Towards MAGMaS: Multi-Robot Aerial-Ground Manipulator Systems

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Workshop on Autonomous Structural Monitoring and Maintenance using Aerial Robots

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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 **A**erial-**G**round **Ma**nipulator **S**ystem
MAGMaS

Aerial Manipulator	**Ground** Manipulator
small payload	large payload
unlimited workspace	limited workspace

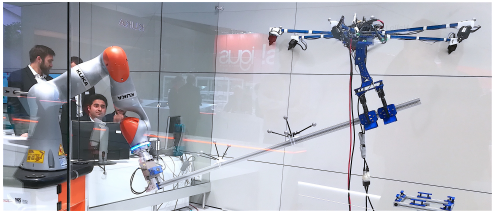
Physical Connection to the Aerial Robots

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



3-Dof passive rotational joint at the CoM

Model

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

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{c}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{u} - \boldsymbol{J}^\top(\boldsymbol{q})\boldsymbol{h},$$

where $\boldsymbol{J} = diag\{\boldsymbol{J}_m(\boldsymbol{q}_m), \boldsymbol{0}_3, \ldots, \boldsymbol{0}_3\}$

Load dynamics

$$\boldsymbol{M}_o(\boldsymbol{x})\ddot{\boldsymbol{x}} + \boldsymbol{c}_o(\boldsymbol{x}, \dot{\boldsymbol{x}}) + \boldsymbol{g}_o(\boldsymbol{x}) = \boldsymbol{h}_e = \boldsymbol{G}\boldsymbol{h}$$

where the **grasp matrix** $\boldsymbol{G}$ is defined as $\boldsymbol{G} = [\boldsymbol{T}_m \quad \boldsymbol{G}_t(\boldsymbol{q})]$.

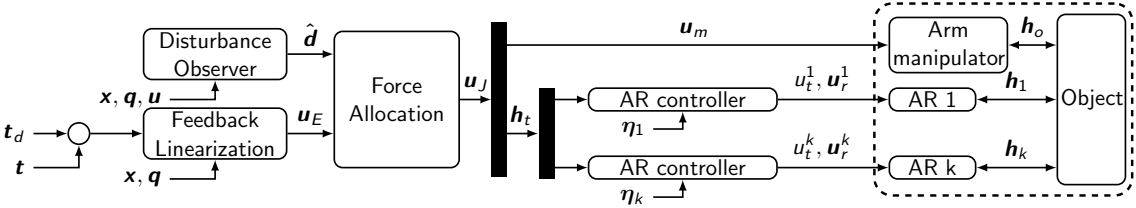
$$\boldsymbol{T}_m = \begin{bmatrix} \boldsymbol{R}_o^\top & \boldsymbol{0} \\ \boldsymbol{S}(\boldsymbol{R}_o^\top \boldsymbol{r}_e) & \boldsymbol{R}_o^\top \end{bmatrix} \qquad \boldsymbol{G}_t(\boldsymbol{q}) = \begin{bmatrix} \boldsymbol{I}_3 & \ldots & \boldsymbol{I}_3 \\ \boldsymbol{S}(\boldsymbol{R}_o^\top \boldsymbol{r}_i) & \ldots & \boldsymbol{S}(\boldsymbol{R}_o^\top \boldsymbol{r}_k) \end{bmatrix}$$

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 $\mathcal{J}(\boldsymbol{u}_J) = \boldsymbol{u}_J{}^\top \boldsymbol{P}\ \boldsymbol{u}_J$,

where $\boldsymbol{P} \in \mathbb{R}^{(n+3k)\times(n+3k)}$, defined as $\boldsymbol{P} = diag\{\boldsymbol{J}_t\boldsymbol{J}_t^\top, \boldsymbol{P}_t\}$

$\boldsymbol{J}_t\boldsymbol{J}_t^T$ increases the force manipulability ellipsoid

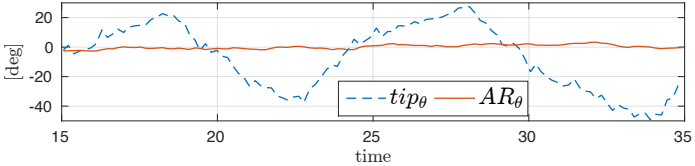
$\boldsymbol{P}_t \in \mathbb{R}^{3k\times 3k}$ weighting ARs and ground manipulator

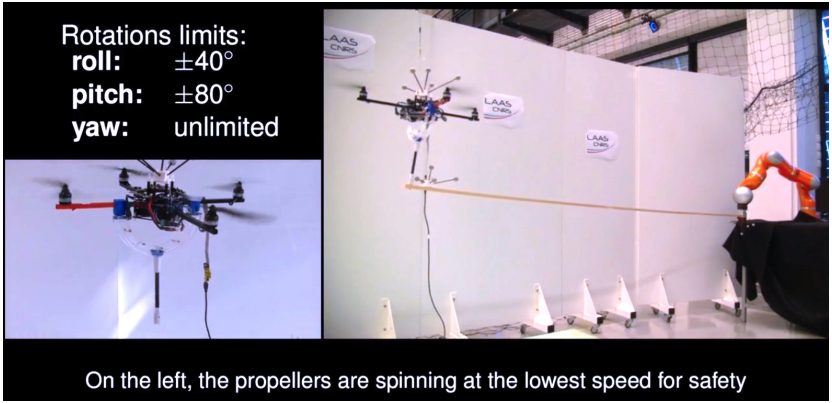
Optimization Problem:

$$
\begin{aligned}
\boldsymbol{u}_J^* = \arg\min_{\boldsymbol{u}_J} \quad & \mathcal{J}(\boldsymbol{u}_J) \\
\text{s.t.} \quad & \chi_i(\boldsymbol{\eta}_i) \leq 0 \quad i = 1, ..., k \\
& \|\boldsymbol{h}_i\| \leq h_i^{\max} \quad i = 1, ..., k \\
& \min(u_m^i) \leq u_m^i \leq \max(u_m^i) \quad i = 1, ..., n \\
& \boldsymbol{\xi}(\boldsymbol{u}_J) = 0.
\end{aligned} \tag{1}
$$

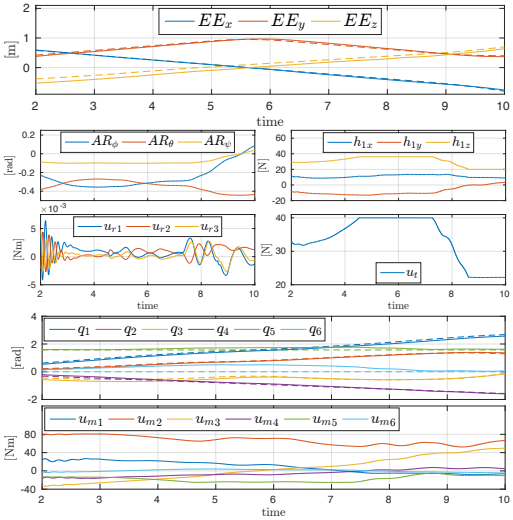
where $\boldsymbol{\xi}(\boldsymbol{u}_J) = 0$ is the constraint associated with the trajectory tracking

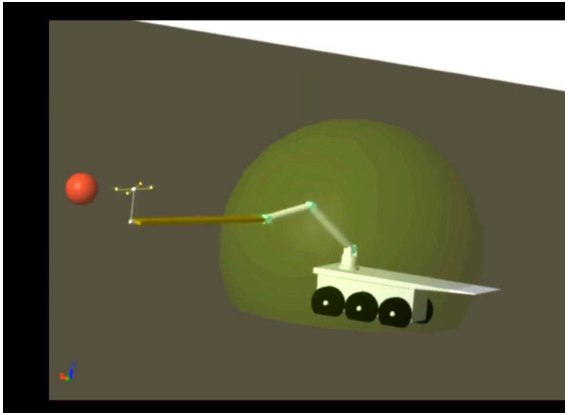
Rotational Decoupling



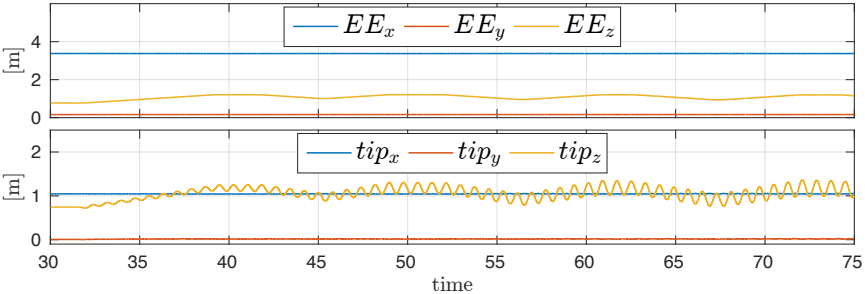


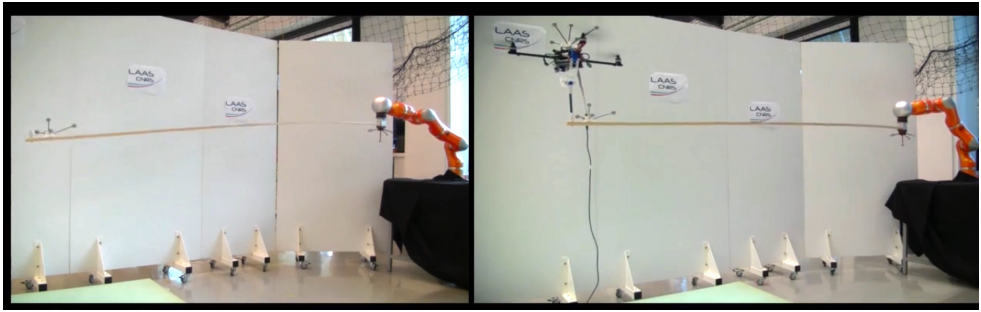
Trajectory Tracking Results





Vibration Suppression





Partially rigid connection

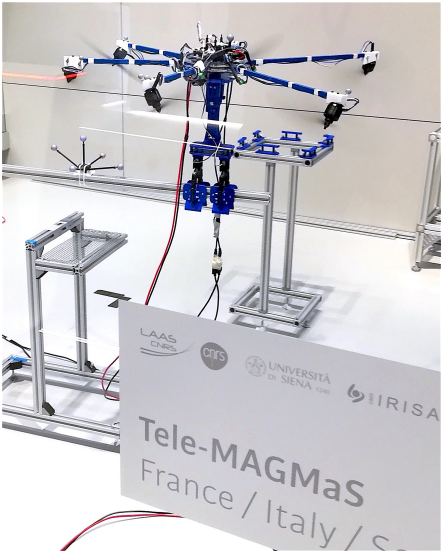
Teke-MAGMaS Demonstration

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



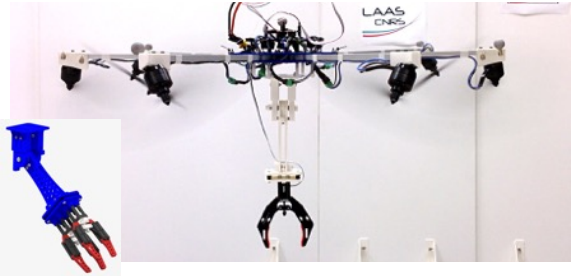
Human-in-the-loop
Multi–robot **A**erial–**G**round
Manipulation **S**ystem

Tele–MAGMaS

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

Components

Open Tilt-Hex (OTHex)



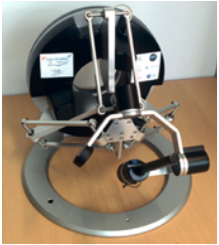
- Novel concept: fully-actuated
- Aerodynamical force control
- No force/torque sensors

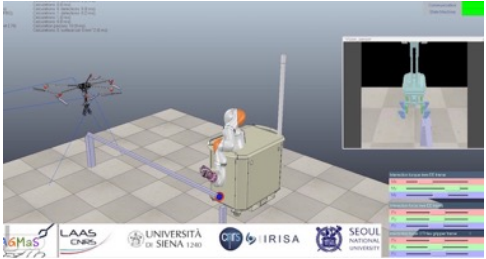
LBR iiwa & FlexFellow

State-of-the-art collaborative robotic arm + mobile platform

Components (con't)

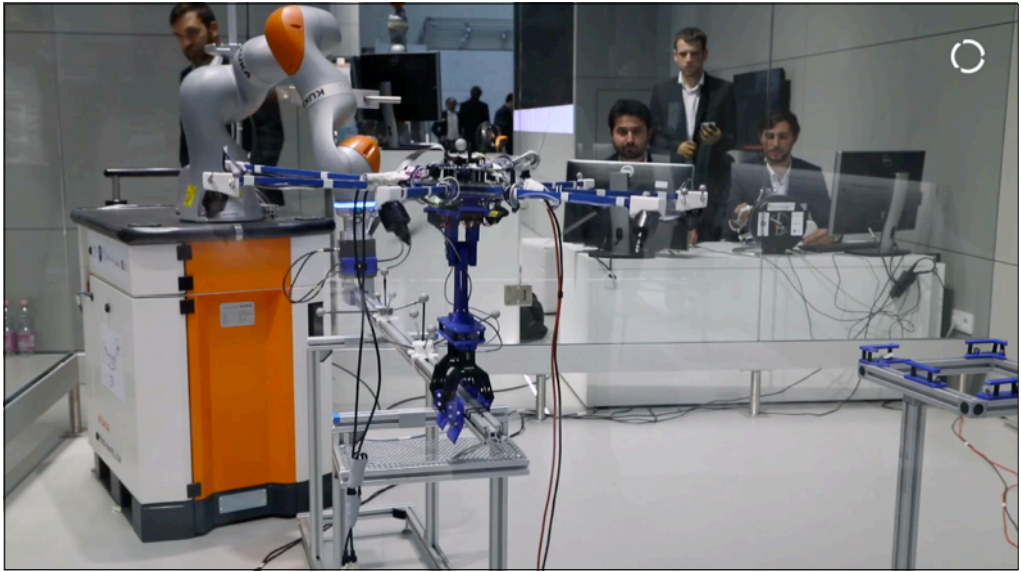
6D input device
3D-force rendering
increase user situation awareness



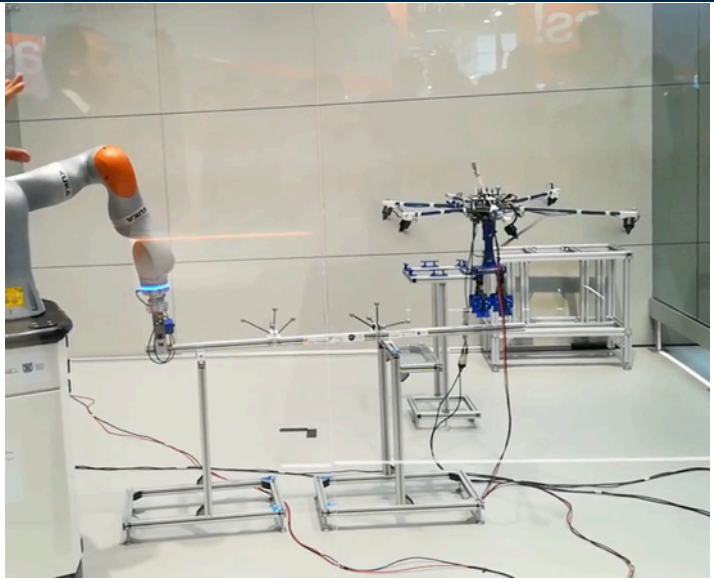


dynamic simulator and end user visualizer

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)

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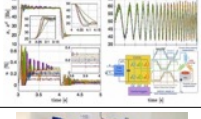
Related Works presented at ICRA

- *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:*
  Ryll M, Muscio G, Pierri F, Cataldi E, Antonelli G, Caccavale F, Franchi A. “6D Physical Interaction with a Fully Actuated Aerial Robot”.

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