

# **Aerial robotic manipulation**

**Anibal Ollero**

**Professor and head of GRVC University of Seville  
(Spain)**

**[aollero@us.es](mailto:aollero@us.es)**

**Scientific Advisor of the Center for Advanced Aerospace  
Technologies (Seville, Spain)**

**[aollero@catec.aero](mailto:aollero@catec.aero)**

# Outline

- Introduction
- ARCAS FP7 project
  - Motivation and generalities
  - Aerial robots in ARCAS
  - Control
  - Perception
  - Planning
- AEROARMS H2020 project
- Conclusions

# Introduction



Unmanned Aerial  
Systems



Mobile Robotic  
Manipulation

**Aerial robotic  
manipulation**

## Introduction: 2014 RPAS Projects at CATEC and USE

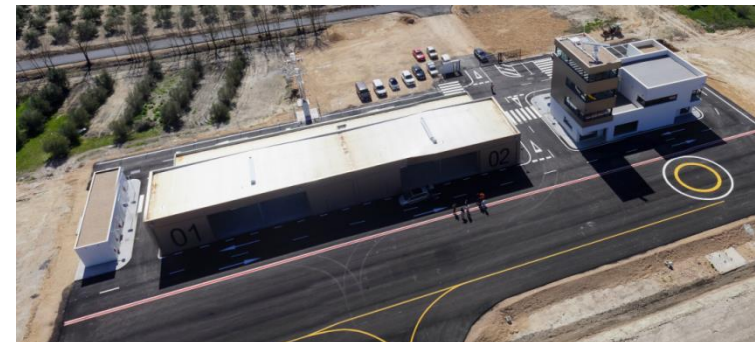
- 90 researchers and technicians working on aerial robotics and UAS
- 20 running projects (28 contracts) in 2014
  - 8 European FP7 projects
    - Coordination of 3 projects: ARCAS, EC-SAFEMOBIL, MUAC-IREN
    - Partner in 5 projects: PLANET, FIELDCOPTER, ARIADNA, DEMORPAS, EUROATHLON
  - 12 Spanish Projects
    - 1 Project National Programme: CLEAR
    - 1 Regional Programme: UAVLIDETECT
    - 2 INNPRONTA (6 contracts with companies): ADAM, PERIGEO
    - 2 CENIT (4 contracts with companies): SINTONIA, PROMETEO
    - 2 INNPACTO: IGNIS and ADALSCOM
    - 2 INNERCONNECTA (4 contracts with companies): CITIUS, ARIDLAP
    - 2 additional contracts with companies on VTOL systems and simulation for training (ARIDLAP)

## FADA-CATEC UAV fleet



## Flight experimentation facilities

- Indoor
  - Testbed 16x15x6 m
  - VICON System
  - Able to fly more than 10 vehicles at the same time
- ATLAS RPAS Experimentation facility
  - Segregated aerial space: 35 x 30 Km , Altitude: up to 5000 ft
  - 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





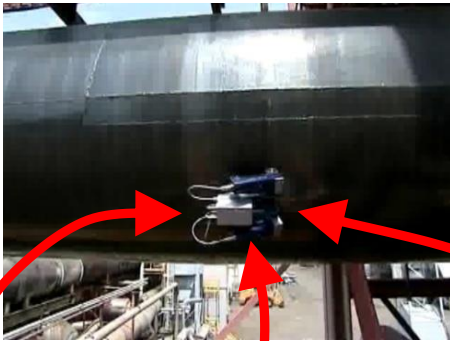
Coordinator: A. Ollero

Large-scale integrating project (IP) Project No. 287617 • FP7-ICT-2011-7

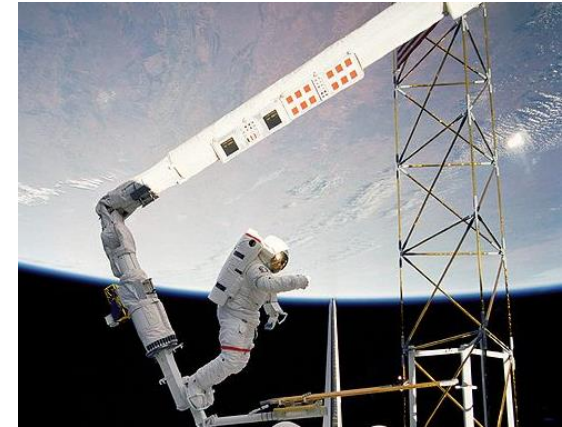


# Aerial Robotics Cooperative Assembly System FP7 ARCAS (2011-2015)

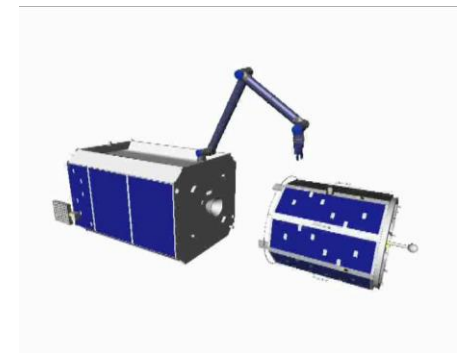
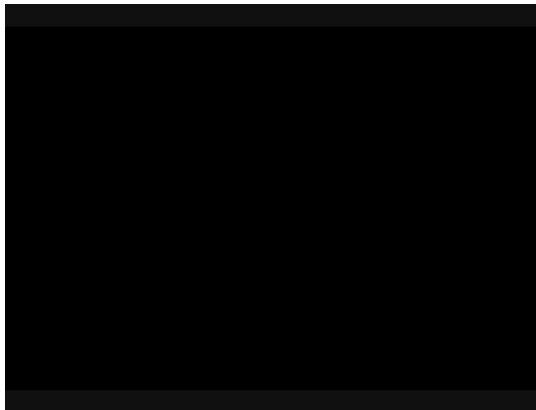
Flying + Manipulation + Perception + Multi-robot Cooperation



Aerial Robotics Applications



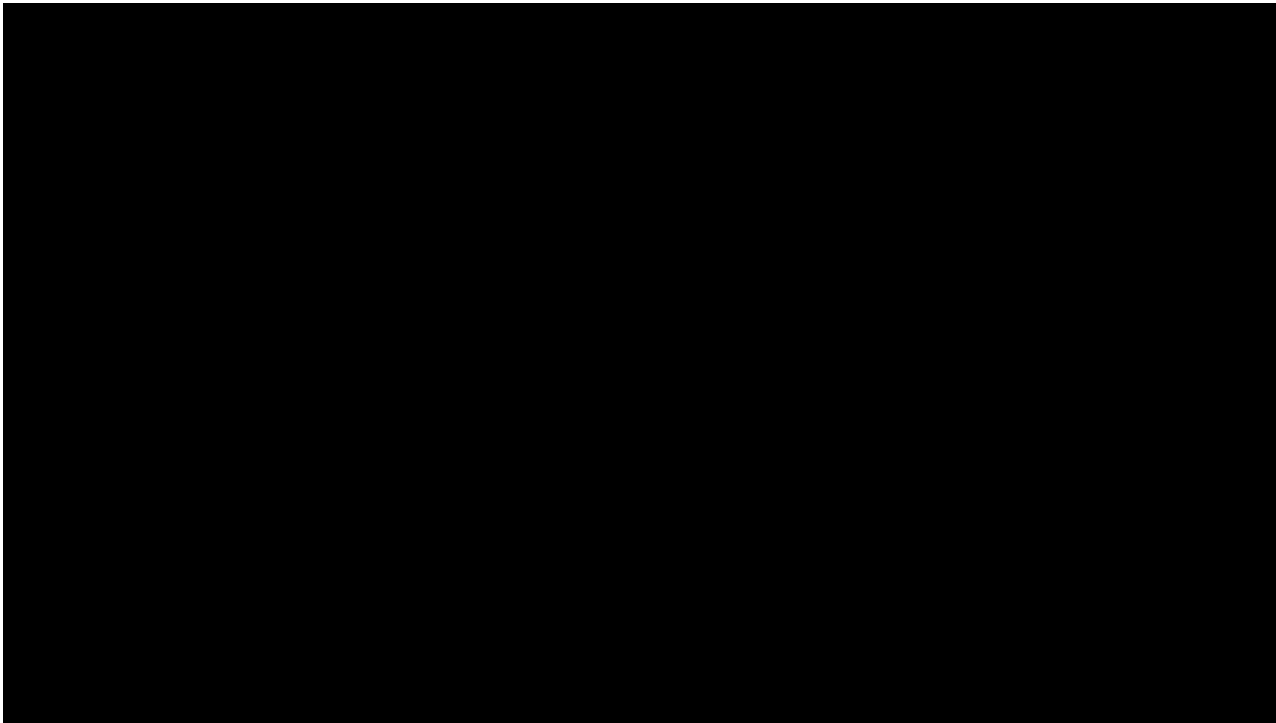
Space  
Applications





# 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.



# Objectives

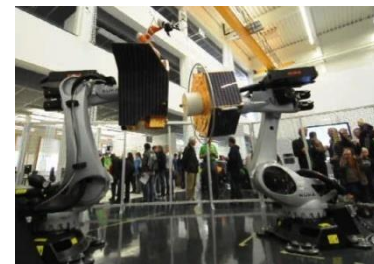
**Motion control.** Manipulator in contact with a grasped object and coordinated control of multiple cooperating flying robots with manipulators in contact with the same object

**Perception.** Model, identify and recognize the scenario, guidance in the assembly operations, Range only SLAM, cooperative perception.

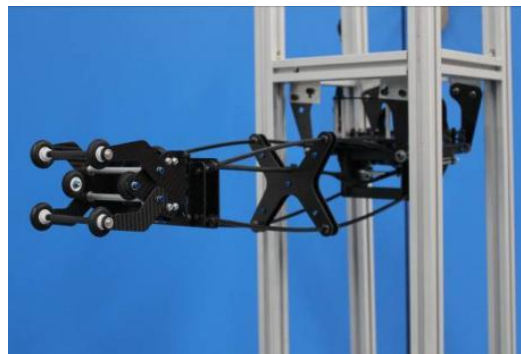
**Cooperative assembly planning.** Mission planning, task planning, collision detection and avoidance.

**Integration.** ARCAS system

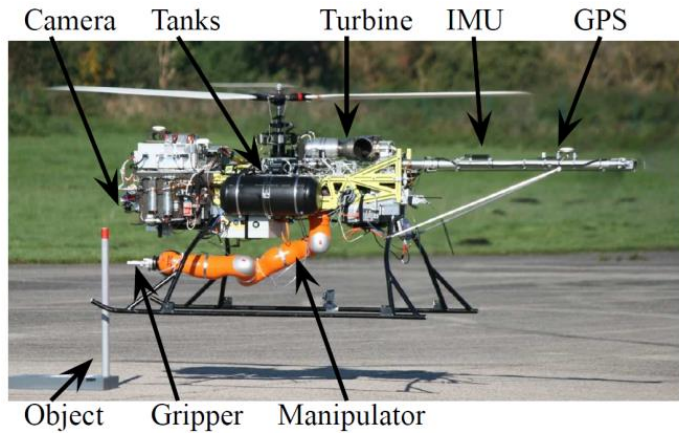
**Validation**



# ARCAS New aerial platforms and arms



## First world-wide helicopters with industrial 7DoF arms



Flettner helicopter





# Aerial robots in ARCAS

**First world-wide multi-rotor with 6 joints Very Light arm**

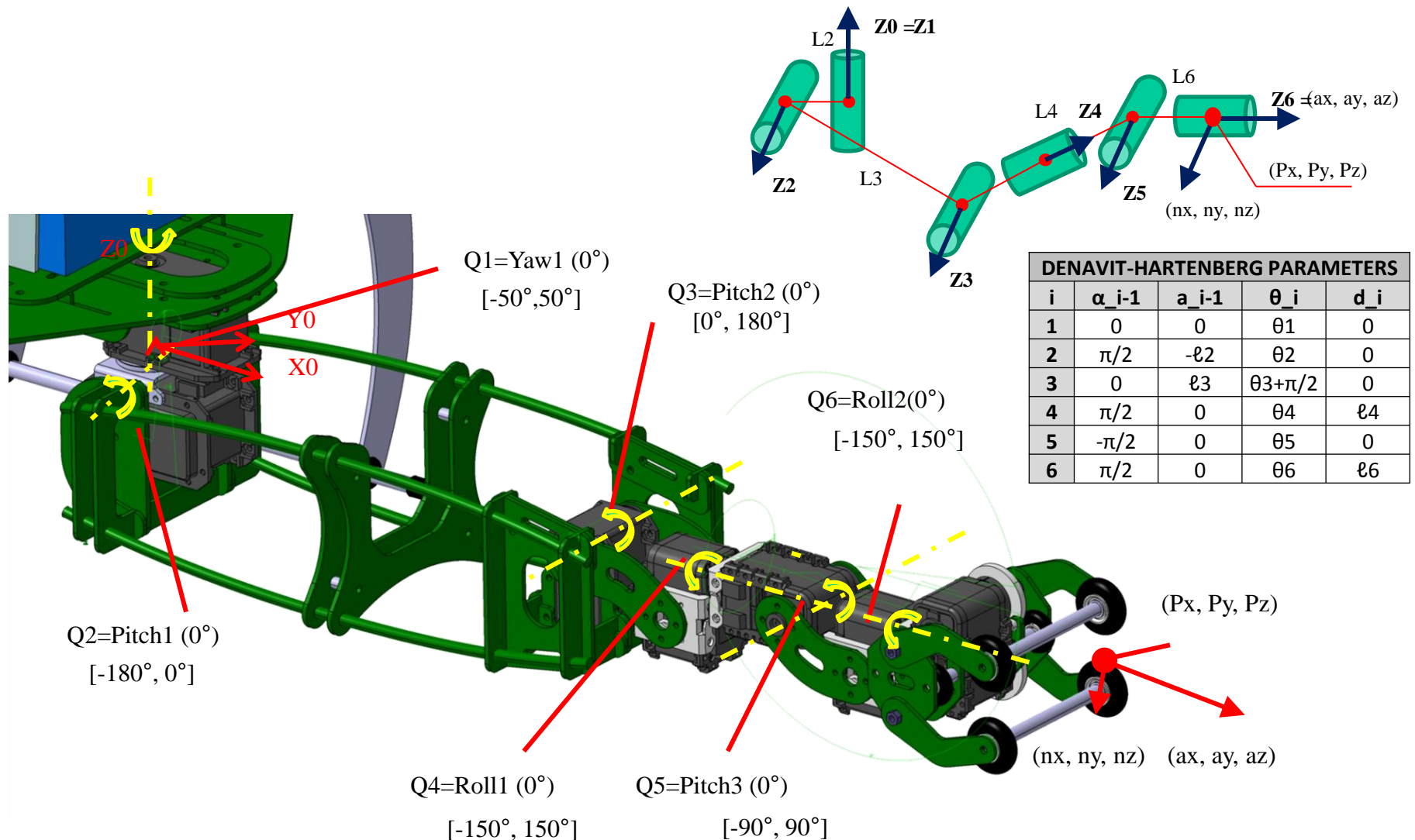


**First world-wide multi-rotor with 7 joint arm**



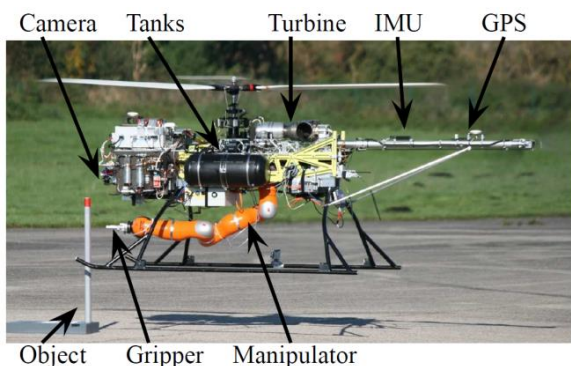


# AERIAL ROBOT IN ARCAS V3 arm kinematic model





## Helicopters with 7DoF arms



Analysis of interactions  
between helicopter and  
manipulator  
Dynamic model inversion

## Multi-rotors with 2/6/7 DoF arms



Impedance control  
Image based control

Integral backstepping  
Adaptive control  
Passivity  
Force/moment estimator

## Space environment



Cooperative Control of Servicer  
Satellite and Manipulator  
Client trajectory following



## Adaptive Integral Backstepping Controller

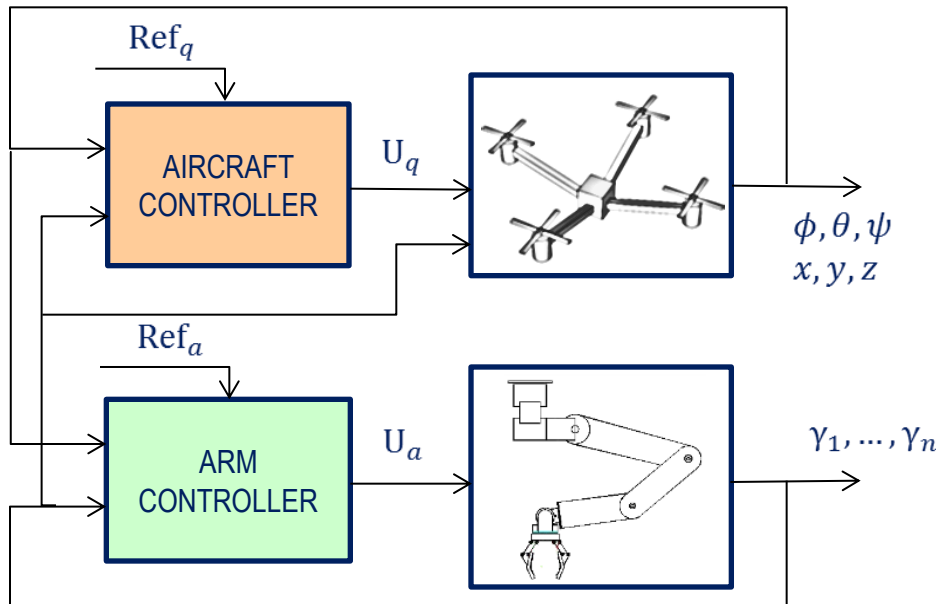
Variable parameter Integral Backstepping Control

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

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

Three rotational degrees of freedom neglecting aerodynamic effects:

$$\begin{aligned}\ddot{\phi} &= \dot{\theta}\dot{\psi}a_1 + (\dot{\phi}\dot{\psi} - \ddot{\theta})a_2 - (\dot{\theta}\dot{\phi} + \ddot{\psi})a_3 + (\dot{\psi}^2 - \dot{\theta}^2)a_4 + \dot{\theta}a_5\Omega_r + d_1U_2 + T_{arm1}(\gamma) \\ \ddot{\theta} &= \dot{\phi}\dot{\psi}b_1 - (\dot{\psi}\dot{\theta} + \ddot{\phi})b_2 + (\dot{\phi}^2 - \dot{\psi}^2)b_3 + (\dot{\theta}\dot{\phi} - \ddot{\psi})b_4 - \dot{\phi}b_5\Omega_r + d_2U_3 + T_{arm2}(\gamma) \\ \ddot{\psi} &= \dot{\phi}\dot{\theta}c_1 + (\dot{\theta}^2 - \dot{\phi}^2)c_2 + (\dot{\theta}\dot{\psi} - \ddot{\phi})c_3 - (\dot{\psi}\dot{\phi} + \ddot{\theta})c_4 + d_3U_4\end{aligned}$$



$a_i, b_i, c_i, d_i$  : coefficients that depend on inertia moments, vary with position of arm ( $\gamma$ ).

External torque  $T_{arm}(\gamma)$  and inertia matrix  $J(\gamma)$  vary with position of arm ( $\gamma$ : arm joint angles).

## Quadrotor controller: Variable Parameter Integral Backstepping

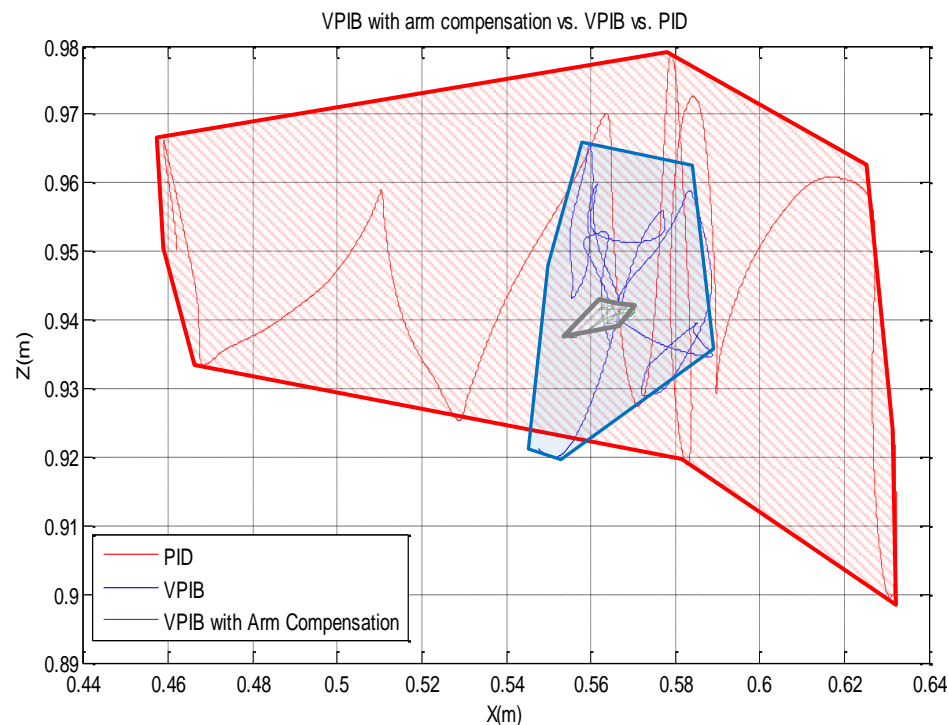
- **Feedforward controller:** feedforward term compensates torques generated by arm joints and links and picked object  $T_{arm}(\gamma)$ .
- **Variable Parameter Integral Backstepping (VPIB):**  
Backstepping controller with integral term. Inertia moments appear explicitly in controller parameters, vary with movement of joints.
- Roll VPIB controller:

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

- $e_1, e_2$ : roll and roll angular velocity errors.
- $d_1, a_j$ : coefficients depending on inertia moments.
- $k_1, \lambda_1$ : adjustable positive parameters
- Pitch and yaw controllers are derived similarly.



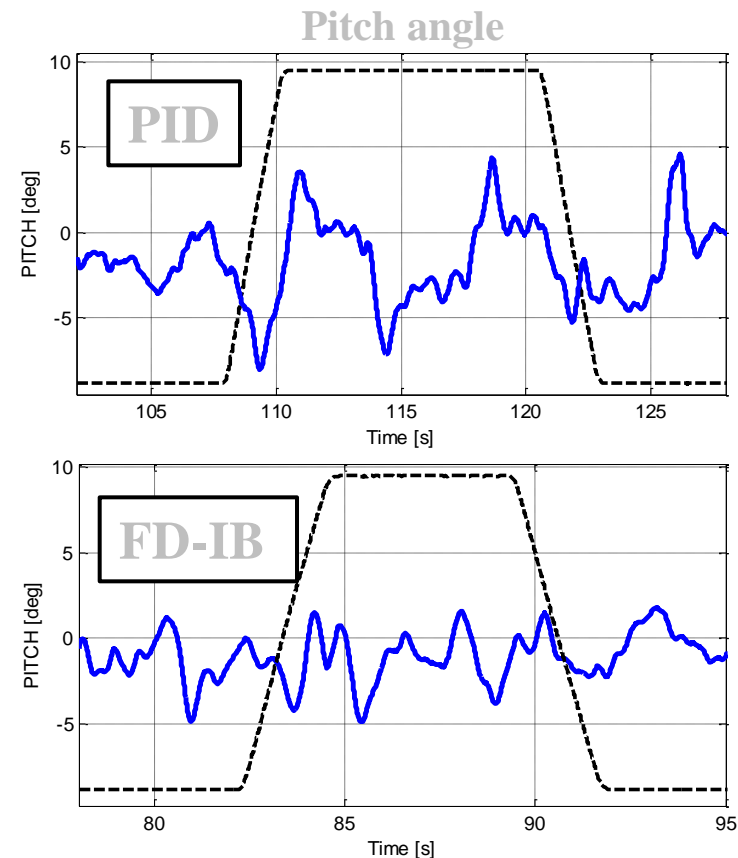
## Adaptive Integral Backstepping Controller Vs PID





## FD-IB attitude control experiments

- Experiments with AMUSE multirotor with 7 dof arm.
- Multirotor in hover, command large excursion movements to arm (worst case, large variations of mass center and inertias).
- Comparison of FD-IB with standard PID: oscillations with PID almost double FD-IB.
- Remaining oscillations due to wind and position controller.





# Control of Multirotor Aerial Manipulator

- **Full-Dynamics Integral Backstepping (FD-IB)**
  - **Full 3D multicopter+arm dynamic model** considered in controller.
  - **Implementation-oriented formulation** for easy adaptation and tuning starting from standard PID-based baseline multirotor controllers.
- If  $U$  is the control input vector, the controller terms can be rearranged in the following matrix form:

$$U = K_{VG} [K_P e_p + K_D e_v + K_I e_I] + G(q) + D(q, \ddot{q}) + C_1(q, \dot{q})$$

$K_{VG}$ : variable gain matrix (depends on arm joints)

$K_P, K_D, K_I$ : diagonal matrices, PID parameters

$e_p, e_v, e_i$ : position, velocity and integral error vectors

$G$ : gravity compensation term ;  $D, C_1$  : dynamic torque compensation terms



## Arm controller

- Hardware restrictions for arm controller: use of Dynamixel or standard servos for arm joint actuation. Difficult to use torque input.
- Implementation of **admittance controller** for contact tasks: command a desired cartesian position for arm end effector  $\Sigma_d$ :

$$\Sigma_d = \Sigma_{TCP} + \Sigma_{int}$$

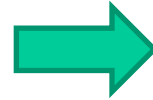
- $\Sigma_{TCP}$ : desired cartesian position of Tool Center Point(TCP).
- $\Sigma_{int}$ : additional displacement that would get the desired interaction forces and torques between end-effector and objects/environment.
- Then,  $\Sigma_d$  is transformed through the manipulator inverse kinematics  $K^{-1}$ . Desired joint position setpoints are transmitted to servos.
- **Arm inverse kinematics  $K^{-1}$ :**
  - Jacobian-based first-order algorithm. **Redundant 7-DoF arm motion**: generated through jacobiannull space.
  - Arm extra DoF: **maximize distance from mechanical joint limits**.
  - **Robust behavior close to singular configurations**: modified pseudoinverse with variable damping factor based on gaussian-weighted functions of the manipulability measure.



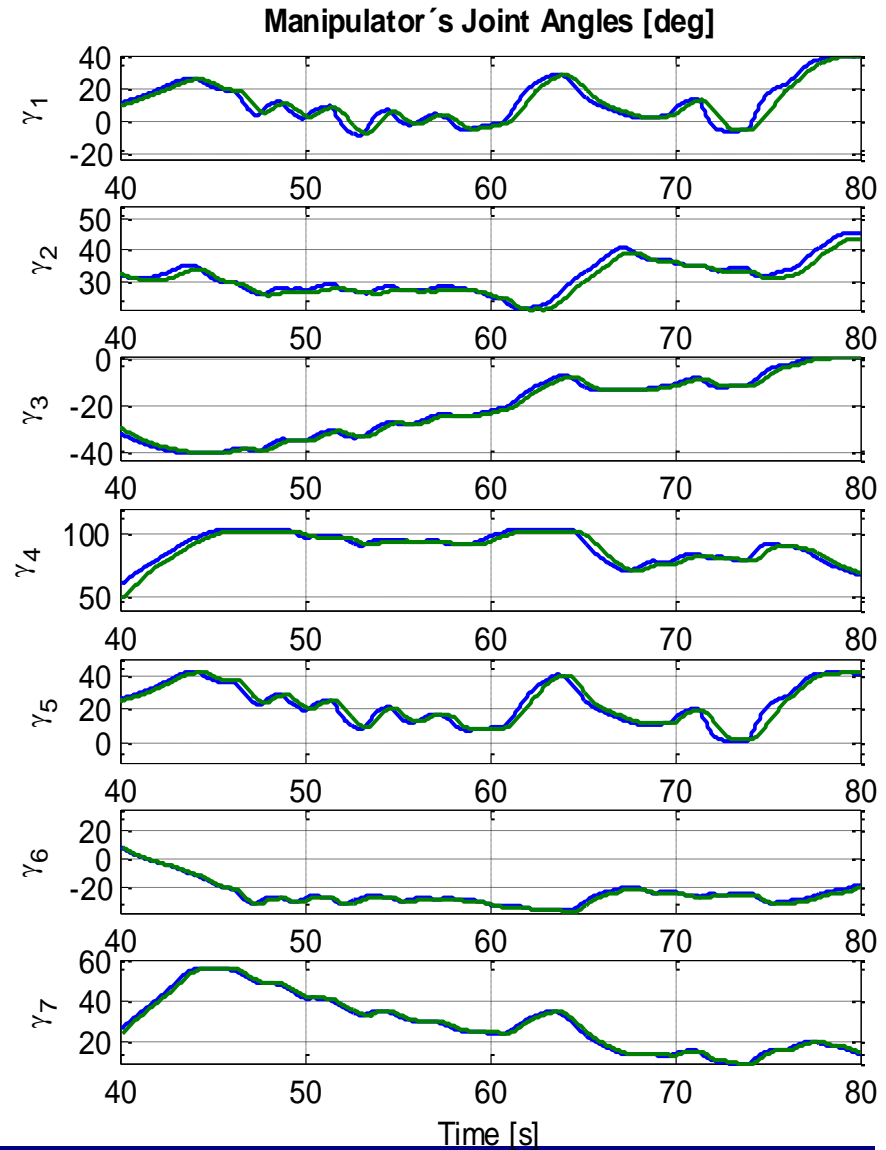
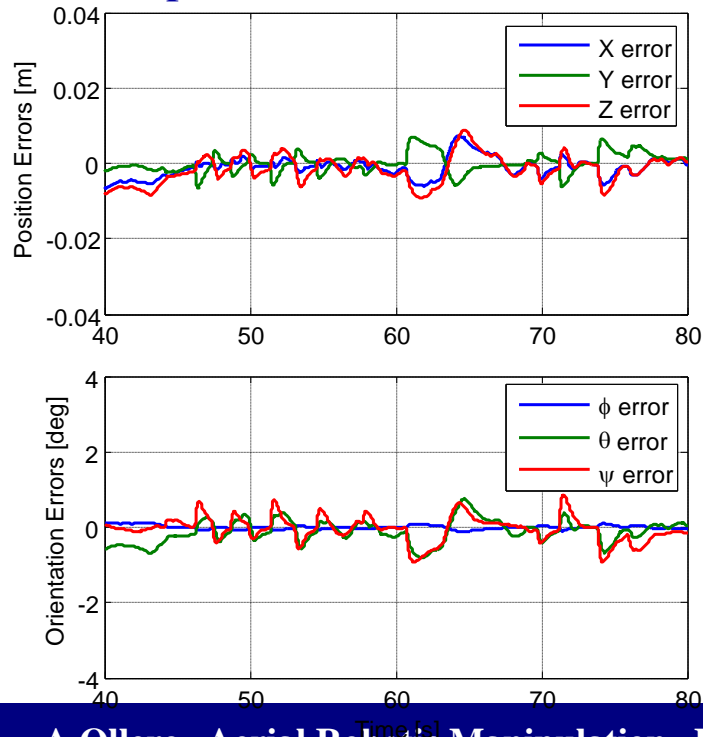
## Arm control experiments

- Experiments with arm following references from video system:

- **Blue**: joint references computed by arm controller.
- **Green**: joint trajectories.



### End-effector position and attitude errors



## Control and grasping experiments

Backstepping Attitude  
and Position Controller

AERIAL ROBOTIC MANIPULATION  
OUTDOOR PLATFORM

- **Passivity-Based Control**
  - **Fully actuated systems:** many results (PD/PD/PID/Computed Torque, Adaptive & Robust Control, Output feedback).
  - **Underactuated systems:** Results for Fully actuated robots are no longer applicable.
- Theoretical extension needed: Possibility of recovering Passivity, but Partial Differential Equations (PDEs) need to be solved.
- *Energy-Shaping* Methodology: Interconnection and Damping Assignment Passivity-Based Control, IDA-PBC (Hamiltonian)
- Solving PDEs is required to compute control action

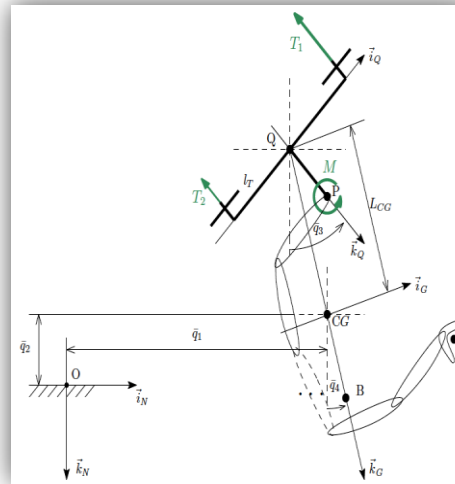
$$H_d(q, p) = \frac{1}{2} p^\top M_d^{-1}(q) p + V_d(q)$$

$$\hat{F}(q, p) = G^\dagger (\nabla_q H - M_d M^{-1} \nabla_q H_d + J_2 M_d^{-1} p)$$

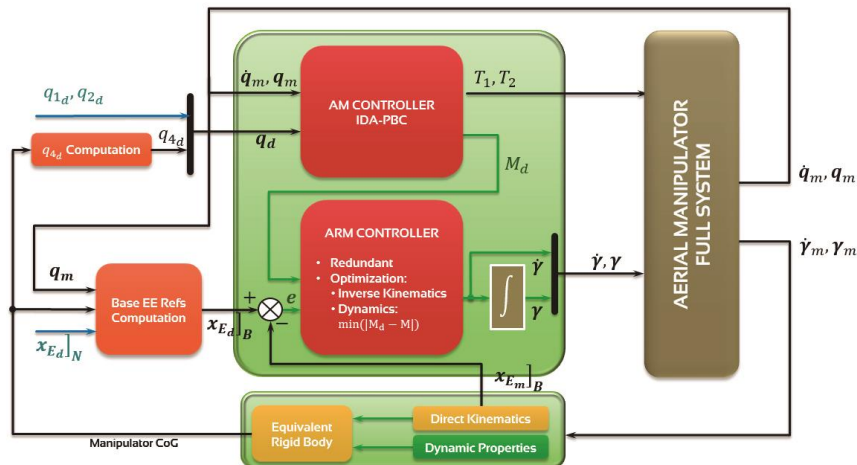
- Boundedness and Stability are assured
- Analytical solutions of IDA-PBC in the plane

$$\begin{aligned} V_d(\bar{q}) &= -g k m_B \frac{I_{22}}{m_{13}} \ln(\cos \bar{q}_3) \\ &+ \Phi \left( \bar{q}_2 - \frac{I_{22}}{m_{13}} \ln(\cos \bar{q}_3), \bar{q}_3 - \frac{m_{13}}{I_{22}} \bar{q}_1, \bar{q}_4 \right) \end{aligned}$$

$$M_d(\bar{q}) = k \cdot \begin{bmatrix} m_B & 0 & m_{13}/k & 0 \\ 0 & m_B & 0 & 0 \\ m_{13}/k & 0 & I_{22}/k & 0 \\ 0 & 0 & 0 & m_Q L_{CG}(\bar{q}_3, \bar{q}_4)^2 \end{bmatrix}$$

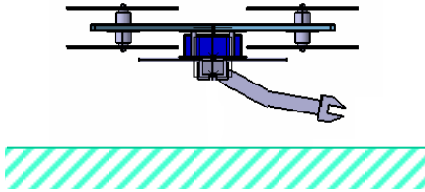


## 2D AERIAL MANIPULATOR CONTROL BLOCK SCHEME

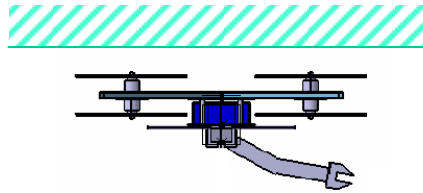


## Aerodynamic effects of proximity to surfaces

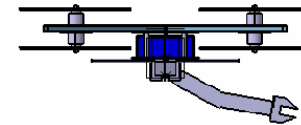
- Study aerodynamic effects when multirotors fly near surfaces.
- Three main cases:



**Ground effect**



**Ceiling effect**



**Wall effect**



- Test stand for motor/rotor characterization: measure thrust, rotor speed and pwm input, controlled from a console with a data acquisition GUI.
  - Tests with different distance/ inclination angle to surfaces.
  - Single or coaxial rotors.
  - Allows dynamic tests.

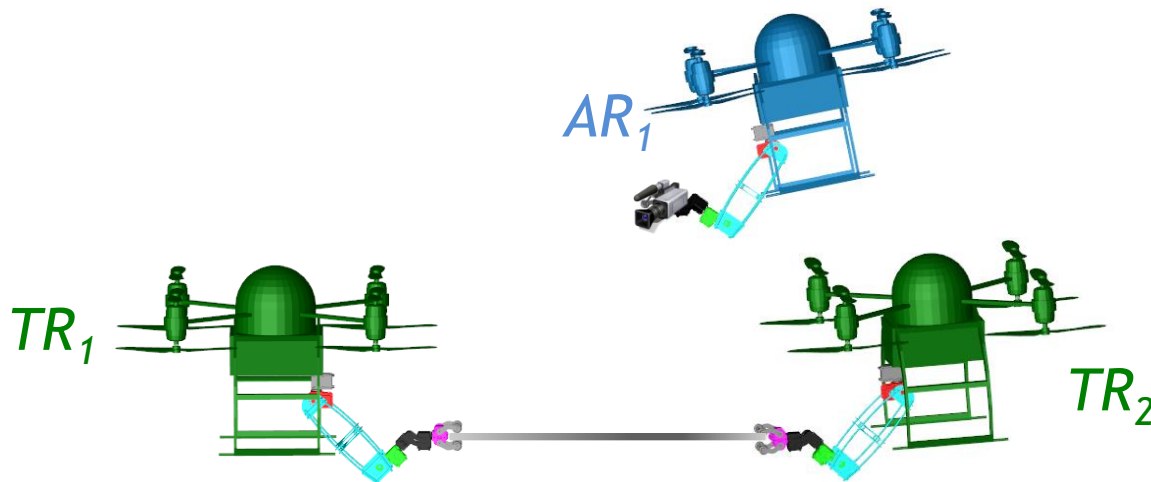
**Effects:** Ground, Ceiling, Wall, Tube effect, Ground + vertical wall, Ground (Complete quadrotor), Ground (Dual rotor), Ground (Dual rotor + Surface).



## Coordinated Control: General configuration

The task formulation is developed for multi-robot systems composed by two types of robots:

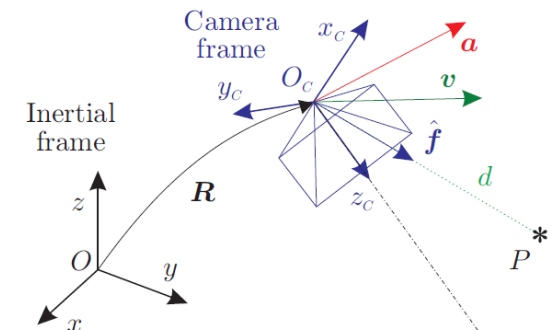
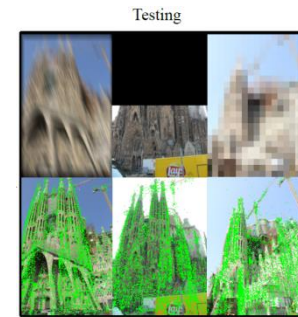
- $N_T$  **Transporting Robots (TRs)**, i.e. robots grasping an object and move it according to a planned trajectory
- $N_A$  **Auxiliary Robots (ARs)**, i.e. robots whose motion needs to be coordinated with that of the object grasped by TRs





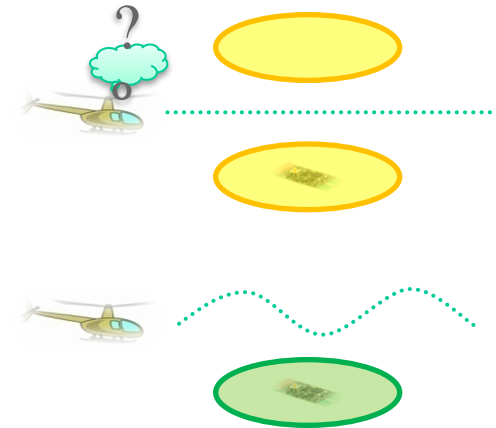
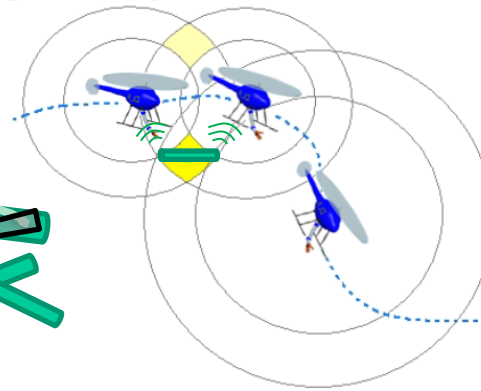
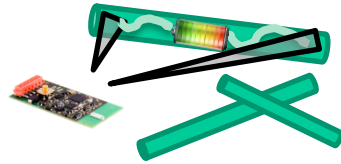
## Environment perception in ARCAS

- **Pose estimation from low resolution images:** apply a classifier trained with high resolution images (3D map) to compute the robot pose from low resolution images taken from the robot (robust to motion blur, image degradation, and occlusions) and low computational cost.
- **Object detection and recognition** by means of n-line Random Ferns, Rotationally-invariant.
- **Detection of landing areas** (landing or building the structure) without training based on 3D maps (built with visual odometry with refined Map/Pose and dense mapping) and local plane fitting.
- **Reliable tracking of 3D objects in unstructured environment.** 3D Pose Estimation and Tracking, uncalibrated system, Uncalibrated Image-Based Visual Servo, Image-based UAV onboard velocity estimation (close for solution using visual and inertial data)



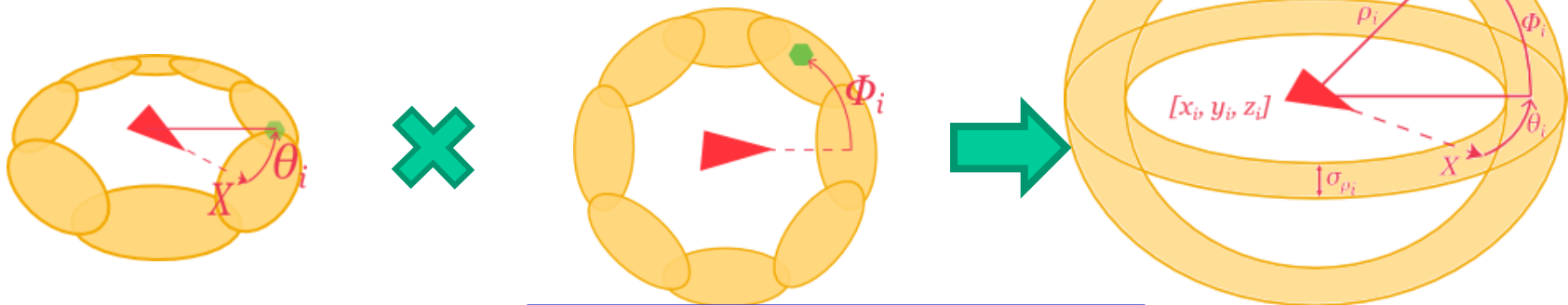
## Interest of **Range Only SLAM**

- Known data association
- Non direct LOS required.
- Size/weight/cost



## EKF State Parametrization

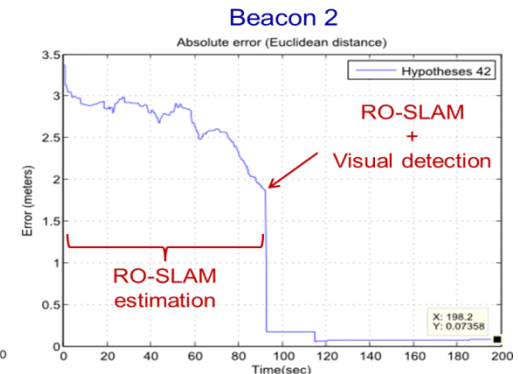
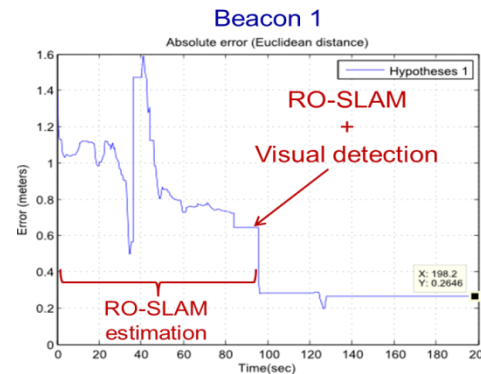
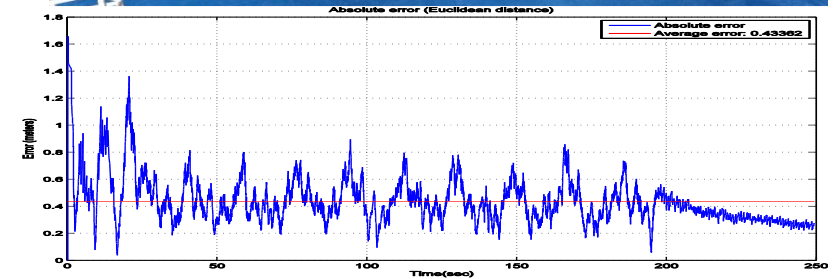
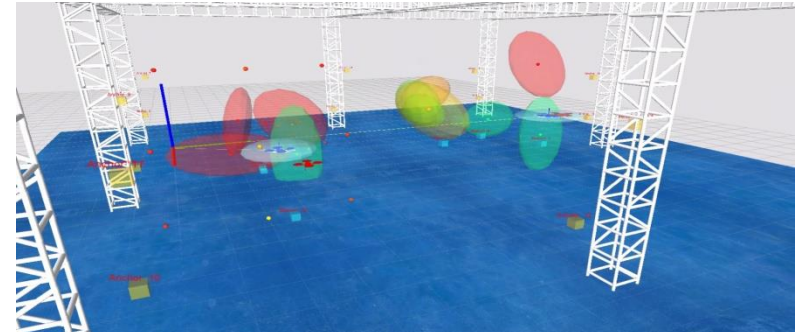
- EKF:  $\mathbf{x}_t = [\mathbf{x}_r \mathbf{f}_1 \mathbf{f}_2 \mathbf{f}_3 \mathbf{f}_4 \dots \mathbf{f}_m]$ ; Robot 3D pose  $\mathbf{x}_r$ ; Map features  $\mathbf{f}_i$  correlation between robot and features
- Initial spherical uniform distribution of a feature included into a Gaussian filter with only one range measurement: spherical parametrization (2 multi-modal variables), Multi-hypotheses solutions (Gaussian mixtures allows the integration into a single EKF)



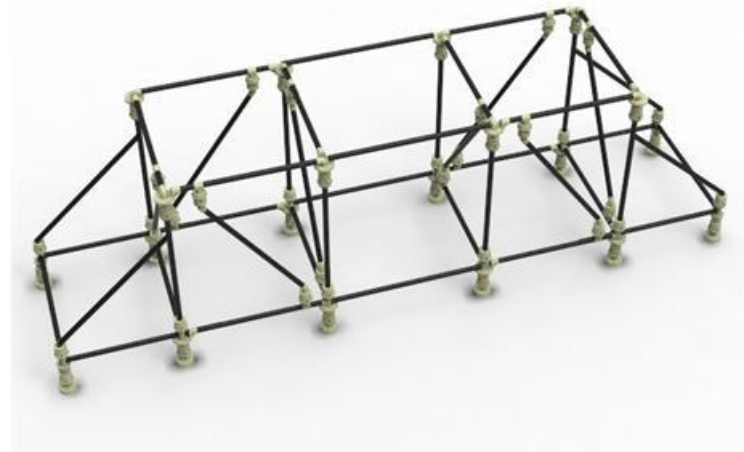
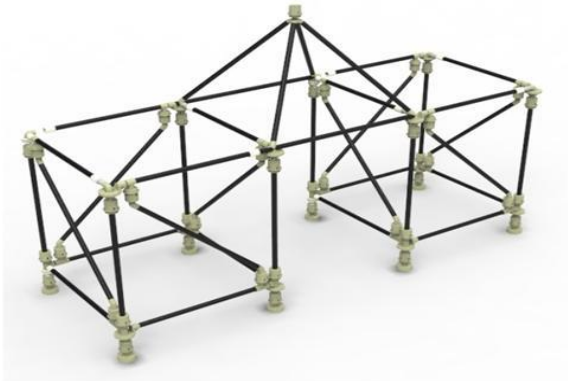
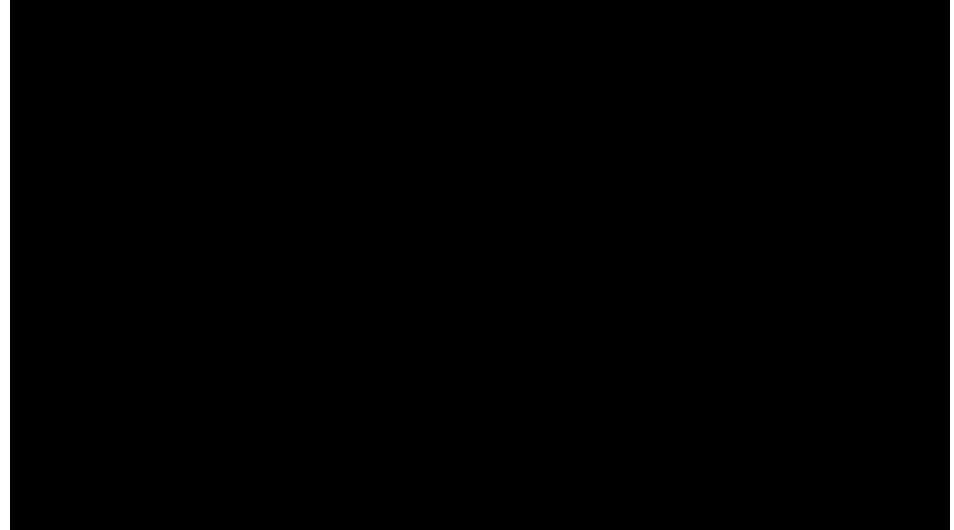
$$\mathbf{f}_i = [x_i \ y_i \ z_i \ \rho_i \ \theta_i \ \Phi_i]^T$$

## Range-only localization and multi-sensor SLAM

- Simultaneous Localization and Mapping integrating multiple sensors and multiple vehicles:
  - Localization based on range-only sensors and inertial information.
  - Mapping of the range sensors.
  - Centralized EKF for sensor fusion.
  - Gaussian Mixture Models with undelayed initialization.
  - Integration of visual markers for improved accuracy of map landmarks.
  - Cooperative localization and mapping

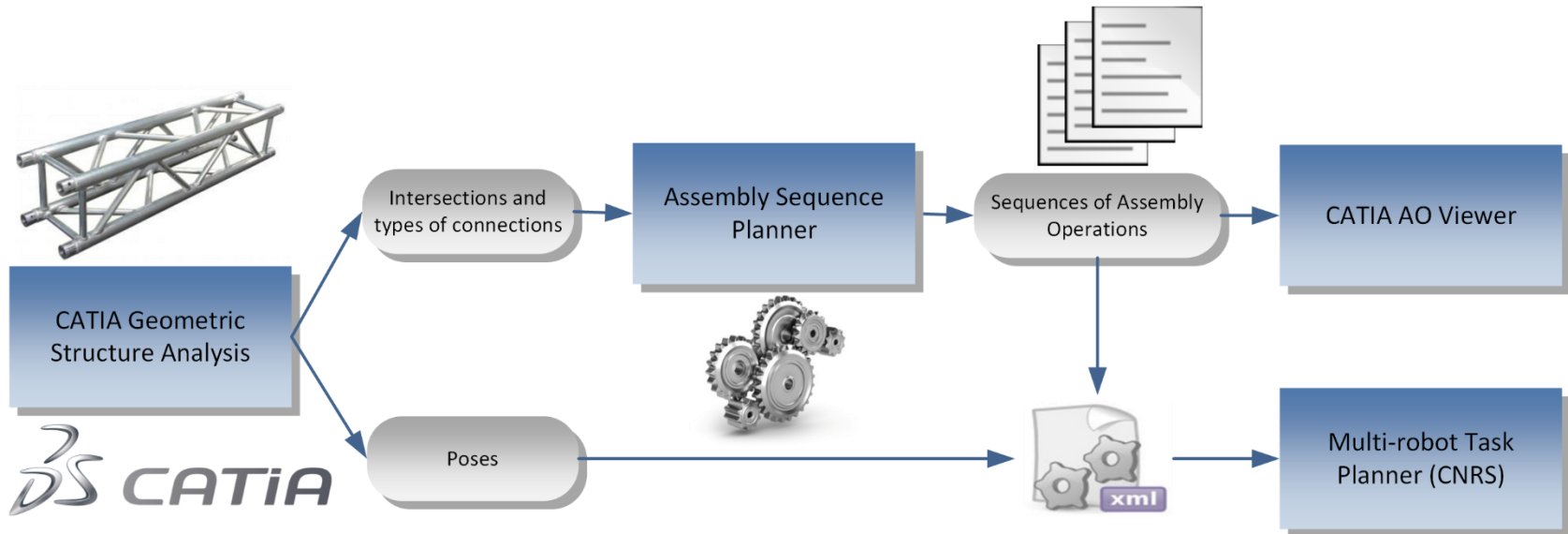
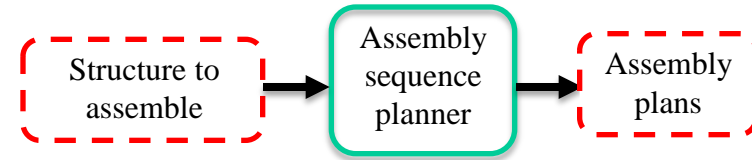


## Structure Assembly



## Assembly sequence planning

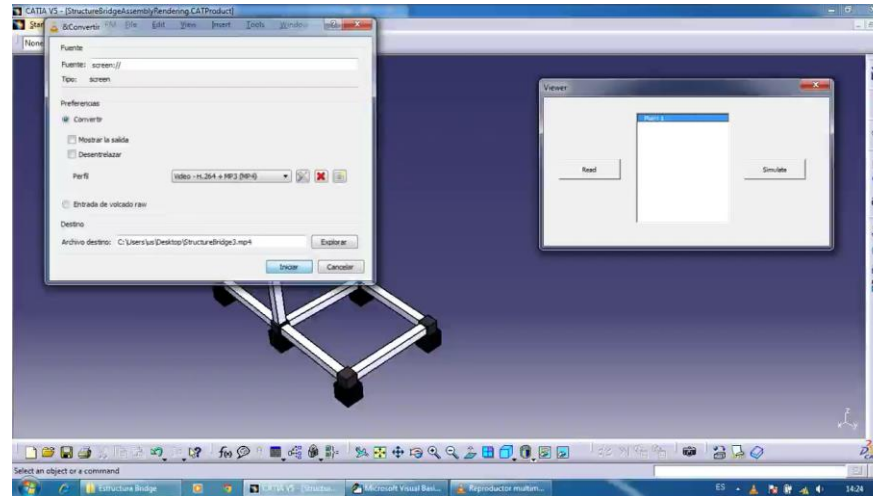
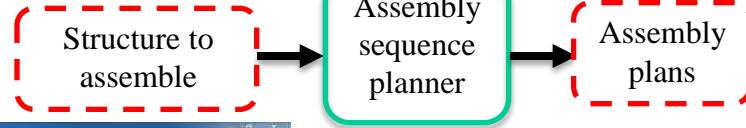
- Architecture overview



# 3. Teaming: ARCAS

## Assembly sequence planning

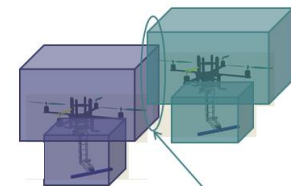
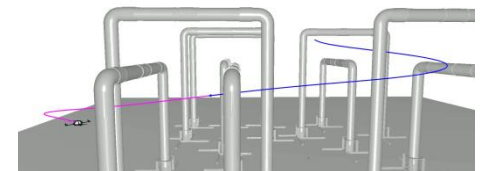
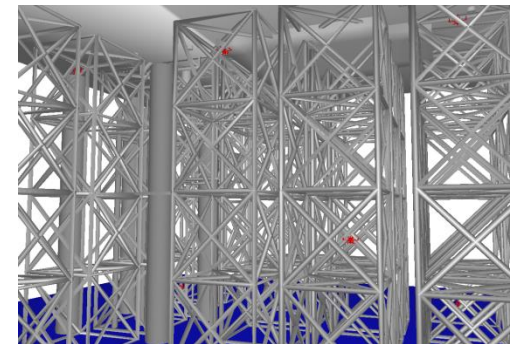
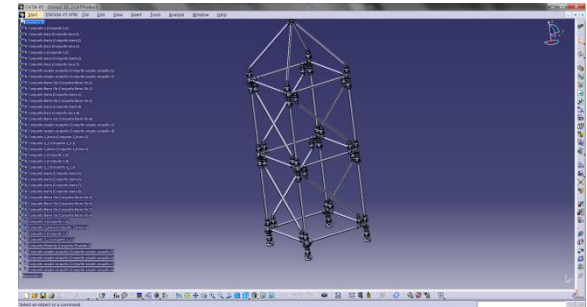
- AO viewer





## Structure Assembly in ARCAS

- **Assembly sequence planning.** Construction of a non-directional blocking graph, get sequence plans from assembly-by-disassembly technique, select best sequence by a metric value.
- **Task Planning** Several UAVs working in parallel, link with assembly planner (through a parser), assembly grammar defined to represent assembly plan
- **Motion planning.** Industrial inspection problem (mockup created with AIR), the planner computes good-quality paths and a good order to move between points, Multi-T-RRT with clearance-based cost (CPU time = 8 sec).
- **Multi-UAV real time Collision detection and resolution.** Efficient any-time optimal approach approach

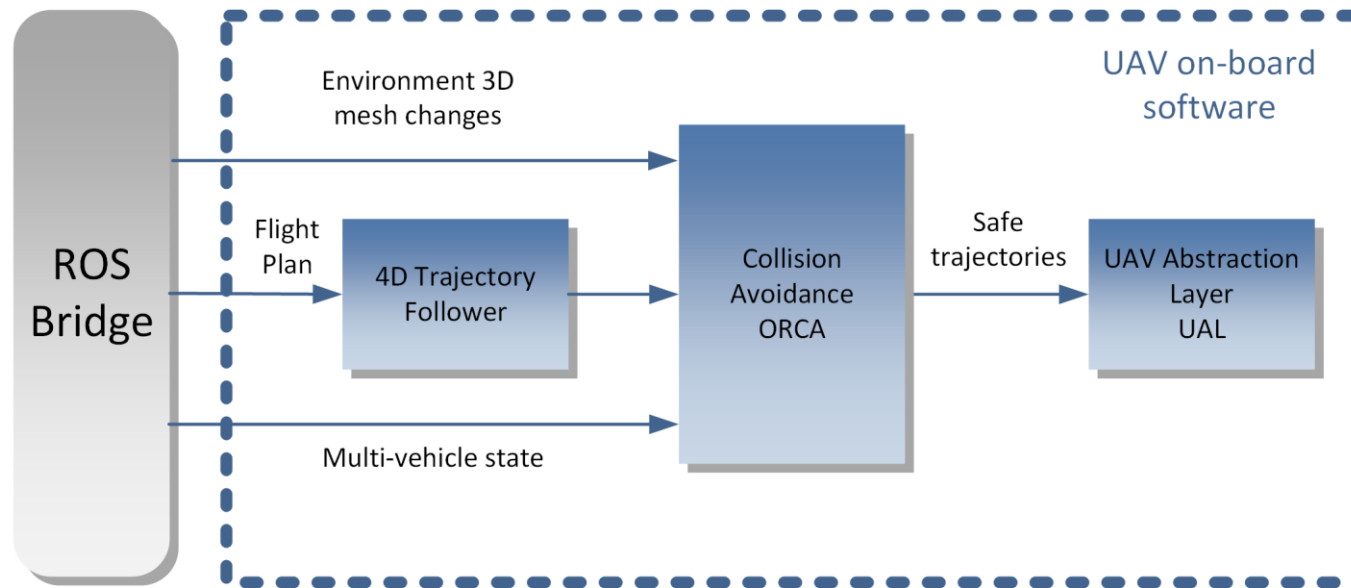


Collision



# Planning in ARCAS

*Safe coordinated trajectories generation and execution with collision detection and avoidance*

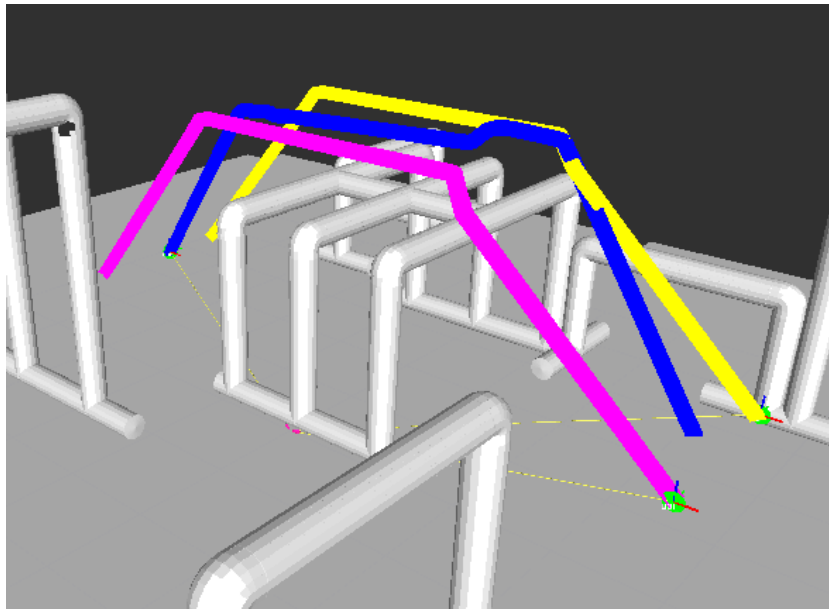


## Optimal Reciprocal Collision Avoidance (ORCA)

- Time horizon  $\tau$  for the detection and avoidance
- Works in the velocity space (first order algorithm)
- Avoidance effort shared among the involved vehicles in each potential collision
- Minimize the difference with the planned cruise speeds
- Characteristics: Low computation time ( $< 1$  ms); Kinematic constraints modeled; Changes triggered when the safety regions overlap in the velocity space; Velocity vector changes allowed (module and direction); Static obstacles are considered (meshes import - assimp library); PQP (proximity query package) collision detection library; ROS module generated

## Experiments (oct 2014)

- 3 aerial robots with obstacles





## Experiments

- ARCAS Summary Year 1 and Year 2

<http://www.arcas-project.eu/multimedia>

- ARCAS Second year video

<http://www.arcas-project.eu/multimedia>

- ARCAS in Euronews (youtube)

[https://www.youtube.com/watch?v=Xrpi5mA6gDA&list=P  
LyMUk47rPuqoGtsuuBB1BQ0QfeVZryT40&index=1](https://www.youtube.com/watch?v=Xrpi5mA6gDA&list=P<br/>LyMUk47rPuqoGtsuuBB1BQ0QfeVZryT40&index=1)

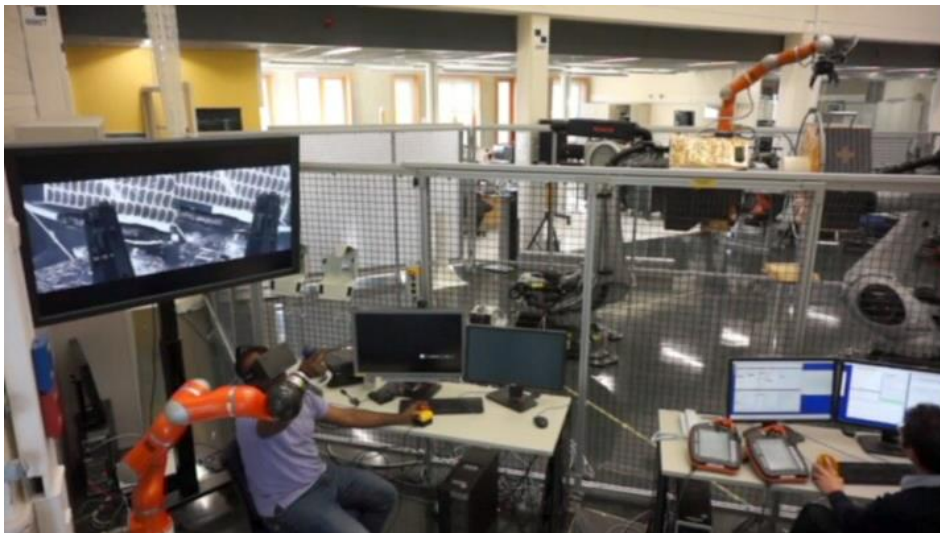
- ARCAS Summary May 2014

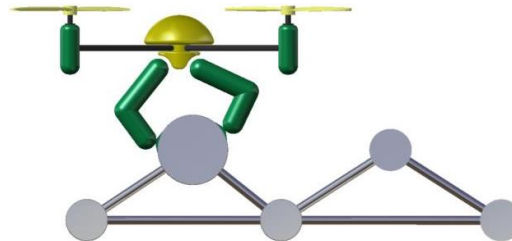
# Aerial Robotics Cooperative Assembly System (ARCAS) FP7-ICT-2011-7

First cooperative free-flying robot system for assembly and structure construction



# ARCAS Teleoperation applications





# H2020

**AERial ROBotic system integrating multiple  
ARMS and advanced manipulation  
capabilities for inspection and  
maintenance  
(AEROARMS)**



**Coordinator: A. Ollero**



# Inspection and Maintenance of oil and gas industries



Infrared inspection of leakages



Maintenance procedures

# Robotic Inspection



Mobile crawler robots for inspection

# Robotic applications to inspection and maintenance

## Problems:

Locomotion system: Access to the sites to be inspected or maintained

Scaffolding needed for deploying and maintenance of the robots



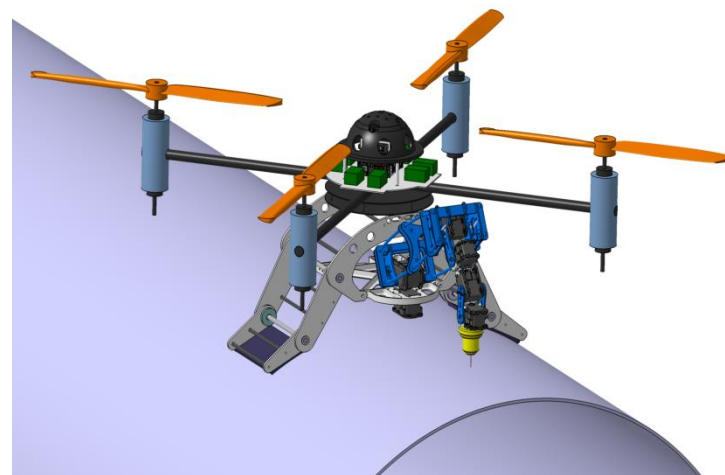
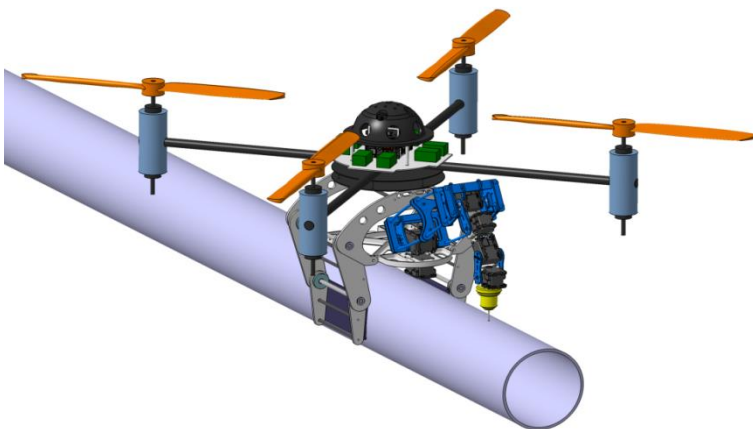
Scaffolding required for pipe inspection and deployment of mobile robots.



# AEROARM project (2015-2019)

**Aerial RObotic system integrating multiple ARMS and advanced manipulation capabilities for inspection and maintenance (AEROARMS)**

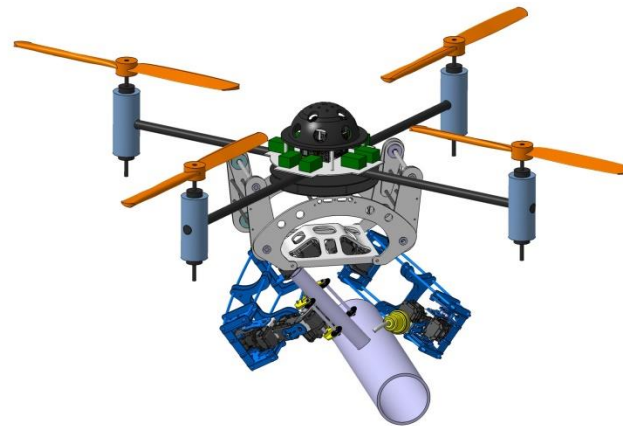
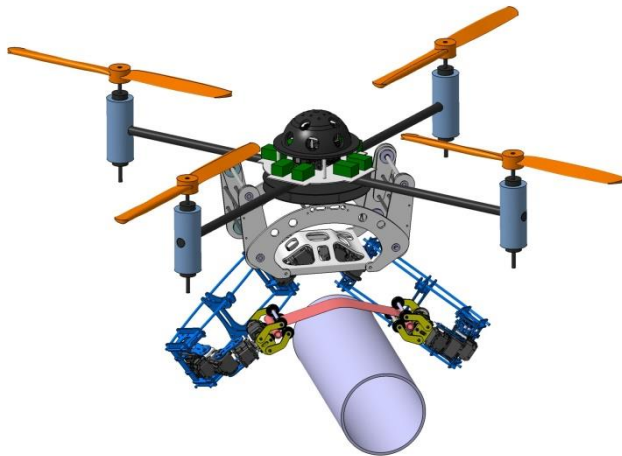
- Multi-rotor platform anchored to perform drilling tasks



# AEROARM project (2015-2019)

## **Aerial RObotic system integrating multiple ARMS and advanced manipulation capabilities for inspection and maintenance (AEROARMS)**

- Aerial robot with two arms operating in free flying for the placing of light weight elements such as a tape on the surface of a pipe or a apply sealant in the pipe junction.



# AEROARM project (2015-2019)

**AErial RObotic system integrating multiple ARMS and advanced manipulation capabilities for inspection and maintenance (AEROARMS)**

## **Validations in industrial environments**

- **Application 1:** Installation and maintenance of permanent Non Destructive Tests (NDT) sensors on remote components such as pipe works, fire flares or structural components.. The application involves the preparation of structures to install the sensors (drilling a hole into insulation, removing paint etc.), the installation of the sensors and the finishing of the structure.
- **Application 2:** Deploying and maintaining a mobile robotic system permanently installed on a remote structure. Assuming the presence of a newly designed mobile robot allowing easy exchange and maintenance of components (e.g., batteries etc.), the application consists of the use of the aerial robot to maintain the robot permanently installed in the structure without costly and dangerous human operations.

# AEROARM project (2015-2019)

## Applications of aerial robotics for inspection and maintenance

### Applications

- Infrared and visual non-contact inspection
- Contact inspection
  - Eddy current
  - Ultrasonic
- Installation of sensors in inaccessible locations
- Deployment and maintenance of robots in inaccessible locations
- Other maintenance activities

- First steps in general aerial robotic manipulation
- First world-wide demonstrations: aerial robots general manipulation with multi-joint arms
- Further R&D contributions to new safe and efficient aerial robotics systems as well as to the integration in non segregated aerial spaces are needed:
  - Cooperative manipulation
  - Increase safety
  - Emergency landing
  - Fault detection and reconfiguration
  - More reliable detect and avoid
  - Technologies for long term missions
  - New communication and security paradigms
- Aerial robotic manipulators for the maintenance of large scientific equipment