Safe operation of UAS systems in risky operations

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1st AETOS conference "Research challenges for future UAV systems“,
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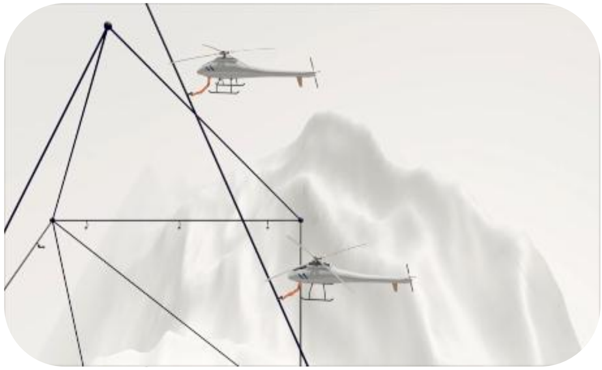
Outline

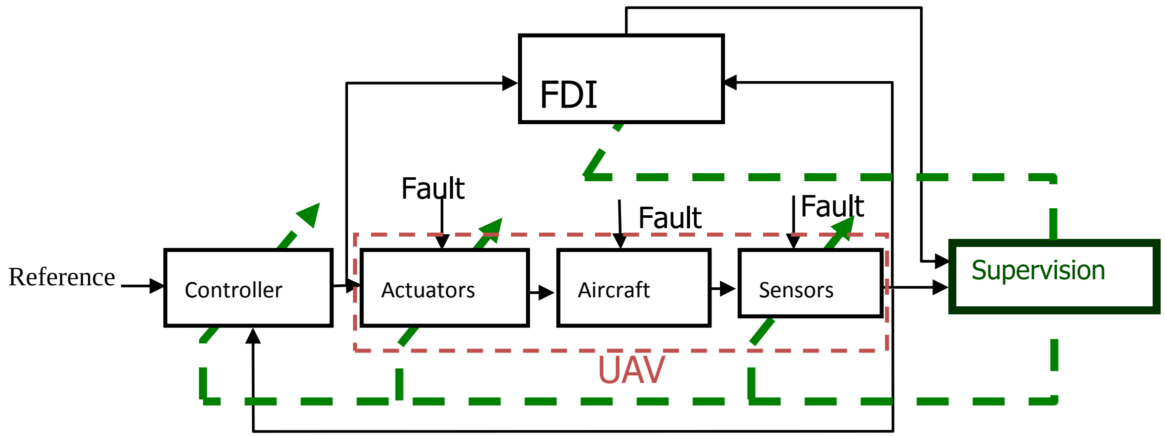
- Introduction
- Single UAV
- Multiple UAV
- Physical interactions

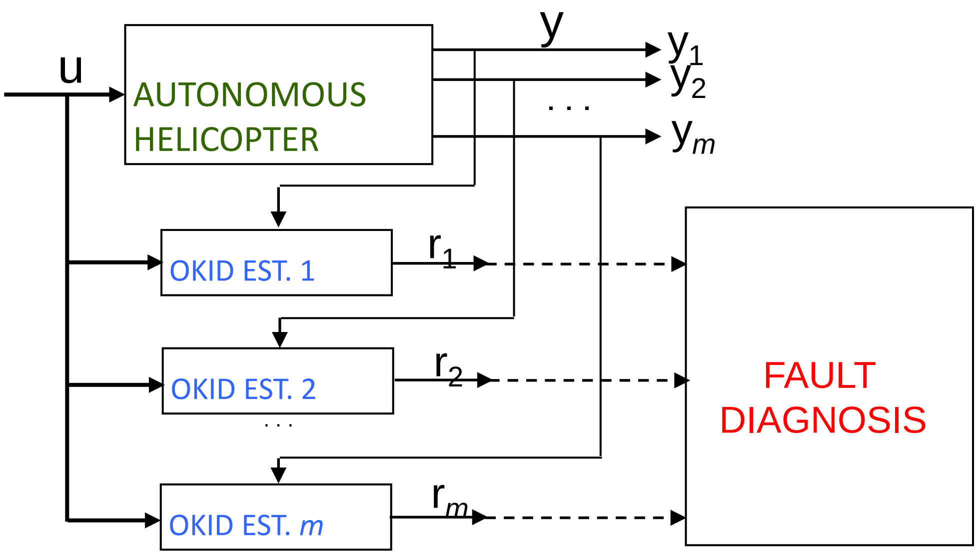


Introduction

- Safe operations
  - Single UAV
    - Fault detection and reconfiguration
    - Positioning (GPS problems)
    - Landing
  - Multiple UAV
    - Collisions
      - Other aircrafts
      - Environment
  - Physical interactions

Fault detection, identification and reconfiguration





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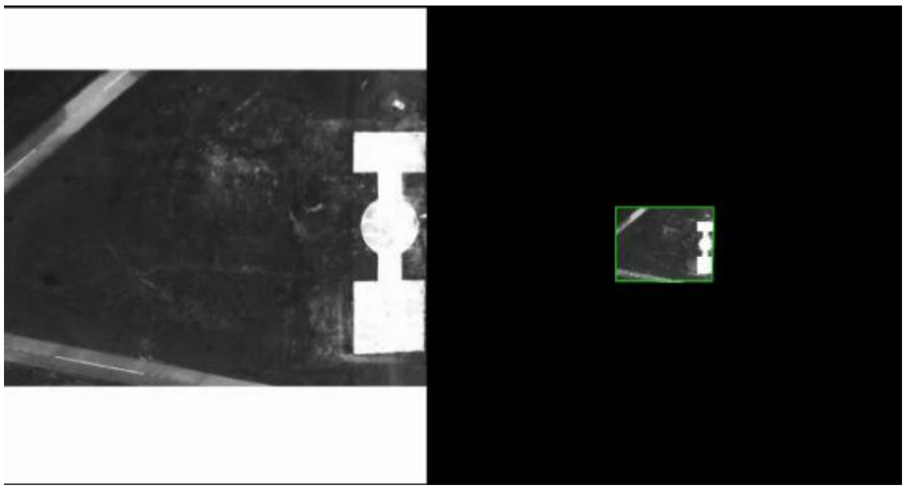
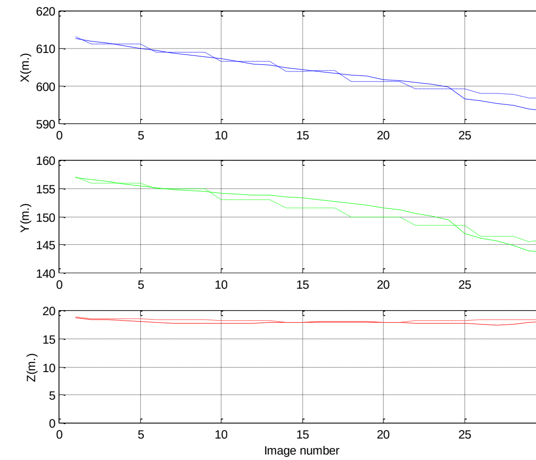
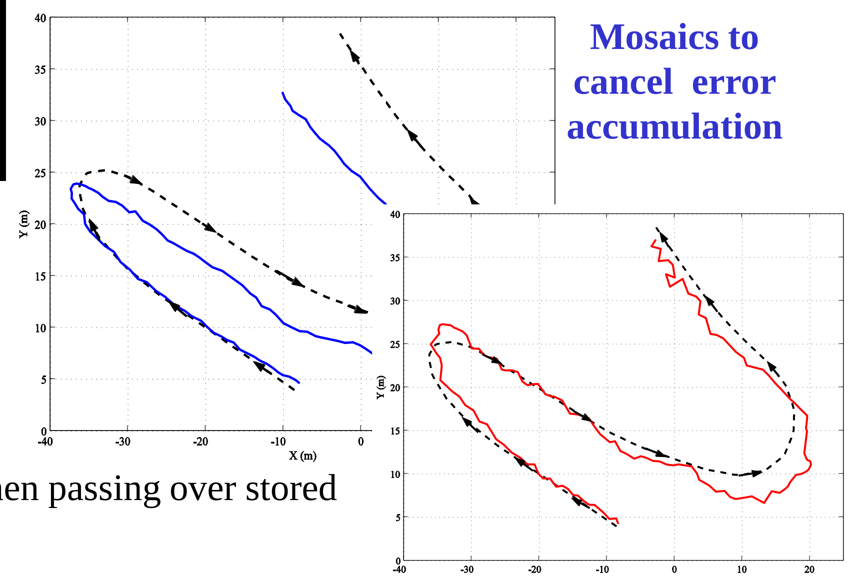
Vision-based position estimation and navigation

Aplication of homographies: Estimation of the motion of the aircraft with respect to ground (plane): translation and rotation.



Position:
Vision vs GPS



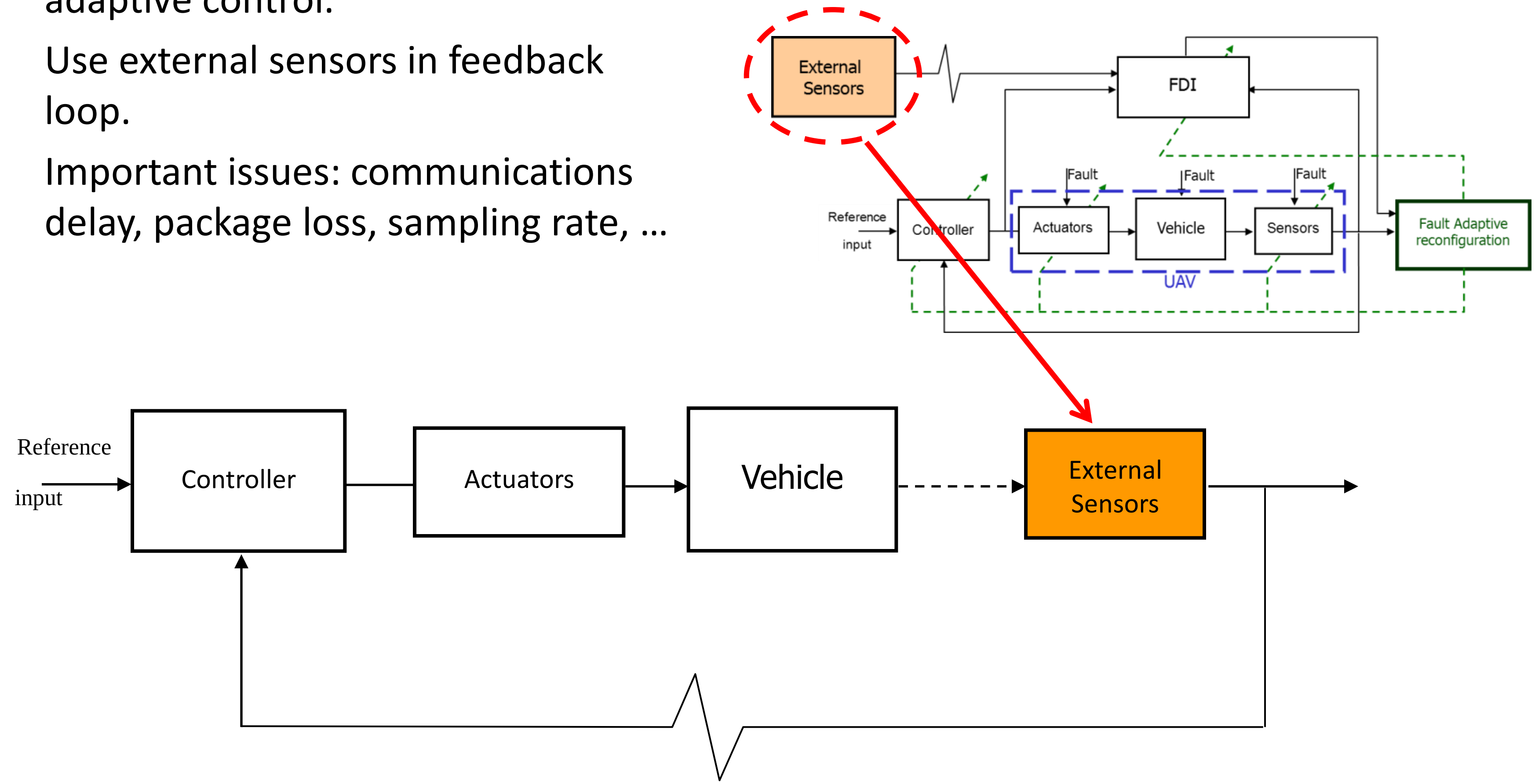


Mosaics to cancel error accumulation

Drift canceled when passing over stored areas.

Fault adaptive cooperative networked control

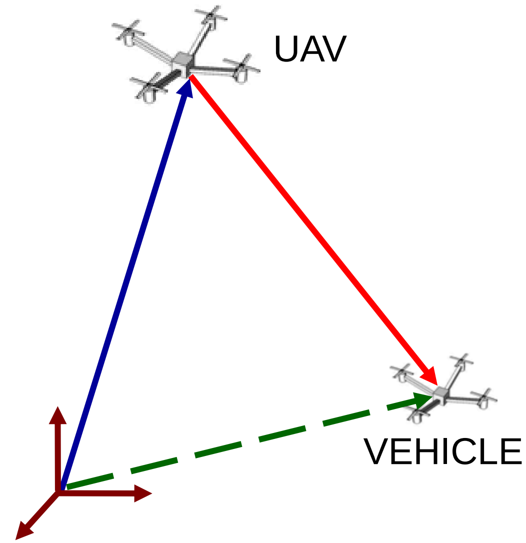
- Develop direct-structure Networked Control System (sensors, actuators or controller connected through communication channel) for networked fault adaptive control.
- Use external sensors in feedback loop.
- Important issues: communications delay, package loss, sampling rate, …



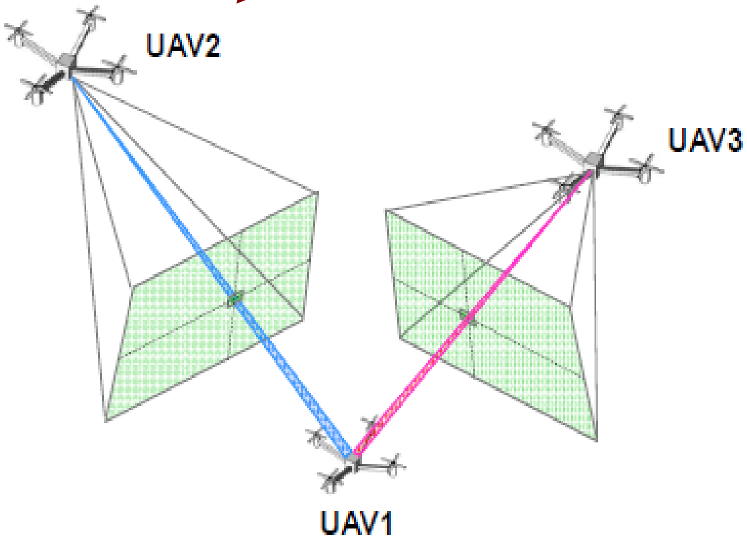
System level fault detection and recovery

- Visual sensors to estimate relative position of other vehicles:

- External position estimation
  - UAV estimates relative position of VEHICLE (red).
  - UAV uses its own position estimation (blue) to derive VEHICLE absolute position estimation (dashed green), and transmits to VEHICLE.
  - VEHICLE does FDI using estimation from external sensor.
- Fusion with other technologies
  - Range-only positioning
  - Range sensor.
  - Barometric sensors (relative altitude).

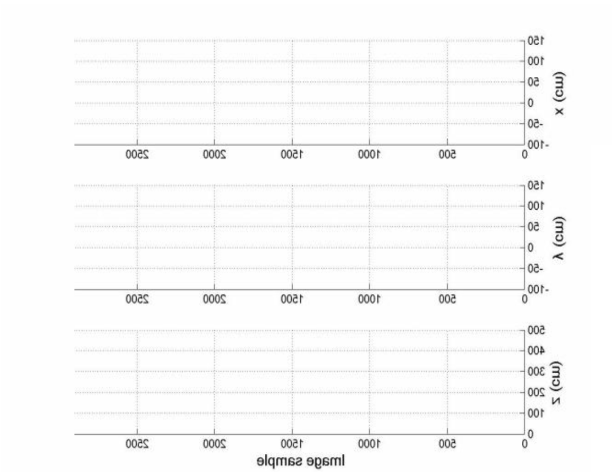


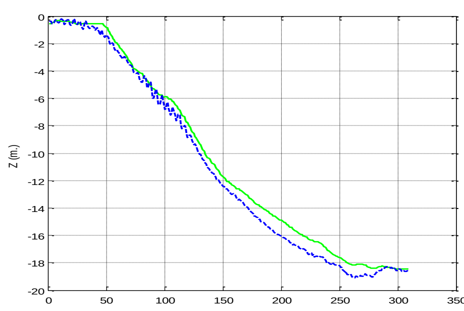
Two UAVs with cameras estimate position of a third UAV, experiments in FADA-CATEC indoor testbed.



Landing using computer vision

– Detection of planar pattern and homography computation for full position estimation
– Implementation on a smart-camera at 30 Hz.





Landing without using patterns

EC-SAFEMOBIL (FP7 ICT, 2011-2015)

http://www.ec-safemobil-project.eu

Validations:

- Landing on mobile platforms
- UAV deployment from aircrafts

Emergency landing of a UAV In severe fault conditions

<u>Fixed wing</u>

Viewer Parachute deployment

Helicopters: Autorotation

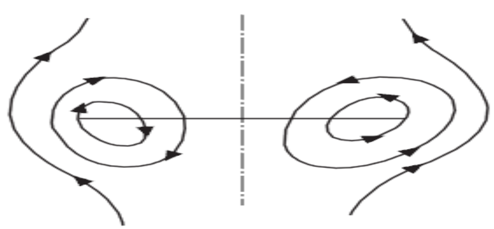
- Energy exchange (Potential and kinematic energy)

Velocity Altitude → RPM main rotor → Controlled descent

Small UAVs helicopters platform limitations:

•Less main rotor Inertia ➔ Less energy storage capacity
•Mass increment of avionics and payload respect to original setup

Vortex ring state (Descending movement)
Unstable state, capacity to produce lifting force and the cyclic effectiveness are drastically reduced.



Autorotation phases:

•**Entry/Steady state (1):** ➔ Engine is not being powered anymore, the helicopter is descending. The aim is to increase the translational kinetic energy

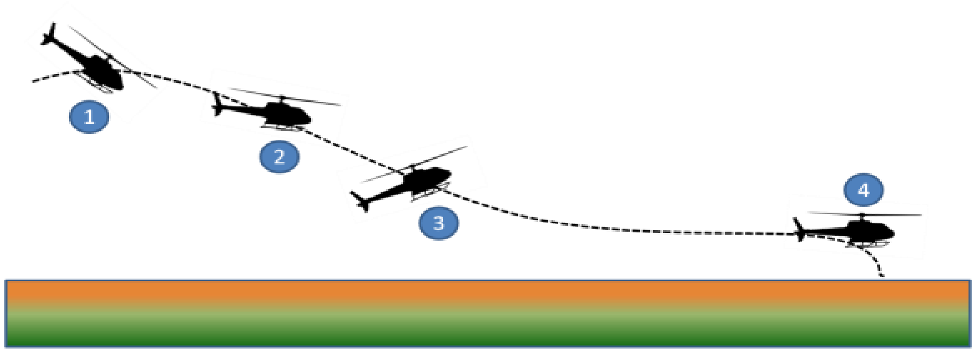
•**Flare:**

First sub-phase (2) ➔ Reduce the airspeed and the sink rate and increasing the blade energy accumulated in the main rotor.

Second sub-phase (3) ➔ Stop the vertical descent movement at about one meter above the ground using the stored energy of the main rotor by applying the proper collective pitch control.

Control: collective (δcol -> 0 minimize main rotor drag) and pitch control

- **Final landing (4)** ➔ Remaining energy in the main rotor is used to reduce the forward speed that had not been canceled yet. When the rpm measurement of the main rotor falls below certain threshold value, the helicopter is allowed to gently touchdown



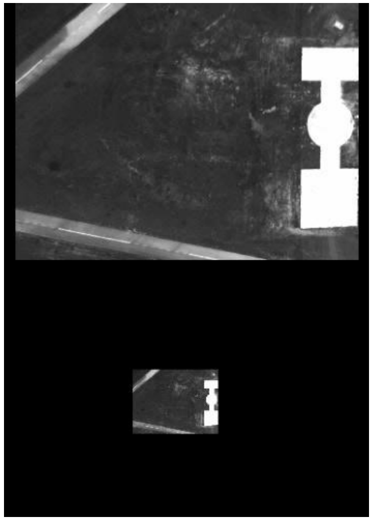
Control:

- δcol altitude control
- Pitch control to minimize forward velocity
- Roll -> 0 for landing

Multiple autonomous aerial vehicles

FP5 COMETS (2002-2005)

Real-time coordination and control of multiple heterogeneous unmanned aerial vehicles



RED-UAS demonstration (Nov, 2011)

- Heterogeneity and team complementarities
  Detection and localisation of alarms
- Grid-based Bayes filter for integration of sensor readings and prior information
- Information filters for data fusion
- Updating the classification of the alarms by using binary filters
- Communication relay and mapping
- Cooperative perception

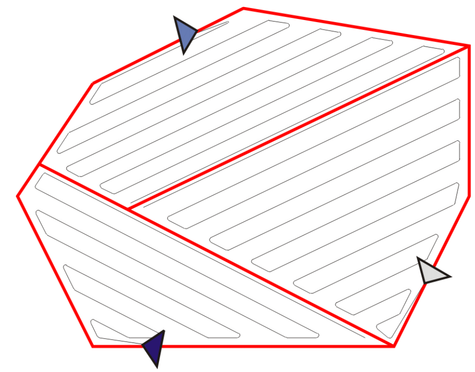
Integration of UAS with ground systems

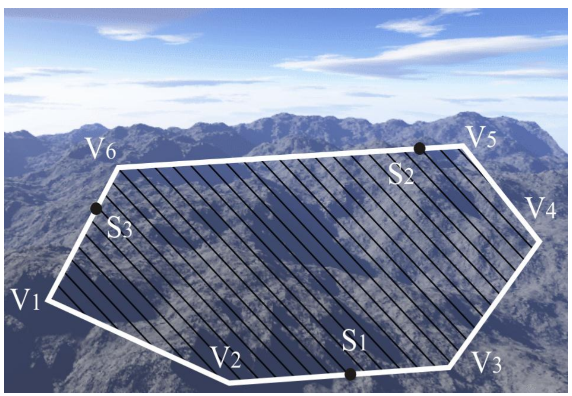
- Exploration by means of UAS
- Automatic detection
- Computation and transmission of coordinates
- Automatic ground actuation

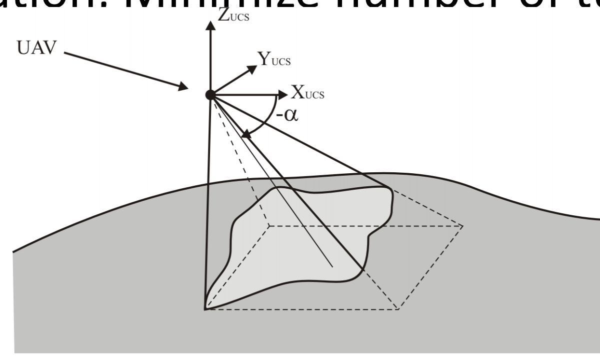
AWARE FP6 (2006-2009)

Cooperative missions: Multi-UAV Area coverage

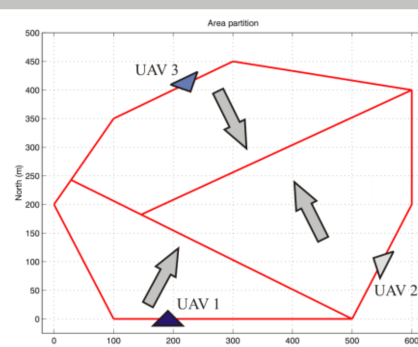
- Multiple UAVs: constrained in flying endurance.
- "Event detection" mission: cooperatively search a given area to detect objects of interest.
- Divide area taking into account UAV's relative capabilities (speed, altitude, remaining fuel, consumption) and initial locations.
- Each area covered using a zigzag pattern.
- Objectives: Real time operation. Minimize number of turns.

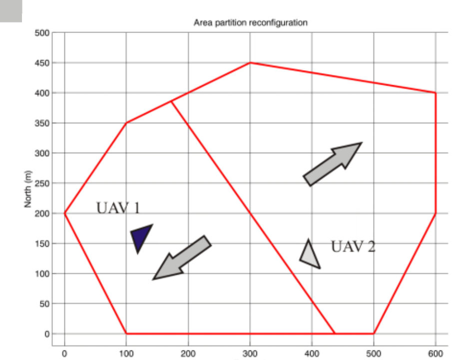






Dynamic reconfiguration





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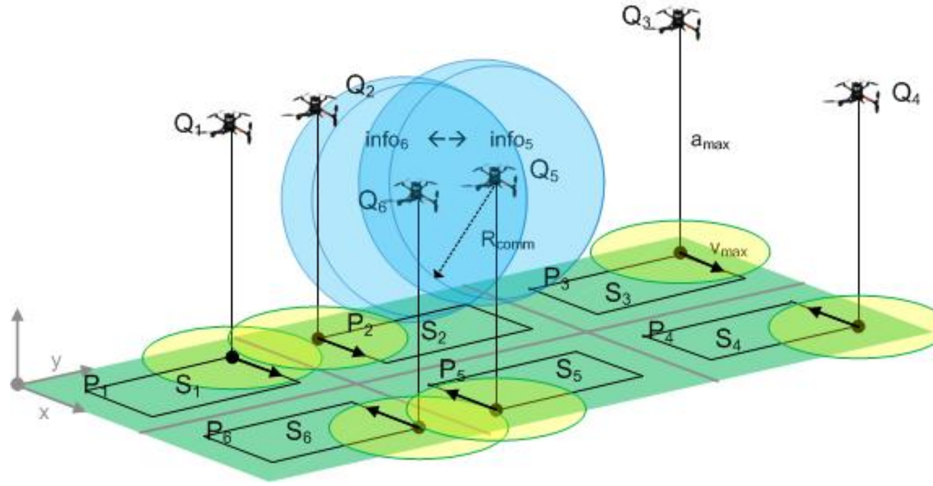
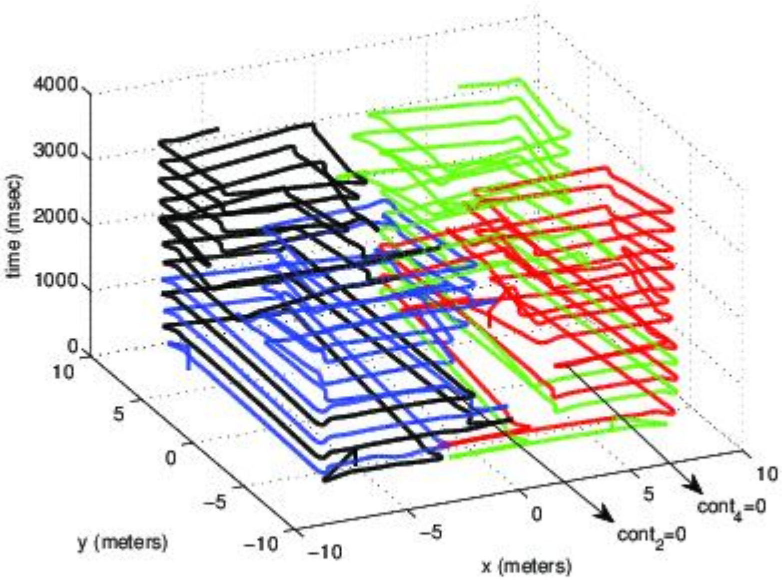
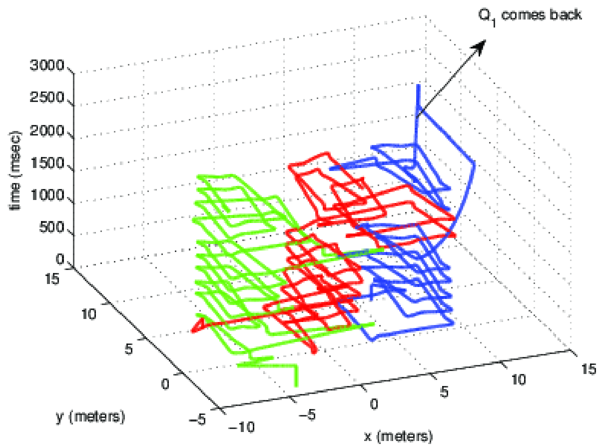
Distributed area surveillance

- Dividing area
- Maximizing coverage ratio
- Periodical communications

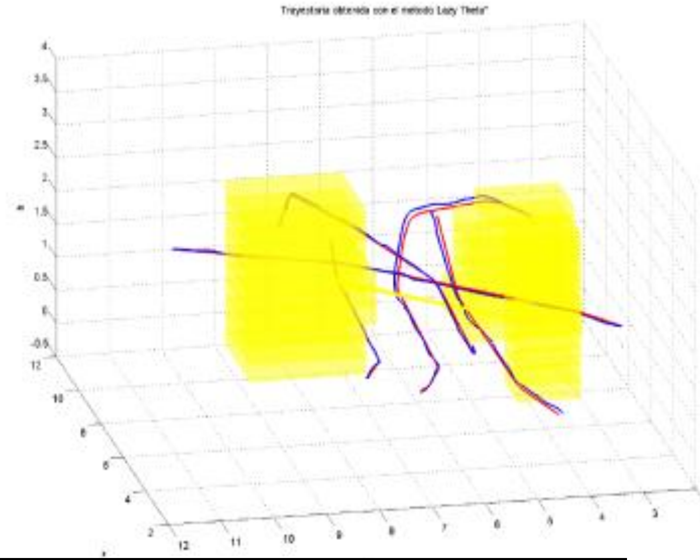






Multi- UAV trajectory planning

- Approaches:
  - Priorities
  - Global optimization
  - Dynamic characteristics
  - Anytime approach
- Implementation of Dynamic Lazy Theta* to improve search in 3D
- Implementation in the CATEC indoor testbed



Conflict resolution: Problem Formulation

- Multiple UAVs in a common airspace
- Safety distance → Potential collision?
- Discretization of the airspace: cubic cells
  - Trajectory is parameterized by a number of cells, entrance and departure time
  - Safety distance is given by a number of cells
  - Time spent in a cell depends on the aircraft model
  - All aircraft trajectories are known
- OBJECTIVE: to find a collision-free trajectory while minimizing the total deviation from the initial 4D trajectory

Velocity Assignment Problem

- UAV={UAV_1,…,UAV_n} set of UAVs
  - 3D dimensional
  - constant initial velocity (v_i)
  - straight lines
- Constrained interval of possible velocities for each UAV
- Collision detected: → Modify velocities of UAVs

Velocity Assignment Problem

- Criterion: minimize the total deviation with respect to the predicted stay time in each cell

$$J = \sum_{i=1}^{n} \sum_{j=1}^{C_i} \left(t_{ij} - t'_{ij} \right)^2$$

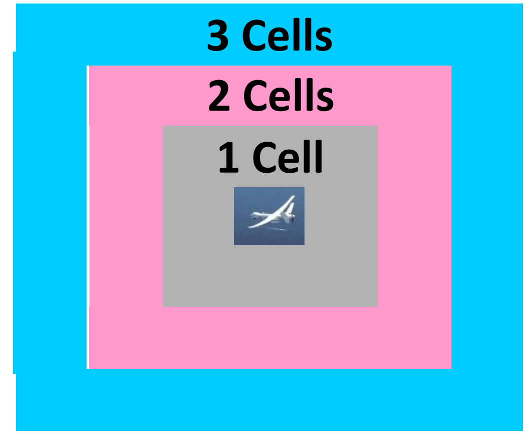
- *n* is the number of UAVs,
- C_i is the number of cells crossed by the UAV_i
- tij and t'ij are the stay time of the UAV_i when crossing the C_j
- Models and velocity constraints

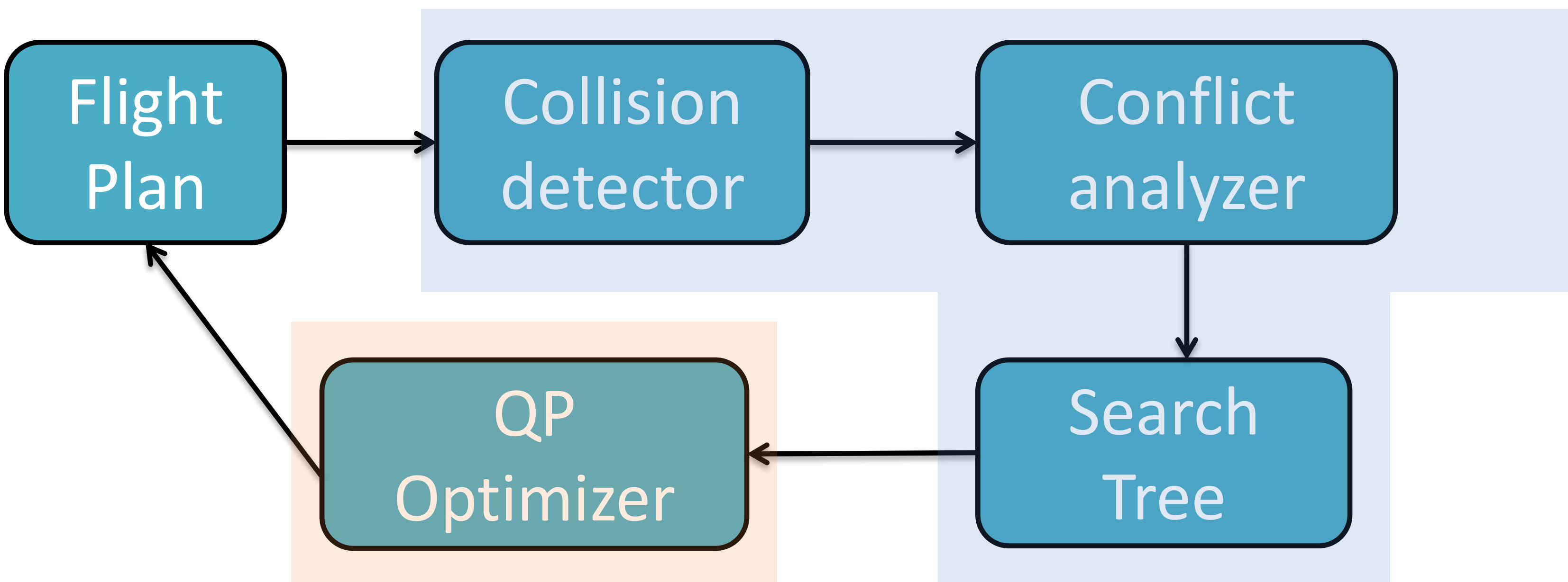
Implemented methods

- Efficient conflict resolution methods for UAVs sharing airspace:
  1. Greedy method
  2. Discrete Velocity Allocation problem (DVA)
  3. Heuristic velocity planning with optimization phase

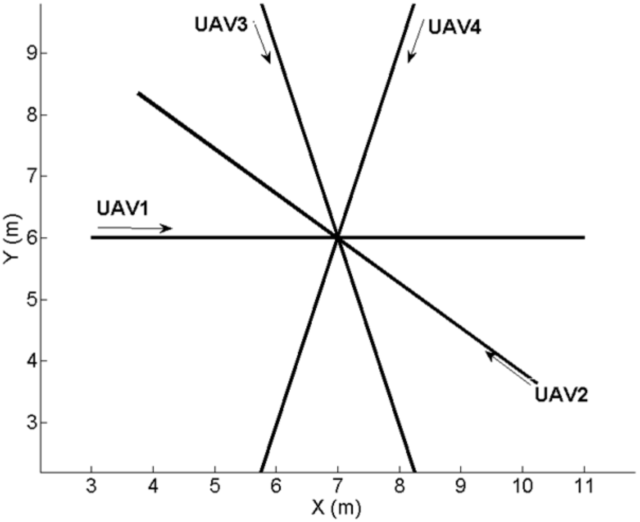
Conflict detection and resolution

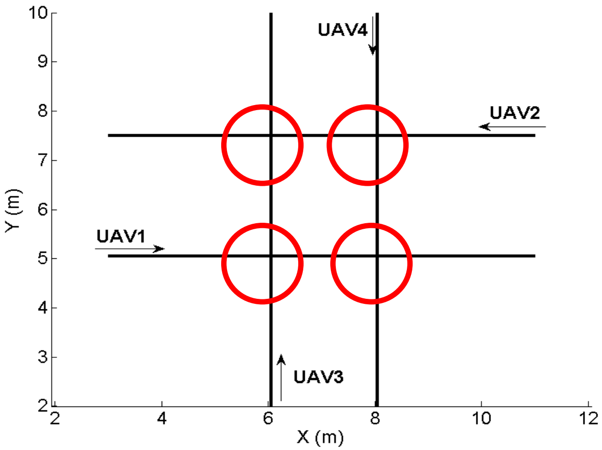
– Ensure safety: Safety zone surrounding all vehicles
– Minimize trajectory changes
– Only modifies the speed
– Discretized space
– Bounded execution time

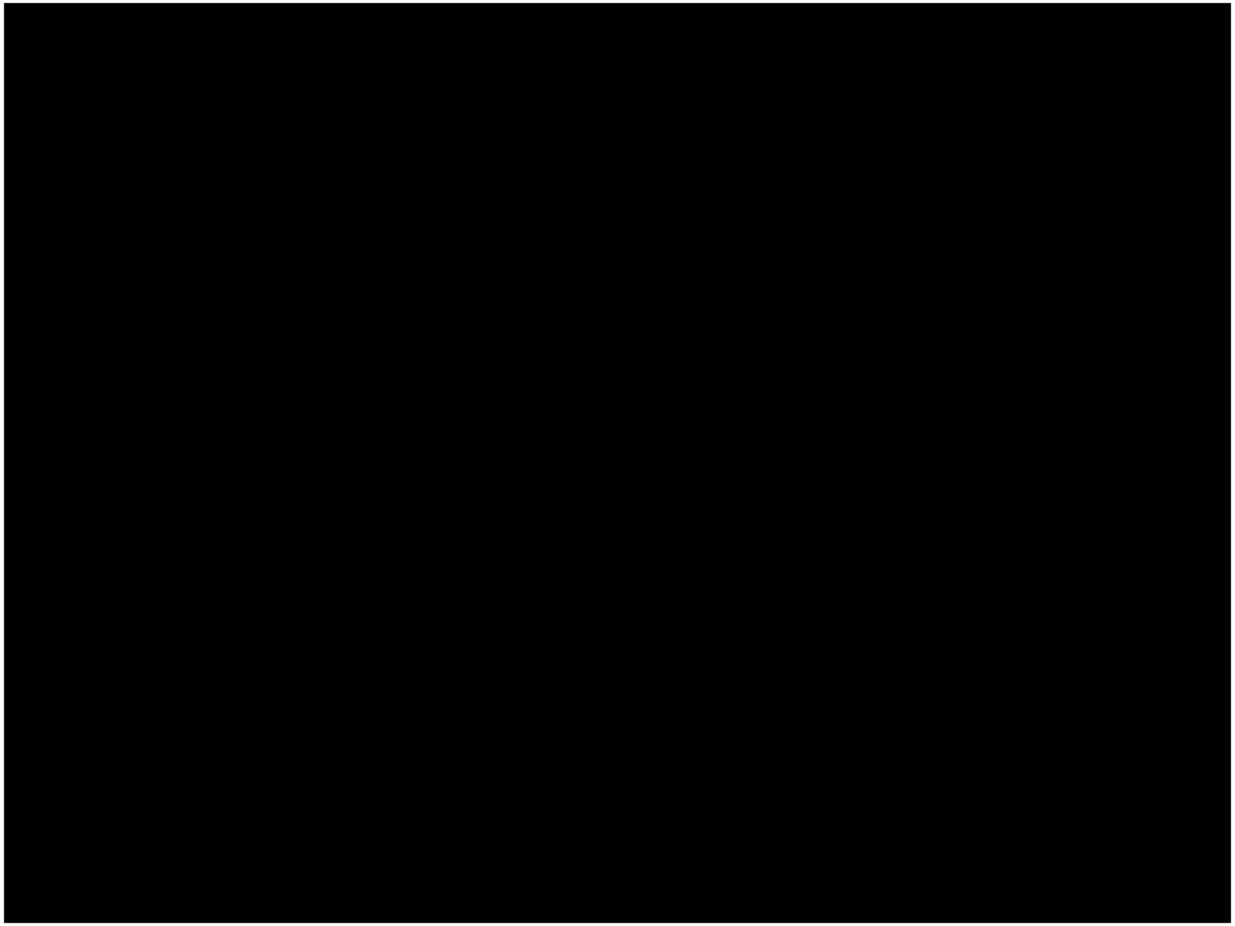




Application in the CATEC testbed







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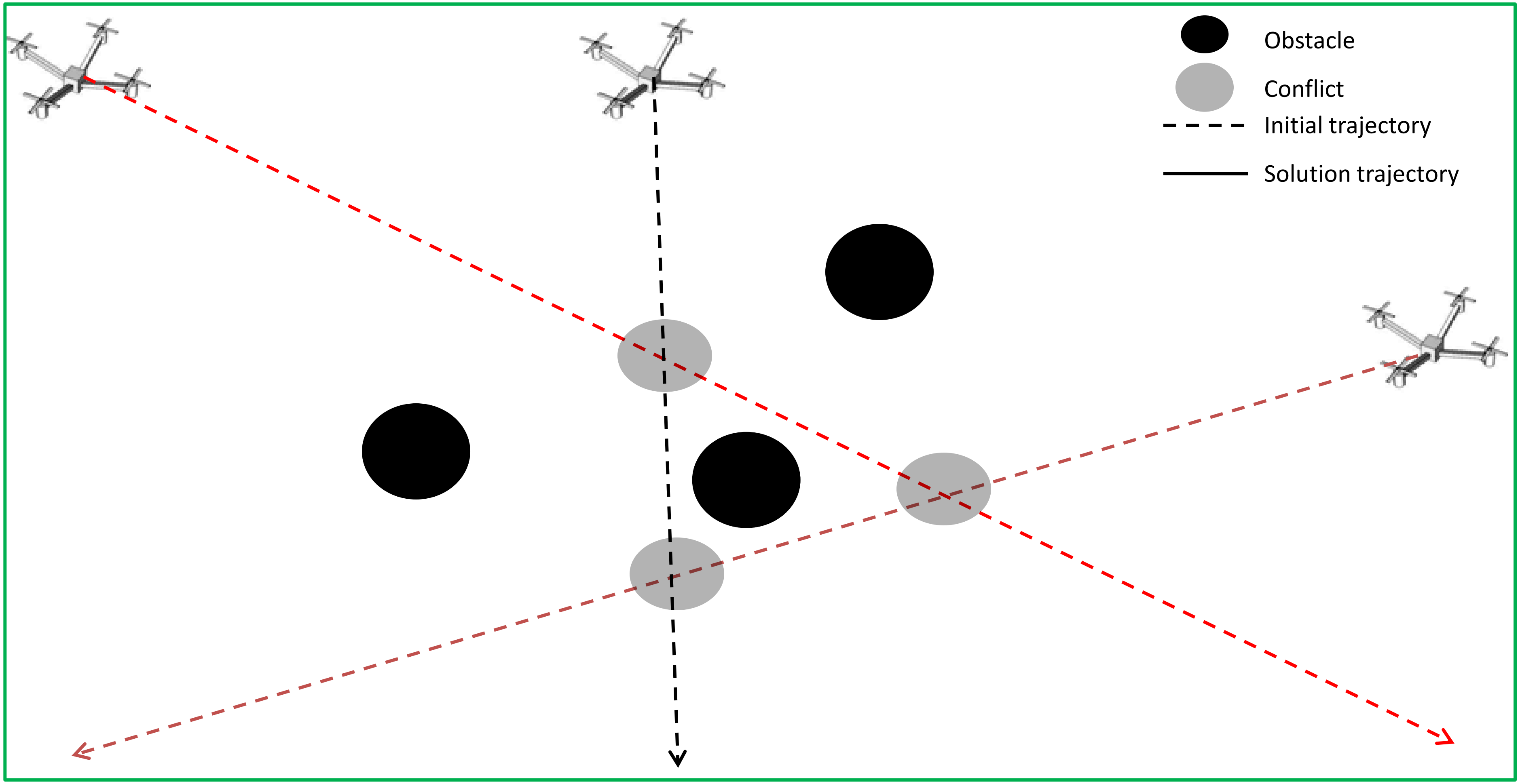
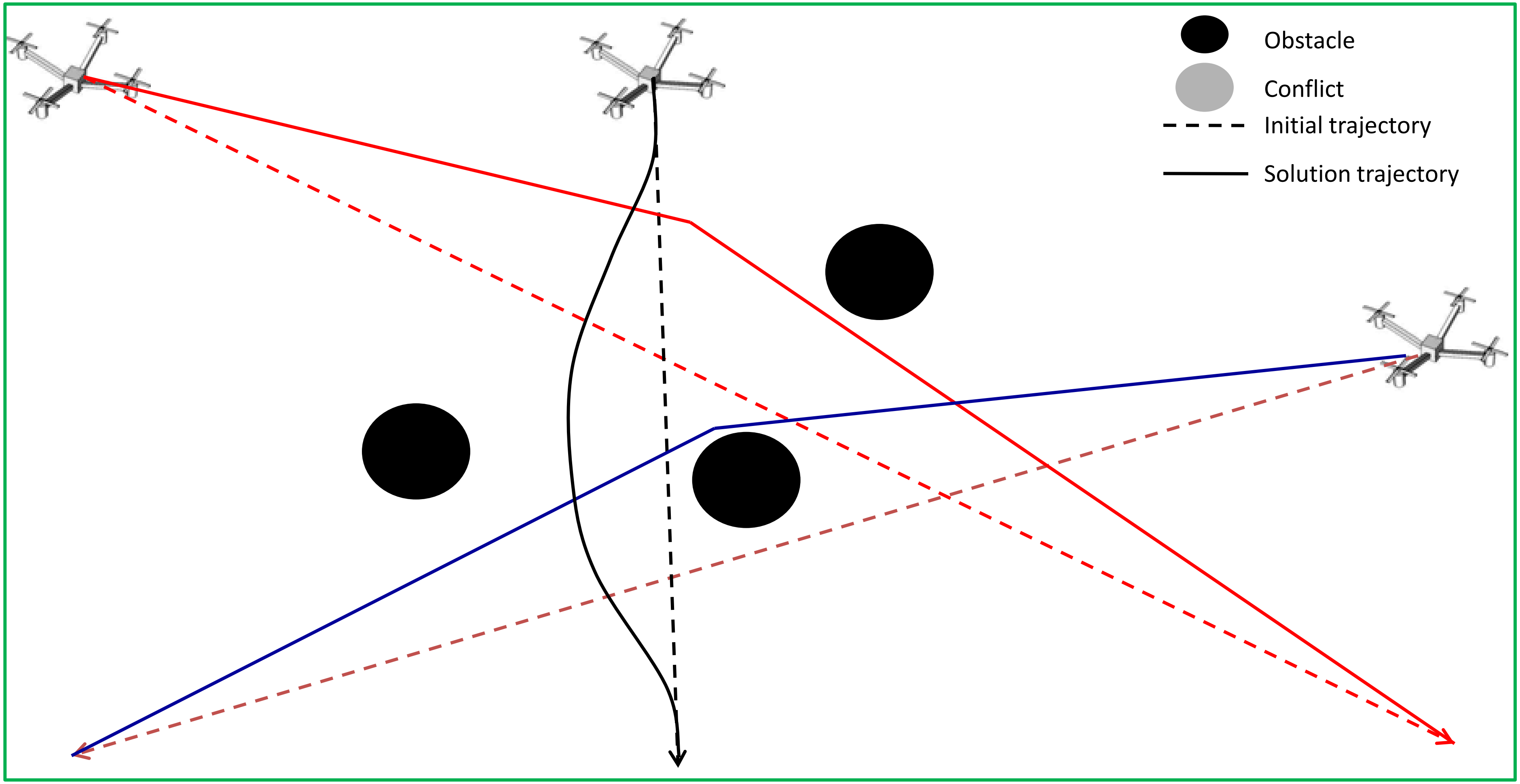
Example: multi-UAV trajectory planning for collision avoidance

- Multi-UAV scenario ⟷ conflict detection and resolution system



Example: multi-UAV trajectory planning for collision avoidance

- **Multi-UAV scenario** ⟷ **conflict detection and resolution system**



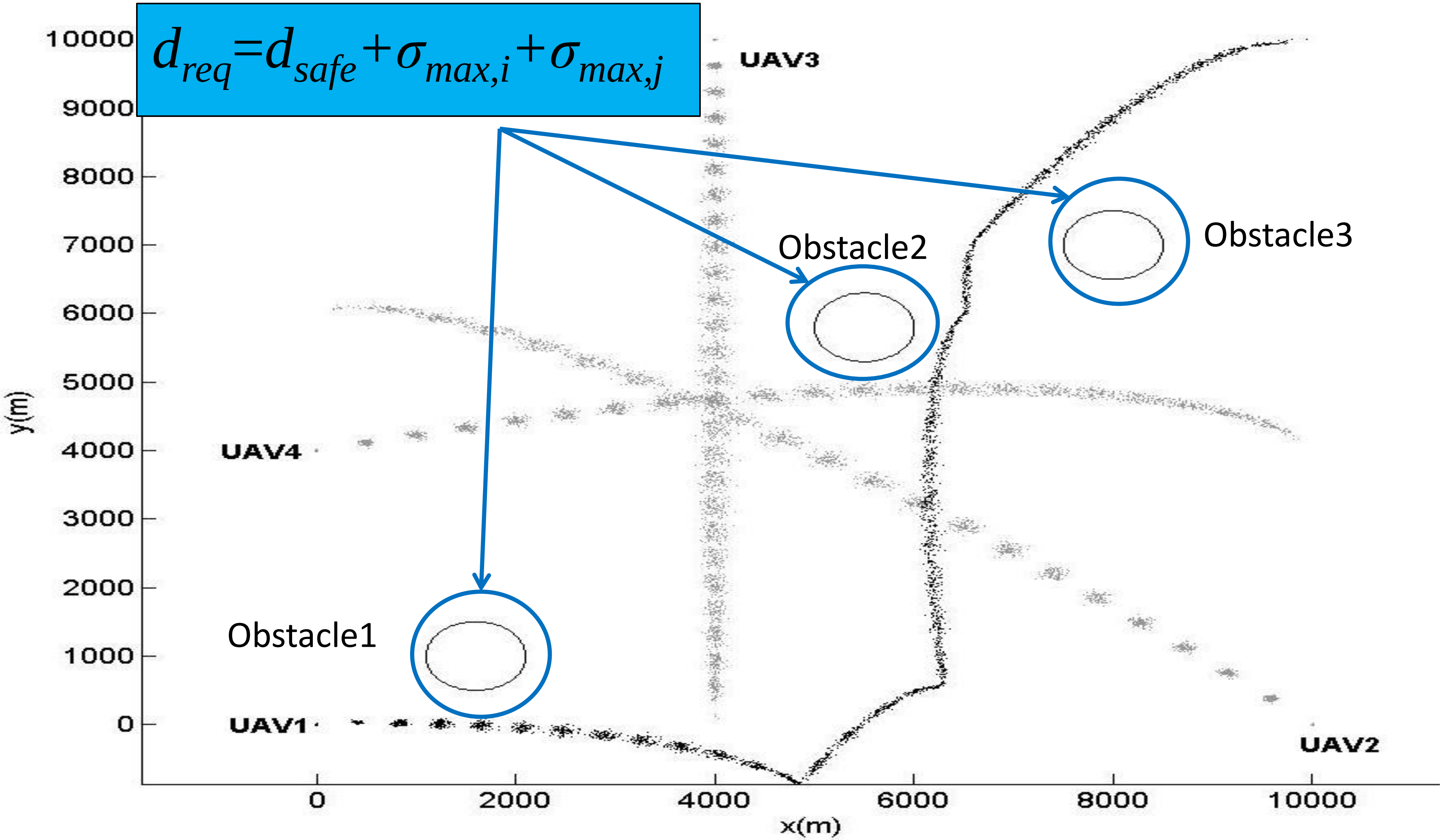
Trajectory optimization

- Multiple UAVs in a common airspace: collision-free trajectories
- A new UAV comes in this airspace
- Separation among UAVs should be greater than a given safety distance → Potential collision?
- New UAV has to change its trajectory →Intermediate waypoints
- Information that the UAV needs:
  - Sequence of waypoints that each UAV will follow
  - Parameters of the model of each UAV
  - Position of the static obstacles
  - Wind model parameters
- OBJECTIVE: to find a collision-free path while minimizing the changes of the trajectory

Resolution based on three stages

1. **Detection algorithm** based on a grid model
2. **Monte-Carlo method** to predict the trajectories under uncertainties (wind, the UAV model inaccuracies, etc.)
3. **Genetic algorithms** or **Particle Swarm** to compute the collision-free path
4. **Collocation methods**

SIMULATIONS



EC-SAFEMOBIL (FP7 ICT, 2011-2015)

http://www.ec-safemobil-project.eu

Safety in tracking

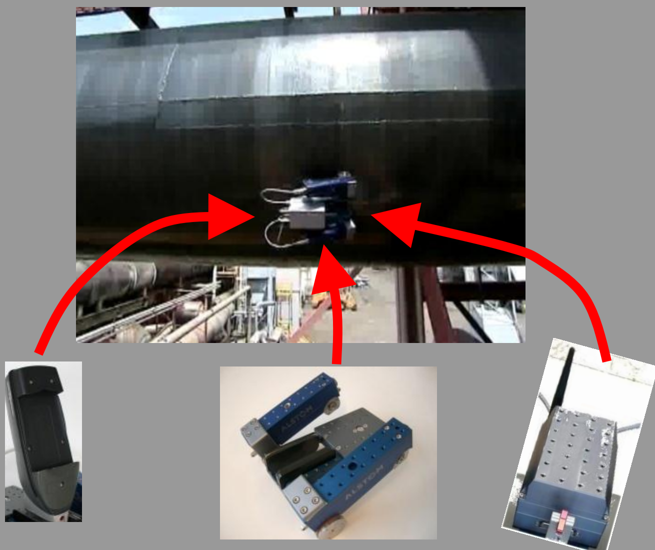
Methods:

- Distributed estimation
  POMDPs
- Distributed decision and control
  POMDPs, distributed negotiations

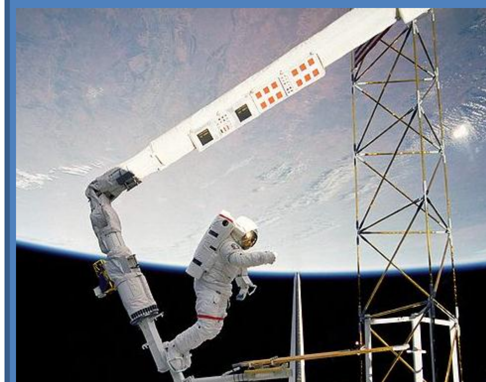
Physical interactions with the environment
Aerial Robotics Cooperative Assembly System
FP7 ARCAS (2011-2015)

Application Scenarios

Flying + Manipulation + Perception + Multi-robot Cooperation



Aerial Robotics Applications



Space Applications

- Joint load transportation

FP6 AWARE (2006-2009)

Aerial Robotics Cooperative Assembly System (ARCAS)
FP7-ICT-2011-7

Development and experimental validation of the first cooperative free-flying robot system for assembly and structure construction

Several robotic aircrafts: enhanced manipulation capabilities, increased reliability and reduced costs.

Quadrotor with arm

- Quadrotor without arm: center of mass at vertical of quadrotor geometrical center.
- Quadrotor with arm: arm center of mass displaced from vertical of geometrical center ➡ generates external torque T_{arm}.

$$m\dot{V} + \Omega \times (mV) = F_{prop} + F_{aero} + F_{grav} + F_{contact}$$

$$J(\gamma)\dot{\Omega} + \Omega \times (J(\gamma)\Omega) = T_{prop} + T_{aero} + T_{arm}(\gamma) + T_{contact}$$

- External torque $T_{arm}(\gamma)$ and inertia matrix $J(\gamma)$ vary with position of arm (γ: arm joint angles).
- If the arm picks an object, also m and F_{grav} vary.
- Contact of picked object with environment generates $F_{contact}$, $T_{contact}$.

Quadrotor with arm

- Simulation
  - Arm kinematic/dynamic equations: Denavit-Hartenberg formulation using HEMERO toolbox, or simplified model.
  - Implement quadrotor dynamic equations in Simulink, including variable inertia matrix and variable arm external torque.
- Quadrotor control
  - Estimation of arm external torque on quadrotor:

$$T_{arm} = T_{struct} + T_{object} \quad \text{and} \quad T_{contact}$$

- T_{struct}: torque generated by the mass and inertia of arm joints and links. Can be known very accurately using arm joint angle sensors and kinematic model.
- T_{object}: torque generated by the object picked with the arm. Can be known approximately if Motion Planner provides characteristics of object (weight, inertia matrix).
- $T_{contact}$: torque generated by the contact forces/torques of the object interacting with the environment and structure. Can be known if load cell installed on grip. If not, unknown.
  - Total external torque Tarm can be measured if load cell installed at arm base.

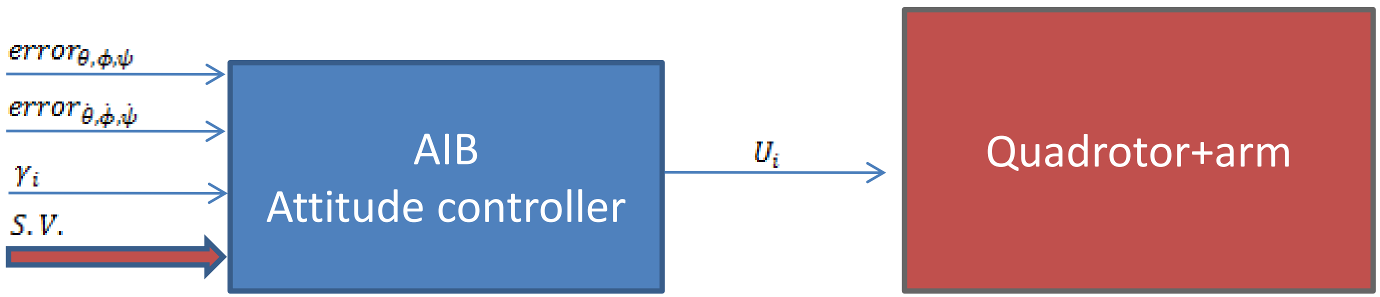
Quadrotor controller design approaches

– Baseline controller: standard quadrotor controller, integral term and feedback compensates deviation.
  - Classical cascaded PID.
  - Integral backstepping.
– Feedforward controller: feedforward term compensates torques generated by arm joints and links and picked object $T_{arm}(\gamma)$.
  - Classical cascaded PID.
  - Integral backstepping.
  – Contact forces/torques of object with environment: can be large due to quadrotor movement. Then measure/estimate and include in controller.
  – Load cell installed on grip or estimation using nonlinear observer.

Controller Scheme

- Adaptive Integral Backstepping(AIB) and PID controllers

  AIB: Nonlinear backsteping with integral term
- Control law with parameters varying with arm motions
- γ_i are joint angles of the arm; S.V. are state variables of quadrotor



Roll AIB controller

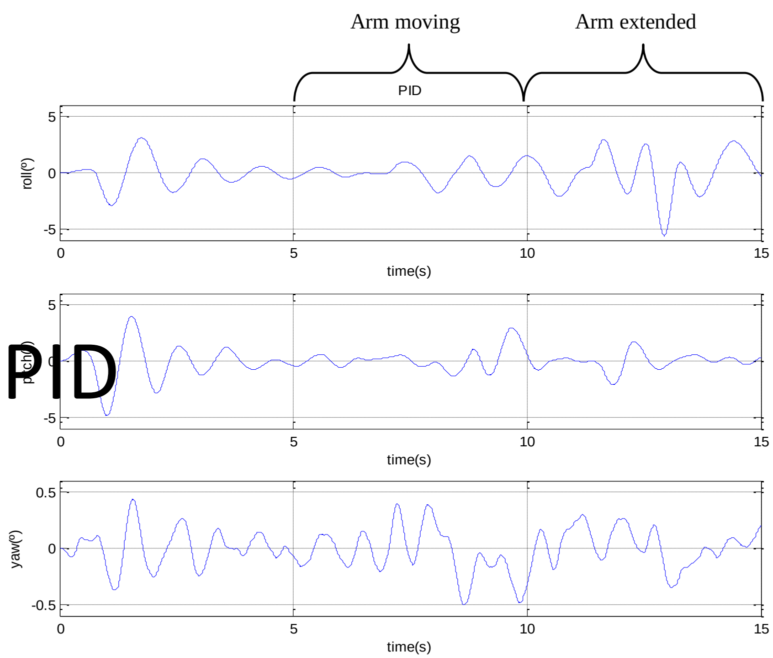
$$U_2 = \frac{1}{d_1}[(1 - k_1^2 + \lambda_1)e_1 + (k_1 + k_2)e_2 - k_1\lambda_1\chi_1 + \ddot{\phi}_d - \dot{\theta}\dot{\psi}a_1 - (\dot{\phi}\dot{\psi} - \ddot{\theta})a_2 + (\dot{\theta}\dot{\phi} + \ddot{\psi})a_3 - \left(\dot{\psi}^2 - \dot{\theta}^2\right)a_4 - \dot{\theta}a_5\Omega_r]$$

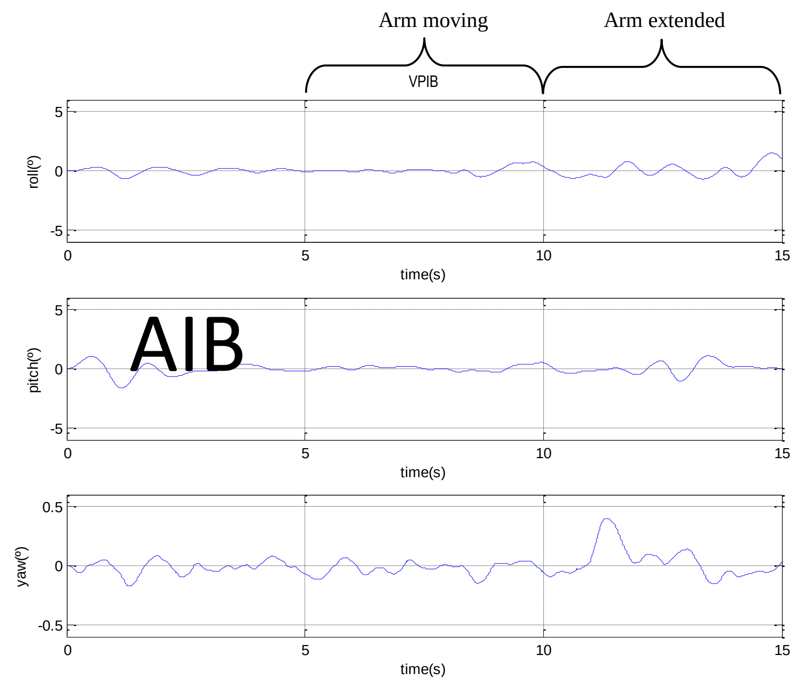
$e_1 = \phi_d - \phi,;\ e_2 = \omega_{xd} - \omega_x$; and $\chi_1 = \int_0^t e_1(\tau)\ d\tau$

$Variable\ parameters\ a(\gamma) = [a_1, a_2, a_3, a_4, a_5]$, obtained from the inertia matrix $\mathrm{I}(\gamma)$

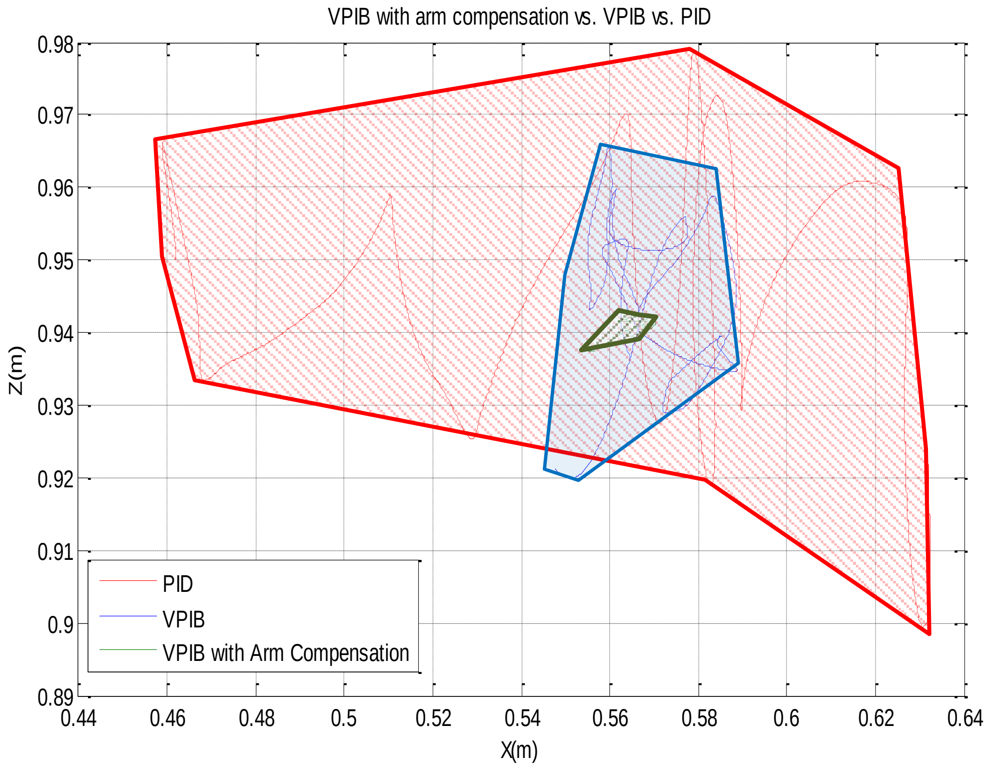
Controller Scheme

Quadrotor trying to maintain hover with arm motions (Simulations):





AIB Controller Vs PID Controller



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ARCAS First designs: Manipulation

Feedforward controller to compensate torques generated by arm joints and links and picked object $T_{arm}(\gamma)$.

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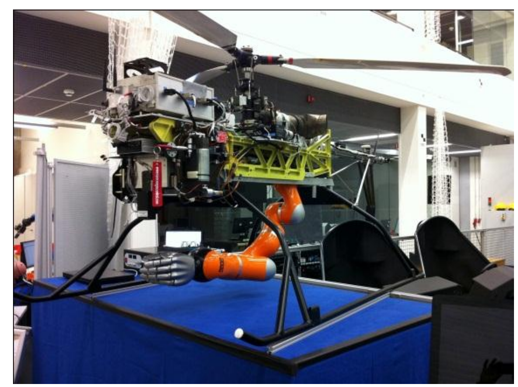
ARCAS First designs

Electrical helicopter with advanced gripper mounted on actuated cardan joint.

The cardan joint will be replaced by a manipulator with five degrees of freedom



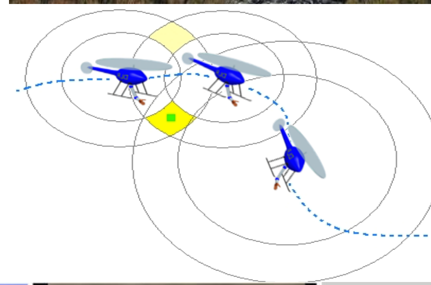
Perception in ARCAS

Scene recognition

- Detection and localization of the parts to be used in structure assembly: Illumination invariants, recognition with challenging orientation variation
- Identification of a suitable location for the structure

Fast 3D model generation

- SGM-Method for close range 3D-modelling



Range only SLAM in structure assembly

- Structure parts and aerial robots with radio systems in structure assembly
- Gaussian Mixture approaches for EKF and EIF

Reliable tracking of 3D objects

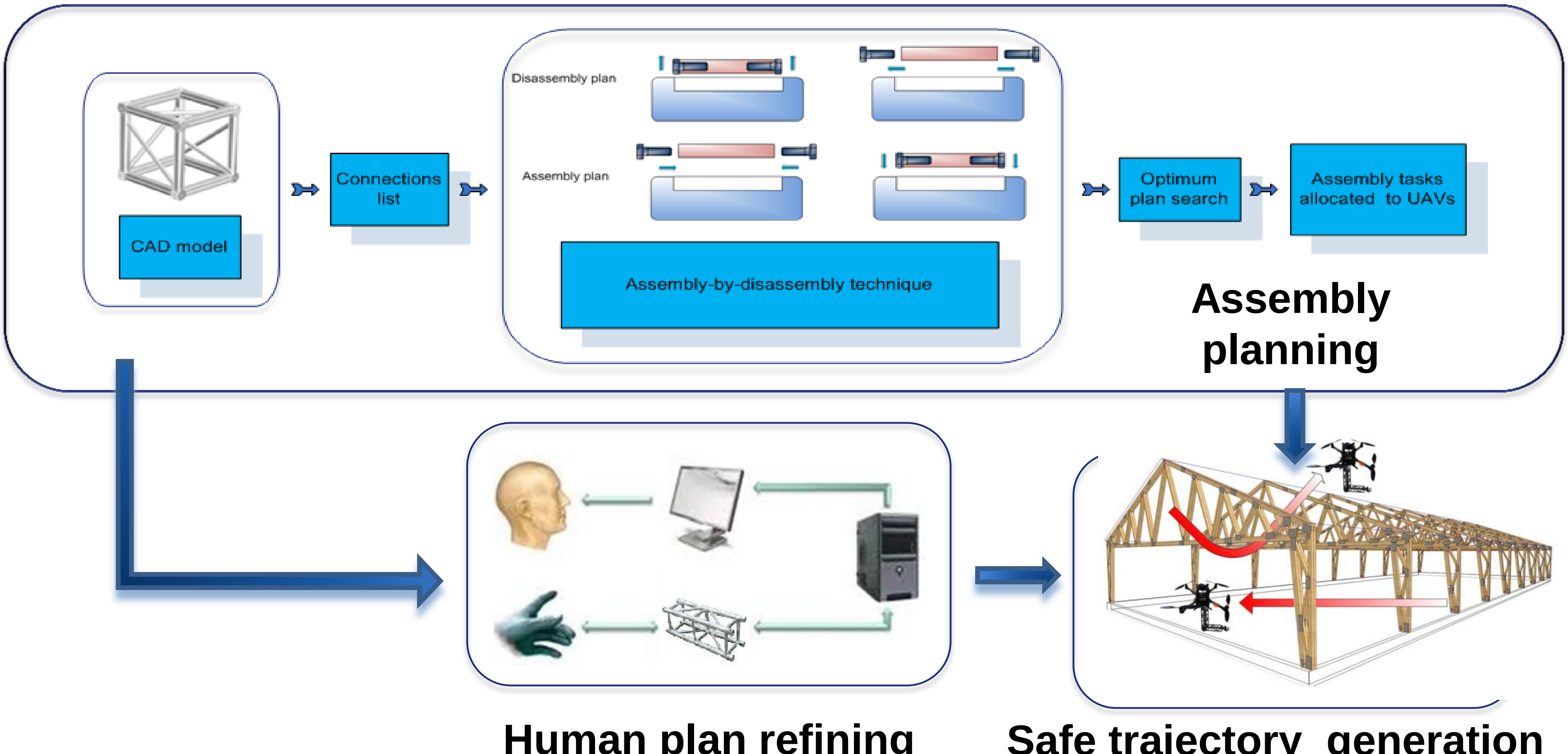
- 3D Object tracking using cameras with varying focal length: To be used in visual servoing
- Uncallibrated image-based visual servoing

Cooperative perception

- Combine the information from multiple aerial robots
- Distributed methods: decentralized GMM-based filters
- Active perception

ARCAS Planning

- **Assembly planning:** symbolic/geometric, SHOP & assembly from dissasembly, adaptability and replanning for dynamic environments
- **Human plan refining** using mixed initiatives
- **Safe coordinated trajectories** generation and execution: collision detection and avoidance (UAV+arm+object), trajectory optimization for cooperating UAVs



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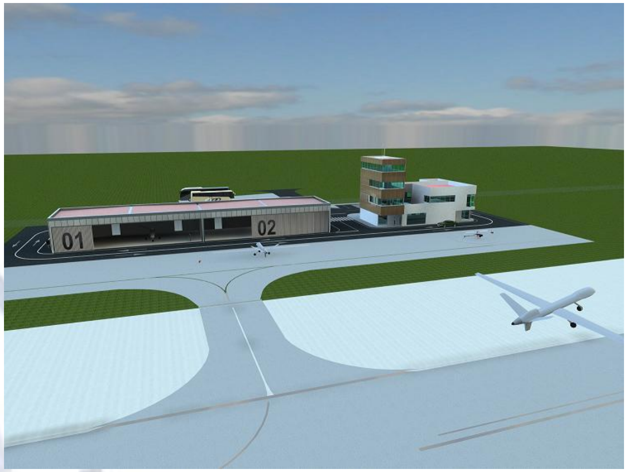
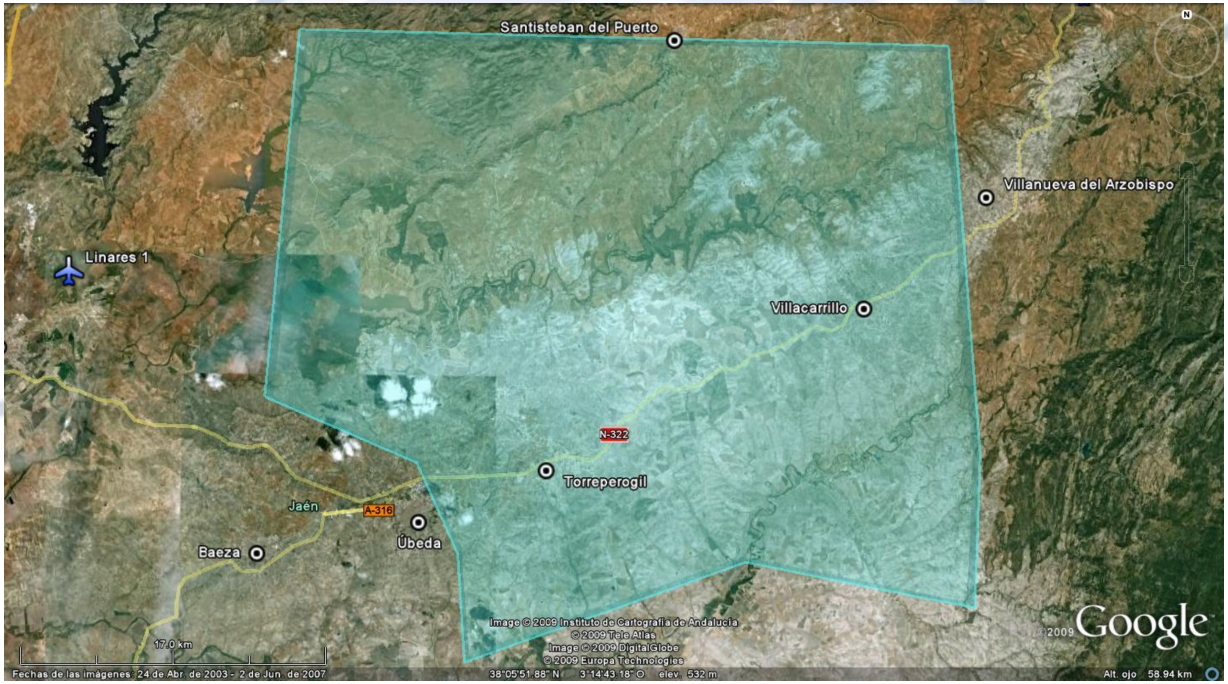
- Center of Experimental Flights **ATLAS**
  - Ground installations: (15 Ha)
    - Main runway: 800m x 18m
    - Auxiliary sand runway: 400m x 15m
    - Control center for mission operations
    - Independent Hangars for different customers
    - Logistic and Technical support
  - Segregated air space
  - UAS < 650 Kg MTOW
  - Technology validation Center; avionics and other technologies
  - UAS regulation and certification
  - Pilot training center



- Segregated Air Space
  - Size: 35 x 30 Km aprox.
  - Altitude: up to 5000 ft



Conclusions

- First steps
- Better platforms
- Need of new technologies and methods
- Validation and experimentation needs
  - ATLAS facility
- Regulations and safety assurance