UAV Autonomous Navigation
in a GPS-limited Urban Environment

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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»
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.
Optical flow estimation

- Robust estimation of Affine model optical flow field (DTIM)
  - Feature point matching on a small window
  - RANSAC approximation
  - ~10Hz

\[ \phi x_{p_k} = A_k x_{p_k} + b_k \]
Optical flow estimation

- vs. OpenCV

**Mean of Estimation Error**

~ Bias

**Std. Deviation of Estimation Error**

~ Noise
Onboard system architecture

Flight avionics

Flight Safety

Flight Management

Flight Guidance & Control

EKF

Low-pass filter

Serial com.

P/L processor

- AMD 4x1.5GHz
- Linux Debian

UAV

Flight Safety

communication

Flight Guidance & Control

Environmental information

Decision & Mission Planning

and/or

Advanced Guidance Law

Perception

Camera

Lidar

• AMD 4x1.5GHz • Linux Debian

µblox : 4Hz

GPS

Baro

SBG : 50Hz

INS

laser

alt.AGL

pos./vel

alt.MSL

filtered acc., angular vel.

6 dof state

50Hz

6 dof state + sensor measurements

operator commands
Onboard system architecture with GPS-independent navigation

- Flight avionics
  - Flight Safety
  - Flight Management
  - Flight Guidance & Control
  - EKF
  - Low-pass filter

Serial com. to P/L processor
- • AMD dual core 1.6GHz
- • Linux Debian

Flight mode request to Decision & Mission Planning
- and/or Advanced Guidance Law
- Perception + OF Estimation

Sensor measurements:
- Baro: alt.MSL
- INS: filtered acc., angular vel.
- EKF: pos./vel.
- Camera: optical flow
- Lidar: alt.AGL
- Serial com.: • AMD dual core 1.6GHz • Linux Debian

Operator commands to Flight mode request

UAV: laser, alt.AGL, pos./vel.
- **OF + INS + Barometer**
  - with or w/o laser (alt. AGL)
  - over a slope

![Graphs showing flight test results](image)
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)
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 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

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
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

**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 = $(2\sigma + ds)$-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
  - Sampling-based (PRM, RRT) : [Peppy 2006], [Luders 2013], [Bopardikar 2014] etc.
  - POMDP : [Candido 2010] etc.

The localization mode is imposed
Related Work (2/2)

- **Path and observation strategy planning**
  

- **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

- **Point cloud data**
- **3D voxel occupancy map**
- **Safe path planner**
  - A*
  - Theta*
  - RRT*
  - RRT-Theta*
- **Localization models**
  - GPS/INS
  - INS-only
  - VINS
  - Landmark
- **Sensor characteristics**
- **Sensor availability map**

**Mission objective**

**Guidance law**

**Flight plan generation**

**Flight plan**

**Node**

**Localization uncertainty**
Example 1 : No VINS

- Path planning with GPS availability map
  - No vision-aided navigation mode available onboard

<table>
<thead>
<tr>
<th>Safe path planner</th>
<th>Cube</th>
<th>Wall Baffle</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><img src="image1" alt="Cube Path Planning" /></td>
<td><img src="image2" alt="Wall Baffle Path Planning" /></td>
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→ fly over the obstacles to avoid no GPS zones

→ collisions due to divergence in localization error covariance
### Example 2 : with VINS

<table>
<thead>
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**Remark :** Dependence on optical flow measurement noise
Example 3: with VINS + Landmarks

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Flight plan:
- INS-only
- GPS / INS
- Vision / INS
- Landmark 1
- Landmark 2

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.)