Towards MAGMaS:
Multi-Robot Aerial-Ground Manipulator Systems

Antonio Franchi

CNRS, LAAS-CNRS, Université de Toulouse, Toulouse, France

Workshop on Autonomous Structural Monitoring and Maintenance using Aerial Robots

2017 IEEE ICRA, Singapore, May 29th, 2017
Motivation

Extend ground manipulator capabilities to objects that are:

- long
- awkwardly shaped
- not graspable close to their Center of Mass

Application fields

- Logistics
- Plant Decommissioning
- Urban Search And Rescue (USAR)

Challenges

- High Torques
- Vibrations
- Limited Grasping Areas
Multiple Aerial-Ground Manipulator System
MAGMaS

<table>
<thead>
<tr>
<th>Aerial Manipulator</th>
<th>Ground Manipulator</th>
</tr>
</thead>
<tbody>
<tr>
<td>small payload</td>
<td>large payload</td>
</tr>
<tr>
<td>unlimited workspace</td>
<td>limited workspace</td>
</tr>
</tbody>
</table>
Physical Connection to the Aerial Robots

**Case A**
3-Dof passive rotational at the CoM

- Rotational dynamics is added to the system dynamics
- Rotational dynamics is decoupled
- Helpful for underactuated aerial vehicles: orientable total thrust

**Case B**
Partially/Fully rigid connection

- Rotational dynamics is fully (or partially) fixed with the load dynamics
- Good only for fully-actuated platforms
- Simpler connection
- Allows to transmit also torques

Antonio Franchi – http://homepages.laas.fr/afranchi/
3-Dof passive rotational joint at the CoM
Model

**Robot** dynamics (grounded manipulator dyn. + \( k \) aerial vehicle rotation dynamicss)

\[
M(q)\ddot{q} + c(q, \dot{q}) + g(q) = u - J^T(q)h,
\]

where \( J = \text{diag}\{J_m(q_m), 0_3, \ldots, 0_3\} \)

**Load** dynamics

\[
M_o(x)\ddot{x} + c_o(x, \dot{x}) + g_o(x) = h_e = Gh
\]

where the **grasp matrix** \( G \) is defined as \( G = [T_m \ G_t(q)] \).

\[
T_m = \begin{bmatrix} R_o^T & 0 \\ S(R_o^T r_e) & R_o^T \end{bmatrix} \quad G_t(q) = \begin{bmatrix} I_3 \\ S(R_o^T r_i) \\ \vdots \\ S(R_o^T r_k) \end{bmatrix}
\]
Control Strategy

**Control Objectives:** trajectory tracking and vibration cancellation

Overall Control Method

1. **Feedback** Linearization of MAGMaS dynamics
2. **Disturbance Observer** to increase robustness
3. **Force Allocation** scheme based on Optimization
4. Aerial Robot **low–level control** loop
Optimization Problem

MAGMaS redundant actuation $\Rightarrow$ more freedom in control input selection

**Cost Function:** $\mathcal{J} : \mathbb{R}^{(n+3k)} \mapsto \mathbb{R}$ defined as $\mathcal{J}(u_J) = u_J^\top P u_J,$

where $P \in \mathbb{R}^{(n+3k)\times(n+3k)},$ defined as $P = \text{diag}\{J_t J_t^\top, P_t\}$

$J_t J_t^\top$ increases the force manipulability ellipsoid

$P_t \in \mathbb{R}^{3k\times3k}$ weighting ARs and ground manipulator

**Optimization Problem:**

\[
\begin{align*}
    u_J^* &= \arg \min_{u_J} \mathcal{J}(u_J) \\
    \text{s.t.} & \quad \chi_i(\eta_i) \leq 0 \quad i = 1, \ldots, k \\
    & \quad \|h_i\| \leq h_i^{\text{max}} \quad i = 1, \ldots, k \\
    & \quad \min(u^i_m) \leq u^i_m \leq \max(u^i_m) \quad i = 1, \ldots, n \\
    & \quad \xi(u_J) = 0.
\end{align*}
\]

where $\xi(u_J) = 0$ is the constraint associated with the trajectory tracking
Rotational Decoupling

Rotations limits:
roll: ±40°
pitch: ±80°
yaw: unlimited

On the left, the propellers are spinning at the lowest speed for safety.
Trajectory Tracking Results
Vibration Suppression

![Graph showing vibration suppression over time](image)

Towards MAGMaS: Multi-Robot Aerial-Ground Manipulator Systems

Partially rigid connection
Teke-MAGMaS Demonstration

Highlights
- finalist of the Kuka Innovation Awards 2017
- demonstrations during the Hanover Messe (HMI)
- first aerial-ground co-manipulation
- flying companion paradigm

Demonstration Content
- heterogeneous system
- force-based control
- tele-operation framework
- fully actuated aerial manipulator
- cooperative manipulation

Antonio Franchi – http://homepages.laas.fr/afranchi/
Human-in-the-loop Multi–robot Aerial–Ground Manipulation System

Tele-MAGMaS

Coordinator: Antonio Franchi (LAAS-CNRS) — Contact: antonio.franchi@laas.fr
Components

Open Tilt-Hex (OTHex)  LBR iiwa & FlexFellow

- Novel concept: fully-actuated
- Aerodynamical force control
- No force/torque sensors

State-of-the-art collaborative robotic arm + mobile platform
Components (con’t)

- 6D input device
- 3D-force rendering
- Increase user situation awareness

Dynamic simulator and end user visualizer
Demonstrations
Demonstrations
Conclusions

- Novel **heterogeneous** multi-robot system

- **Combine** *strengths* of **aerial** and **ground** manipulators (payload & workspace)

- Multiple future **applications**: logistics, construction, decommission, USAR,…

- Main problems to be addressed from the aerial side:
  - **best design** for the task (mechanics, size)
  - **estimation/sensing** (e.g., interaction wrench despite aerodynamic uncertainty)
  - **robust control** (aerodynamic disturbances) and **failure** robustness
  - **online planning** (exploiting redundancy at best)
Tele-Magmas team:

A. Franchi (coordinator)
N. Staub, D. Bicego,
V. Arellano,
Q. Sablé, S. Mishra

D. Prattichizzo
M. Mohammadi

P. Robuffo Giordano
Q. Delamare

Dongjun Lee
H. Yang C. Ha M. Kim

Sponsored by

Partially funded by:
AeRoArms EU H2020

Acknowledgements

Additional Contributors:
Markus Ryll, Anthony Mallet, RIS Team at LAAS
Related Works presented at ICRA

• **Tuesday 2:45PM Planning session:**
  Staub N, Mohammadi M, Bicego D, Prattichizzo D, Franchi A. “Towards Robotic MAGMaS: Multiple Aerial-Ground Manipulator Systems”.

• **Wednesday 9:30AM Aerial Robot 1 session:**
  Michieletto G, Ryll M, Franchi A. “Control of Statically Hoverable Multi-Rotor Aerial Vehicles and Application to Rotor-Failure Robustness for Hexarotors”.

• **Thursday 9:30AM Aerial Robot 5 session:**
  Franchi A, Mallet A. “Adaptive Closed-loop Speed Control of BLDC Motors with Applications to Multi-rotor Aerial Vehicles”.

• **Thursday 9:30AM Aerial Robot 5 session:**

• **Tuesday 4:10PM Aerial Robot 7 session:**
  Tognon M, Yüksel B, Buondonno G, Franchi A. “Dynamic Decentralized Control for Protocentric Aerial Manipulators”.