Autonomous navigation in industrial cluttered environments using embedded stereo-vision

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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
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

Environment modeling

- Multi-sensor State estimation
  - eVO\(^{(1)}\) Stereo SLAM
  - ELAS\(^{(2)}\) Depth map
  - OCTOMAP\(^{(3)}\) 3D model
  - Kalman sensor fusion

Guidance and control
- Low-level control
  - MPC guidance\(^{(4)}\)
  - Waypoint server

Supervision
- Ground station
- Emergency button

2. A. Geiger et al., « Efficient Large-Scale Stereo Matching », ACCV, 2010
Vision-based localization: eVO

**Multi-sensor State estimation**
- eVO Stereo SLAM
- Kalman sensor fusion
- Lidar
- IMU

**Environment modeling**
- ELAS Depth map
- OCTOMAP 3D model

**Guidance and control**
- MPC guidance
- Low-level control
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**Supervision**
- Ground station
- Emergency button

**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

Localization Thread

- KLT tracking
- Outlier filtering
- Predict Features
- Motion Prediction
- Track Features
- Compute Pose
- New Keyframe

Mapping Thread

- Harris points
- Homogeneous repartition in image

Other features

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

3-point algorithm
- Robust RANSAC
- Nonlinear refinement

Epipolar exhaustive search
- Multi-scale
- Outlier filtering
Multi-sensor state estimation

Environment modeling

- Stereo rig
  - eVO Stereo SLAM
    - ELAS Depth map
      - OCTOMAP 3D model
        - Kalman sensor fusion
          - Lidar
          - IMU

Guidance and control

- Low-level control
  - MPC guidance
    - Waypoint server
      - Ground station
        - Emergency button

Supervision

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]

\[
\begin{align*}
\hat{P}(k+1) &= \hat{P}(k) + \hat{v}(k) \delta t \\
\hat{v}(k+1) &= \hat{v}(k) + (R(\theta(k))a_{IMU} + g) \delta t \\
\theta(k+1) &= \theta_{IMU}
\end{align*}
\]

- Correction using eVO position measurements [20 Hz]

Illustration filtration position

Positions filtrées - trajectoire en 8

Vitesses estimées - trajectoire en 8
Environment modeling for safe navigation

**Multi-sensor State estimation**

- **Lidar**
- **IMU**

- **Kalman sensor fusion**

**Guidance and control**

- **Low-level control**
- **MPC guidance**
- **Waypoint server**

**Environment modeling**

- **Stereo rig**
- **ELAS**
  - Depth map
- **eVO Stereo SLAM**
- **OCTOMAP**
  - 3D model

**Supervision**

- **Ground station**
- **Emergency button**

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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

(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

Guidance for autonomous navigation

Environment modeling

Multi-sensor
State estimation

Lidar
IMU

Kalman sensor fusion

Low-level control

MPC guidance

Waypoint server

Guidance and control

Stereo rig

eVO Stereo SLAM

ELAS Depth map

OCTOMAP 3D model

Ground station

Emergency button

Supervision
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

\[
U^*_k = \text{Arg Min}_{U_k \in U^{H_c}} J \left( x_k, U_k, X_k \right)
\]

Sequence of \( H_c \) control inputs: \( U_k = \{ u_k, u_{k+1}, \ldots, u_{k+H_c-1} \} \)

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

- Takes into account future behaviour and environment
- Handle constraints on control inputs
- Optimization required \( \Rightarrow \) 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

Multi-sensor State estimation

Environment modeling

Lidar
IMU

Low-level control
MPC guidance
Waypoint server

Supervision

Stereo rig

eVO Stereo SLAM
Kalman sensor fusion

ELAS Depth map
OCTOMAP 3D model

Ground station
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Supervision – state machine for flight phases

- **Taking-off**
  - Human pilot activates autopilot
  - Thrust stick at takeoff value

- **Landed**
  - 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

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)
Autonomous Exploration

Mobile Object Tracking and avoidance

FP7 EUROC – Freestyle results
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
- H. Roggeman, J. Marzat, A. Bernard-Brunel, G. Le Besnerais, Autonomous exploration with prediction of the quality of vision-based localization, IFAC WC 2017