Aerial robots: From physical interactions to aerial robotic manipulation

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Outline

• Physical interaction of aerial robots
• Aerial manipulation
  – Modelling and control
  – Perception
  – Planning
  – Integrated experiments
• Conclusions
Physical interactions

• Introduction
Physical interactions

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

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

Global Hawk refuelling

DC 130 Hercules and BQM34 Fire bee
Physical interactions: Tethered Helicopter

EC-SAFEMOBILE FP7 project

- Spherical conf. variables + Cartesian motion variables

\[
\mathbf{p}^{N \to H} = \mathbf{p}^{N \to P} + \mathbf{P}^{P \to H}
\]

\[
\mathbf{p}^{N \to P} = q_9 \mathbf{c}_3
\]

\[
N \mathbf{v}^{H} = u_1 \mathbf{n}_1 + u_2 \mathbf{n}_2 + u_3 \mathbf{n}_3
\]

- 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)

\[
\begin{bmatrix}
\dot{q}_7 \\
\dot{q}_8 \\
\dot{q}_9
\end{bmatrix}^T = M \cdot \begin{bmatrix}
u_1 \\
\cdots \\
u_6
\end{bmatrix}^T
\]
\[
\dot{q}_4 = -(s_6u_5 - c_6u_4)/c_5
\]
\[
\dot{q}_5 = s_6u_4 + c_6u_5
\]
\[
\dot{q}_6 = u_6 + s_5(s_6u_5 - c_6u_4)/c_5
\]

\[
(m_F + m_{MR})\dot{u}_1 = RHS_1-TCs_8
\]
\[
(m_F + m_{MR})\dot{u}_2 = RHS_2+Tcs_7c_8
\]
\[
(m_F + m_{MR})\dot{u}_3 = RHS_3-TCc_7c_8
\]
\[
K_{4p4}\dot{u}_4 = RHS_4+TC(d_{O-P,3} - d_{O-H^o,3}) \cdot (c_7c_8(s_4c_6 + s_5s_6c_4) - s_7c_8(c_4c_6 - s_4s_5s_6) - s_6s_8c_5)
\]
\[
K_{5p5}\dot{u}_5 = RHS_5+TC(d_{O-P,3} - d_{O-H^o,3}) \cdot (s_7c_8(s_6c_4 + s_4s_5c_6) - c_7c_8(s_4s_6 - s_5c_4c_6) - s_8c_5c_6)
\]
\[
K_{6p6}\dot{u}_6 = RHS_6
\]
Physical interactions: Tethered helicopter

\[ K_{4p1}\dot{u}_4 = t_{MR,1} + d_{O-H^o,3} f_{TR,2} + (K_{456}u_6 + K_{45})u_5 + 
+ T_C(d_{O-P,3} - d_{O-H^o,3}) \cdot (c_7c_8(s_4c_6 + s_5s_6c_4) - s_7c_8(c_4c_6 - s_4s_5s_6) - s_6s_8c_5) \ \{ RHS_4 \] 

\[ K_{5p5}\dot{u}_5 = t_{MR,2} + t_{TR,2} + (K_{546}u_6 + K_{54})u_4 + 
+ T_C(d_{O-P,3} - d_{O-H^o,3}) \cdot (s_7c_8(s_6c_4 + s_4s_5c_6) - c_7c_8(s_4s_6 - s_5c_4c_6) - s_8c_5c_6) \ \{ RHS_5 \] 

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

\[ t_{MR,1} = t_{MR,1} | C^{ROT} - T_C^{est} (d_{O-P,3} - d_{O-H^o,3}) \cdot (c_7^{est} c_8^{est} (s_4c_6 + s_5s_6c_4) - s_7^{est} c_8^{est} (c_4c_6 - s_4s_5s_6) - s_6s_8^{est} c_5) \] 

\[ t_{MR,2} = t_{MR,2} | C^{ROT} - T_C^{est} (d_{O-P,3} - d_{O-H^o,3}) \cdot (s_7^{est} c_8^{est} (s_6c_4 + s_4s_5c_6) - c_7^{est} c_8^{est} (s_4s_6 - s_5c_4c_6) - s_8^{est} c_5c_6) \] 

- 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)

\[ |p_{P \rightarrow H}^O \times T_C| < t_{MR1,2}^{\text{max}} \Rightarrow |d_{O-P,3} - d_{O-H,3}| T_C < t_{MR1,2}^{\text{max}} \]

\[ T_C < \frac{t_{MR1,2}^{\text{max}}}{|d_{O-P,3} - d_{O-H,3}|} (\approx 0.2 \cdot f_{MR,3}^{\text{hover}}) \]

=> 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 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

Q1 = Yaw1 (0°) [-50°, 50°]
Q2 = Pitch1 (0°) [-180°, 0°]
Q3 = Pitch2 (0°) [0°, 180°]
Q4 = Roll1 (0°) [-150°, 150°]
Q5 = Pitch3 (0°) [-90°, 90°]
Q6 = Roll2 (0°) [-150°, 150°]

DENAVIT-HARTENBERG PARAMETERS

<table>
<thead>
<tr>
<th>i</th>
<th>α_i-1</th>
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</tr>
<tr>
<td>6</td>
<td>π/2</td>
<td>0</td>
<td>θ6</td>
<td>ℓ6</td>
</tr>
</tbody>
</table>

X0
Y0
Z0

L2
L3
L4
L6
Z1
Z2
Z3
Z4
Z5
Z6 = (Px, Py, Pz)

(Px, Py, Pz)
(nx, ny, nz)
(ax, ay, az)
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

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 Vs PID

Variable parameter Integral Backstepping Control

\[ m\ddot{V} + \Omega \times (mV) = F_{\text{prop}} + F_{\text{aero}} + F_{\text{grav}} + F_{\text{contact}} \]

\[ J(\gamma)\dot{\Omega} + \dot{\Omega} \times (J(\gamma)\Omega) = T_{\text{prop}} + T_{\text{aero}} + T_{\text{arm}(\gamma)} + T_{\text{contact}} \]
• **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:

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

$K_{VG}$: 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 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 jacobianneul 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**

![Graph showing manipulator's joint angles and position errors over time.](image)
Control and grasping experiments

Backstepping Attitude and Position Controller
Integration Experiment Results

- Integration at the control level
  - Behavior-based control
  - Control algorithms to compensate manipulator effects

(Movie accelerated at 5x)
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

1st Layer

**Multi-vehicle coordinated control**

\[ \begin{align*}
\mathbf{p}_{TEi,d} &\quad \mathbf{R}_{TEi,d} &\quad \mathbf{p}_{AEi,d} &\quad \mathbf{R}_{AEi,d} \\
\dot{\mathbf{p}}_{TEi,d} &\quad \omega_{TEi,d} &\quad \dot{\mathbf{p}}_{AEi,d} &\quad \omega_{AEi,d}
\end{align*} \]

2nd Layer

**Vehicle-manipulator coordinated control**

\[ \begin{align*}
\mathbf{p}_{v,d} &\quad \psi_{v,d} &\quad \mathbf{q}_{d} \\
\dot{\mathbf{p}}_{v,d} &\quad \dot{\psi}_{v,d} &\quad \dot{\mathbf{q}}_{d}
\end{align*} \]

3rd Layer

**Low-level control**

From off-line Motion planner

\[ f_v \quad \tau \]
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 $\tau$ 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
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
2014 Indoor Experiments
Summary of Experiments
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 planning 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