Visual Air-to-Ground Target Tracking and self-localization of a UAV in a GPS denied Environment

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ONERA
THE FRENCH AEROSPACE LAB

retour sur innovation

Outline

- Introduction
- Optimal Guidance Design
  for vision-based relative estimation
- Visual Target Tracking
  in a GPS-denied environment
- Summary and Future Work

I. Introduction

Introduction

❖ **Unnamed Aerial Vehicles (UAVs)**

- Cost-effective
- No risk in the loss of human pilot life

↓

Autonomous Flight System

enables UAV to achieve a high-level mission
in an unknown (possibly adversarial) environment

❖ **Vision-Based Navigation, Guidance & Control**

- Nature-inspired ⟶ *bio-inspired approaches*
- Information-rich
- Compact, light-weight, low-cost

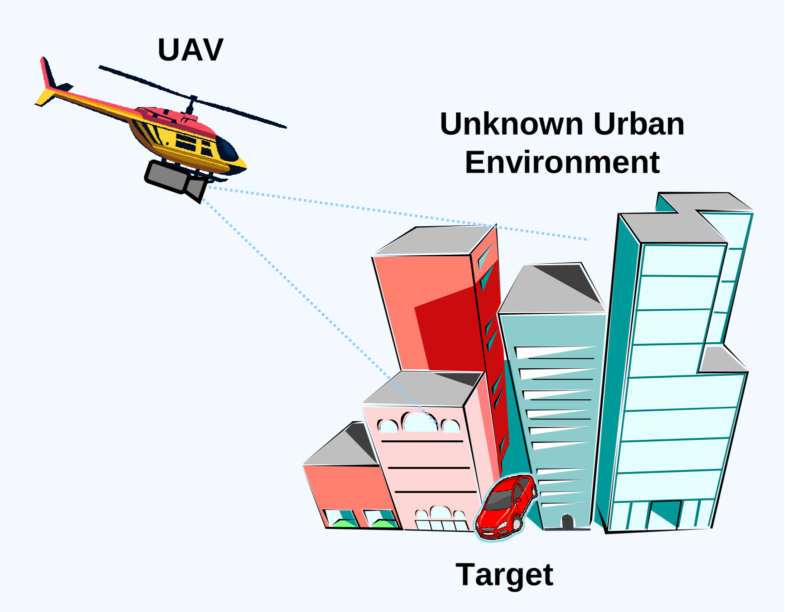
Visual Target Tracking Problem

❖ **Mission Goal**

To detect, localize and pursue a target in unknown urban environment

❖ **Operation Phases**

- Global Mapping
  Gather environmental information
  from high and safe altitude
- Target Search
  Local search at low altitude
  with partial knowledge of the environment
- Target Tracking
  Pursue the target while localizing it



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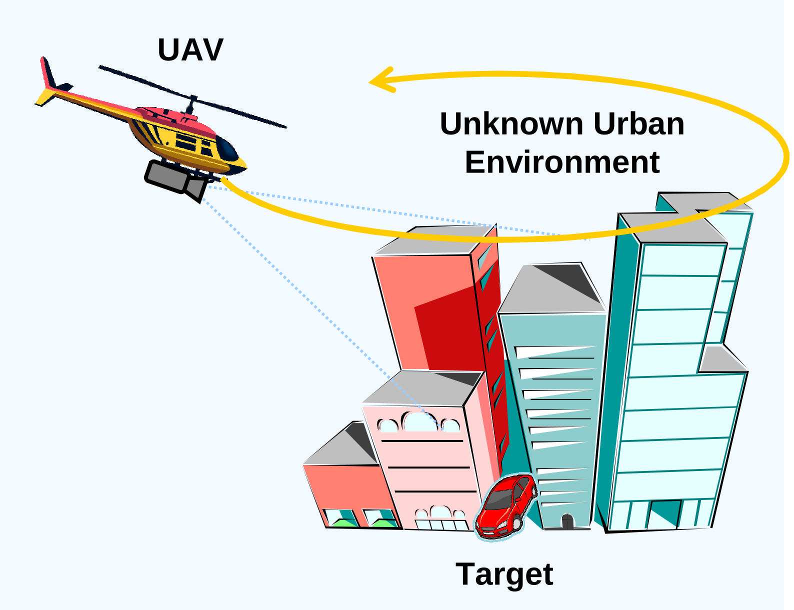


Global Mapping

❖ ReSSAC Project

- Vision-based 2.5D mapping
- Landing site characterization

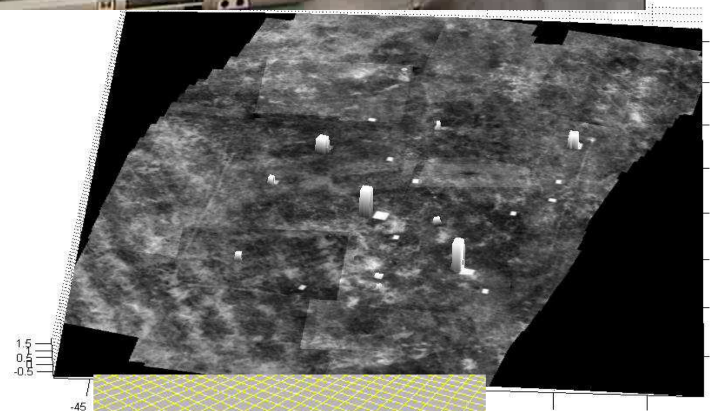
Fabiani et al., "ReSSAC: Flying an Autonomous Helicopter in a Non-Cooperative Uncertain World," AHS 2007.

❖ IDEAS Project

- Safety & Autonomy & UAS in airspaces

Seguin et al., ONERA/DCSD

❖ SPIDER Project



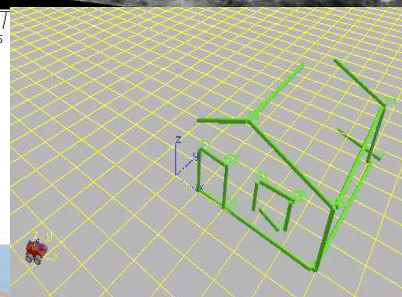
- Vision-based 3D terrain reconstruction

Le Besnerais et Sanfourche, ONERA/DTIM

❖ ACTION Project

- Visual SLAM
- Obstacle mapping with ground robots
- Objects localization by multiple cooperative assets

Barbier et al., ONERA/DCSD *Lacroix et al., CNRS/LAAS*



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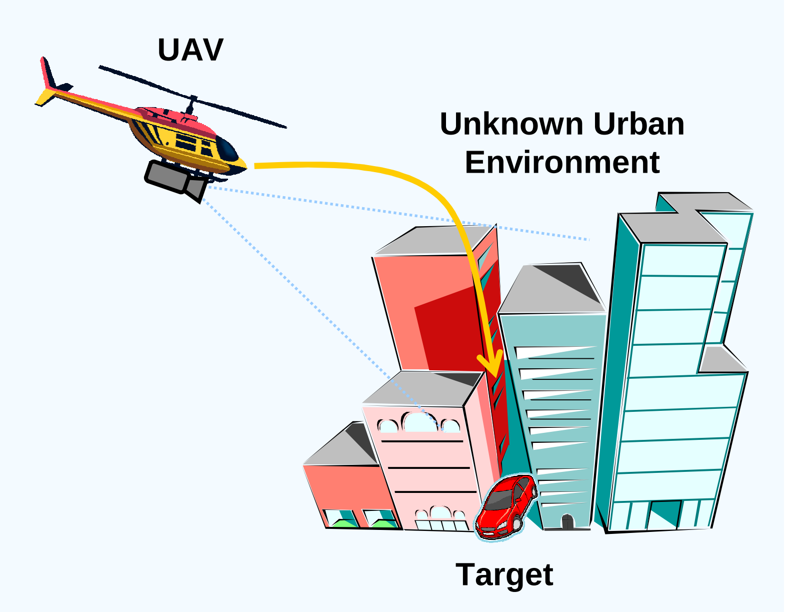
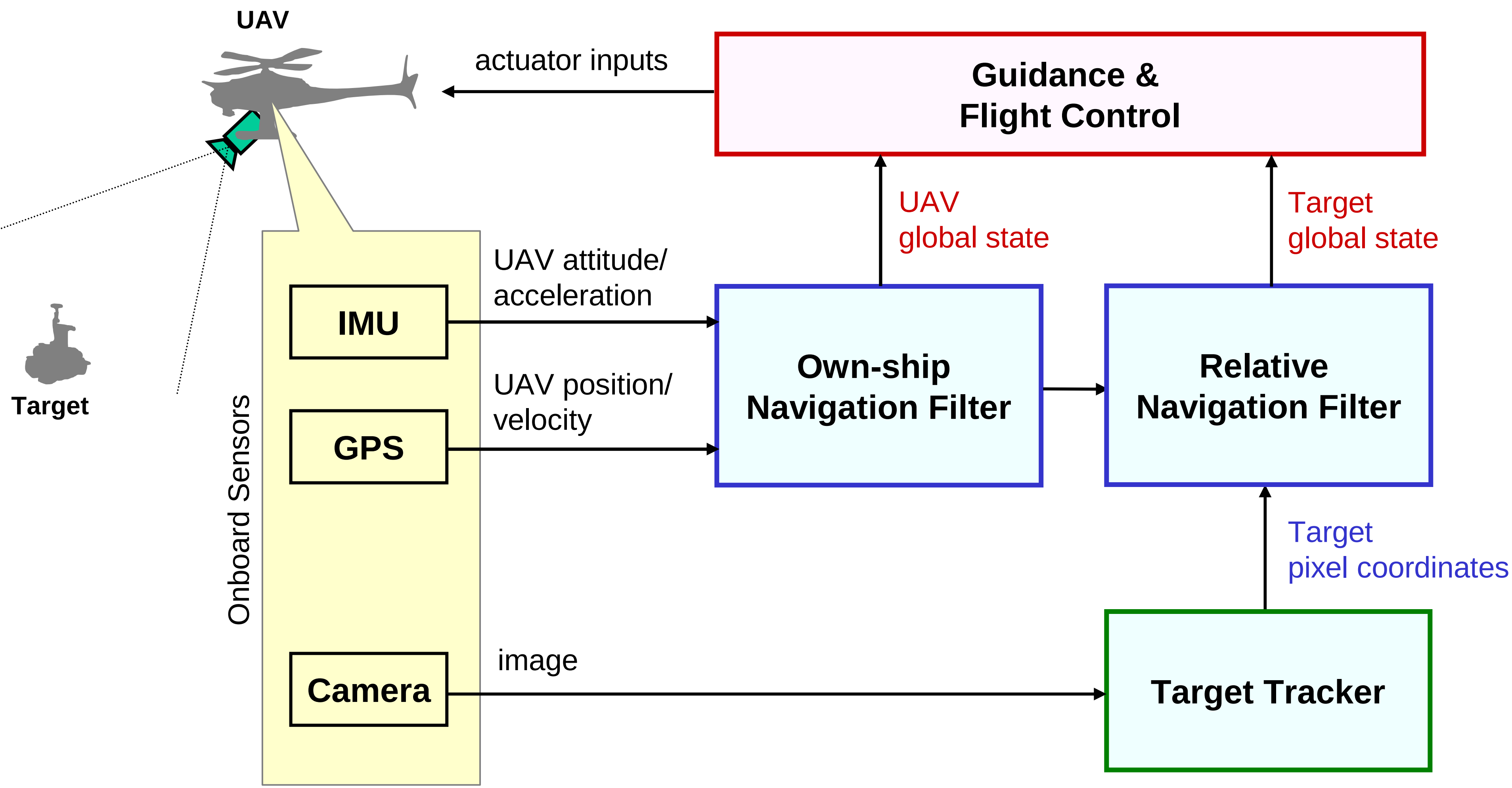


II. Optimal Guidance Design for Vision-Based Relative Estimation

Visual Target Tracking System 1



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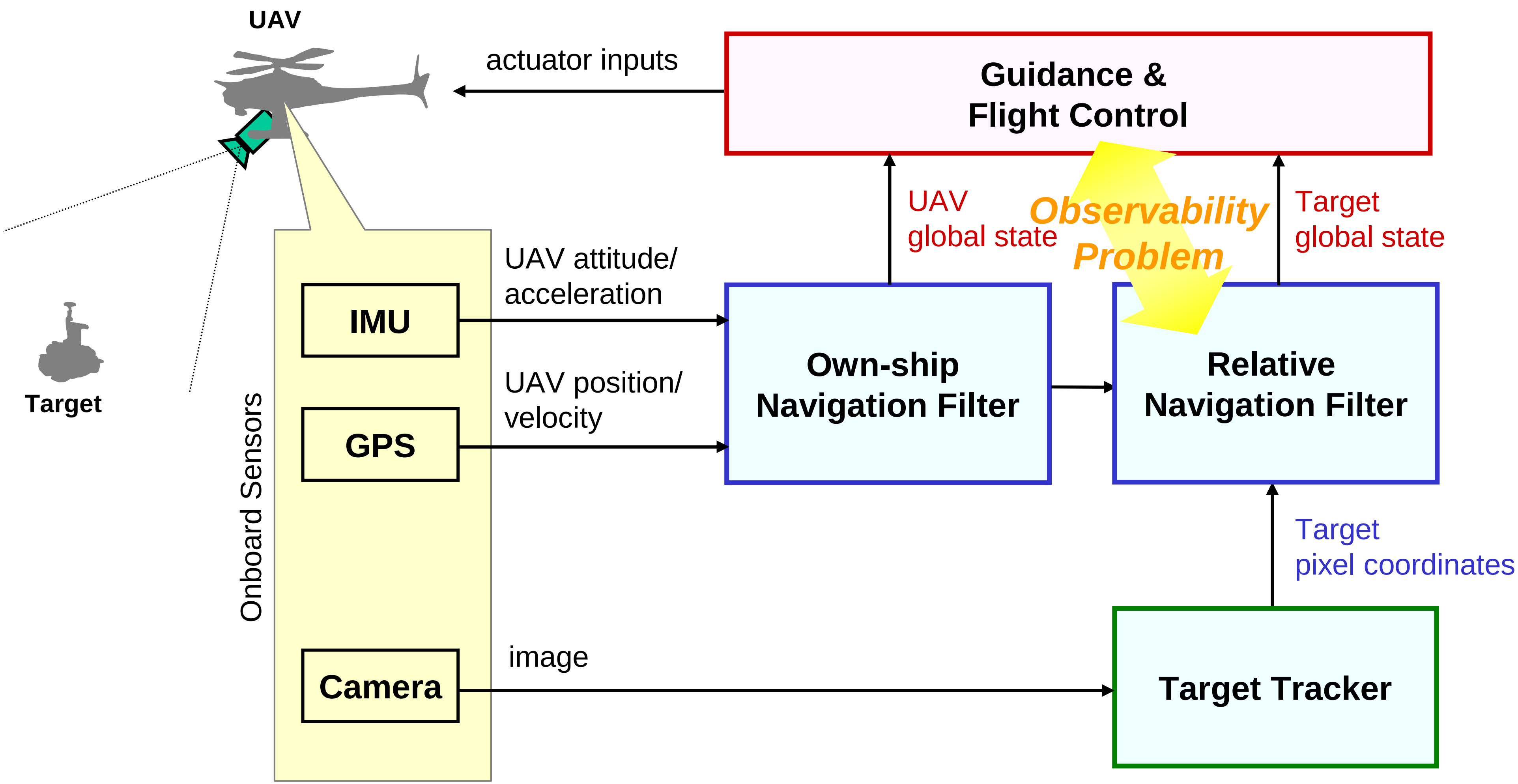
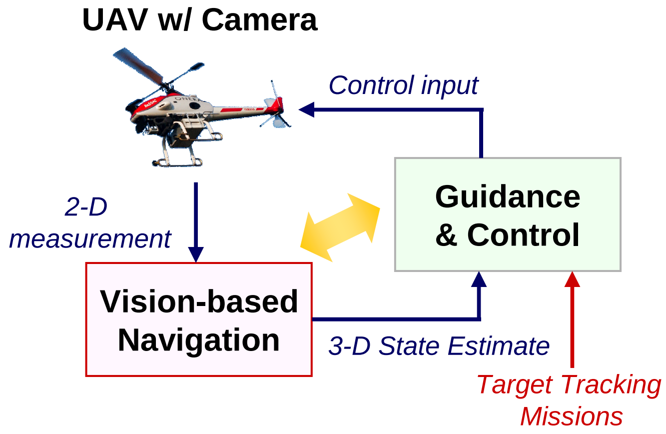


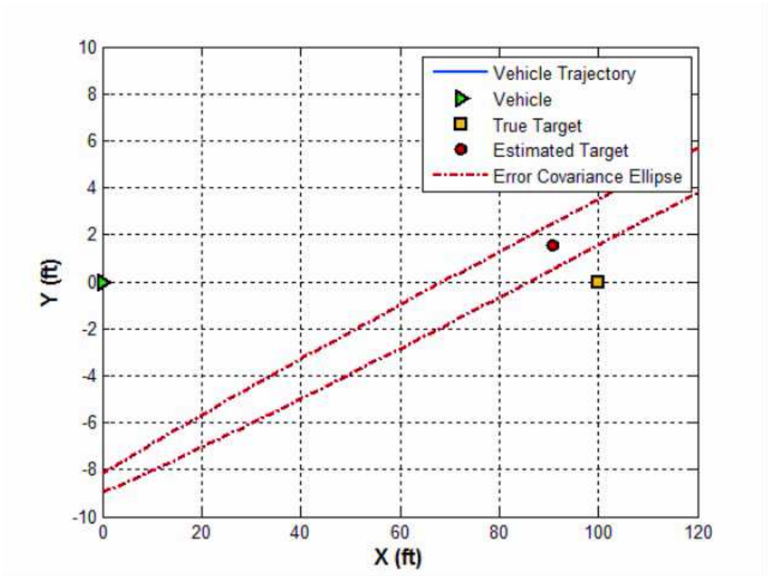
Optimal Guidance Design

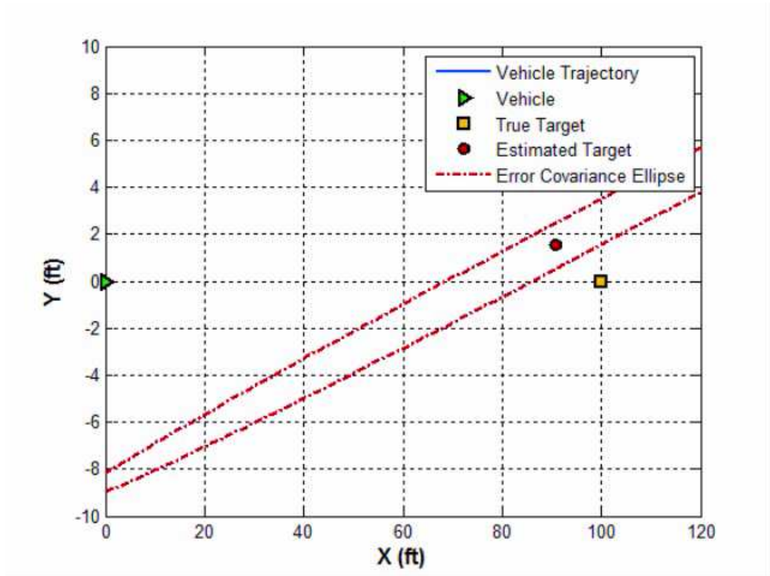
Separation Principal does not hold !

Estimation performance highly depends on the UAV motion relative to the target.



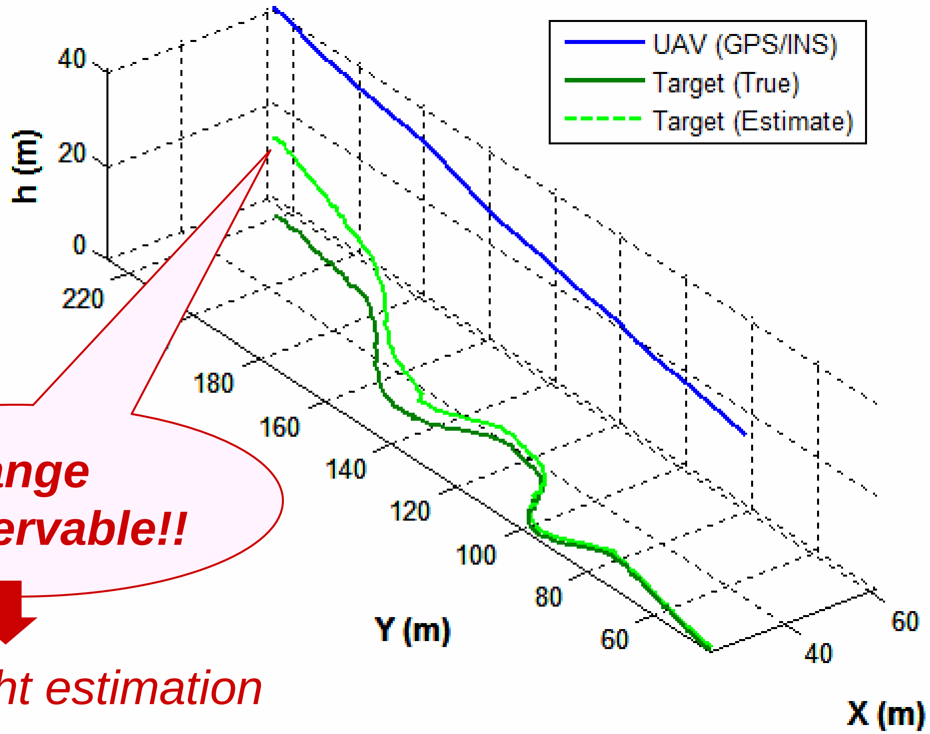
❖ **Example :** Target Position Estimation





Optimal Guidance Design (cont'd)

❖ **Example 2 : Ground Target Tracking** (open-loop test)



Range unobservable!!

drift in height estimation

Optimal Guidance Design (cont'd)

Separation Principal does not hold !

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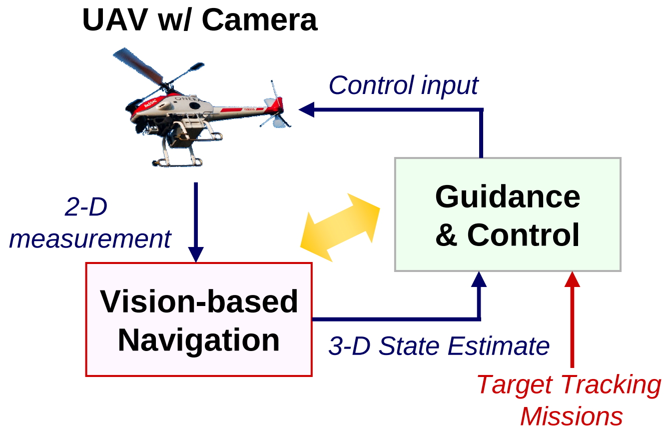


❖ **Objective**

To design a guidance law which :

- achieves the target tracking mission
- maximizes the estimation performance

❖ **Approach**

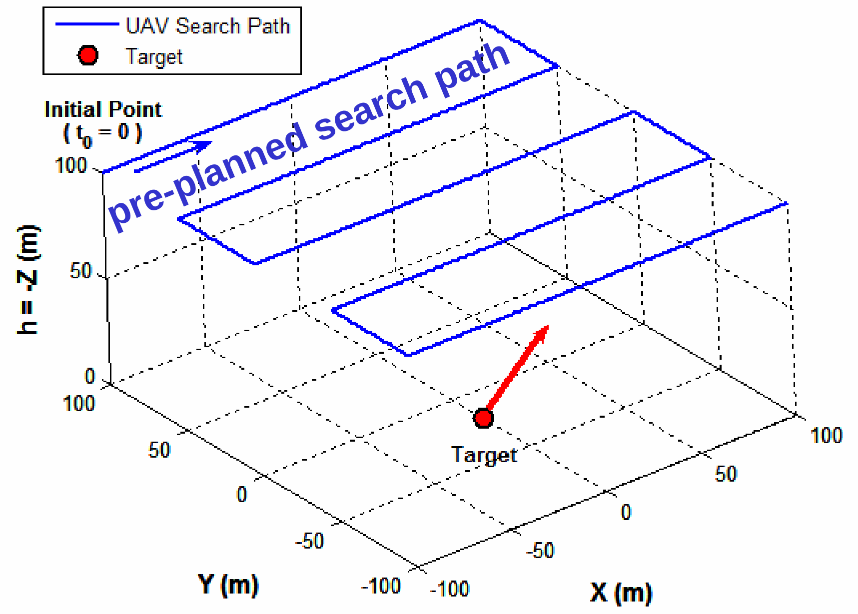
Minimization of the expected guidance error*.

* *Y.Watanabe, "Stochastically Optimized Monocular Vision-Based Navigation and Guidance," PhD Thesis, Georgia Tech, 2008.*

Simulation

❖ **Vision-Based Target Search & Tracking (closed-loop)**

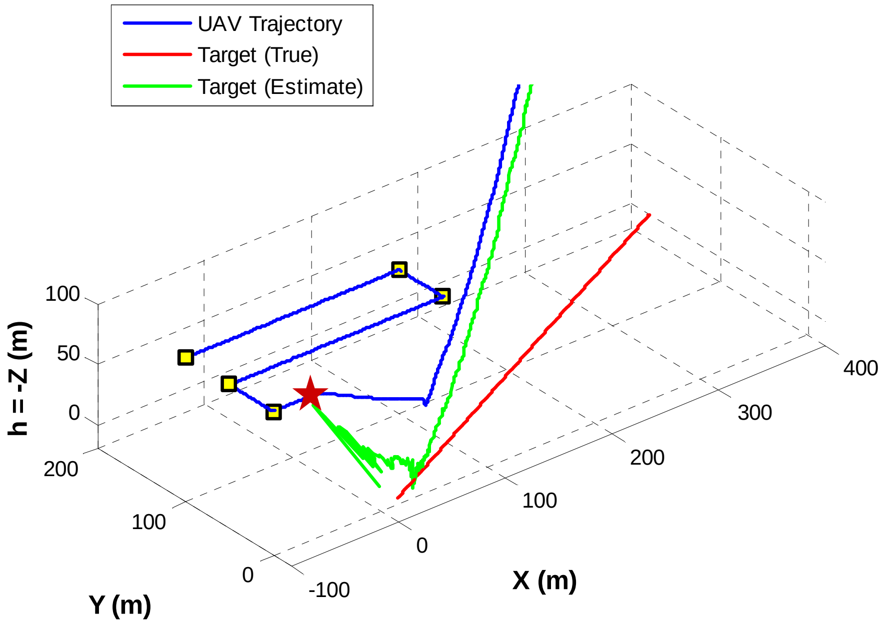
- **Target** : *starts moving with a constant velocity when detected.*
- **UAV** : *follows a given search path until it detects the target.*
  starts tracking the target while localizing it by using the 2D vision information.
  driven by acceleration input.
- **Camera** : *gimbal*
  pointing down

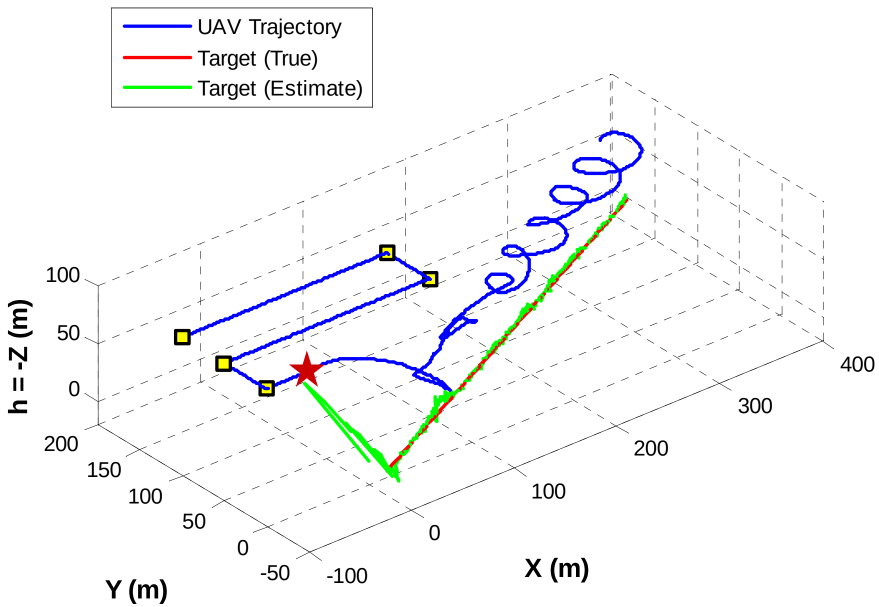


Simulation Results

❖ **Nominal Guidance**
- No relative motion to the target
- A large drift in height estimation
- A large drift in UAV altitude

❖ **Optimal Guidance**
- Circling motion relative to the target
- Accurate height estimation



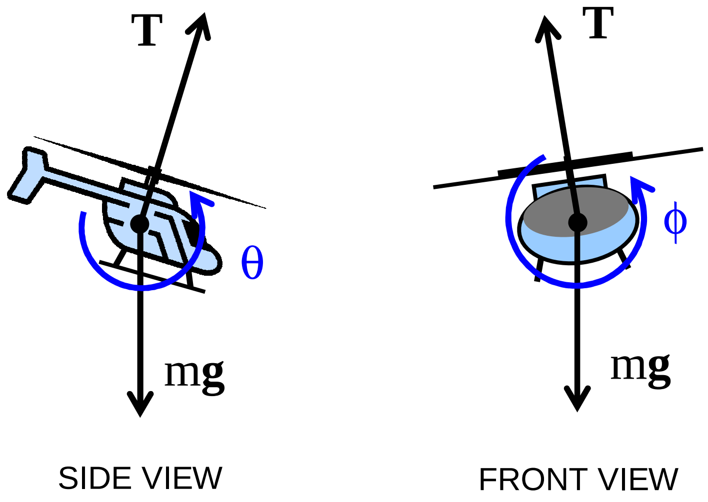


Camera's Field of View

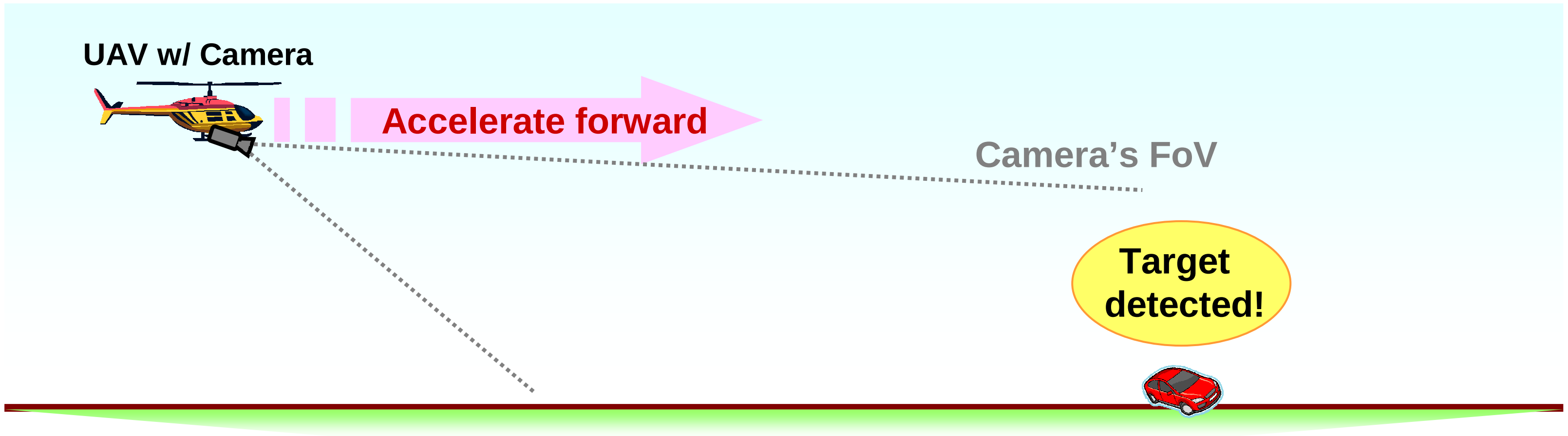
- **Helicopter Dynamics**

$$\begin{cases} \dot{X}_v = V_v, \quad \dot{V}_v = a_v \\ a_v = \frac{1}{m} L_{IB}(\Theta) \begin{pmatrix} 0 \\ 0 \\ -T \end{pmatrix} + \begin{pmatrix} 0 \\ 0 \\ g \end{pmatrix} \end{cases}$$

UAV driven by attitude change



- **Example :**



Camera's Field of View

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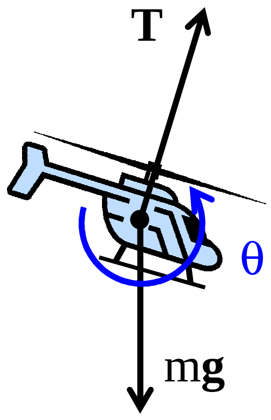
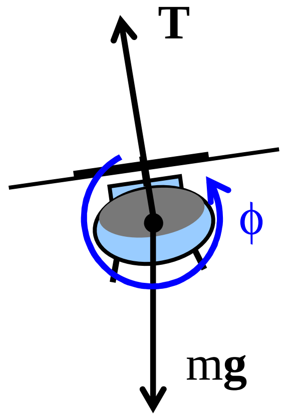
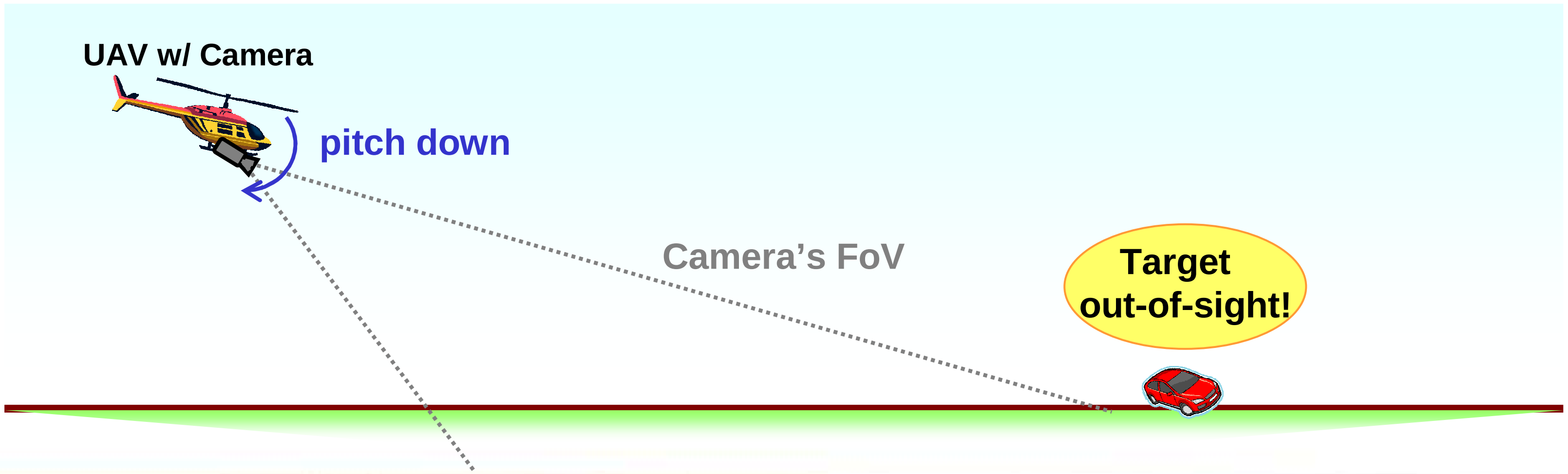


SIDE VIEW



FRONT VIEW

❖ Example :



New Guidance Design

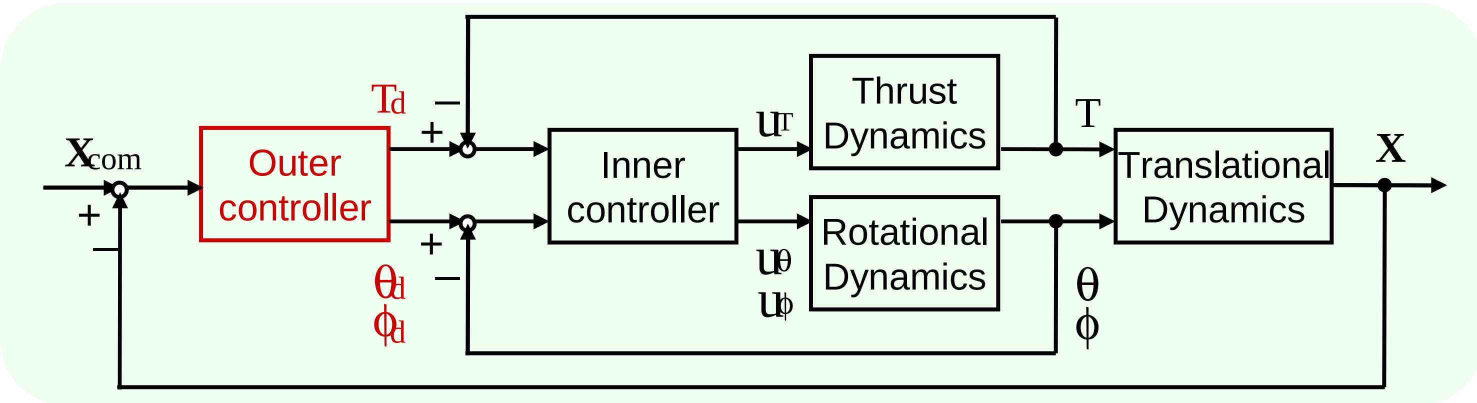
❖ Objective

To design a guidance law which :

- achieves the target tracking mission
- maximizes the estimation performance
- keeps the target inside the FoV

❖ Approach

Integrating the UAV rotational dynamics in the guidance design.

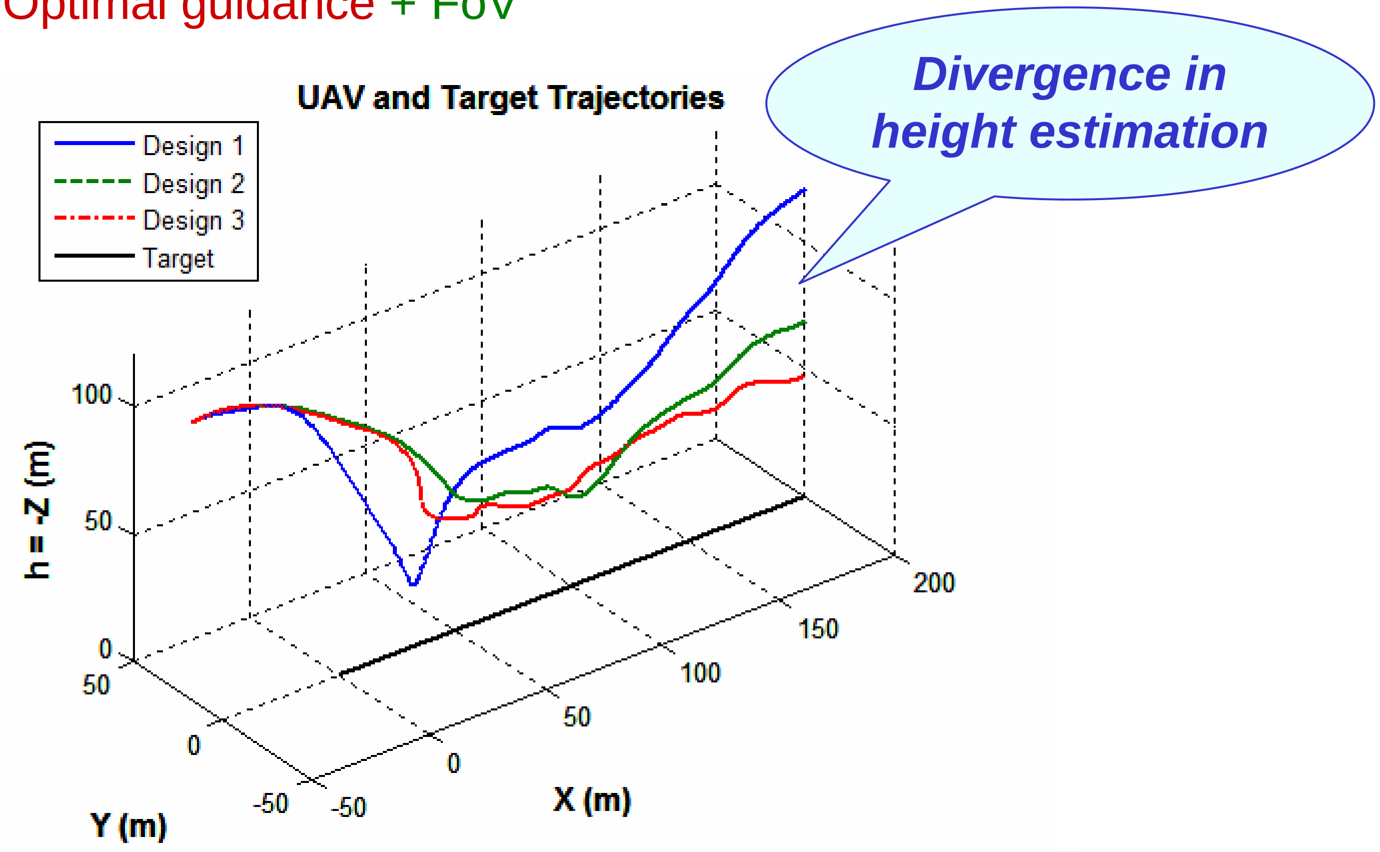


ONERA

Simulation Result 1

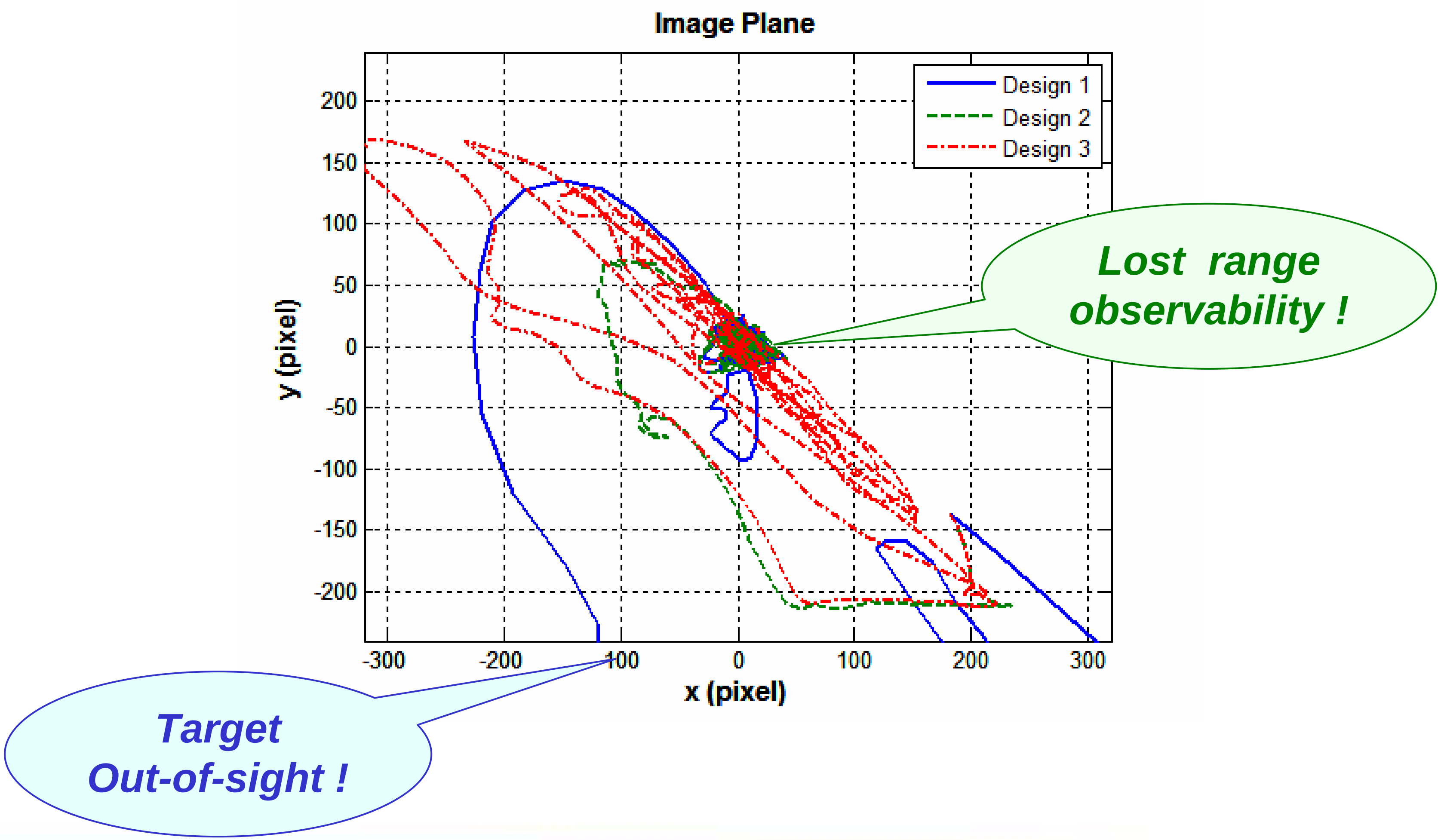
❖ **Vision-Based Target Tracking (closed-loop)**

- Design 1 : Nominal guidance only
- Design 2 : Nominal guidance + FoV
- Design 3 : Optimal guidance + FoV



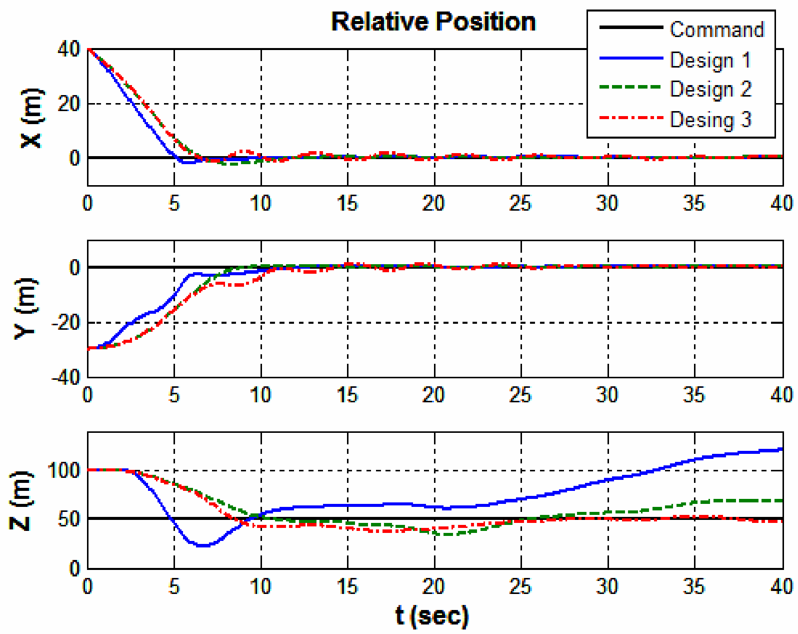
Simulation Result 2

❖ **Target Trajectory on the Image Plane**

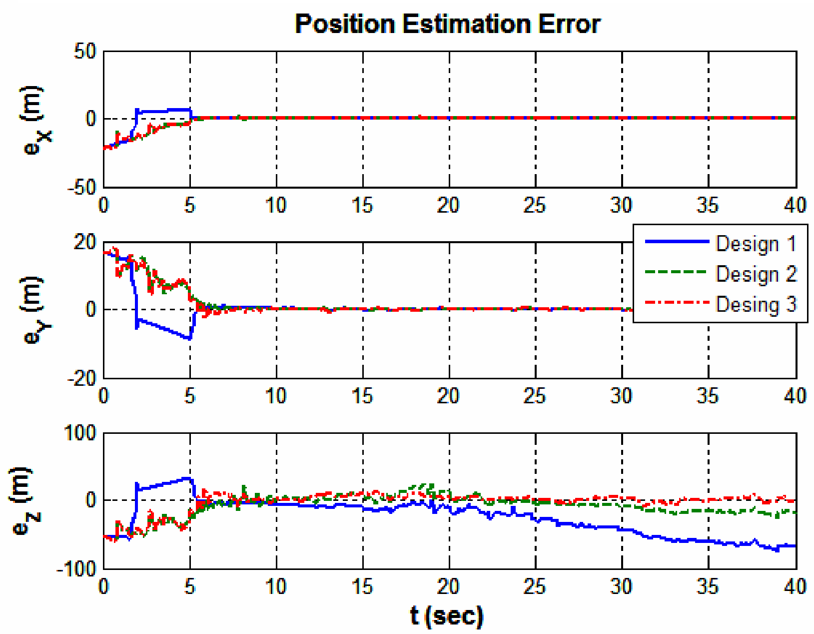


Simulation Result 3

❖ Guidance Performance



❖ Estimation Performance

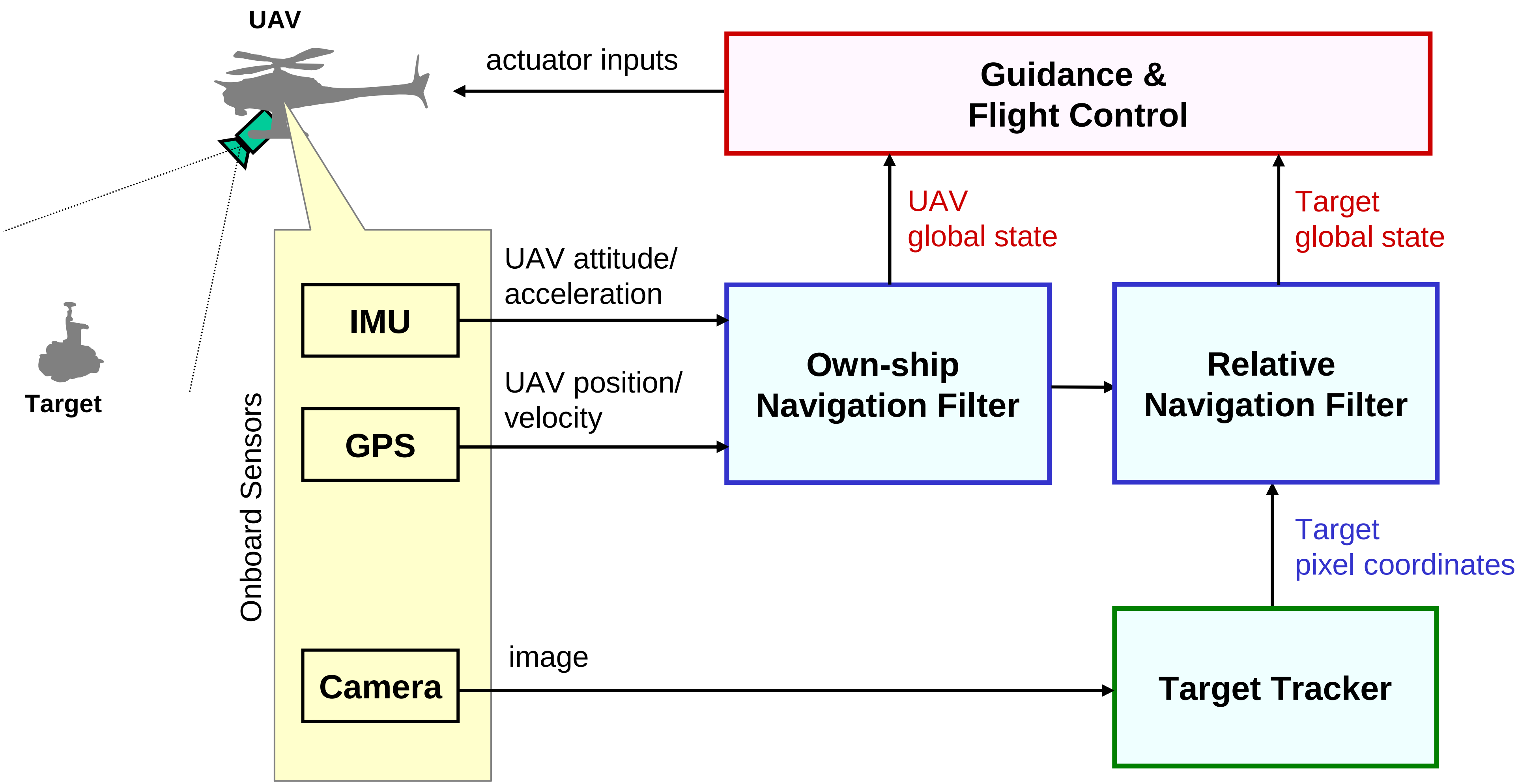


The new guidance law improves the estimation accuracy.

➡ gives the good tracking performance.

III. Visual Target Tracking in a GPS-Denied Environment

Visual Target Tracking System 1



Ground Target Tracking Simulation 1

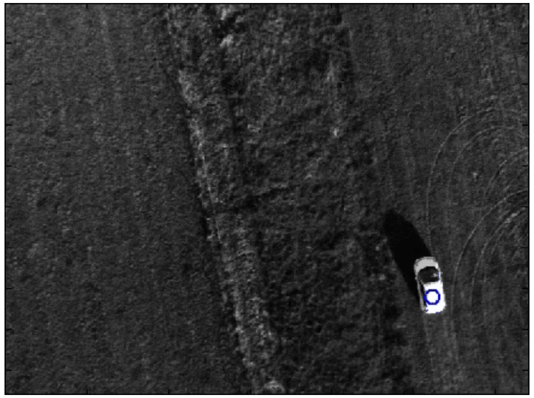
Simulation using Flight Test Data (open-loop)

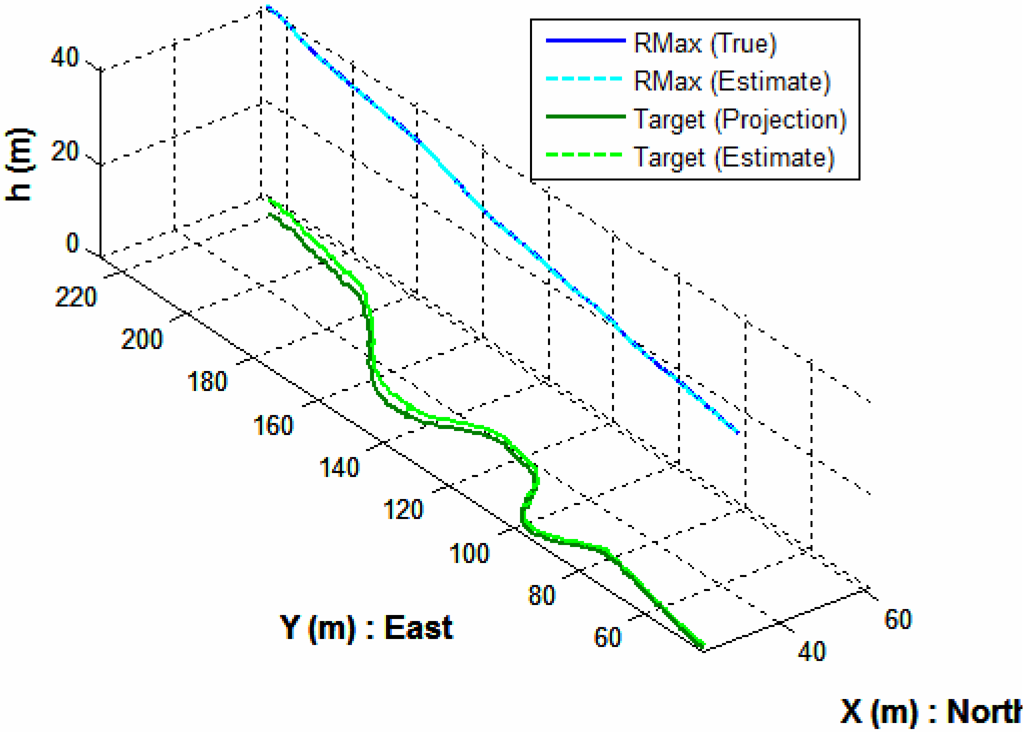
- Camera images
- UAV state data

Synchronically recorded onboard on the ONERA ReSSAC UAV

❖ Normal Configuration

- GPS available
- Ground target constraint





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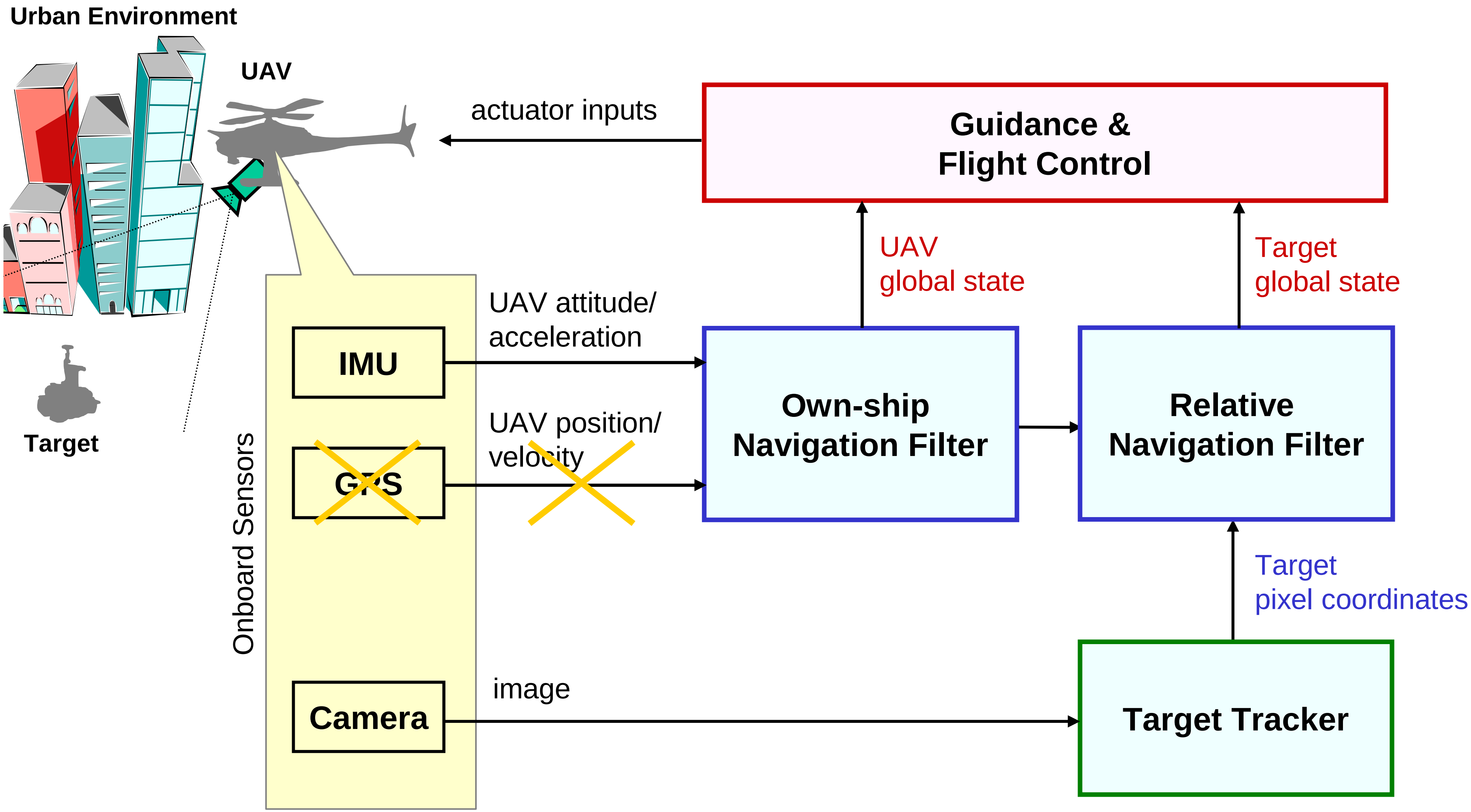


Ground Target Tracking Simulation 2

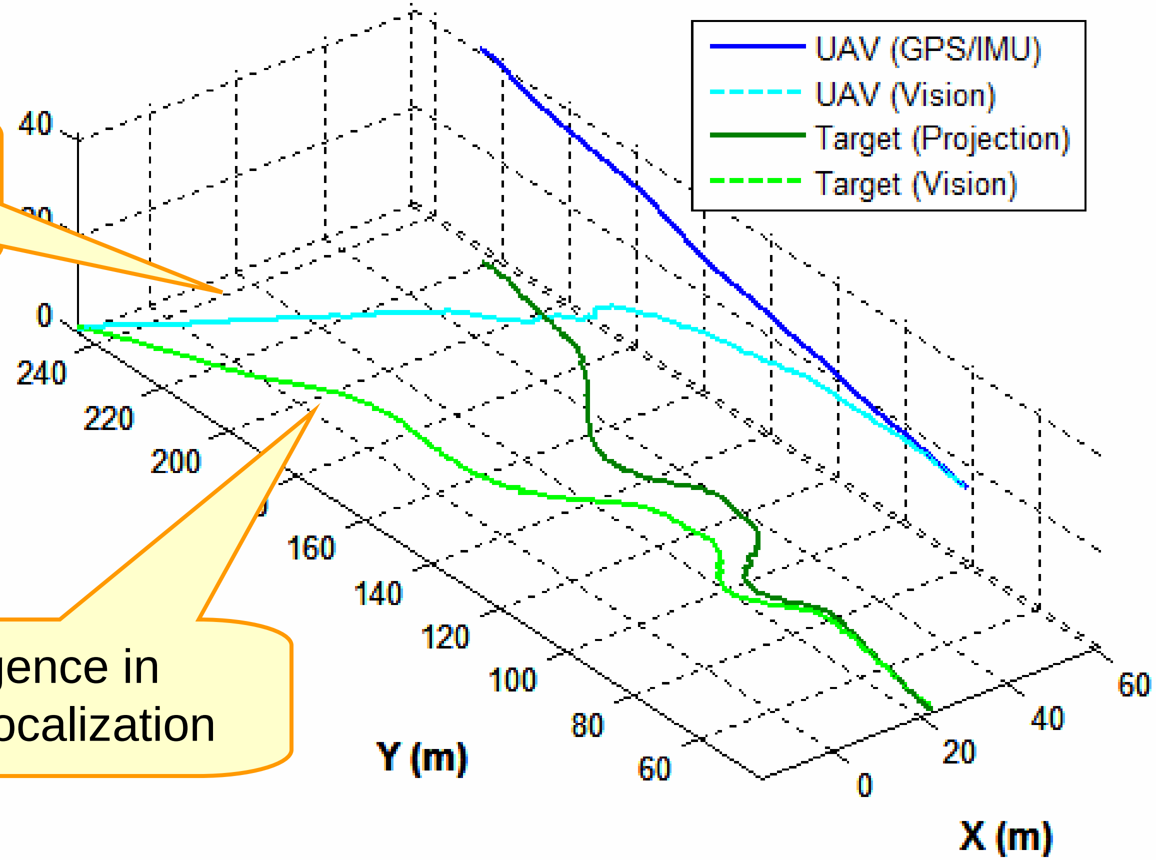
❖ Loss of GPS signals

- INS-only navigation

Divergence in Self-Localization

- *Biased acceleration measurement*

Divergence in Target Localization



Augmented Navigation System

❖ **Objective**

To design a navigation system which *simultaneously* estimates :

- global states of the UAV
- global states of the target

without GPS information.

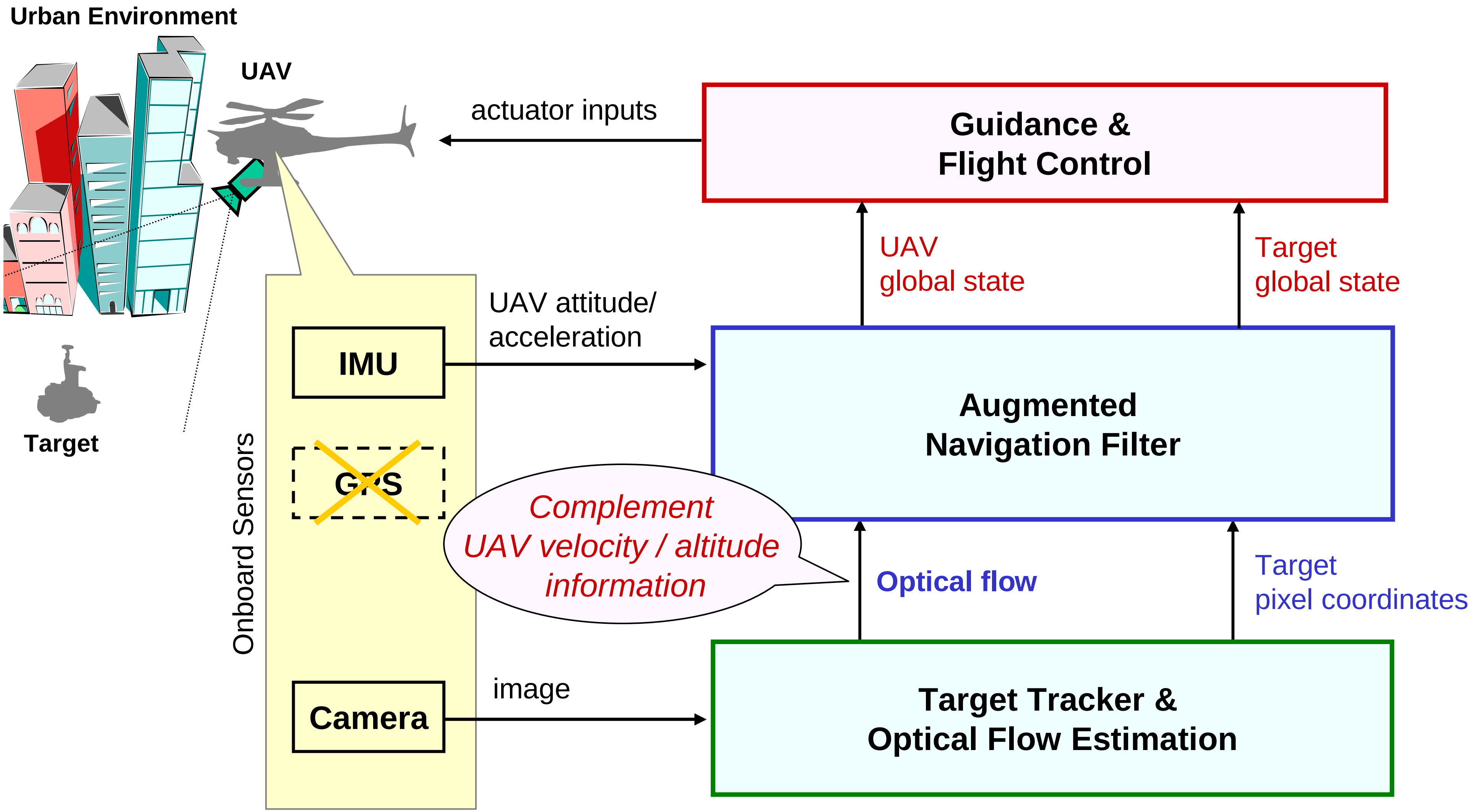
❖ **Approach**

Use ***optical flow*** measurements to complement GPS.

Nature-inspired approach :
Honeybees are using optical flows for self-navigation*.

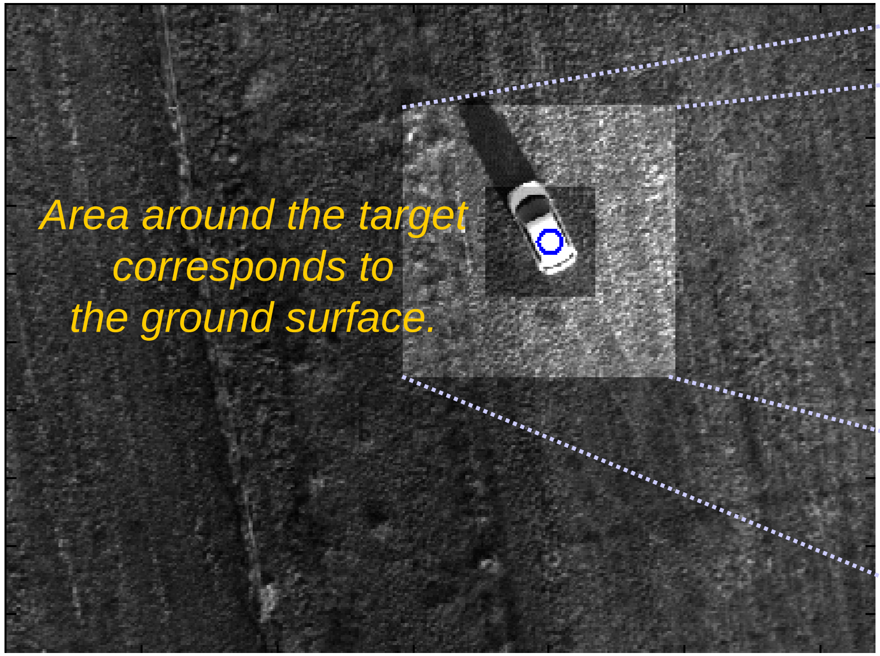
**M.V. Srinivasan et al., "Honeybee Navigation En-Route to the Goal: Visual Flight Control and Odometry," Journal of Experimental Biology, 1996. .*

Visual Target Tracking System 2



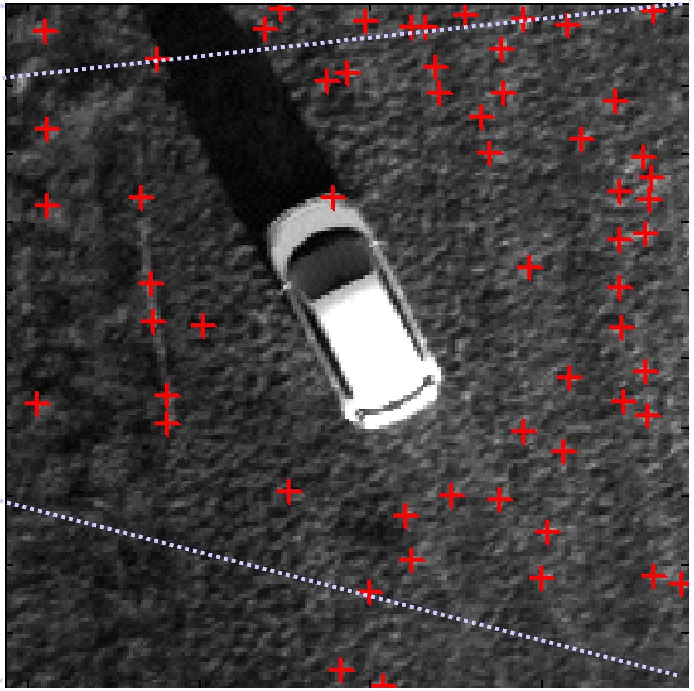
Optical Flow Estimation

- **Step 1 :**
  - Target detection
  - Image masking



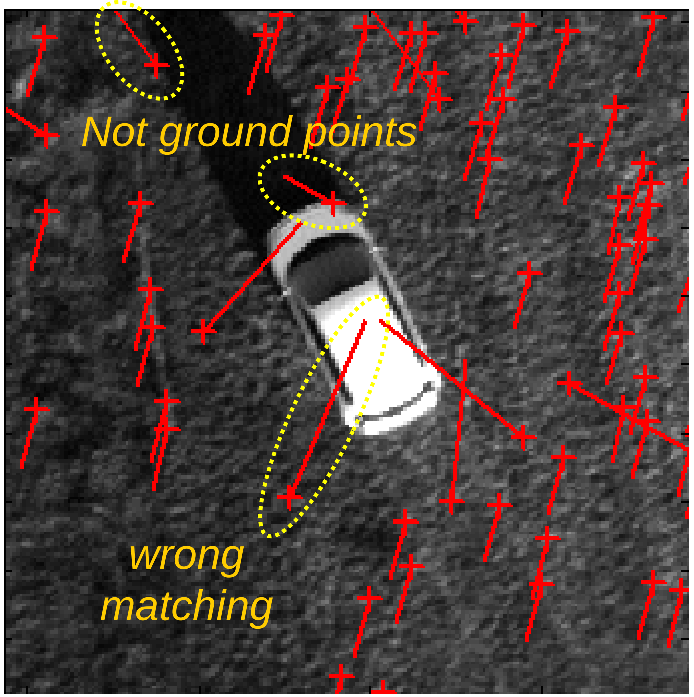
- **Step 2 :**
  - Feature point selection

N ~ 50



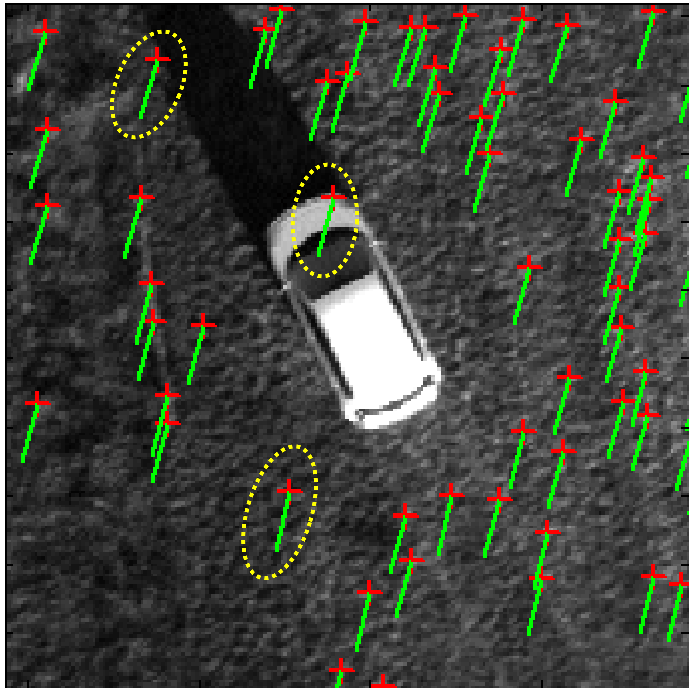
Optical Flow Estimation (cont'd)

❖ **Step 3 :**
- Feature point matching
- Optical flow estimation



❖ **Step 4 :**
- Affine approximation : **(A, b)**

$$\Delta \boldsymbol{x} = \mathbf{A}\boldsymbol{x} + \mathbf{b}$$

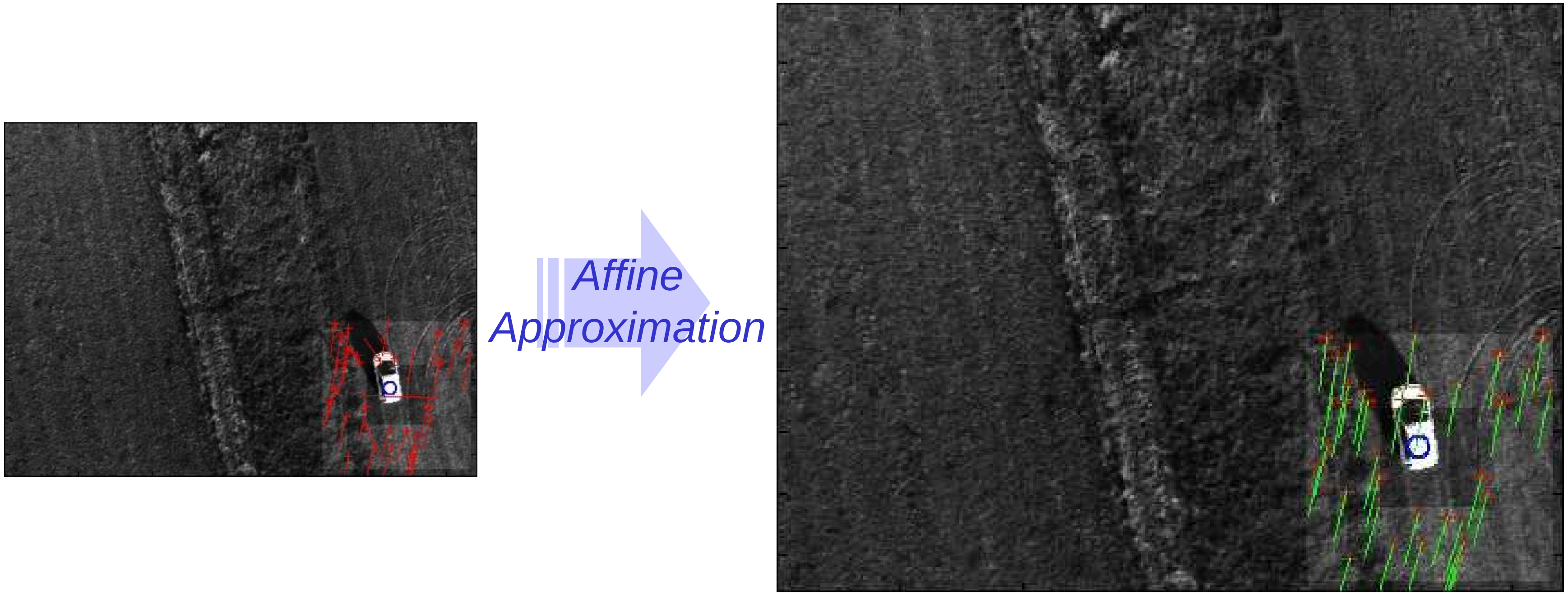


Large errors are eliminated.
Information amount is reduced.

Image Processing Results

- **Image Processing Outputs**
  - Target Tracker : x_t
  - Optical Flow Estimation : $(\mathbf{A}, \mathbf{b})$

Extended Kalman Filter (EKF) is applied for the navigation.



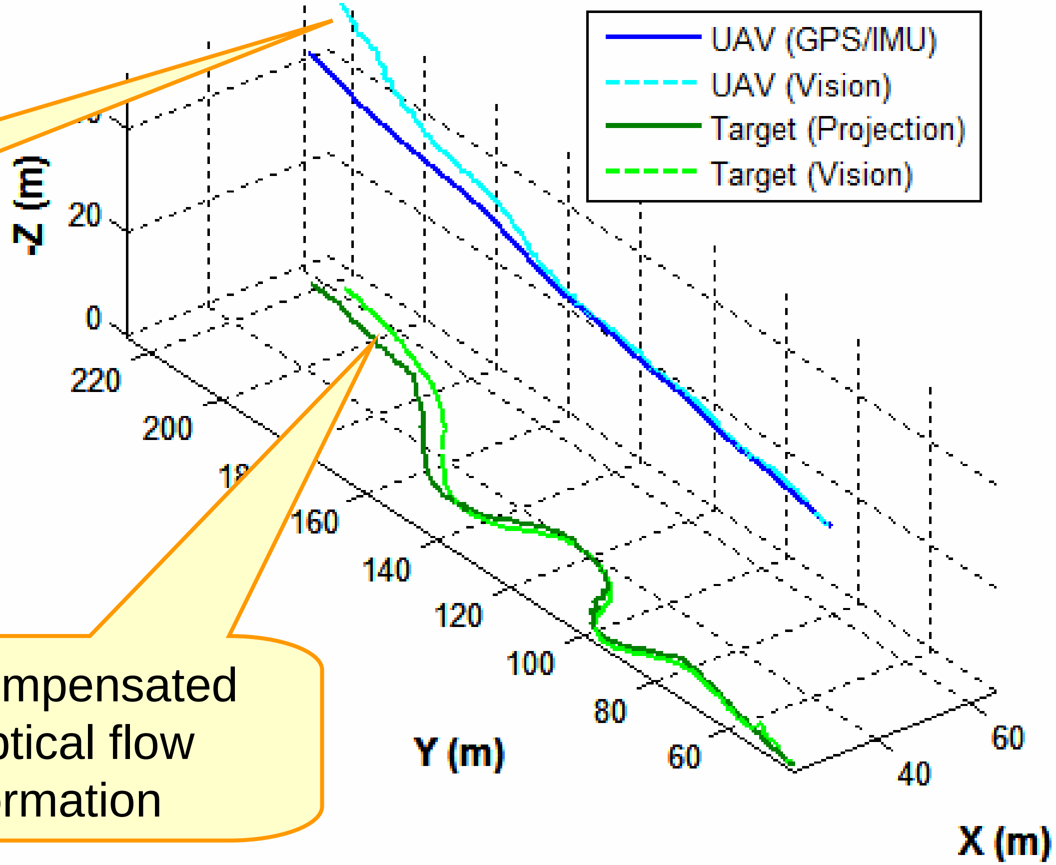
Ground Target Tracking Simulation 3

❖ Loss of GPS signals

- **Integrated INS/Vision navigation**
- Optical flow

Drift in height estimation

- *Image distortion ?*
- *Error in the UAV state data ?*
- *Ground is not flat ?*
- *Error in camera calibration ?*



Drift compensated by optical flow information

IV. Summary and Future Work

Summary

❖ Optimal Guidance Design

- Applied the optimal guidance for visual target tracking problem.
- Developed a new guidance law which treats the limited FoV.
- Demonstrated the performance through simulations.

❖ Target Tracking in a GPS-denied environments

- Developed a visual navigation system which does not rely on GPS.
- Integrated with a real image processing algorithms.
- Demonstrated the performance through simulations using the actual flight test data and images.

Future Work

❖ Flight Experiments

- Open-loop test with the algorithms running onboard
- Closed-loop test with GPS
- Closed-loop test without GPS (in urban site)

❖ Guidance design

- Optimal guidance design
  for optical flow-based navigation

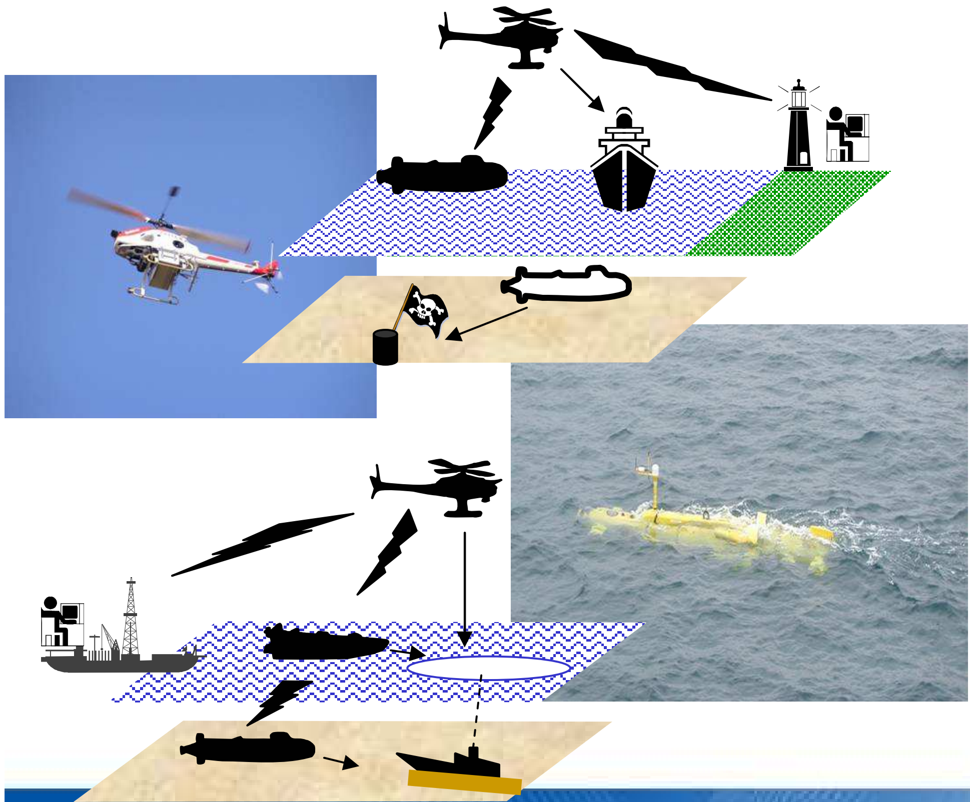
Follow-up Projects ACTION & ROSACE

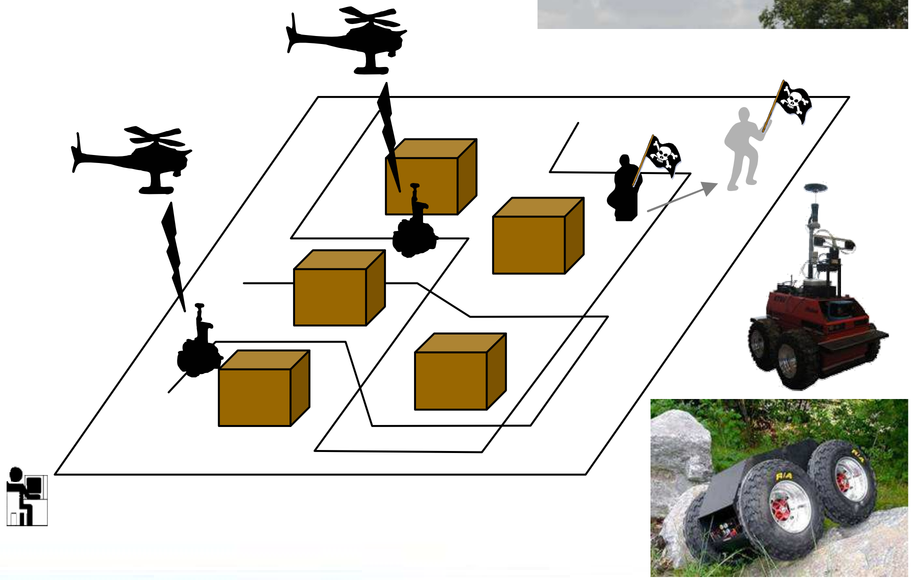
ACTION projects : Cooperative Operations of Multiple Air, Ground & Sea Robotics Communicating Assets

- ⇨ Maritime surveillance
- ⇨ Urban localization of targets

RTRA ROSACE

- foreign postdocs
- seniors researchers





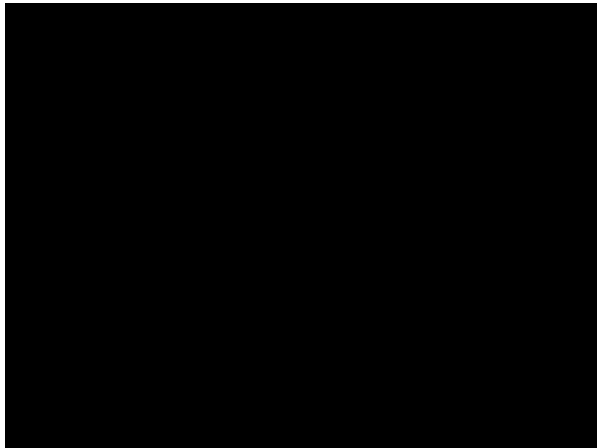
Follow-up Projects on Autonomy at ONERA

SAFETY

AUV avionics reliability & UAVs in Civil air spaces

⇨ IDEAS project

⇨ Developping tools towards certification



RELIABILITY

Perception vision-based decision making navigation guidance & control

⇨ ReSSAC landing site characterization

⇨ SPIDER project

⇨ MAVs (ENAC Paparazzi, ISAE Vertigo)

COMPLEXITY

Communicating Cooperative Air & Ground multi -assets Robotics

⇨ ACTION project

⇨ ROSACE (positions offered)

Oral Presentations

- Y. Watanabe, P. Fabiani and G. Le Besnerais,
  "Air-to-Ground Target Tracking in a GPS-denied Environment using Optical Flow Estimation,"
  AIAA Guidance, Navigation and Control Conference, Aug. 2009. (accepted)

- P. Fabiani, Y. Watanabe, G. Le Besnerais, M. Sanfourche,V. Fuertes, R. Mampey, A. Piquereau
  "Lessons learnt from the ReSSAC project, First results from the SPIDER project
  Towards safe VTOL UAV operations in various environments,"
  AHS International Specialist' Meeting on Rotary UAVs, Jan 2009.

- Y. Watanabe, P. Fabiani and P. Mouyon,
  "Research Perspectives in UAV Visual Target Tracking in Uncertain Environments,"
  ***IEEE/RSJ International Conference on Intelligent RObots and Systems (IROS),
  Workshop on Visual Guidance Systems for Small Autonomous Aerial Vehicles, Sept. 2008.***

- Y. Watanabe, E.N. Johnson and A.J. Calise,
  "Stochastically Optimized Monocular Vision-Based Navigation and Guidance,"
  AIAA Guidance, Navigation and Control Conference, Aug. 2008.

Merci !

Questions ?

Thanks to :
Alain Piquereau, Vincent Fuertes, Roger Mampey, et Pierre Escalas for their assists in the flight test.