Aerial Robotics Manipulation for Structural Monitoring and Maintenance

Anibal Ollero
Professor and Director GRVC Universidad de Sevilla (Spain)
aollero@us.es

Scientific Advisor of the Center for Advanced Aerospace Technologies (Sevilla, Spain)
aollero@catec.aero
Outline

• New developments in aerial robotics manipulation
  – Prototypes
  – Control
  – Perception
  – Planning
• Inspection Applications:
  – Pipes in industrial plants: AEROARMS
  – Bridges: AEROBI
• Conclusions
H2020
AERial RObotic system integrating multiple ARMS and advanced manipulation capabilities for inspection and maintenance (AEROARMS)

Coordinator: A. Ollero
AEROARMS

Objective 1: Aerial manipulation methods and technologies for industrial inspection and maintenance

• New aerial robots to perform dexterous accurate manipulation
• Multirotors with dual arms and fully-actuated aerial platforms (tilted rotors)
• Helicopters with dexterous arms
• New perception, planning and control methods
• Telemanipulation

Objective 2: Validation in the following oil and gas applications:

• Installation and maintenance of permanent Non Destructive Tests (NDT) sensors on remote components
• Deploying a mobile robotic system permanently installed on a remote structure
Aeroarms first period

AErial Robotic system integrating multiple ARMS and advanced manipulation for inspection and maintenance

First Period
February, 2017
AEROARMS prototypes

CNRS

- Tilted hexarotors (Tilt hex)
  - Diameter: 0.7 m.
  - Max payload: 4 kg

- Tilted hexarotors (Fast hex)
  - Diameter: 0.69 m.
  - Max payload: 4 kg
Dual arm aerial robots

- Aerial dual arm manipulators (Univ. Sevilla)
  - Stiff-joint dual arm: 5-DOF (per arm), 1.8 Kg
  - Compliant dual arm: 4-DOF (per arm), 1.3 Kg
  - Enhanced compliant dual arm: 5-DOF, 2.5 Kg (available on Feb. 2018)

  - February 2016 – AMUSE platform
  - November 2016 – DroneTools platform
  - February 2017 – DroneTools platform
First dual arm prototype
University of Seville, 2015

- Two identical 5-DOF, human-size, low weight and low inertia arms

- Interest of the coordinated motion of two arms for torque compensation
- One of the arms is commanded to move from 0 to 90 deg, and from 90 to 0 in 1 s.
Mission control operation modes

1) Take-off & flight mode
- Arms locked during navigation
- Whole rigid body
- Navigation

2) Approaching mode
- Smooth transition for smart allocation of the arms
- Semi rigid/flexible
- Local references

3) Operational mode
- Force/impedance control
- EE grip contact forces (safety)
- Local references
Developed prototypes of lightweight manipulators

- Desired features for the manipulator arms:
  - Very low weight (around 0.5 Kg per arm) and inertia
  - Mechanical joint compliance: ~30 [deg] deflection
  - High speed, robustness, reliability, simplicity
- Technological limitations and challenges:
  - No torque/acceleration feedback or control available on servo actuators
  - Integration of the deflection sensor in a very compact device (mechatronics)
Mechanical joint compliance

- Benefits of mechanical joint compliance:
  - Safety in physical interactions between the aerial manipulator and the environment, protecting servos against impacts and overloads.
  - Reduces the bandwidth needed for control, limited by the servo actuators typically employed in these applications (<50-75 Hz).
  - Estimation and control of torque/force by means of joint deflection.

- Main drawbacks:
  - Lower positioning accuracy due to static deflections
  - More complex control associated to dynamic deflections
Anthropomorphic compliant dual arm system prototype

- **Main features:**
  - Human size, bioinspired design
  - Total weight / max. lift load: 1.3 Kg / 0.4 Kg per arm
  - Actuators: Herkulex smart servos → DRS-0201: 24 [Kg·cm] @ 60 [g]

- **Kinematic configuration:**
  - 4-DOF Positioning: shoulder pitch (base), roll and yaw, elbow pitch
  - 3-DOF Wrist orientation: roll, yaw and pitch → Not developed yet

- **Max. control rate:** ~75 Hz
Dynamic Model of Aerial Manipulator with compliant joints

The dynamic equations of a multirotor equipped with two robotics arms of $N_i$ flexible joints each arm are given by:

\[
M(r)\ddot{\eta} + C(r, \dot{r}) + G(\eta) = \tau + \tau_{ext}
\]

\[
\tau_q = K(q_m - q) + D(\dot{q}_m - \dot{q})
\]

\[
\tau_{q_m} - \tau_q = M_{q_m}\ddot{q}_m - f(q_m)
\]

\[
\eta = \begin{bmatrix} p & \theta & q \end{bmatrix}^T \\
\tau = \begin{bmatrix} F \\ \tau_\theta \\ \tau_q \end{bmatrix}
\]

where $q_m$ and $q$ are the motor and joint angular positions respectively. $K$ and $D$ are the stiffness and damping matrix and $\tau_{ext}$ represents the external forces.
Identification and Analysis of Compliant Dual Arm

- Impact response experiment:
  - An object in free fall hits the end-effector.
  - An IMU attached under the gripper measures the acceleration and angular speed at this point.
  - The deflection signal of the elbow joint follows a typical 2\textsuperscript{nd} order underdamped behavior.

- Motivation for this analysis:
  - **Impacts** between manipulator and environment may arise in the transition from contactless (free flying) to contact (grasping) situations.
  - The arms should support the **mechanical energy** of the whole aerial manipulator.
  - The impact response determines the **bandwidth** of the joints, that is, the rate of energy absorption.
  - This has practical implications in terms of **safety** in the aerial manipulation operation.
Contact detection

- Contact detection – change between modes 2 and 3
  - Define residual signal $r(t)$
  - $r(t)$ should be zero when no contact/collision occurs (up to measurement noise and unmodelled disturbances)

\[
r(t) = K_I \left[ p(t) - \int_0^t (\tau_q + C^T(q, \dot{q})\dot{q} - g(q) + r) \, ds \right]
\]

$K_I$: diagonal gain matrix
$p(t)$: generalized momentum
$\tau_q$: elastic forces/torques

- Evolution of $r(t)$: stable,

\[
\dot{r} = K_I(\tau_{ext} - r)
\]
Robust nonlinear control strategy

- Independent UAV & ARMs target tracking
- (1+2) Proven Robust Stability
- (3) On-going
- “Optimal” interconnection tasks:
  - Main: UAV & EE pose and coupling torque ($\tau^*$)
  - Secondary (Null-space):
    - SNS-based local collision avoidance
    - Early self-avoidance
    - Differentiation between levels of risk
- Realistic simulations with disturbances (noise, gusts of wind) + EE forces
Robust nonlinear control strategy

Full controller block diagram

- Cascade-like strategy:
  - Inner loop (ARMs) as decentralised
  - Outer loop (UAV) with torque estimator (observer)
Robust nonlinear control strategy

UAV - Passivity-based Controller:

• Cascade-like outer loop w.r.t. ARMs closed-loop dynamics
• First try: IDA-PBC, but applicable to passive methodologies
• Passive reduced-order observer to correct the mismatch in $\tau^*$
• ARMs dynamics reduced to CoGs
• Stability & robustness:
  - Disturbance rejection w.r.t. ARMs dynamics
  - Uniformly & ultimately bounded

\[ \text{Theorem: The sequential application of the cascade-like strategy ensures that all trajectories are uniformly bounded during take-off, flight and approaching modes.} \]
Force control strategy – Mode 3

- Joint level impedance controller
- Use contact forces observer $\hat{\tau}_{ext}$ to control contact forces.
- Target dynamics of impedance behavior at virtual equilibrium point $q_d$ ($K_q$ and $D_q$: desired joint stiffness and damping matrices):

$$M(q)\ddot{q} + (C(q, \dot{q}) + D_q)\dot{q} + K_q(q - q_d) = \hat{\tau}_{ext}$$

- Controller: impedance term + gravity compensation

$$u = -K_c(q_m - q_{md}) - D_q\dot{q}_m + \bar{g}(q)$$

- $K_c$ combines “physical impedance” $K$ (infinite bandwidth) and “control impedance” $K_q$ (control bandwidth, up to 75 Hz):

$$K_c = \left(K_q^{-1} - K^{-1}\right)^{-1}$$
Force control strategy

XZ-Axes Force Control

Shoulder and Elbow Pitch Joints Deflection

Force control example with two compliant joints
Aerodynamic effects

- Most multirotor control algorithms based on rotor thrust generation with thrust coefficient $b$ constant $T = bw^2$
  
  Valid when: hover, no wind, no airflow interference with environment nor other rotors

- In real applications (industrial inspection and maintenance): $b = b(x, y, z, mapV, wind)$

  
  - CFD: multiple rotors & other surfaces

Good results for one rotor. Poor results in more complex situations,
Improving the Aerodynamic Effect Modelling – CFD-MRF-Simulations

- Simulate the rotation of the propeller
- Macro results are good and consistent with the real experiments.

- CFD-MRF allow performing more simulations (ceiling effect, full multirotor in ground effect, partial ground effect...) because we are taking into account the rotation of the propeller.
- CFD-MRF does not produce large errors in the proximity of the surface.
- Better results in velocity and pressure fields.

Velocity field in CFD-MFR simulations
Control Design - Flight Aerodynamics of the UAV I

- Advanced **aerodynamic model** based on CFD simulations and **BEMT propulsive model**
  - Improved realism of the simulations, allowing the study of complex control strategies capable of coping with non-linear effects
  - Improve behaviours of previous controllers.
  - Feedforward solutions to cope with ground effect, ceiling effect and partial ground effect
  - Effects of flight speed on rotor thrust
  - Basic geometry of the blade for simulation
  - Tuning and modifying the control strategies to cope with propulsive disturbances such as: Thrust losses, Non-constant thrust coefficients (i.e. $T \neq k \Omega^2$), Ground Effect, Partial Ground Effect
Adaptive vision for accurate grabbing and manipulation (USE)

A) Robust Feature-based Grasping

- Offline
  - Feature matching
  - Bundle Adjustment

- Online
  - Feature matching
  - Pose estimation
**Adaptive vision for accurate grabbing and manipulation**

**B) Probabilistic grasp planning using Gaussian processes**

- Object modeling using Gaussian Process Implicit surfaces.
- Grasp generation for probabilistic surface.
- Probabilistic force closure.
- Probabilistic grasp planning.
- Use of previous knowledge as prior for the reconstruction of the surface.
- Able to reconstruct unobserved fragments of the object (first row better than second): better gasping.
- Effective volume reconstructed enabling better grasp generations.
- Can be applied with depth sensors: Intel, Kinect, etc.
Aeroarms

• Visual grasping
Precise 3D mapping and localization for manipulation with aerial robots in industrial environments

Visual SLAM

• Appearance-based SLAM RTAB map (Labbé and Michaud, 2013)
• Graph-based with loop closure detector with incremental appearance-based loop closure detector.
• Use of bag-of-words for robustly detecting loop closures. Robust detection of SLAM loop closures is critical in our scenario, where settings with similar types of pipes can originate closure detection errors.

Stereo vision is not robust to irregularities in lighting conditions

Multi-sensor mapping (3D LIDAR, stereo and TOF sensors)
Planning and reactivity for safe operation

• Problem definition

  Two operational modes
  – Navigation
    • The UAV travels to the operation point. UAV movement is controlled with continuous actuations: velocity
    • Arms: only a set of discrete configurations are considered
  – Manipulation
    • UAV low speed movements, near the operation point
    • Arms are fully and continuously controlled
Local navigation and operation

• **Motion Planning for the Aerial Robotic System with two arms for Long Reach Manipulation**
  
  − Modeling and control of the ARS-LRM system.
  
  − Algorithm for motion planning: extended planning space and planning optimization according to time / energy indices.
  
  − Application scenario: riveting task in cluttered environments.

  − Dynamic Awareness (DA) in the internal operation of the planner

\[
X_{ini} \quad X_{min} \quad X_{new} \quad RRT^{*}-DA
\]
AEROARMS industrial testing sites

- Industrial plants being analyzed: Oil and gas

- Cement Oven plants
  - Perform flights during programmed stops
  - Diameter: 5 meters
  - Wall thickness measurement needed
  - Wall thickness: ~50mm
  - Wide open space
Inspection of pipes

Site Owners Goal:
Remote Robotic Inspection of difficult-to-reach Piping

Robotic Inspection of a Pipe in VARO Refinery, Cressier (CH) using a GE IR system

Current Systems:
• Tethered,
• Heavy,
• Need Scaffolding to get there
Bridge Inspection: AEROBI H2020 project

Analysis and testing of different UAV configurations (Univ. Sevilla)

1. Multirotor with 5 dof, stiff joints arm.
2. Multirotor with 3 dof, compliant joints arm (version 1)
3. Multirotor with 4 dof, compliant joints arm (version 2)
4. UAV that sticks to the bridge, using ceiling effect (central contact)
5. UAV that sticks to the bridge, using ceiling effect (rotor cover)
Setup of laser measurement system and testing with UAV

- Laser onboard the UAV: impossible to get required accuracy because of errors in UAV position estimation (several cm).
- Adopted setup:
  - Ground laser system: Leica total station MS50/MS60 (TS).
  - Reflector prism onboard UAV.
  - Contact bridge with prism at the arm (configurations 1, 2, 3) or attached at the UAV (configurations 4, 5).
  - Take measurements with TS.

**UAV localization w.r.t. the bridge.**

Base station establish communication with Total Station and UAV, coordinates UAV flight and laser measurements

**Configurations 1, 2, 3**

mm accuracy
Laser measuring system

- Real time visualization of 3D UAV relative position w.r.t. bridge.
Contact Inspection by means of multi-rotors

Aerial Manipulator for Structure Inspection by Contact from the Underside

A.E Jiménez-Cano, J. Braga, G. Heredia and A. Ollero

Multirotor with arm with rigid joints

Multi-rotor stick Arm with compliant joints
Multirotor with arm

- Octorotor platform with larger payload
- Maximum take-off weight: \(~10\) kg
- Arm with stiff joints:
  - when in contact, more stable flight
  - Arm joints support all contact forces
  - Maybe unstable if contact point off-centered
- Arm with compliant joints:
  - Compliant joints absorb perturbation forces/torques instantaneously
  - Compliant joints allow to measure contact forces
  - Force control may increase stability
  - Position control of the arm is more difficult.
Conclusions

- Feasibility of dual arms autonomous aerial robot operation
- Relevance of compliance
- Effectivity of fully actuated platform,
- Visual servoing feasible without markers
- Planning by using kinodynamic models: off line planning, safe real-time reactions
- Inspection of industrial pipes starting by mockups
- Inspection of bridges on-going
Aeroarms Prototype

• Prototype Univ. Sevilla, May 2019
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