Physically interacting drones: From passive to active robots

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Bio sketch



[2023-today] LAAS-CNRS and UPS (France) CPJ

[2020-2022] Maynooth University (Ireland) Assistant Professor

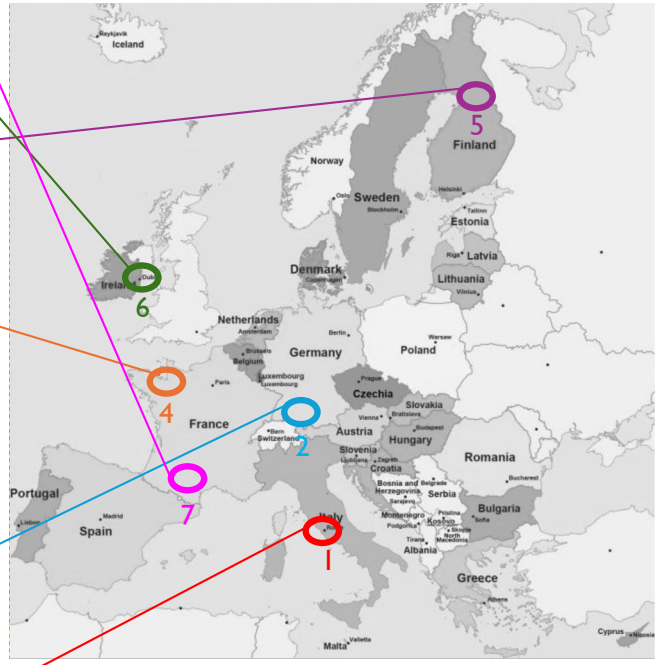
[2020] University of Oulu (Finland) PostDoc

[2017-2019] IRISA/Inria Rennes (France) PostDoc

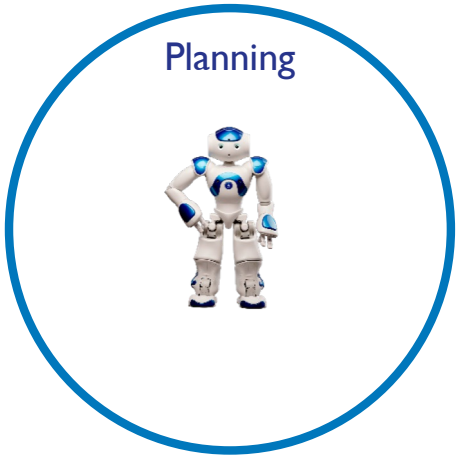
[2015] Carnegie Mellon University (USA) visiting PhD

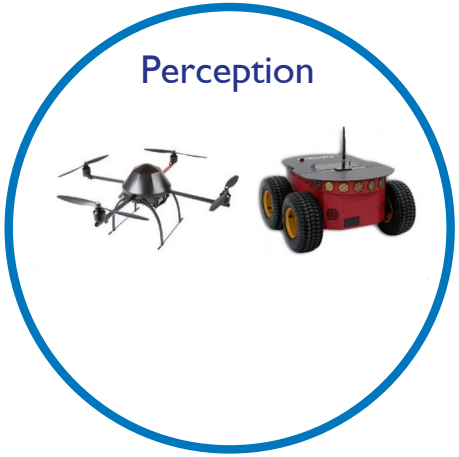
[2013] Max Planck Institute (Germany) visiting PhD

[2012-2016] Sapienza - University of Rome (Italy) PhD



Research contribution areas







Past/present: what drones do

Aerial robots have been proven to be excellent in performing several tasks -- spanning from navigation to surveillance -- mostly thanks to their agility and ability to move quickly



https://www.youtube.com/watch?v=hNcMDoBmhGA



https://www.youtube.com/watch?v=pZ-zJ0Vq0FU

Past/present: what drones do



Emergency response



Urban planning



Inspection

Past/present: what drones do

However, aerial robots have been mostly used as “flying sensors", without considering any physical interaction with the environment, which would significantly extend their range of applications.



[1]



[2]

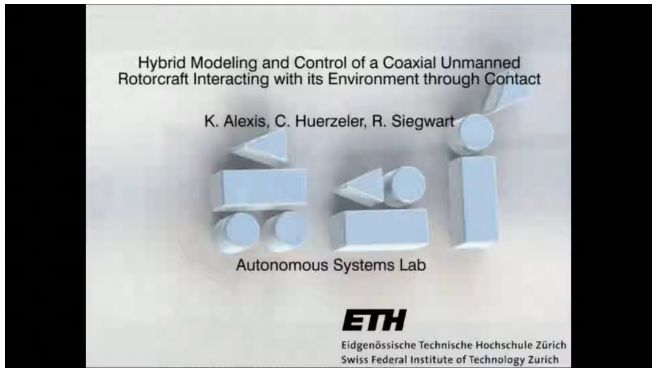
[1] G. Ciofi, L. Bauersfeld, E. Kaufmann, and D. Scaramuzza Learned Inertial Odometry for Autonomous Drone Racing IEEE Robotics and Automation Letters (RA-L), 2023.

[2] Example of teleoperated drone: https://www.youtube.com/shorts/g1USTYUV7E4

Past/present: what drones do

However, aerial robots have been mostly used as “flying sensors", without considering any physical interaction with the environment, which would significantly extend their range of applications.

Only recently, some works started to started to exploit the manipulation capabilities of drones



[1]



[2]

[1] K. Alexis, C. Huerzeler, R. Siegwart, "Hybrid Modeling and Control of a Coaxial Unmanned Rotorcraft Interacting with its Environment through Contact", IEEE International Conference on Robotics and Automation, ICRA

[2] M. Ryll, M. G. Muscio. F. Pierri, E. Cataldi, G. Antonelli, F. Caccavale, D. Bicego, and A. Franchi. 6D Interaction Control with Aerial Robots: The Flying End-Effector Paradigm. In International Journal of Robotics Research, 2019.

Aerial vehicles: Current situation

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Example of tasks that can be done with aerial manipulators

- Sliding: the goal is to keep the contact between the end-effector and a static surface, while the end-effector moves on it [1]
- Manipulation: all operations that require the application of specific forces and torques. Examples are the bending of a pipe or a bar, the opening/closing of a door [2]

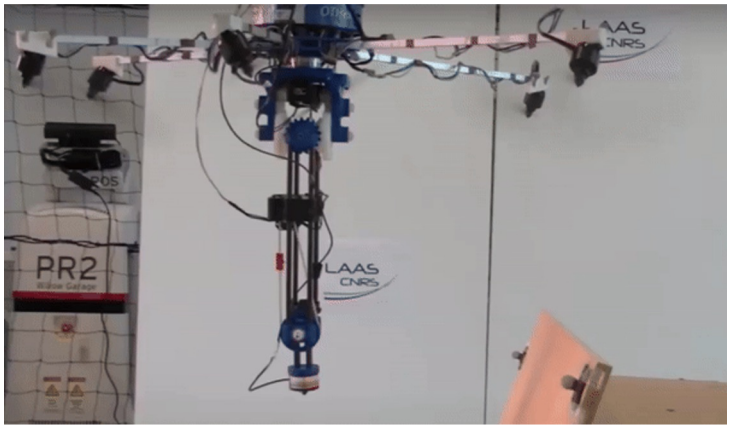


[1] Tognon, M., Chávez, H. A. T., Gasparin, E., Sablé, Q., Bicego, D., Mallet, A., … and Franchi, A. (2019). A truly-redundant aerial manipulator system with application to push-and-slide inspection in industrial plants. IEEE Robotics and Automation Letters, 4(2), pp. 1846-1851
[2] Cuniato, E., Geles, I., Zhang, W., Andersson, O., Tognon, M., & Siegwart, R. (2023). Learning to Open Doors with an Aerial Manipulator. arXiv preprint arXiv:2307.15581

Aerial vehicles: Current situation

What is the main difference between these videos?





Apart from the speed, to interact with the environment (including humans), the robot needs an arm

Why do we need an arm?

- There might be collisions of objects with the propellers
- Potential danger for humans

Research perspectives at LAAS-CNRS

Three main axes

1. Conception of innovative aerial manipulators

2. Interaction with the environment

3. Human-drone interaction

Research perspectives at LAAS-CNRS

Three main axes

1. Conception of innovative aerial manipulators

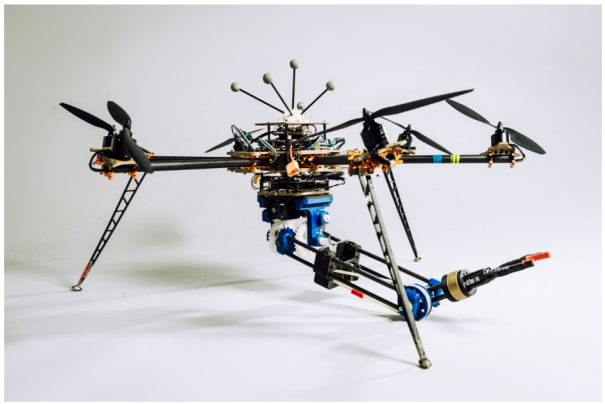
2. Interaction with the environment

3. Human-drone interaction

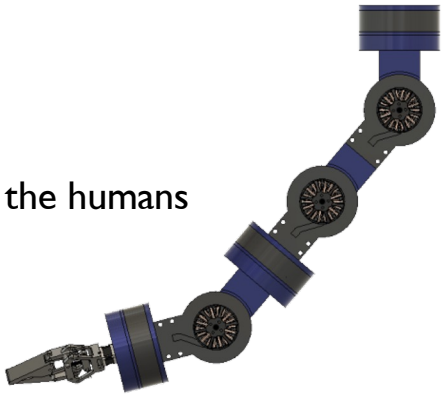
Research perspectives at LAAS-CNRS

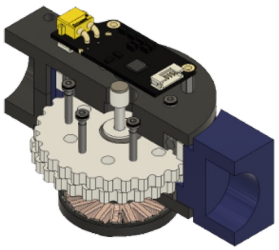
Why are we building our drones?

An aerial platform for pHRI is not available on the market











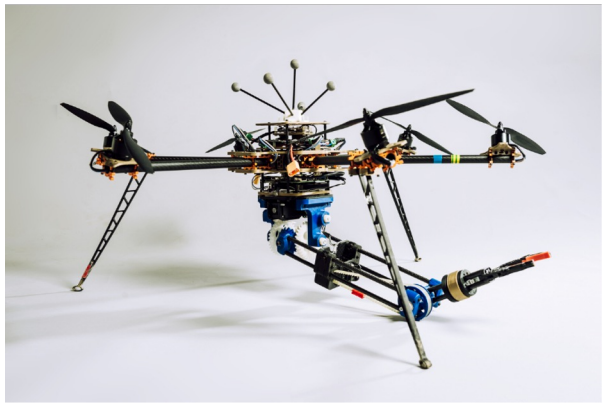
We developed our own hexarotor (TiltHex)

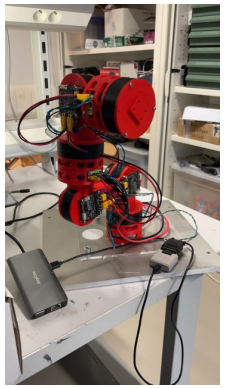
1. Design of the propeller guards for protecting the humans
2. Design of a robotic arm. Requirements
   a. Light-weighted (<2 kg)
   b. Torque-controlled

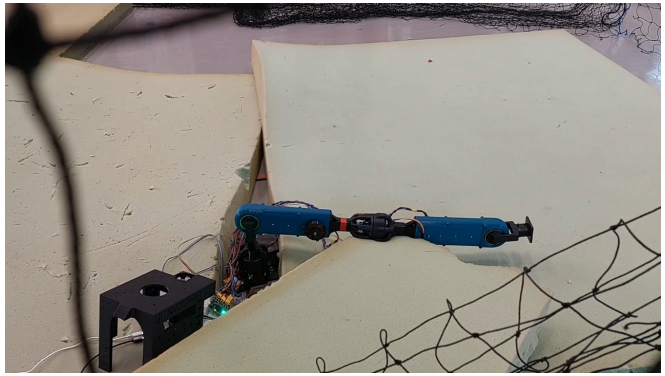
Research perspectives at LAAS-CNRS

Why torque-controlled aerial manipulators?

Interaction forces appear at the acceleration level of the robot dynamics, and any position/velocity controller would require to integrate the commands -> delays -> less reactiveness







Drone interacting with the environment

Three main axes

1. Conception of innovative aerial manipulators

2. Interaction with the environment

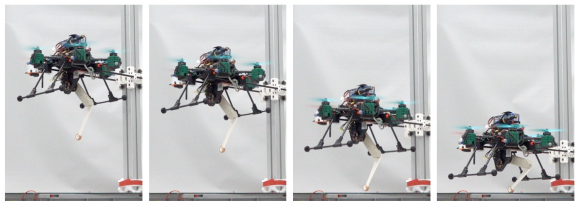
3. Human-drone interaction

Drone interacting with the environment

Interaction appears whenever the drone is exchanging forces with an external entity



[1]



[2]

Problem: How to let a drone to come into contact (switch from non-interaction to interaction phases)?

Our approach: Combine Model Predictive Control (MPC) with Linear Complementarity Problem (LCP)

Challenge: How to model the interaction forces without the need of switching models?

[1] P.J.Cruz and R.Fierro, "Cable-suspended load lifting by a quadrotor uav: hybrid model, trajectory generation, and control, "Autonomous Robots,vol.41,pp.1629–1643,2017.
[2] Martí-Saumell, J., Duarte, H., Grosch, P., Andrade-Cetto, J., Santamaria-Navarro, A., & Solà, J. (2023). Borinot: an open thrust-torque-controlled robot for research on agile aerial-contact motion. arXiv preprint arXiv:2307.14686.

Drone interacting with the environment

Discrete equations of motion of an aerial robot subject to interaction force:

$$\begin{cases} \boldsymbol{q}_{k+1} = \boldsymbol{q}_k + \dot{\boldsymbol{q}}_{k+1}\Delta t \\ \dot{\boldsymbol{q}}_{k+1} = \dot{\boldsymbol{q}}_k + \boldsymbol{M}_k^{-1}\left(\boldsymbol{\tau}_k\Delta t + \boldsymbol{B}_k\boldsymbol{u}_k\Delta t + \boldsymbol{J}_k^T f_{k+1}^{\text{int}}\Delta t\right) \end{cases}$$

where:

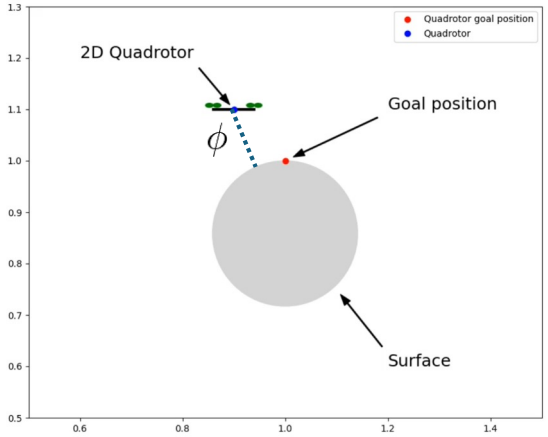
$\boldsymbol{q}_k \quad \boldsymbol{u}_k$	Generalized coordinate and control input.
$\boldsymbol{M}_k \; \boldsymbol{B}_k \; \boldsymbol{\tau}_k$	Inertia matrix, input matrix, and gravitational-Coriolis term.
$f_{k+1}^{\text{int}} \quad \boldsymbol{J}_k$	Interaction force and interaction Jacobian.

The problem is how to model the interaction forces: $\lambda_{k+1} = f_{k+1}^{\text{int}}\Delta t$

Drone interacting with the environment

We define a function $\phi(\boldsymbol{q}_{k+1}) \geq 0$ such that:

- When $\phi > 0$, we have $\lambda = 0$
- When $\phi = 0$, we have $\lambda > 0$



Complementarity relationship between ϕ and λ.

Drone interacting with the environment

Linear Complementarity Problem (LCP): [after some math…]

$$0 \leq \lambda_{k+1} \perp a_k \lambda_{k+1} + b_k \geq 0$$

$$\begin{aligned} a_k &= \boldsymbol{J}_k \boldsymbol{M}_k^{-1} \boldsymbol{J}_k^T \ \Delta t \\ b_k &= \phi(\boldsymbol{q}_k) + \boldsymbol{J}_k \boldsymbol{M}_k^{-1} \boldsymbol{c}_k \ \Delta t \\ &= \phi(\boldsymbol{q}_k) + \Delta t \ \boldsymbol{J}_k \left(\dot{\boldsymbol{q}}_k + \boldsymbol{M}_k^{-1} \boldsymbol{\tau}_k \Delta t + \boldsymbol{M}_k^{-1} \boldsymbol{B}_k \boldsymbol{u}_k \Delta t \right) \end{aligned}$$

Drone interacting with the environment

Goal: Reach a reference state $\boldsymbol{x}_g$ and minimize the control effort dealing with possible interaction forces.

$$\min_{(\boldsymbol{X},\boldsymbol{U})} \sum_{k=0}^{N-1} l(\boldsymbol{x}_k, \boldsymbol{u}_k) + l_f(\boldsymbol{x}_N)$$

$$\boldsymbol{X} = \{\boldsymbol{x}_0, \ldots, \boldsymbol{x}_N\}$$
$$\boldsymbol{U} = \{\boldsymbol{u}_0, \ldots, \boldsymbol{u}_{N-1}\}$$

$$l(\boldsymbol{x}_k, \boldsymbol{u}_k) = (\boldsymbol{x}_k - \boldsymbol{x}_g)^T \boldsymbol{Q} (\boldsymbol{x}_k - \boldsymbol{x}_g) + \boldsymbol{u}_k^T \boldsymbol{R} \boldsymbol{u}_k$$
$$l_f(\boldsymbol{x}_N) = (\boldsymbol{x}_N - \boldsymbol{x}_g)^T \boldsymbol{Q}_T (\boldsymbol{x}_N - \boldsymbol{x}_g)$$

Constraints:

$$\boldsymbol{x}(t_k) = \boldsymbol{x}_0,$$
$$\boldsymbol{x}_{k+1} = \boldsymbol{f}(\boldsymbol{x}_k, \boldsymbol{u}_k)$$

Drone interacting with the environment

$$\begin{pmatrix} \boldsymbol{q}_{k+1} \\ \dot{\boldsymbol{q}}_{k+1} \end{pmatrix} = \boldsymbol{f}(\boldsymbol{q}_k, \boldsymbol{u}_k) = \begin{pmatrix} \boldsymbol{q}_k + \dot{\boldsymbol{q}}_{k+1}\Delta t \\ \boldsymbol{M}_k^{-1}\left(\boldsymbol{c}_k + \boldsymbol{J}_k^T f_{k+1}^{\text{int}}\Delta t\right) \end{pmatrix}$$

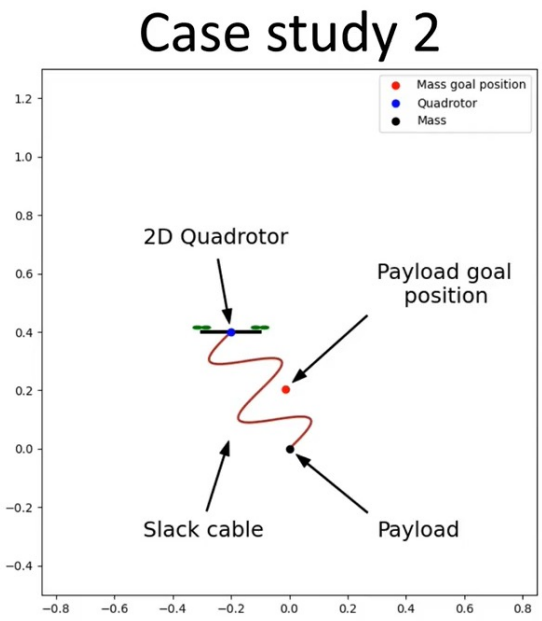
$$\boldsymbol{c}_k = \boldsymbol{M}_k\dot{\boldsymbol{q}}_k + \boldsymbol{\tau}_k\Delta t + \boldsymbol{B}_k\boldsymbol{u}_k\Delta t$$

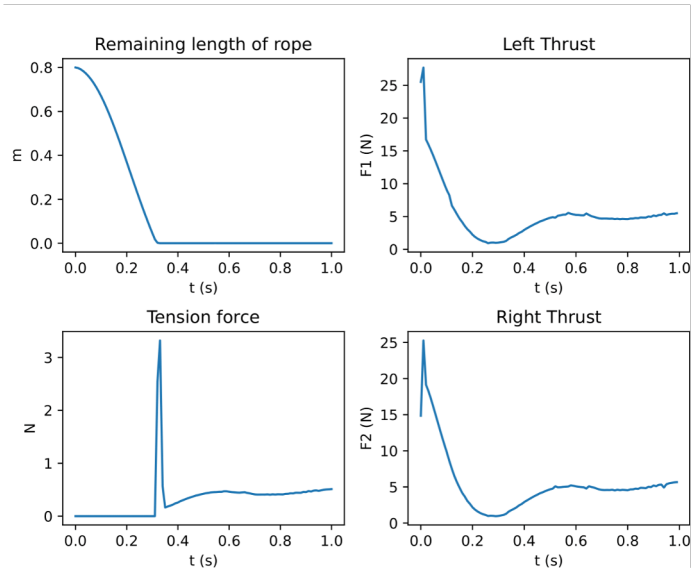
MPC depends on the interaction force f^{int} .

We integrate the LCP inside the MPC obtaining 2 nested optimization problems:

- Inner one (LCP), that computes interaction force f^{int}.
- Outer one (MPC), that computes optimal control using the interaction force.

Drone interacting with the environment





Research perspectives at LAAS-CNRS

Three main axes

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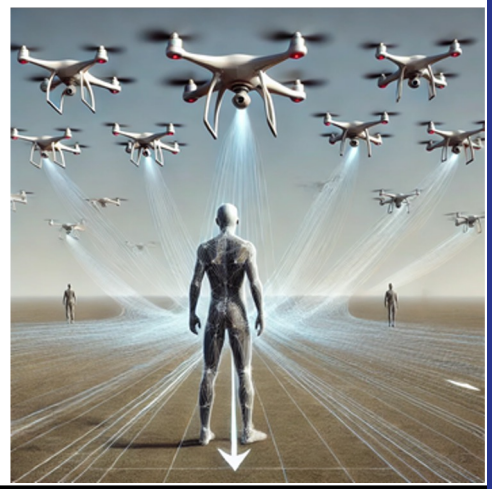
Why thinking about human-drone interaction

Why thinking about physically-interacting drones?

- A drone can reach remote places much faster than other mobile robots, especially on rough terrains
- A drone can reach high altitudes

The human-drone interaction paradigm is different w.r.t. the human-robot paradigm

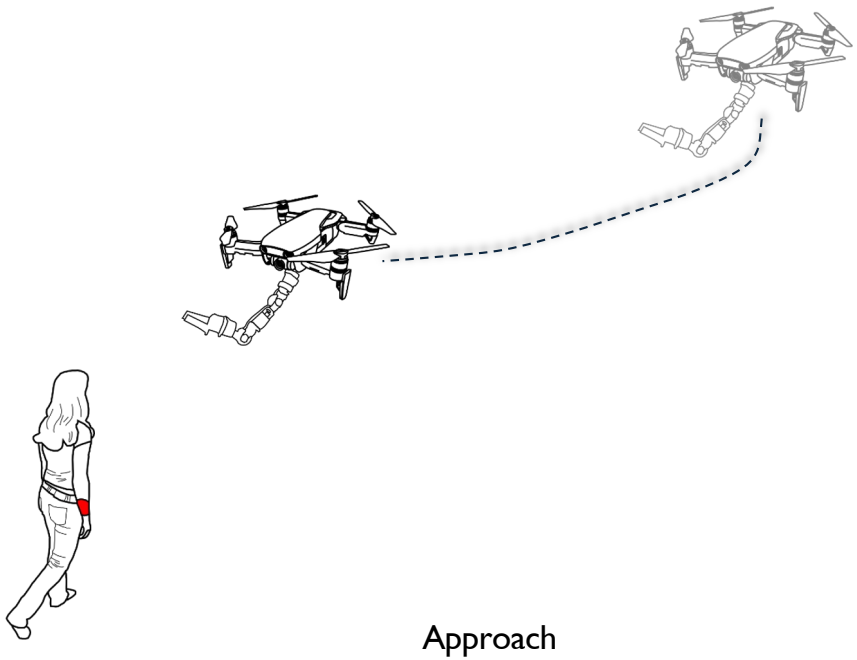
- The robot can approach the human from any direction in 3D
- The robot can reach high speeds
- The robot's propellers produce noise that can scare the human
- The robot can easily lose stability for unknown external forces



Human-drone interaction

Human-drone interaction in three possible ways

- Approach: The robot is far from the human, and it should approach him/her. No contacts

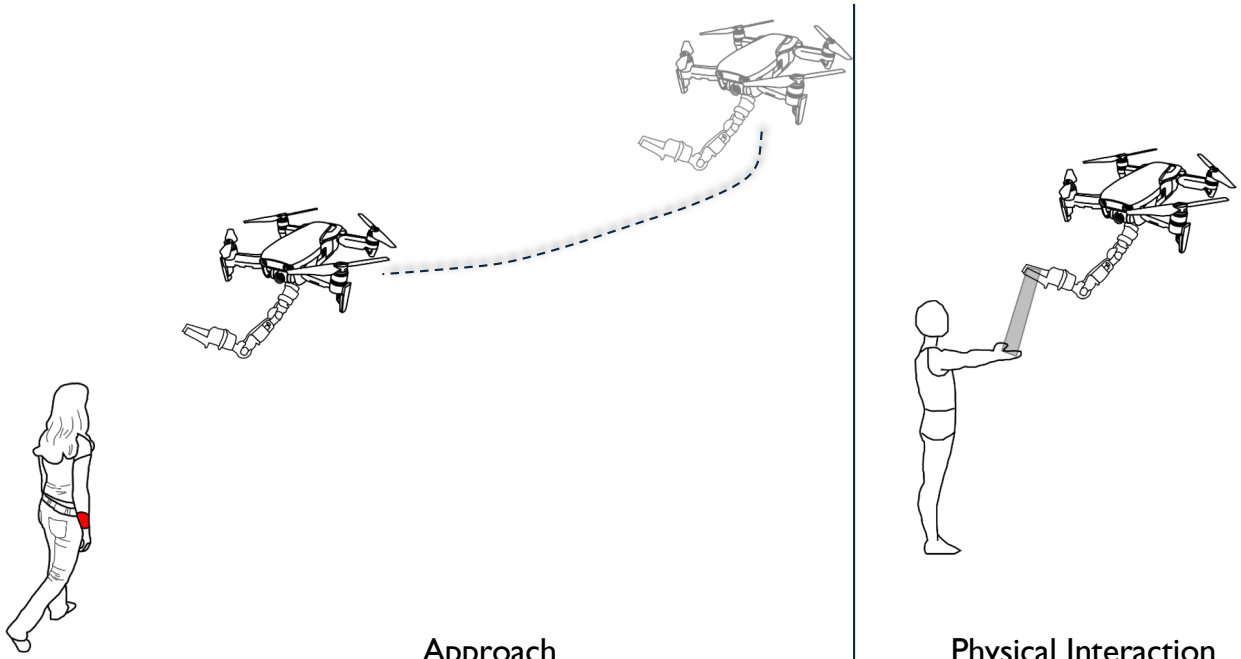


Approach

Human-drone interaction

Human-drone interaction in three possible ways

- Approach: The robot is far from the human, and it should approach him/her. No contacts
- Physical Interaction: The human and the robot physically interact



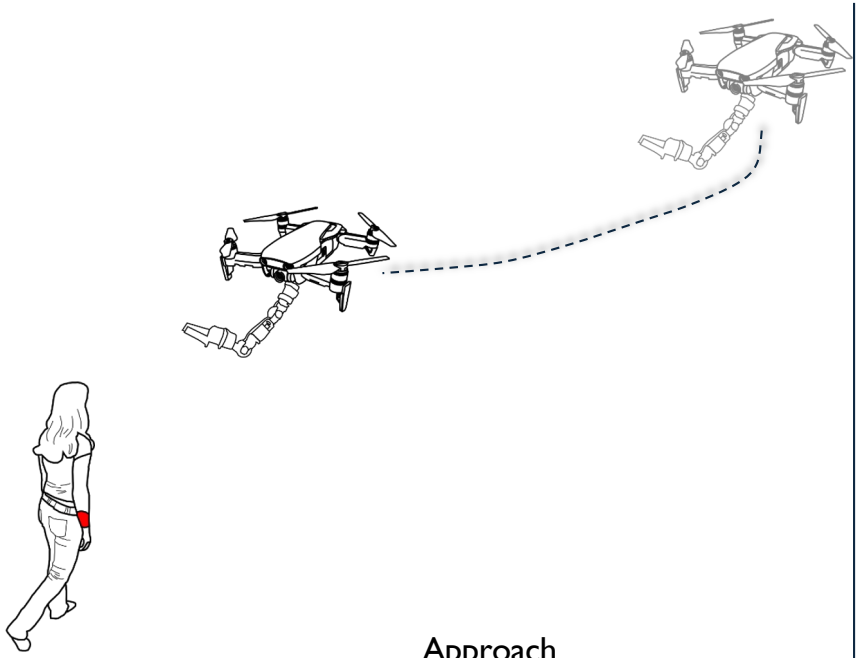
Approach

Physical Interaction

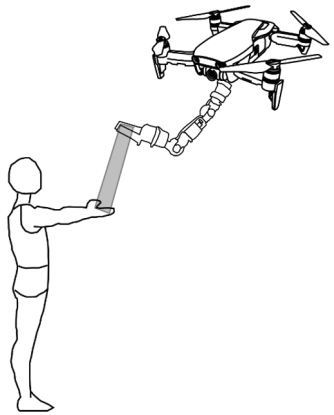
Human-drone interaction

Human-drone interaction in three possible ways

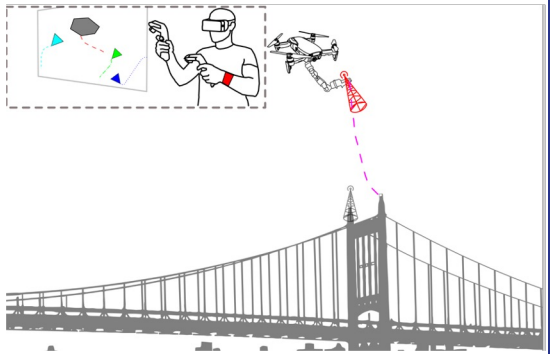
- Approach: The robot is far from the human, and it should approach him/her. No contacts
- Physical Interaction: The human and the robot physically interact
- Remote interaction: The human is remotely located



Approach



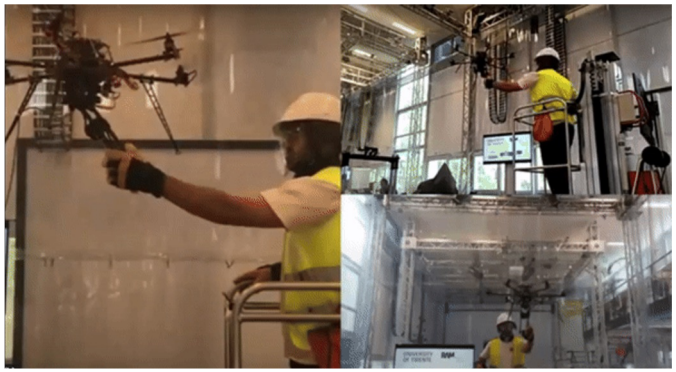
Physical Interaction



Remote interaction

Human-drone interaction

At the moment, we are focusing on physical human-drone interaction



Main research questions

- How can we estimate the intentions of the human? [Human-to-robot]
- Which feedback information should be provided from the drone to the human? [Robot-to-Human]
- How can we control the robot for ensuring its stability/safety for both the human and the robot?

Human-drone interaction

Two main research axes

1. Prediction of human-related features for physical human-robot interaction

2. Control for physical human-robot interaction

Human-drone interaction

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1. Prediction of human-related features for physical human-robot interaction

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Human-drone interaction: Human intentions

Goal: estimate the human intentions (e.g., interaction forces) during a human-drone interaction

Motivations:

1. Any unmodelled action (e.g., from the human) on the drone can bring the robot into instability
2. If the robot knew in advance the human actions, it could perform preemptive actions
3. Some controllers (e.g., MPC) need a prediction of some human information within a time horizon
4. In human-human collaborations, we have expectations of the other person actions

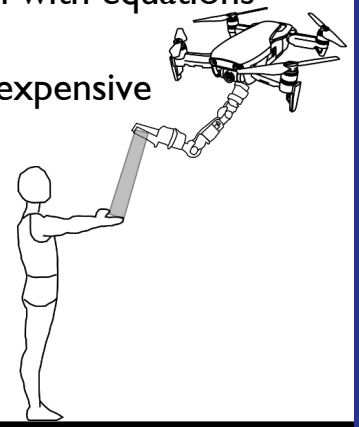
Current approach: supervised learning – transformers

Why learning: There are human factors (e.g., fatigue / level of expertise) hard to model with equations

Problem: doing experiments (for getting the training set) with an aerial manipulator is expensive

- Potential stability issue
- Dataset very "noisy"

Idea: use a manipulator for generating the "training set" and then transfer to an aerial manipulator (work-in-progress)

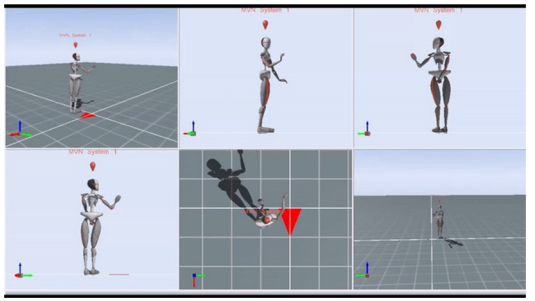


Human-drone interaction: Human intentions

Assumptions:

- The human wears a haptic suit, that provides kinematic data about the human
- The robot implements an impedance controller, reducing it to a known mass-spring-damper system





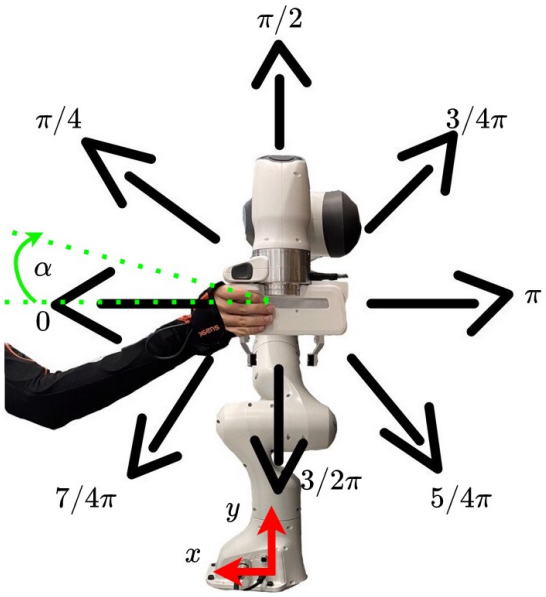
A. Fusco, V. Modugno, D. Kanoulas, A. Rizzo and M. Cognetti, "Transformer-Based Prediction of Human Motions and Contact Forces for Physical Human-Robot Interaction," 2024 IEEE International Conference on Robotics and Automation (ICRA), Yokohama, Japan, 2024, pp. 3161-3167, doi: 10.1109/ICRA57147.2024.10611211

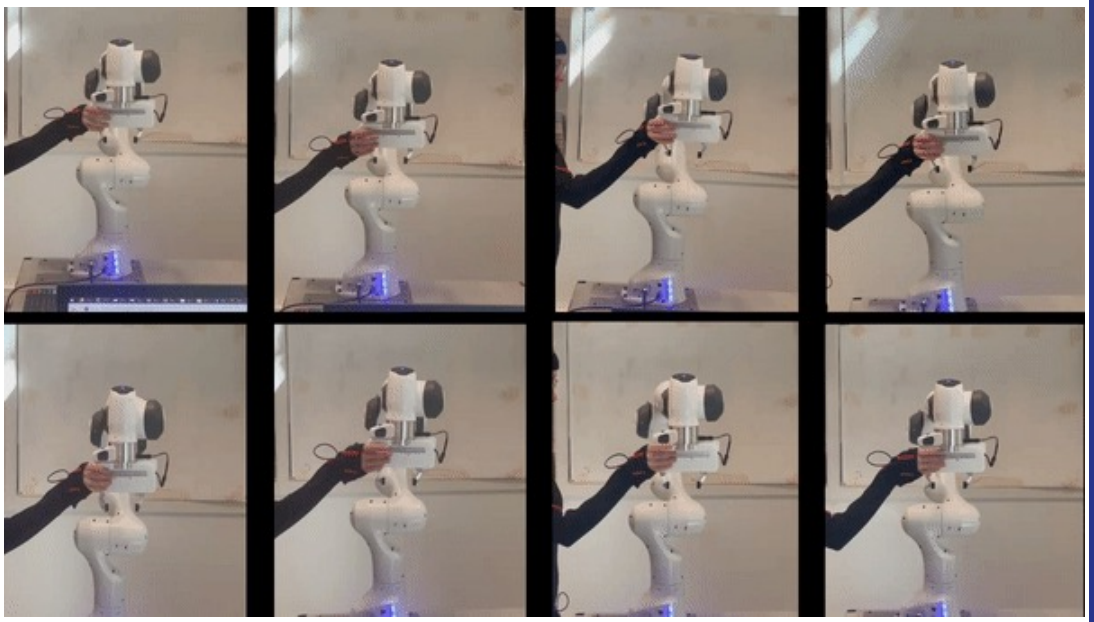
Human-drone interaction: Human intentions

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Training set

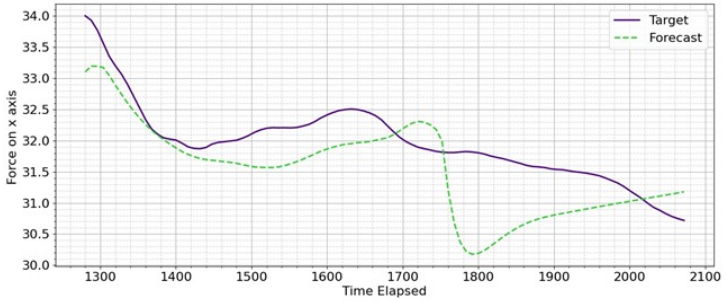
Different training motions were collected. In each of them, the robot starts from its resting configuration, and the human moves it along one of 8 equally spaced planar directions

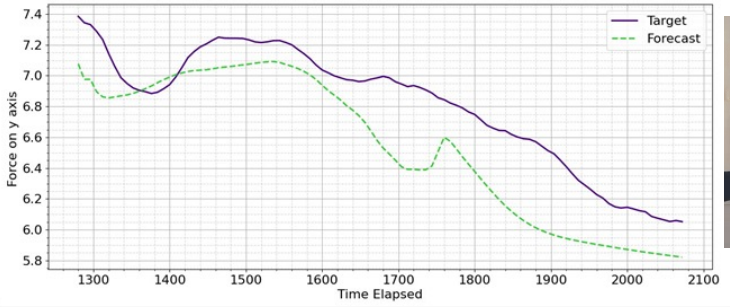


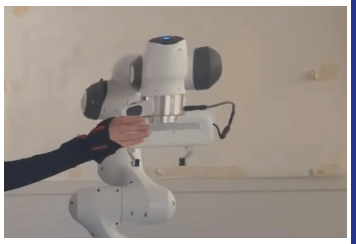


Human-drone interaction: Human intentions

The network was tested on motions that were not included in the training data set.
In these plots we can see the measured force values in purple, the forces predicted by our model in green







Prediction errors (mean)

Architecture	**Joint angles** [deg]	**Cartesian velocities** [m/s]	**Cartesian accelerations** [m/s^2]	**Force on x axis** [N]	**Force on y axis** [N]	**Force on z axis** [N]
Our model	**8.22**	0.031	0.181	**0.477**	**0.720**	**1.276**
Pure Transformer model	9.21	0.029	0.179	3.309	9.799	6.325

Human-drone interaction

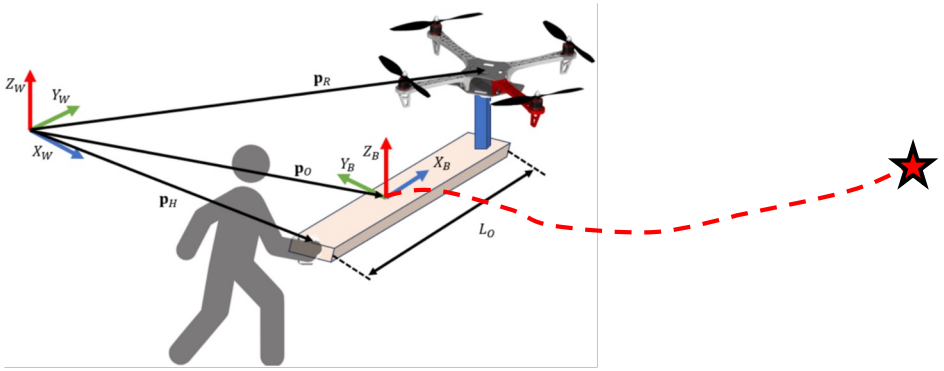
Two main research axes

1. Prediction of human-related features for physical human-robot interaction

2. Control for physical human-robot interaction

Control for physical human-robot interaction

Collaborative transportation tasks



Control for physical human-robot interaction

Optimal control problem: cost function

Two main objectives

1. Track a reference object trajectory. A reference trajectory for the object is supposed to be given.

2. Minimize the control effort

$$\sum_{k=0}^{N}\left(\left|\left|\boldsymbol{p}_{Ok}-\boldsymbol{p}_{O}^{ref}\right|\right|_{\boldsymbol{W}_{p_0}}^{2}+\left|\left|\boldsymbol{\eta}_{Ok}-\boldsymbol{\eta}_{O}^{ref}\right|\right|_{\boldsymbol{W}_{\eta_0}}^{2}+\left|\left|\boldsymbol{v}_{Ok}-\boldsymbol{v}_{O}^{ref}\right|\right|_{\boldsymbol{W}_{v_0}}^{2}+\left|\left|\boldsymbol{\omega}_{Ok}-\boldsymbol{\omega}_{O}^{ref}\right|\right|_{\boldsymbol{W}_{\omega_0}}^{2}\right)+\sum_{k=0}^{N-1}\left|\left|\boldsymbol{u}_{k}\right|\right|_{\boldsymbol{W}_{u}}^{2}$$

Where the control variables are the torques of the robot ($\boldsymbol{u}_R$) and the ones of the human ($\boldsymbol{u}_H$). Thus,

$$u=[\boldsymbol{u}_A^T,\boldsymbol{u}_H^T]^T$$

And we imposed several constraints…

Control for physical human-robot interaction



Optimal control problem: equality constraints

$$\dot{\boldsymbol{p}}_O = \boldsymbol{v}_O$$
$$\dot{\boldsymbol{\eta}}_O = \boldsymbol{T}_O \boldsymbol{\omega}_O$$
$$m_O \dot{\boldsymbol{v}}_O = {}^W\boldsymbol{R}_O \boldsymbol{f}_H^{int} + {}^W\boldsymbol{R}_O \boldsymbol{f}_R^{int} - m_O g \boldsymbol{z}_O$$
$$\boldsymbol{J}_O \dot{\boldsymbol{\omega}}_O = \frac{L_O}{2} \boldsymbol{x}_O \times \boldsymbol{f}_R^{int} - \frac{L_O}{2} \boldsymbol{x}_O \times \boldsymbol{f}_H^{int} - \boldsymbol{\omega}_O \times \boldsymbol{J}_O \boldsymbol{\omega}_O$$
$$\dot{\boldsymbol{p}}_R = \boldsymbol{v}_R$$
$$\dot{\boldsymbol{v}}_R = \boldsymbol{M}_A^{-1}(-\boldsymbol{B}_A \boldsymbol{v}_R - {}^W\boldsymbol{R}_R \boldsymbol{f}_R^{int} + \boldsymbol{u}_A)$$
$$\dot{\boldsymbol{p}}_H = \boldsymbol{v}_H$$
$$m_H \dot{\boldsymbol{v}}_H = {}^W\boldsymbol{R}_H \boldsymbol{u}_H - m_H g \boldsymbol{z}_H - {}^W\boldsymbol{R}_H f_H^{int}$$
$$z_H = z_H^0$$

$$\boldsymbol{p}_R = \boldsymbol{p}_O + {}^W\boldsymbol{R}_B \frac{L_O}{2} \boldsymbol{x}_B$$
$$\boldsymbol{p}_H = \boldsymbol{p}_O - {}^W\boldsymbol{R}_B \frac{L_O}{2} \boldsymbol{x}_B$$

On the left, the physical constraints of the models of the object, the robot, and the human.
On the right, they are additional constraints for ensuring that the human and the object are rigidly attached, as well as the robot and the object.

Control for physical human-robot interaction

Optimal control problem: inequality constraints

- The human and the robot have some bound constraints on their inputs

$$\boldsymbol{u}_{H,min} \leq \boldsymbol{u}_H \leq \boldsymbol{u}_{H,max}$$
$$\boldsymbol{u}_{A,min} \leq \boldsymbol{u}_A \leq \boldsymbol{u}_{A,max}$$

where $\boldsymbol{u}_{A,min}, \boldsymbol{u}_{A,max}, \boldsymbol{u}_{H,min}, \boldsymbol{u}_{H,max}$ are the minimum/maximum torques for the robot and the human

- Human velocities. Limit the forward/lateral velocity of the human

$$\boldsymbol{v}_{H,min} \leq {}^{W}\boldsymbol{R}_B^T \boldsymbol{v}_H \leq \boldsymbol{v}_{H,max}$$

In particular, the higher the human forward velocity, the tighter the constraint on the lateral human velocity

Control for physical human-robot interaction

<u>Optimal control problem: experimental results</u>

- Admittance filter implemented on the robot (for reducing it to a point mass from a control point of view). Parameters: K = 0.1 and B = 2.4.
- MPC solver: Acados with HPIPM.
- MPC parameters: time horizon is 1s, N = 5, integration step is 1ms, control frequency is 100Hz.
- Drone mass: 2.6Kg.



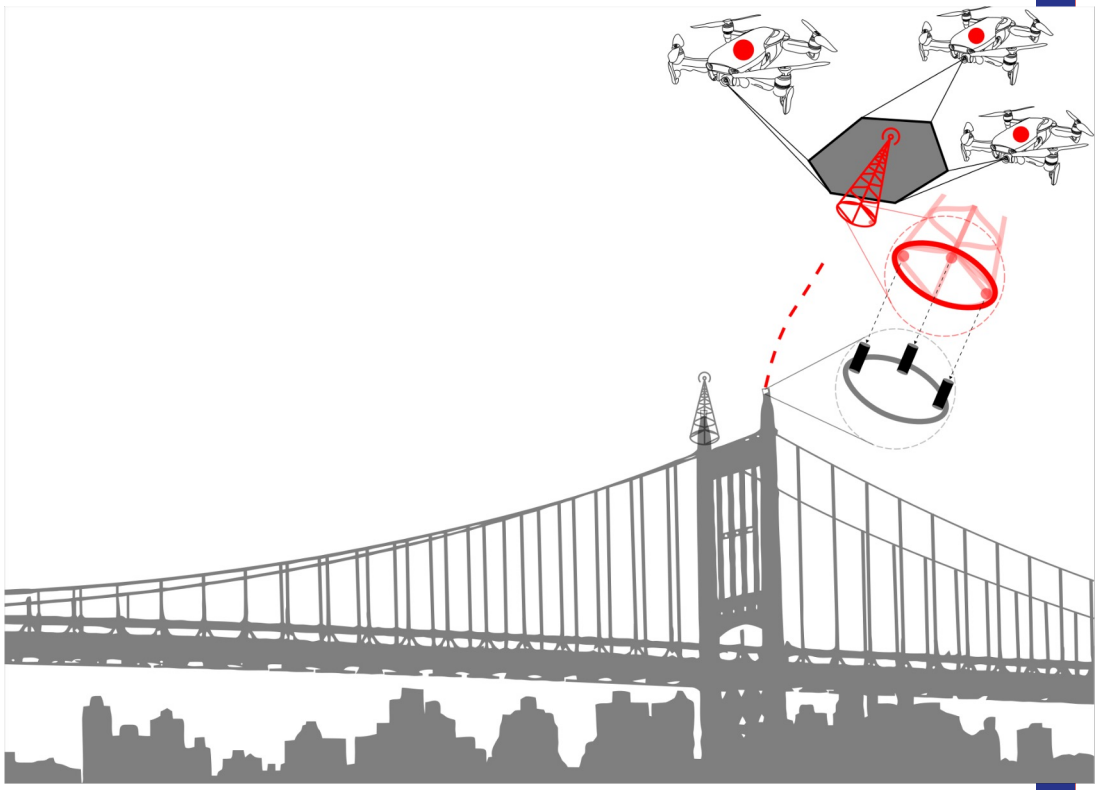
What's next: MATES

Main idea

- Collaborative transportation of objects
- Suitable for applications that are potentially dangerous for humans and require physical interaction with the environment on uneven grounds or high structures

Three subteams

- main drone team (object collaborative transport)



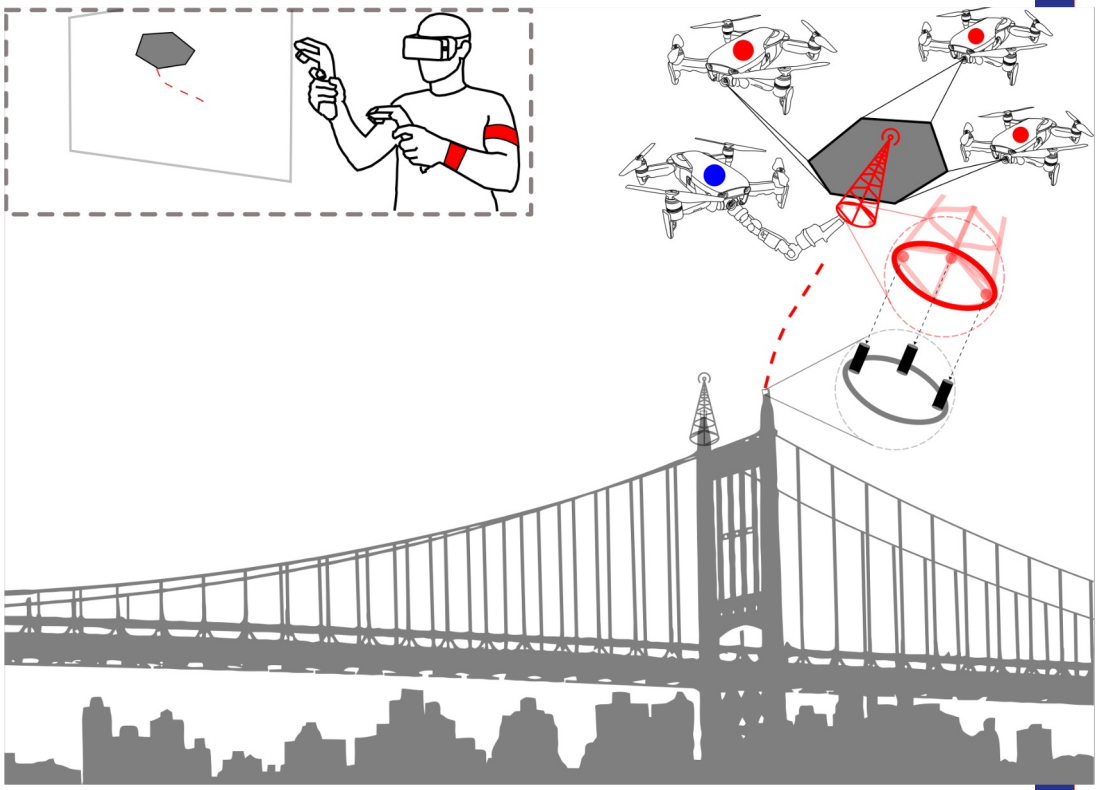
What's next: MATES

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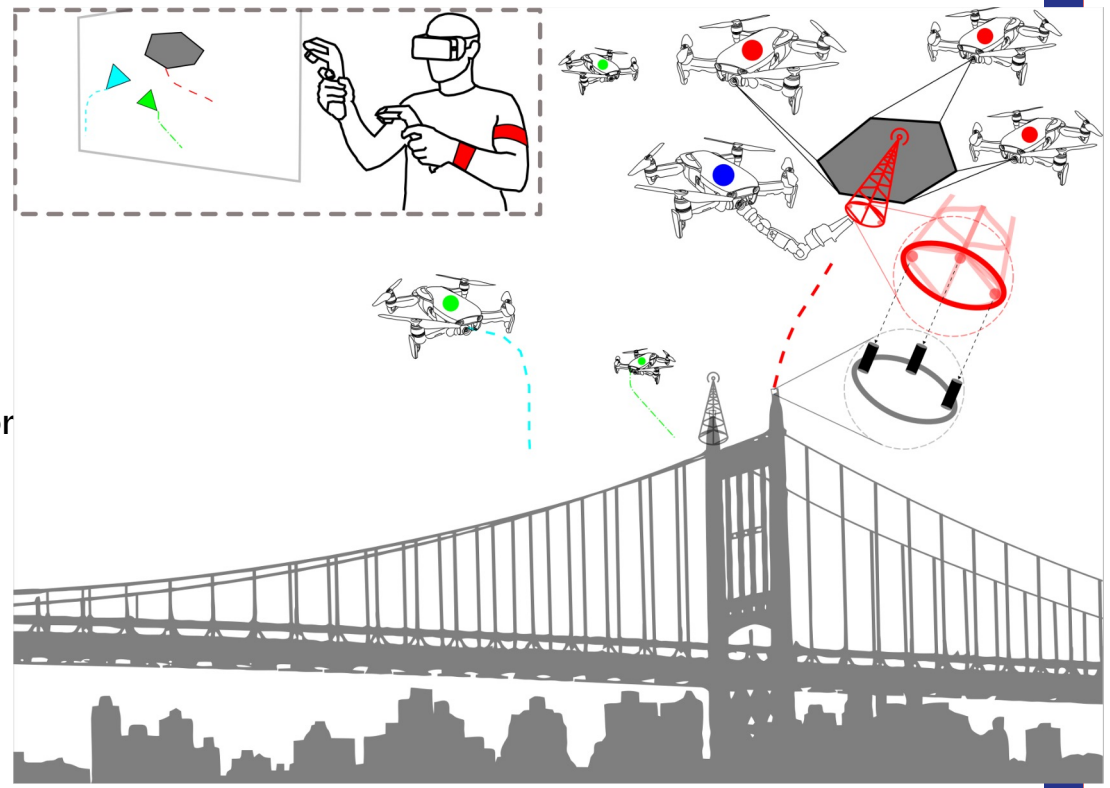
- main drone team (object collaborative transport)
- aerial manipulator (teleoperated by human)



What's next: MATES

Main challenges

- How to ensure stability of the robotic system
- How to let a drone to fulfill manipulation tasks
- How to let a single human operator to control a multi-robot system (e.g., which is the human input)
- How to provide feedback to a human operator
- How to decide the autonomy of the team



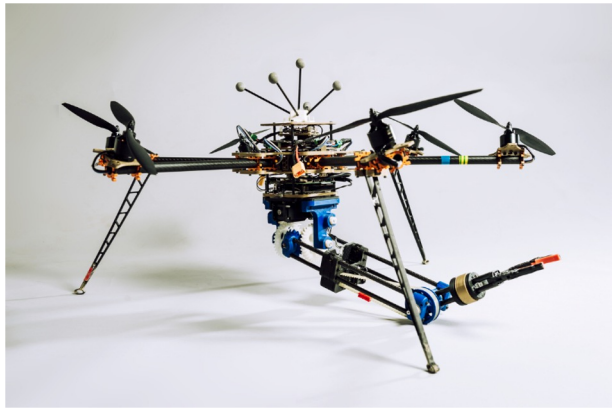
Conclusions: Open challenges

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Open challenges for aerial manipulators interacting with the humans

1. Design of innovative aerial manipulator (no one available in the market)
2. What the robot should control autonomously (e.g., stability during manipulation (a.k.a. control) / safety in the interactions with persons/objects) and what should be controlled with/by the human
3. Human factors: Understand which human factors are important for human-drone interaction
4. How to interact with humans: how to engage, how to interact, which feedback to provide (limited channels for the human)
5. Reliable decisional autonomy: Adaptation of the robot autonomy based on human factors (e.g., fatigue, level of expertise)
6. Understand how a single operator can control a multi-robot aerial team, and which feedback should be given to the human

Approach: fuse planning, perception, machine-learning, and control



Thank you!

