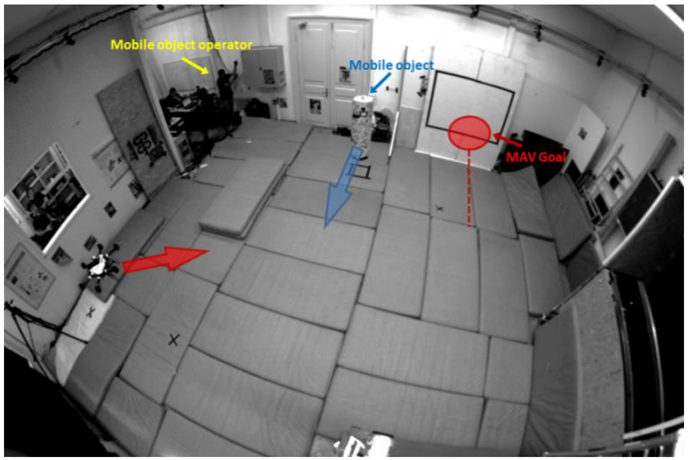
FP7 EUROC – Freestyle results

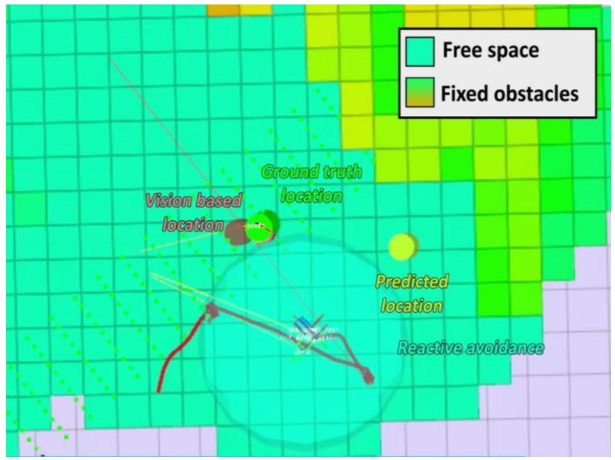
Autonomous Exploration



Mobile Object Tracking and avoidance







Autonomous navigation in presence of mobile objects

Stereo-vision for detection and motion estimation

1. Dense residual optical flow
2. Sparse feature-clustering

Model Predictive Control for safe trajectory definition

- Multi-objective criterion
- Systematic search approach

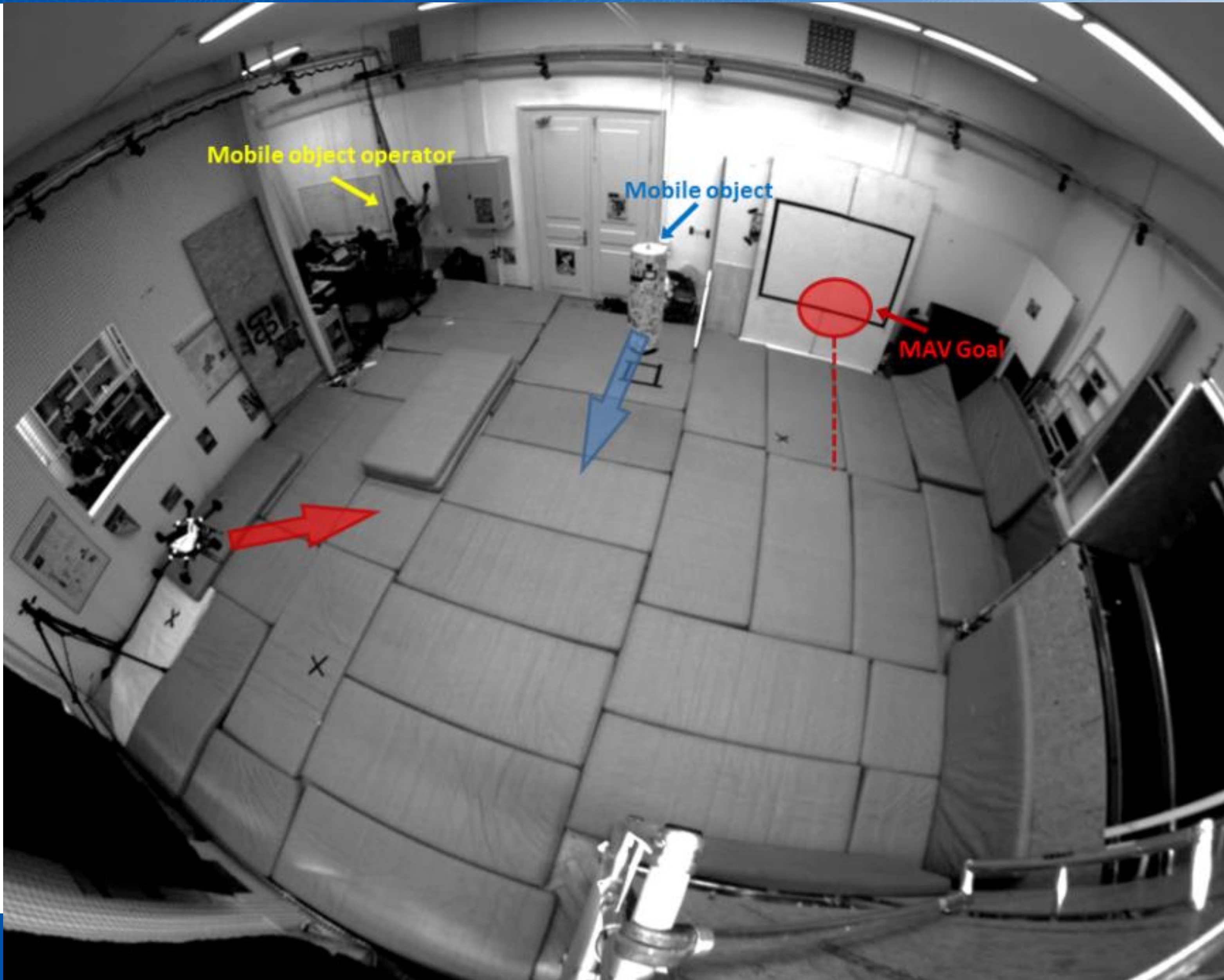
+

- ✓ **Detection and avoidance of mobile objects**
- ✓ **Everything computed on-board**
- ✓ **Successful experiments**

Mobile robot with GPU

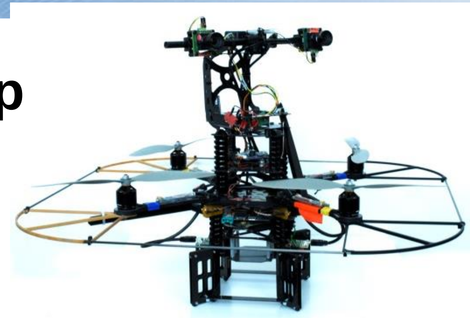
MAV with embedded CPU

FP7 Euroc – Avoidance of Mobile object



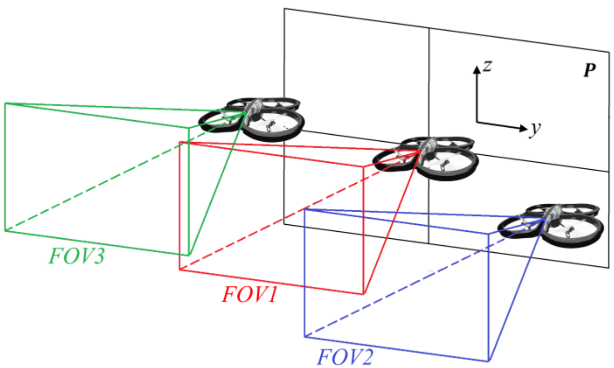
Current and future work

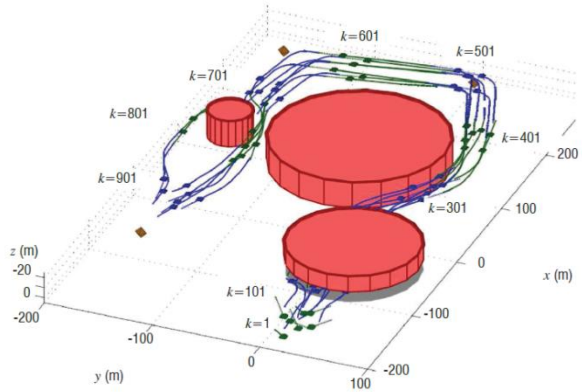
- **New demonstrations in ONERA / SNCF partnership**
  - Wall inspection
  - Mobile objects
  - Demonstration at IFAC WC (Toulouse) in July 2017



- **FP7 Euroc Showcase**
  - Autonomous exploration (volume coverage) in presence of thin / hollow structures

- **ONERA project on perception and guidance for multiple vehicles (2017 – 2020)**





Related publications

- J. Marzat, S. Bertrand, A. Eudes, M. Sanfourche, J. Moras, Reactive MPC for autonomous MAV navigation in indoor cluttered environments: flight experiments, IFAC WC 2017
- D.K. Phung, B. Hérissé, J. Marzat, S. Bertrand, Model Predictive Control for Autonomous Navigation Using Embedded Graphics Processing Unit, IFAC WC 2017
- H. Roggeman, J. Marzat, A. Bernard-Brunel, G. Le Besnerais, Autonomous exploration with prediction of the quality of vision-based localization, IFAC WC 2017
- H. Roggeman, J. Marzat, A. Bernard-Brunel, G. Le Besnerais, Prediction of the scene quality for stereo vision-based autonomous navigation, IFAC IAV 2016
- N. Piasco, J. Marzat, M. Sanfourche, Collaborative localization and formation flying using distributed stereo-vision, ICRA 2016
- J. Marzat, J. Moras, A. Plyer, A. Eudes, P. Morin, Vision-based localization mapping and control for autonomous MAV - EuRoC challenge results, ODAS 2015
- H. Roggeman, J. Marzat, M. Sanfourche, A. Plyer, Embedded vision-based localization and model predictive control for autonomous exploration, IROS VICOMOR 2014
- S. Bertrand, J. Marzat, H. Piet-Lahanier, A. Kahn, Y. Rochefort, MPC Strategies for Cooperative Guidance of Autonomous Vehicles, AerospaceLab Journal, 2014
- M. Sanfourche, A. Plyer, A. Bernard-Brunel, G. Le Besnerais, 3DSCAN: Online ego-localization and environment mapping for micro aerial vehicles. AerospaceLab Journal, 2014