Robots aéreos interaccionando físicamente con el entorno

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Outline

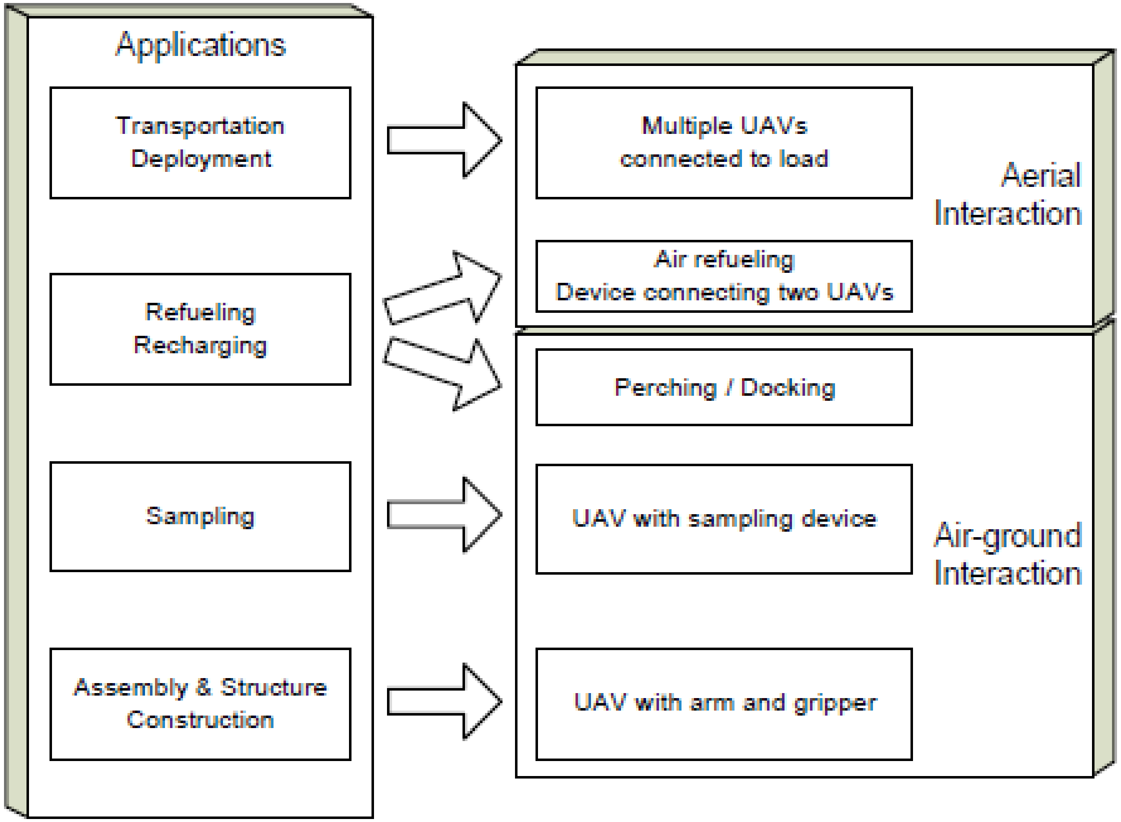
- Physical interaction of aerial robots
- Aerial manipulation
  - Modelling and control
  - Perception
  - Planning
  - Integrated experiments
- Conclusions

2013 Aerial Robots /RPAS Projects at USE and CATEC

- 80 researchers and technicians working in aerial robotics and RPAS
- 24 papers in 2013 (9 in Journals and 15 in Conf. Proceedings)
- 21 running projects in 2013
  - 8 European FP7 projects
    - Coordination of 3 projects: ARCAS, EC-SAFEMOBIL, MUAC-IREN
    - Partner in 5 projects: PLANET, FIELDCOPTER, ARIADNA, DEMORPAS, EUROATHLON
  - 13 Spanish Projects
    - 2 Projects National Programme: CLEAR, UGAV
    - 1 Project Regional Programme: UAS-WSAN
    - 2 INNPRONTA (6 contracts with companies): ADAM, PERIGEO
    - 2 CENIT (4 contracts with companies): SINTONIA, PROMETEO
    - 2 INNPACTO: IGNIS and ADALSCOM
    - 1 INNTERCONECTA (3 contracts with companies): CITIUS
    - Regional Programme (contract with company): TERMOFLY
    - 2 additional contracts with companies on VTOL systems

Physical interactions

- Introduction



Physical interactions

- Air-air refuelling
  - Interactions: boom or hose
  - Effects of the tanker stream

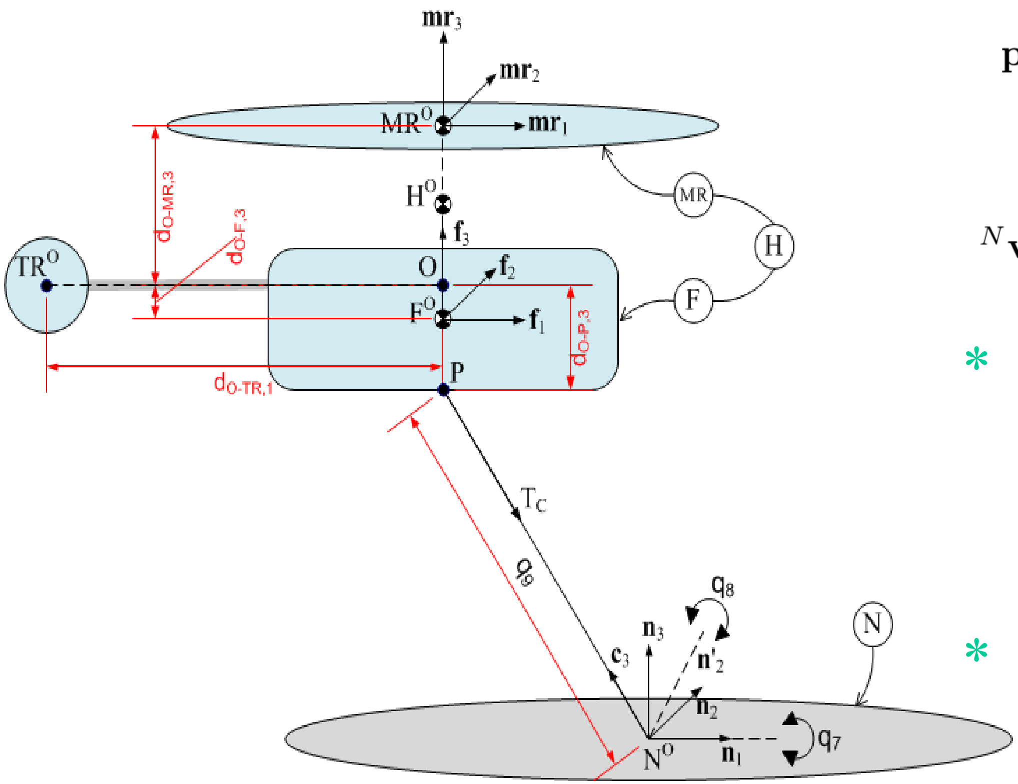
Global Hawk refuelling

- Deployment
  - Mechanics and aerodynamics in the releasing process
  - Stabilization

DC 130 Hercules and BQM34 Fire bee

Physical interactions: Tethered Helicopter

EC-SAFEMOBILE FP7 project

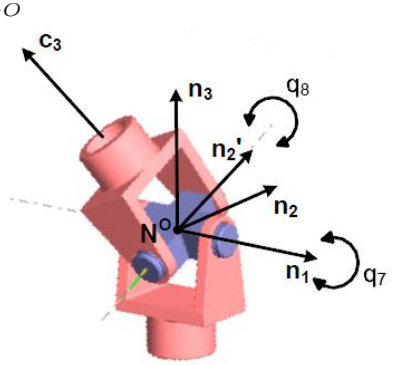


* Spherical conf. variables + Cartesian motion variables

$$\mathbf{p}^{N^O \to H^O} = \mathbf{p}^{N^O \to P} + \mathbf{p}^{P \to H^O}$$

$$\mathbf{p}^{N^O \to P} = q_9 \mathbf{c_3}$$

$${}^N\mathbf{v}^{H^O} = u_1 \mathbf{n_1} + u_2 \mathbf{n_2} + u_3 \mathbf{n_3}$$



* Elastic tether mode

$$\mathbf{T_C} = -T_C \mathbf{c}_3 = -K_C (q_9 - L_N) \mathbf{c}_3$$

$$K_C \begin{cases} = 0 & \text{for } q_9 < L_N \\ > 0 & \text{for } q_9 > L_N \end{cases}$$

* Ground device for tension control

$$\frac{dL_N}{dt} = U_C$$

Physical interactions: Tethered helicopters

- Tether influence in system dynamics
  - Tension force: stabilizing properties in translational dynamics
  - Tension moment: undesired coupling (translation affects rotation)

$$\begin{bmatrix}\dot{q}_7 & \dot{q}_8 & \dot{q}_9\end{bmatrix}^T = \mathbf{M} \cdot \begin{bmatrix}u_1 & \cdots & u_6\end{bmatrix}^T$$

$$\begin{aligned}\dot{q}_4 &= -\left(s_6 u_5 - c_6 u_4\right)/c_5 \\ \dot{q}_5 &= s_6 u_4 + c_6 u_5 \\ \dot{q}_6 &= u_6 + s_5\left(s_6 u_5 - c_6 u_4\right)/c_5\end{aligned}$$

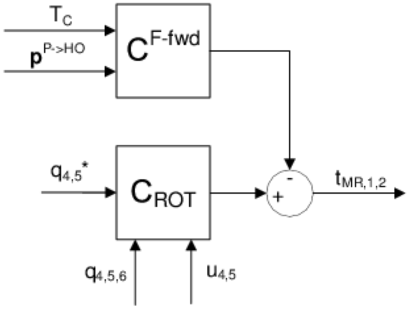
$$\begin{aligned}(m_F + m_{MR})\dot{u}_1 &= RHS_1 - T_C s_8 \\ (m_F + m_{MR})\dot{u}_2 &= RHS_2 + T_C s_7 c_8 \\ (m_F + m_{MR})\dot{u}_3 &= RHS_3 - T_C c_7 c_8 \\ K_{4p4}\dot{u}_4 &= RHS_4 + T_C(d_{O-P,3} - d_{O-H^O,3}) \cdot (c_7 c_8(s_4 c_6 + s_5 s_6 c_4) - s_7 c_8(c_4 c_6 - s_4 s_5 s_6) - s_6 s_8 c_5) \\ K_{5p5}\dot{u}_5 &= RHS_5 + T_C(d_{O-P,3} - d_{O-H^O,3}) \cdot (s_7 c_8(s_6 c_4 + s_4 s_5 c_6) - c_7 c_8(s_4 s_6 - s_5 c_4 c_6) - s_8 c_5 c_6) \\ K_{6p6}\dot{u}_6 &= RHS_6\end{aligned}$$

Physical interactions: Tethered helicopter

$$K_{4p4}\dot{u}_4 = t_{MR,1} + d_{O-H^O,3} f_{TR,2} + (K_{456}u_6 + K_{45})\,u_5 + $$
$$+T_C(d_{O-P,3} - d_{O-H^O,3}) \cdot (c_7 c_8 (s_4 c_6 + s_5 s_6 c_4) - s_7 c_8 (c_4 c_6 - s_4 s_5 s_6) - s_6 s_8 c_5) \quad \} \; RHS_4$$

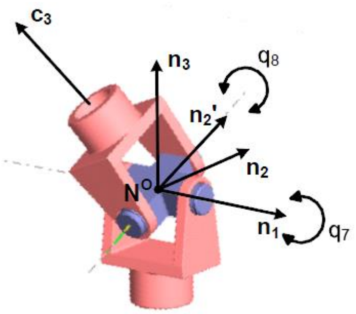
$$K_{5p5}\dot{u}_5 = t_{MR,2} + t_{TR,2} + (K_{546}u_6 + K_{54})\,u_4 + $$
$$+T_C(d_{O-P,3} - d_{O-H^O,3}) \cdot (s_7 c_8 (s_6 c_4 + s_4 s_5 c_6) - c_7 c_8 (s_4 s_6 - s_5 c_4 c_6) - s_8 c_5 c_6) \quad \} \; RHS_5$$

- Feed-Forward to counteract tether moment
  - Estimated moment is subtracted from moments calculated by helicopter orientation controller



$$t_{MR,1} = t_{MR,1}|^{C_{ROT}} - T_C^{est}(d_{O-P,3} - d_{O-H^O,3}) \cdot (c_7^{est} c_8^{est} (s_4 c_6 + s_5 s_6 c_4) - s_7^{est} c_8^{est} (c_4 c_6 - s_4 s_5 s_6) - s_6 s_8^{est} c_5)$$
$$t_{MR,2} = t_{MR,2}|^{C_{ROT}} - T_C^{est}(d_{O-P,3} - d_{O-H^O,3}) \cdot (s_7^{est} c_8^{est} (s_6 c_4 + s_4 s_5 c_6) - c_7^{est} c_8^{est} (s_4 s_6 - s_5 c_4 c_6) - s_8^{est} c_5 c_6)$$

  - Estimation of tension vector
    - Load cell -> magnitude (T_C)
    - Optical encoders -> orientation (q_7,q_8)



Cardan Joint

Physical interactions: Tethered helicopter

- Landing with cable

FP 7 EC-SAFEMOBIL Project

Tether tension: Higher as possible to maximize stabilizing properties in translation

Bounded since induced moment should be always less than maximum moment exerted by main rotor control action (saturation of cyclic pitch)

$$\left|\mathbf{p}^{P\to H^O} \times \mathbf{T_C}\right| < t^{max}_{MR1,2} \Rightarrow \left|d_{O-P,3} - d_{O-H^O,3}\right| T_C < t^{max}_{MR1,2}$$

$$T_C < \frac{t^{max}_{MR1,2}}{\left|d_{O-P,3} - d_{O-H^O,3}\right|} \qquad \left(\approx 0.2 \cdot f^{hover}_{MR,3}\right)$$

=> Maximum value for tether tension should not exceed 20% of lifting force at hover (for a typical small-size helicopter)

GPS not needed for landing

Physical interactions

- Joint load transportation and deployment

FP6 AWARE (2006-2009)

Physical interactions

- Sampling
  - FP7 PLANET

- Force interaction
  - Contact inspection (i.e. ultrasounds, eddy current)
  - Cleaning with special devices
- Manipulation: Robotic manipulation with multi-joint arms

Robotic manipulation

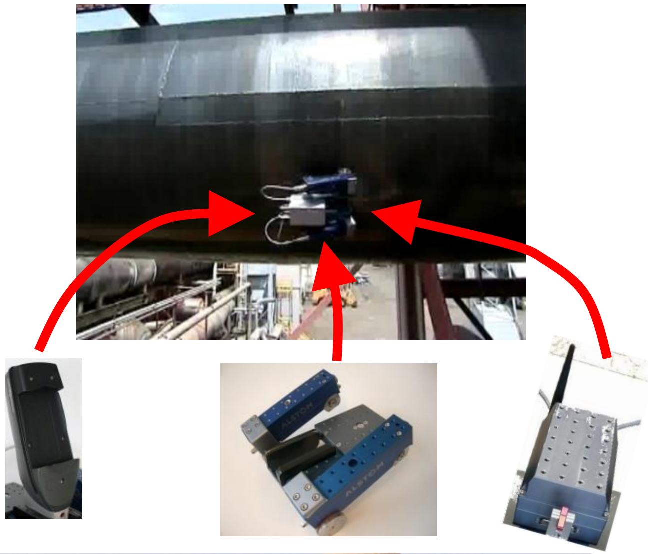
Aerial Robotics Cooperative Assembly System (ARCAS): First Results

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

http://www.arcas-project.eu

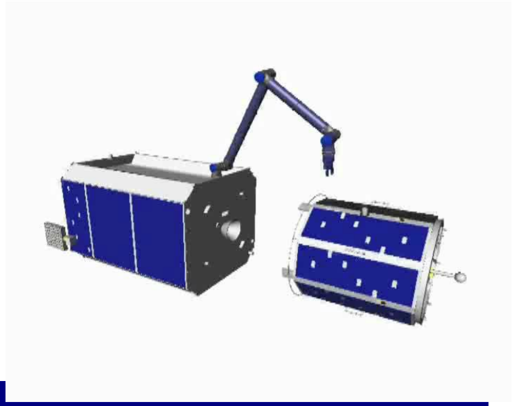
Physical interactions with the environment
Aerial Robotics Cooperative Assembly System
FP7 ARCAS (2011-2015)

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

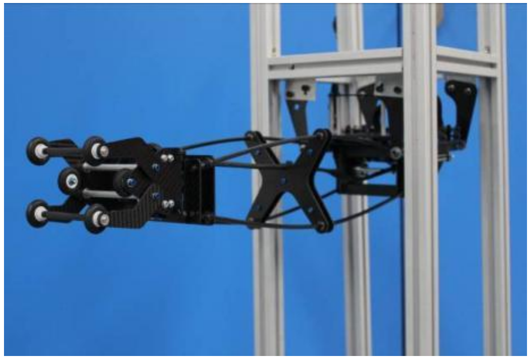
Perception. Model, identify and recognize the scenario, guidance in the assembly operations, Range only SLAM, cooperative perception.

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

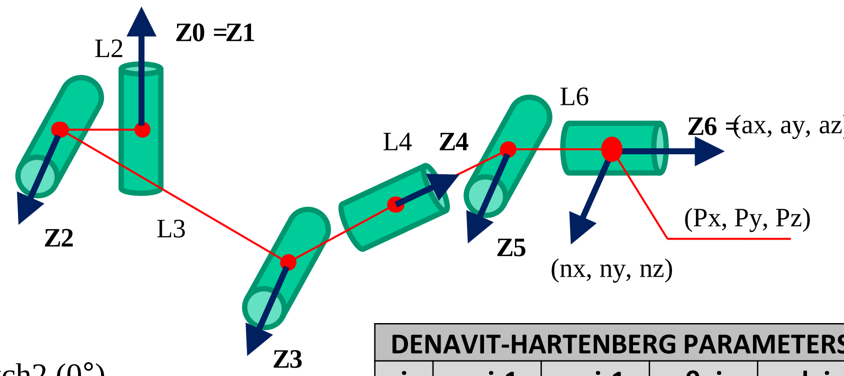
Integration. ARCAS system

Validation

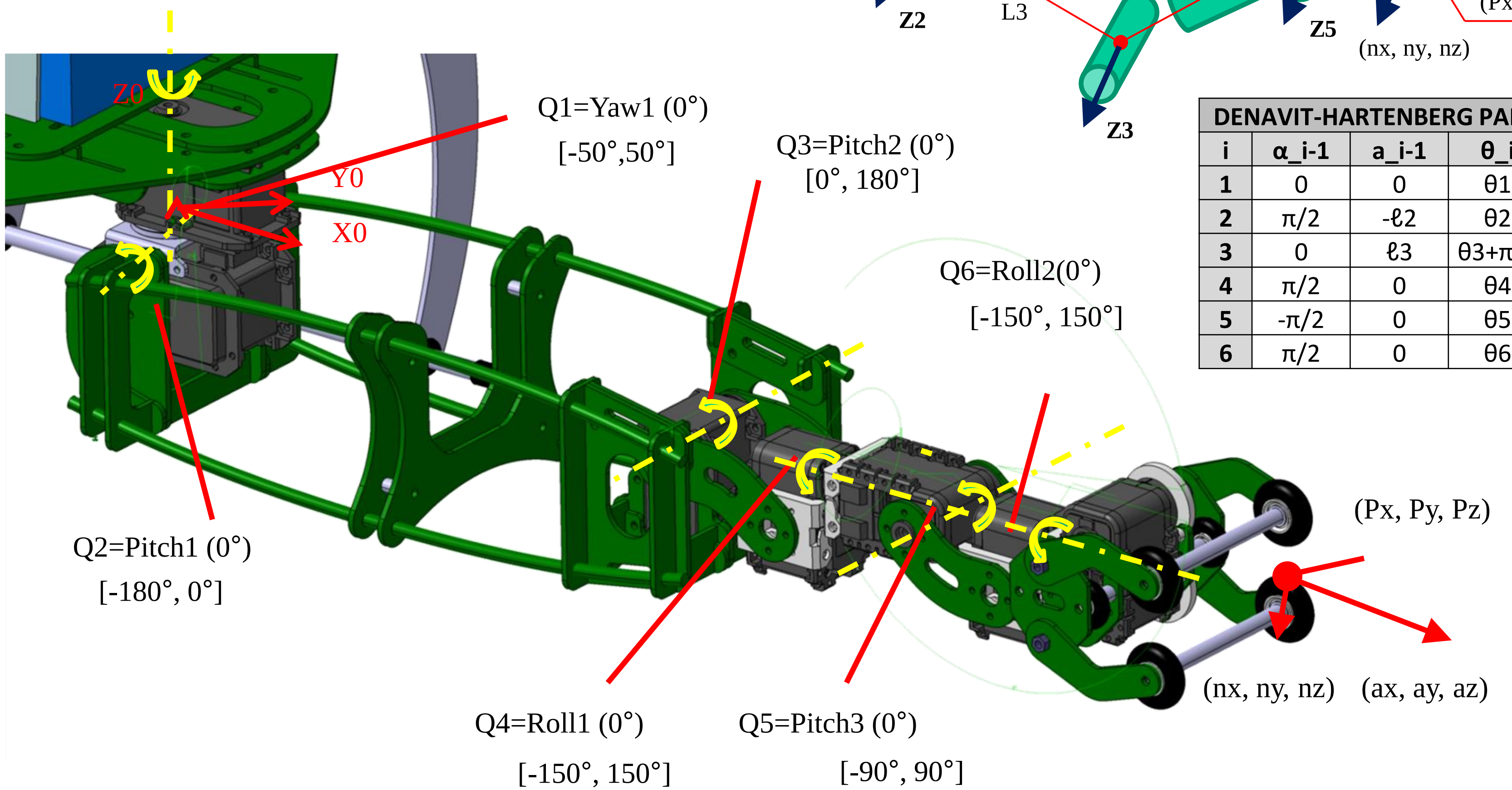
New aerial platforms and arms



V3 arm kinematic model



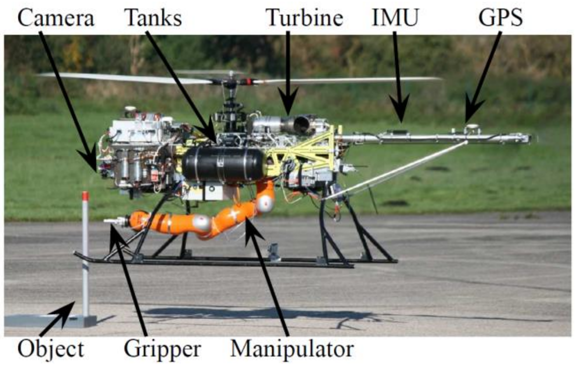
DENAVIT-HARTENBERG PARAMETERS				
i	α_i-1	a_i-1	θ_i	d_i
1	0	0	θ1	0
2	π/2	-ℓ2	θ2	0
3	0	ℓ3	θ3+π/2	0
4	π/2	0	θ4	ℓ4
5	-π/2	0	θ5	0
6	π/2	0	θ6	ℓ6



Modelling and control in ARCAS

Modelling tools: Modelica/Dymola, Matlab/Simulink

Helicopters with 7DoF arms



Analysis of interactions between helicopter and manipulator
Dynamic model inversion
Impedance control

Impedance control
Image based control

Multi-rotors with 2/6/7 DoF arms

Integral backsteping
Adaptive control
Passivity
Force/moment estimator

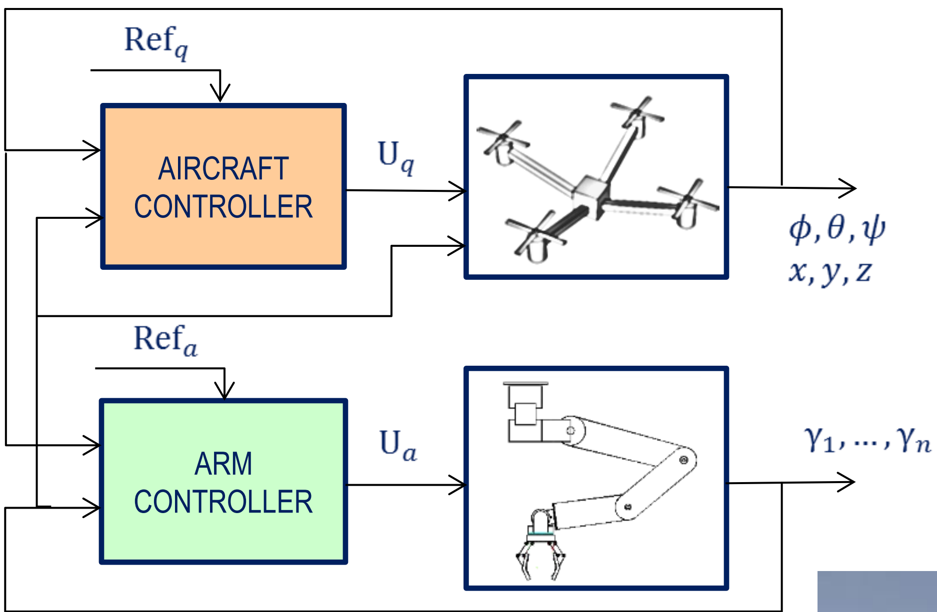
Space environment

Cooperative Control of Servicer Satellite and Manipulator
Client trajectory following

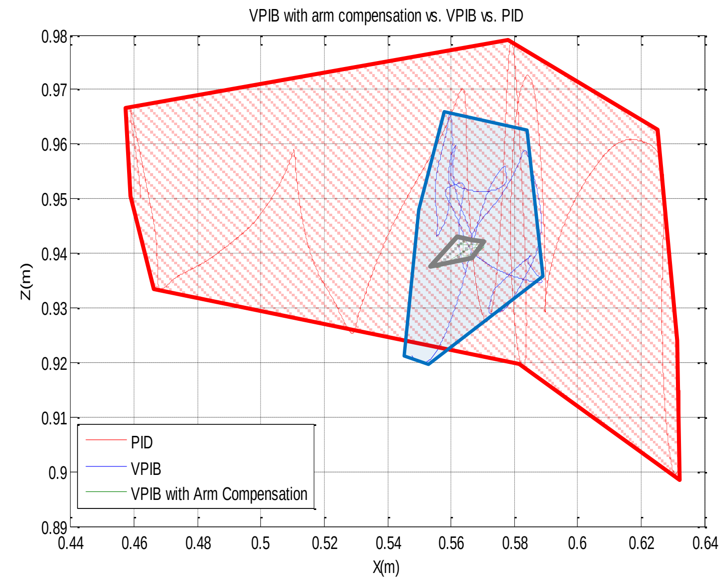
Adaptive Integral Backstepping Controller Vs PID

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

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



Variable parameter Integral Backstepping Control



Control of Multirotor Aerial Manipulator

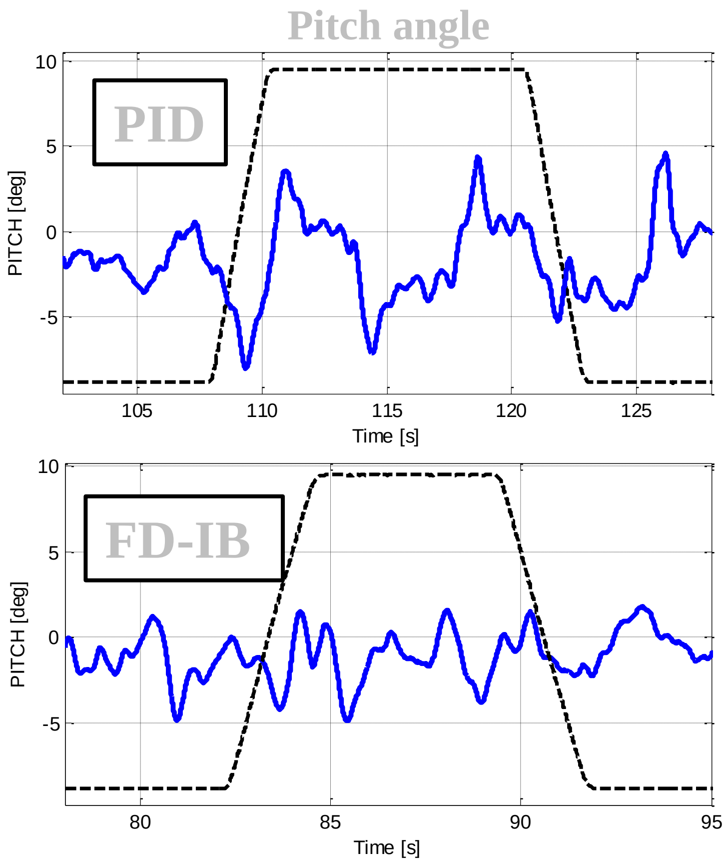
- **Full-Dynamics Integral Backstepping (FD-IB)** controller for Multirotor attitude and position.
  - **Full 3D multicopter+arm dynamic model** considered in controller.
  - **Implementation-oriented formulation** for easy adaptation and tuning starting from standard PID-based baseline multirotor controllers.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

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

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

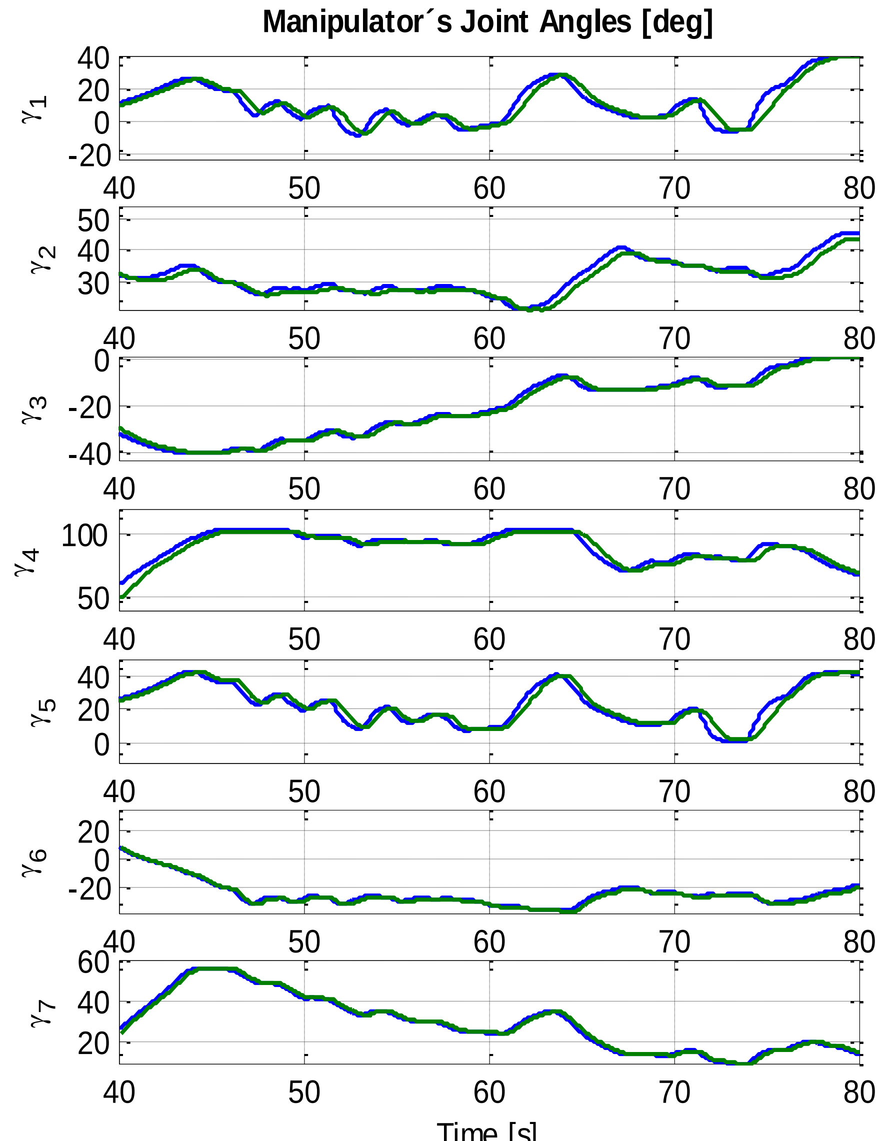
FD-IB attitude control experiments

- 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.

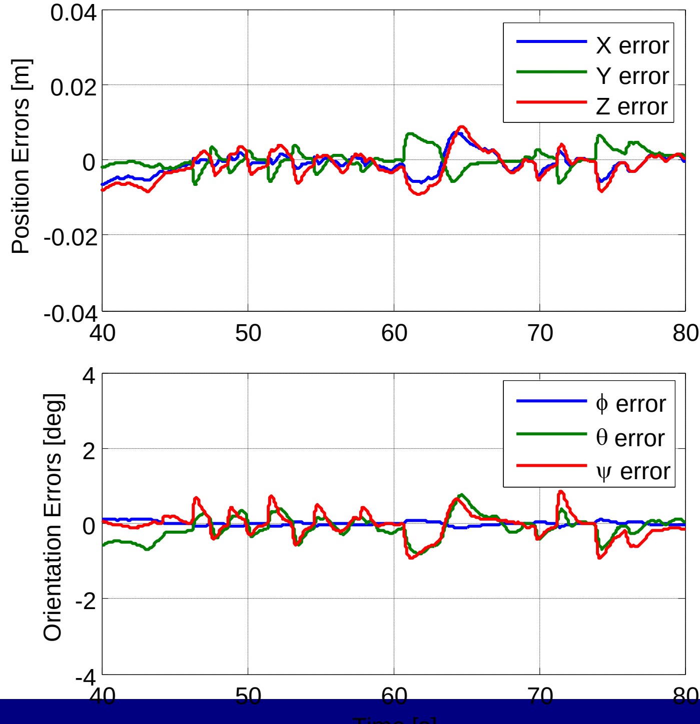


Arm control experiments

- Experiments with arm following references from video system:
  - **Blue**: joint references computed by arm controller.
  - **Green**: joint trajectories.



End-effector position and attitude errors

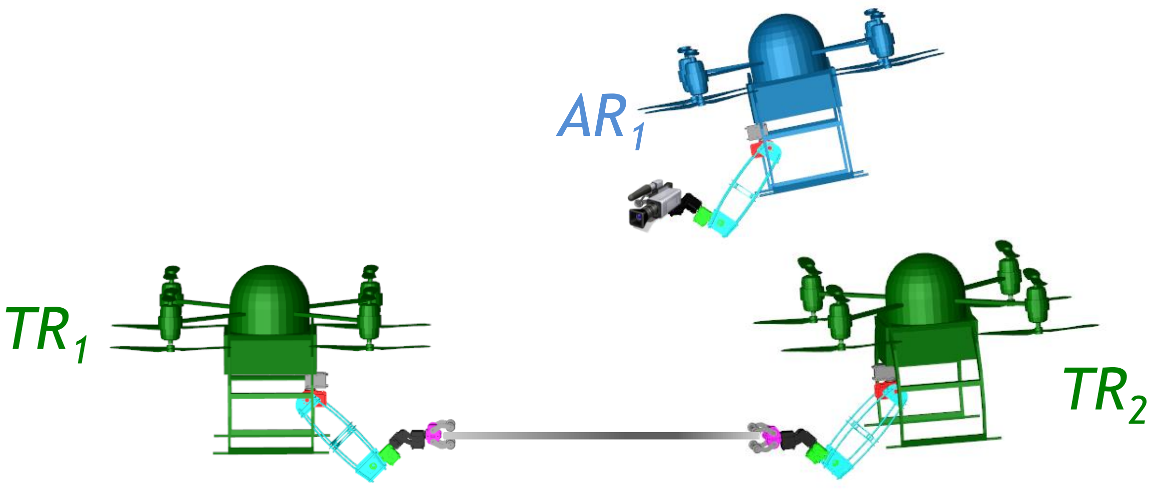


Control and grasping experiments

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



Coordinated control

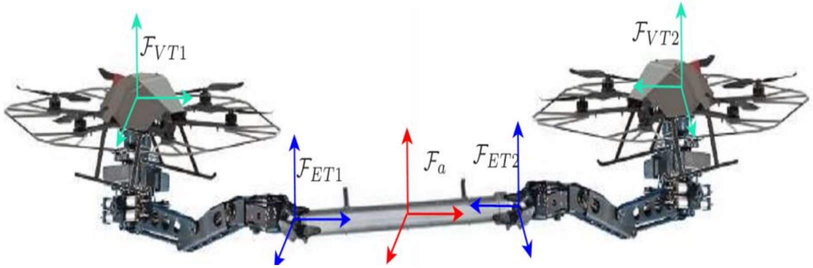
From off-line Motion planner

1st Layer — ***Multi-vehicle coordinated control***

$\boldsymbol{p}_{TEi,d}$ $\boldsymbol{R}_{TEi,d}$ $\boldsymbol{p}_{AEi,d}$ $\boldsymbol{R}_{AEi,d}$

$\dot{\boldsymbol{p}}_{TEi,d}$ $\boldsymbol{\omega}_{TEi,d}$ $\dot{\boldsymbol{p}}_{AEi,d}$ $\boldsymbol{\omega}_{AEi,d}$

2nd Layer — ***Vehicle-manipulator coordinated control***



$\boldsymbol{p}_{v,d}$ $\psi_{v,d}$ $\boldsymbol{q}_{d}$

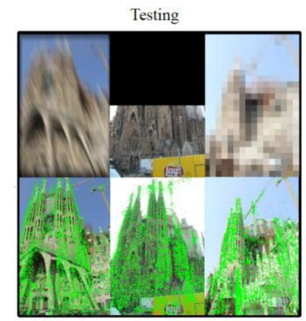
$\dot{\boldsymbol{p}}_{v,d}$ $\dot{\psi}_{v,d}$ $\dot{\boldsymbol{q}}_{d}$

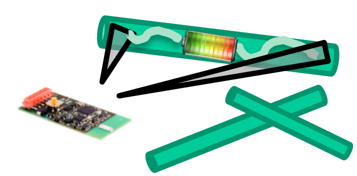
3th Layer — ***Low-level control***

$\boldsymbol{f}_{v}$ $\boldsymbol{\tau}$

Environment perception in ARCAS

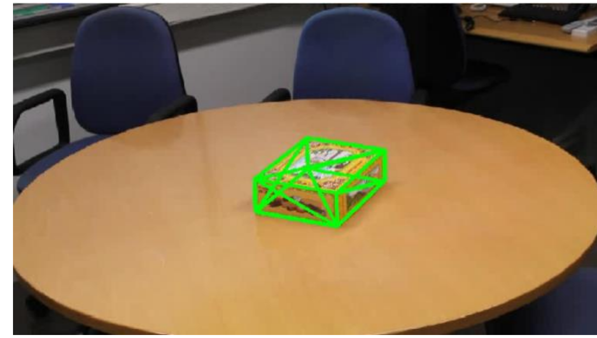
- **Pose estimation from low resolution images:** apply a classifier trained with high resolution images (3D map) to compute the robot pose from low resolution images taken from the robot (robust to motion blur, image degradation, and occlusions) and low computational cost.
- **Object detection and recognition** 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.
- **Range-only SLAM** in structure assembly: SLAM based on radio beacons and ultrasound, structure parts with embedded radio emitters (bearing to be estimated)

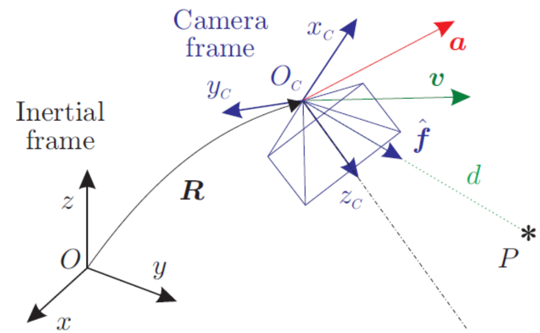


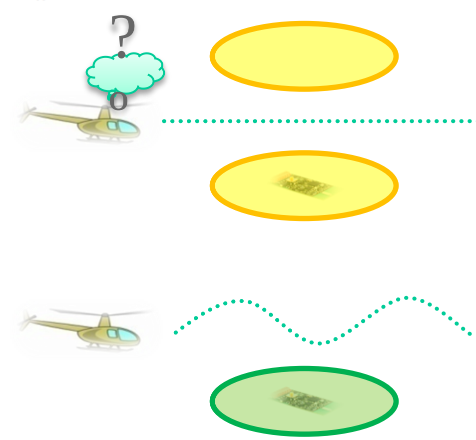


Environment perception in ARCAS

- **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)
- **Cooperative perception.** RO-SLAM techniques combined with robot local sensors and environment perception for enhanced robot localization estimation and map refinement: optimal selection of waypoints to maximize information gathering, POMDP framework for decision making, Generation of waypoints which increase the information gain



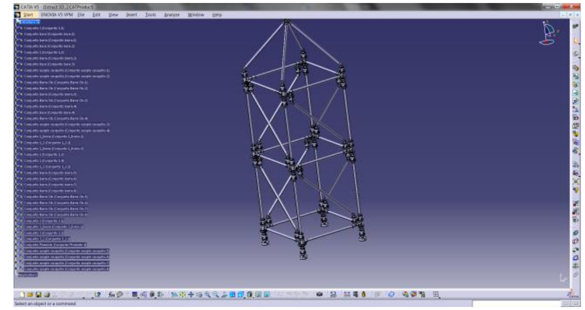


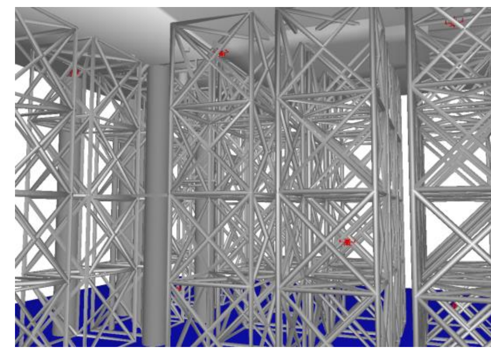


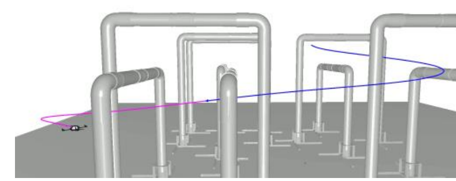
Planning

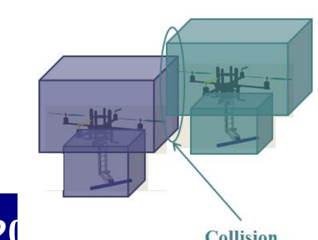
Structure Assembly in ARCAS

- **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

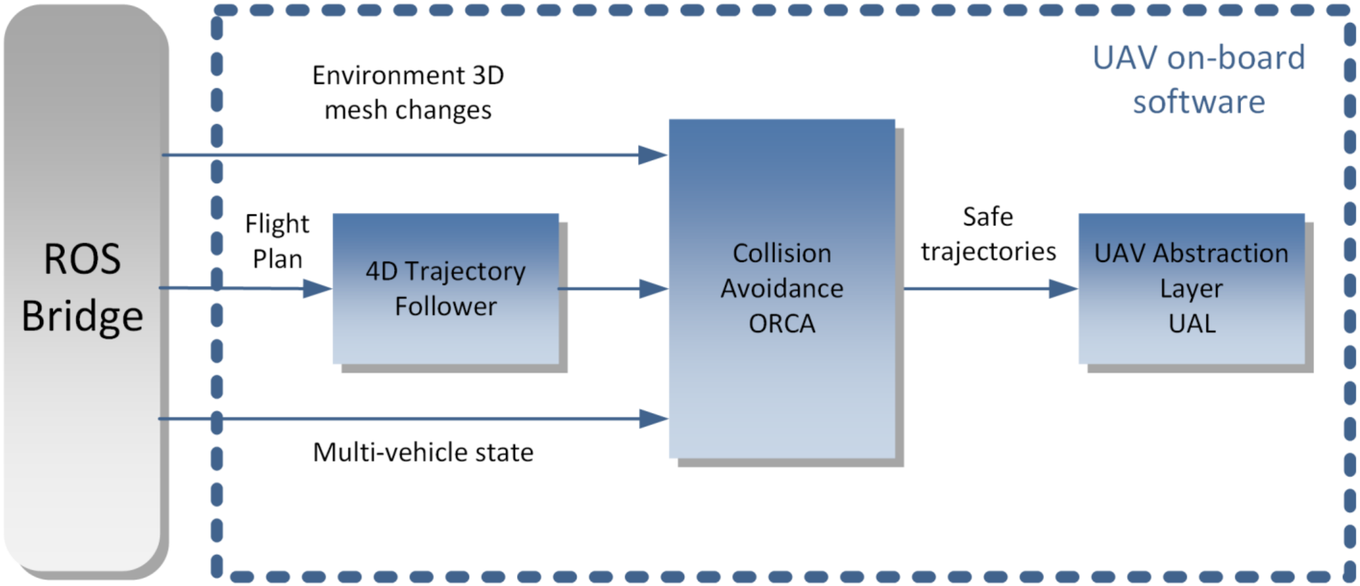








Safe coordinated trajectories generation and execution with collision detection and avoidance



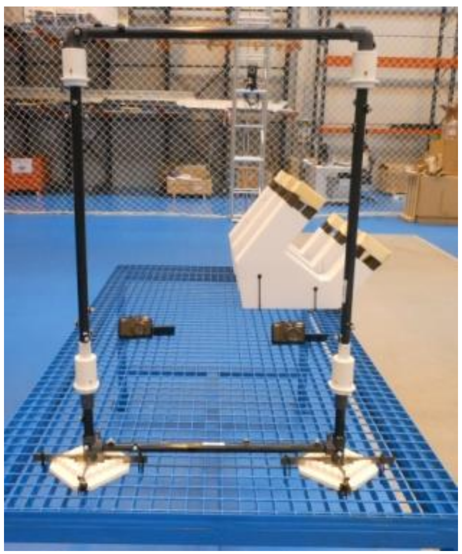
Optimal Reciprocal Collision Avoidance (ORCA)

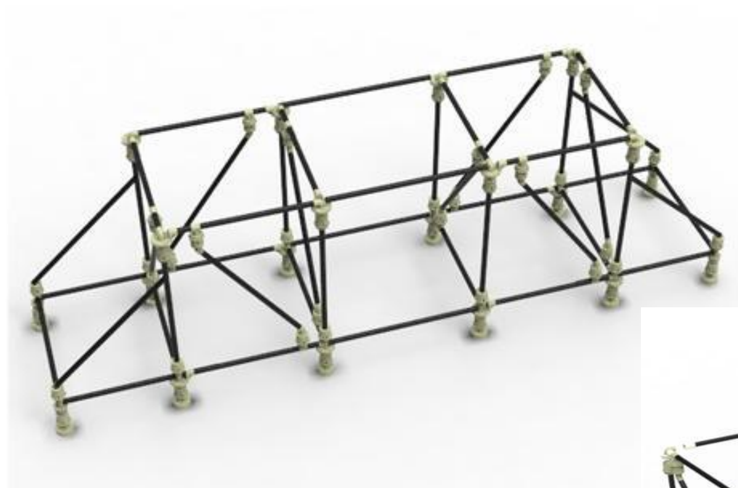
- Time horizon **τ** for the detection and avoidance
- Works in the velocity space (first order algorithm)
- Avoidance effort shared among the involved vehicles in each potential collision
- Minimize the difference with the planned cruise speeds
- Characteristics: Low computation time (< 1 ms); Kinematic 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

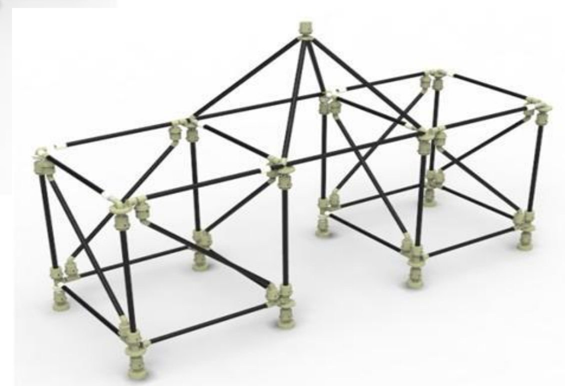
Safe coordinated trajectories generation and execution with collision detection and avoidance

Indoor scenario

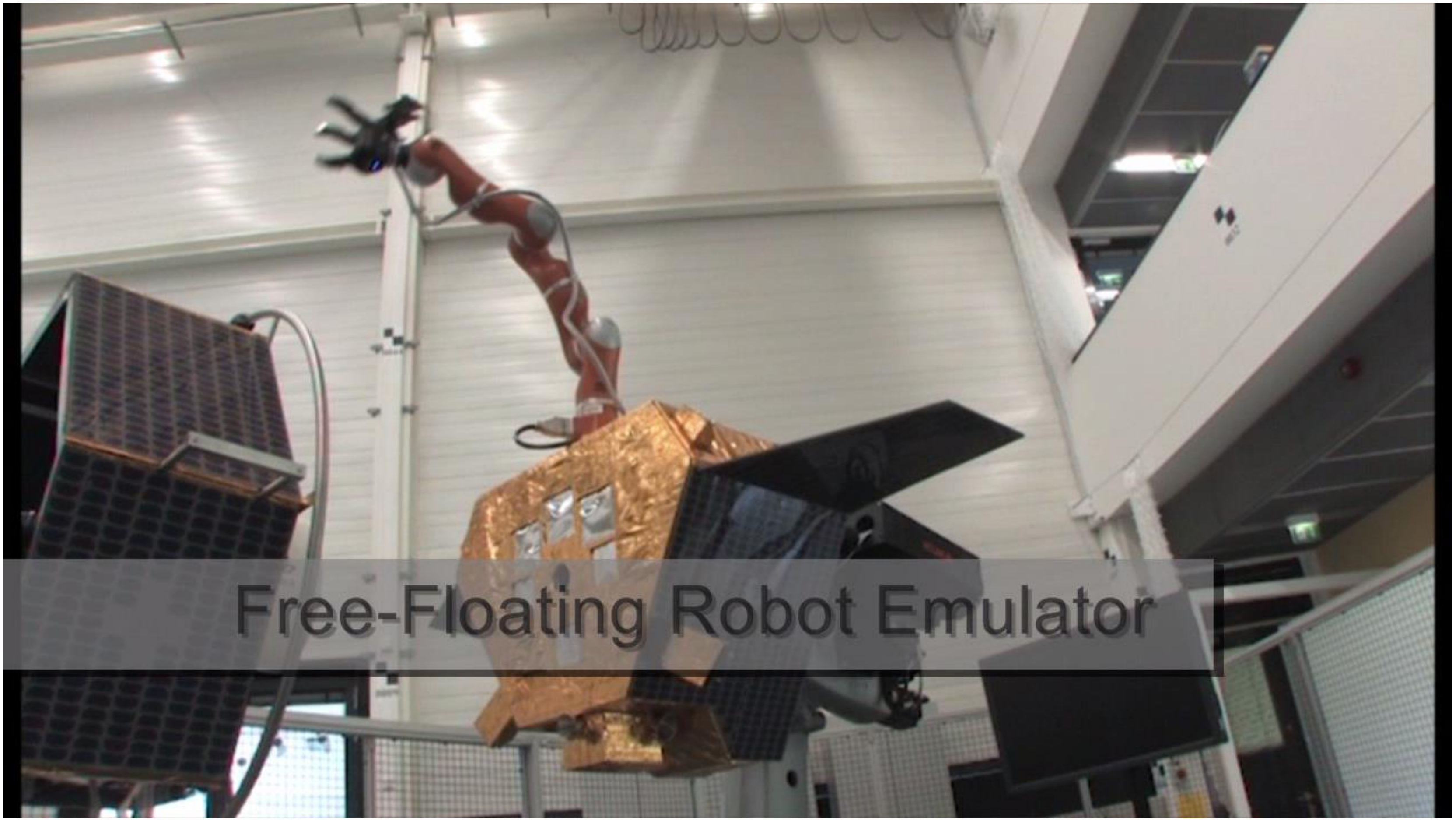
- Preparation of the indoor experiments:
  - Assembly parts (from current 2D to future 3D structure designs)







Emulation of the flying robots assembly tasks by using the DLR manipulator testbed



Experiments Year 1

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2014 Indoor Experiments

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Euronews (September 2014)

Conclusions

- First steps of cooperative aerial manipulation
  - First world-wide demonstrations: aerial robots general manipulation with multi-joint arms, structure assembly
- New control methods: coordinated control, robust and adaptive control, force/torque control

  Full model integrated control

  Decoupled control
- New robust perception techniques
- Integration of new mission (assembly) planning, task plannng and motion planning techniques for multiple UAVs

- Large number of applications
- Intensive experimentation is needed
- Increasing relevance of regulatory issues for industrial applications
- Small systems: More easy/safe application but operational constraints
- Larger systems are required for many applications

AEROARMS