What if my Hand had Flying Fingers?

Antonio Franchi

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

Workshop on Human Multi-Robot System Interaction
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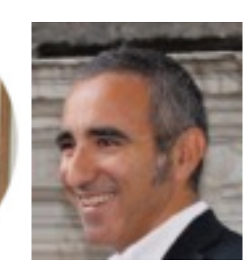
Collaborative work with:

Mostafa Mohammadi & Domenico Prattichizzo

University of Siena and Italian Institute of Technology

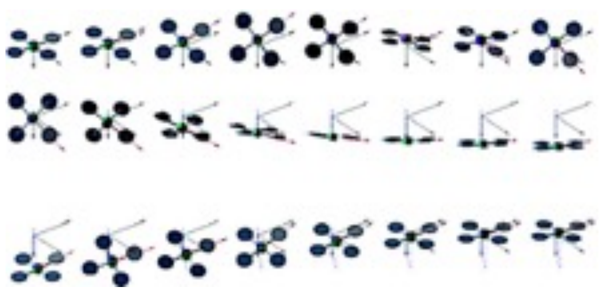
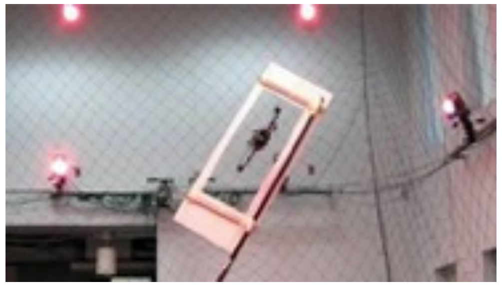


Slides by Domenico Prattichizzo and Antonio Franchi

Service Aerial Robots with Physical Interaction Abilities

LAAS CNRS

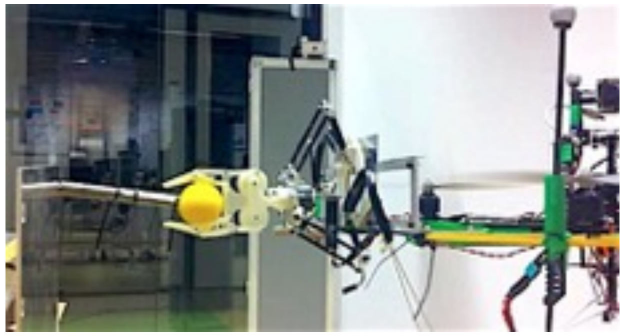
- Main focus in the past: **contact-free aerial robotics**
  - flight control, planning of maneuvers, sensing/perception, design,…


Credits: UPenn, SenseFly

- New trend: focus on **aerial physical interaction**
  - inspection, maintenance, transportation, manipulation…



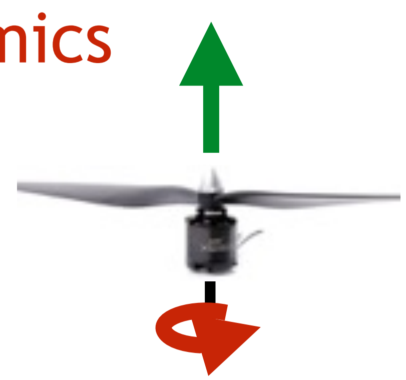



Credits: AIROBOTS and ARCAS EU Projects (CATEC, DLR, UniBologna, USE)

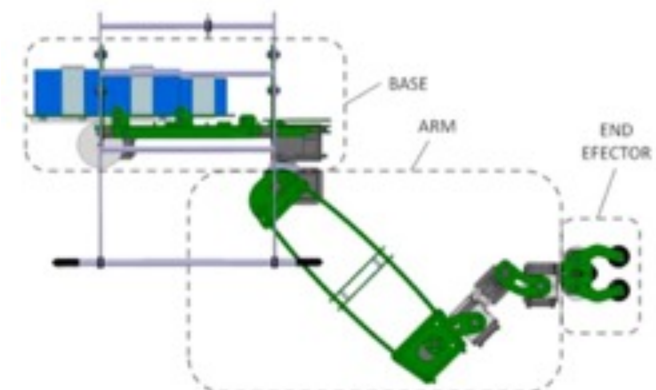
Challenges of Physically Interactive Aerial Robotics

- **Floating** base
  - need for active reaction wrench
  - inaccurate positioning
  - dynamic coupling

- **Actuators** of the base
  - additional aerodynamic layer
    - motor torque ~ propeller acceleration
    - propeller speed ~ thrust force
  - unmodeled aerodynamics



- Need for a **lightweight payload**
  - arms with cheap motors
  - flexibility ⇒ vibrations control challenge



- Need to **save energy**
  - underactuated configurations (i.e., collinear propellers)

image credits: ARCAS (USE,CATEC)

EU H2020 Projects at LAAS-CNRS

- **ARCAS** (2011–2015)
  - aerial robots for **cooperative assembly**

- **AEROARMS** (2015–2019)
  - aerial robots for **plant inspection and maintenance**

Aerial manipulation

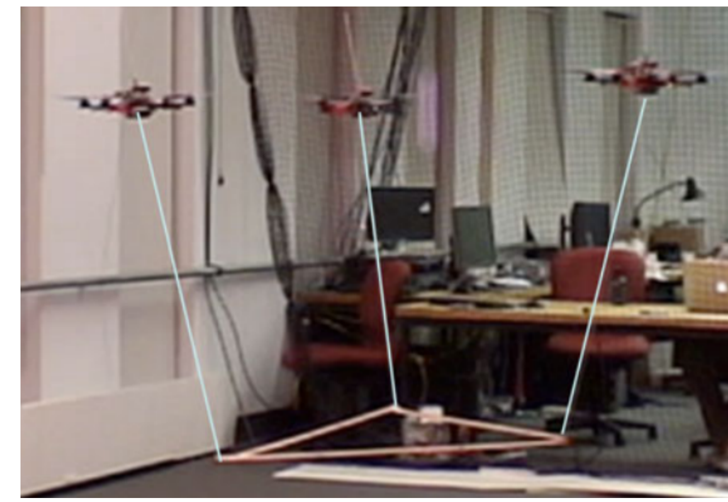
Small scale UAV helicopters with added payload mass under PID control

P. E. Pounds, D. R. Bersak, and A.M. Dollar (Autonomous Robots 2012)

Autonomous helicopter and a 7 degrees of freedom industrial manipulator

K. Kondak, F. Huber, M. Schwarzbach, M. Laiacker, D. Sommer, M. Bejar, and A. Ollero (ICRA 2012)

Cooperative transport with multiple aerial robots



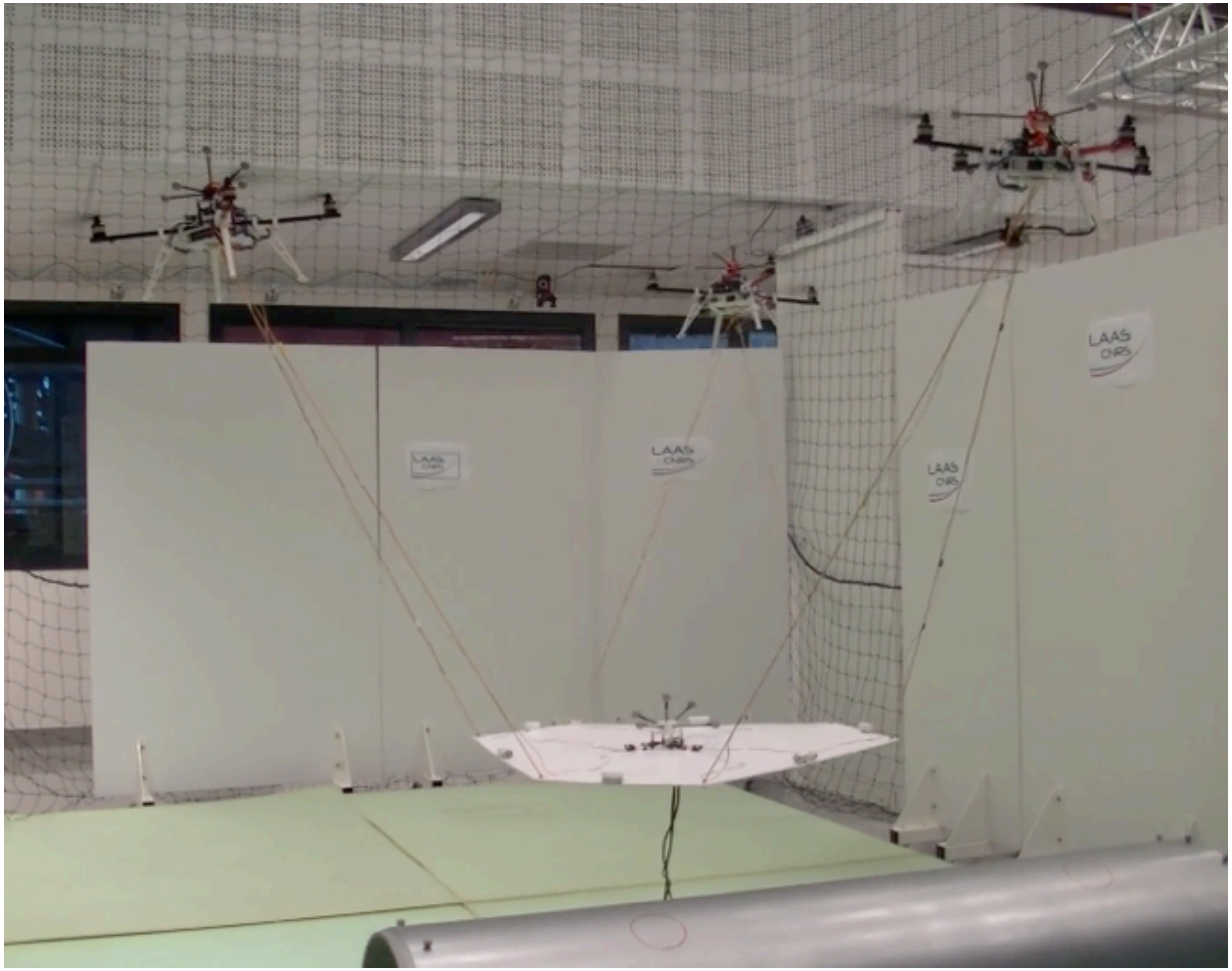
Q. Jiang and V. Kumar (TRO 2013)

Issues:

- **Flexible cables**. More difficult to control during grasping then Unilateral contacts.
- Bilateral contact constraint is **difficult to release**. Unilateral is better

The FlyCrane

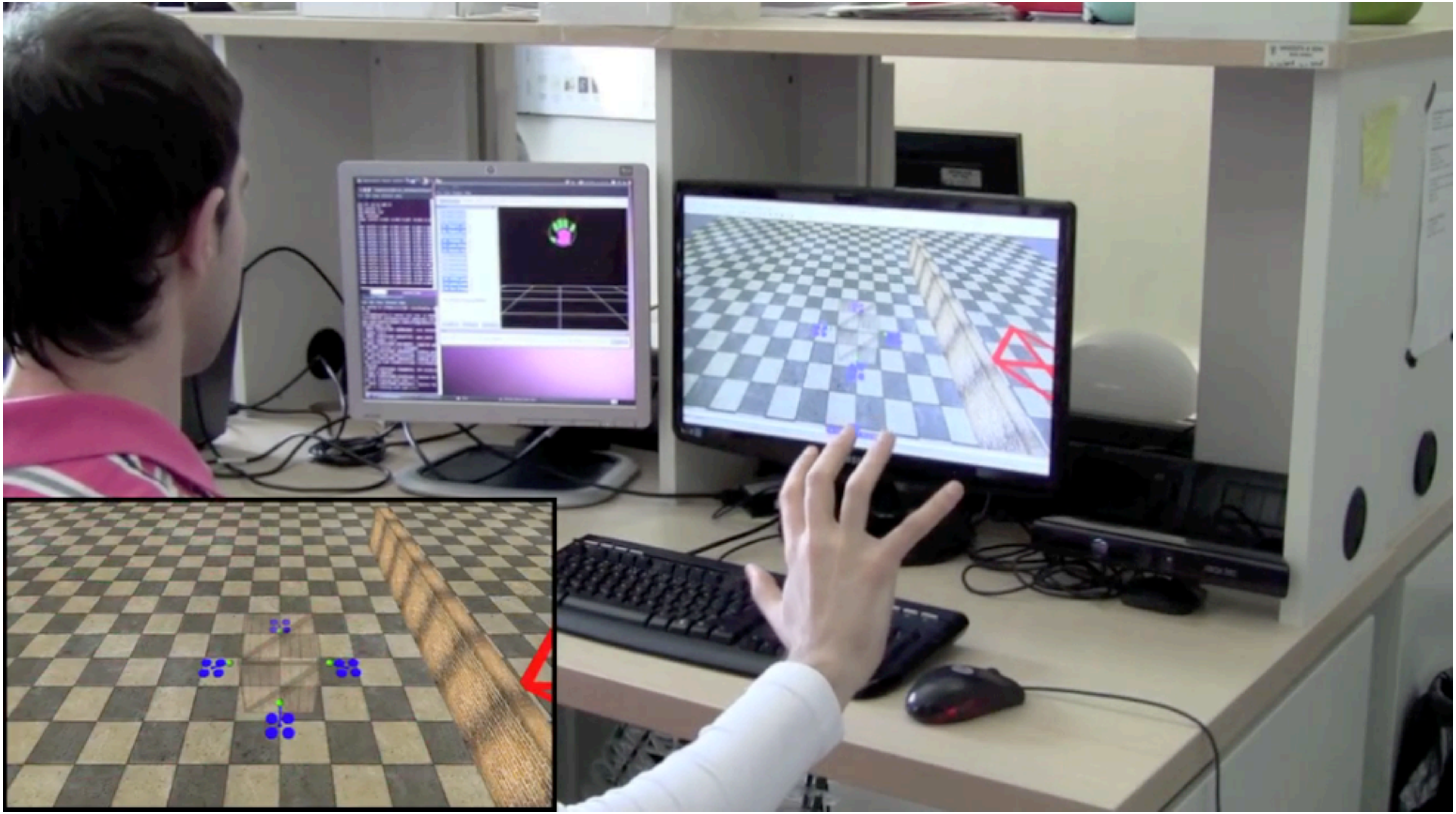
- 6D Manipulation
  - easy to control (position-based)
- but:
  - bilateral constraints
  - difficult to attach—detach



FlyCrane:
Ongoing work at LAAS-CNRS together with Marco Tognon and Juan Cortés

Planning problem studied in :
M. Manubens, D. Devaurs, L. Ros, J. Cortés,
Motion Planning for 6-D Manipulation with Aerial Towed-cable Systems, RSS 2013

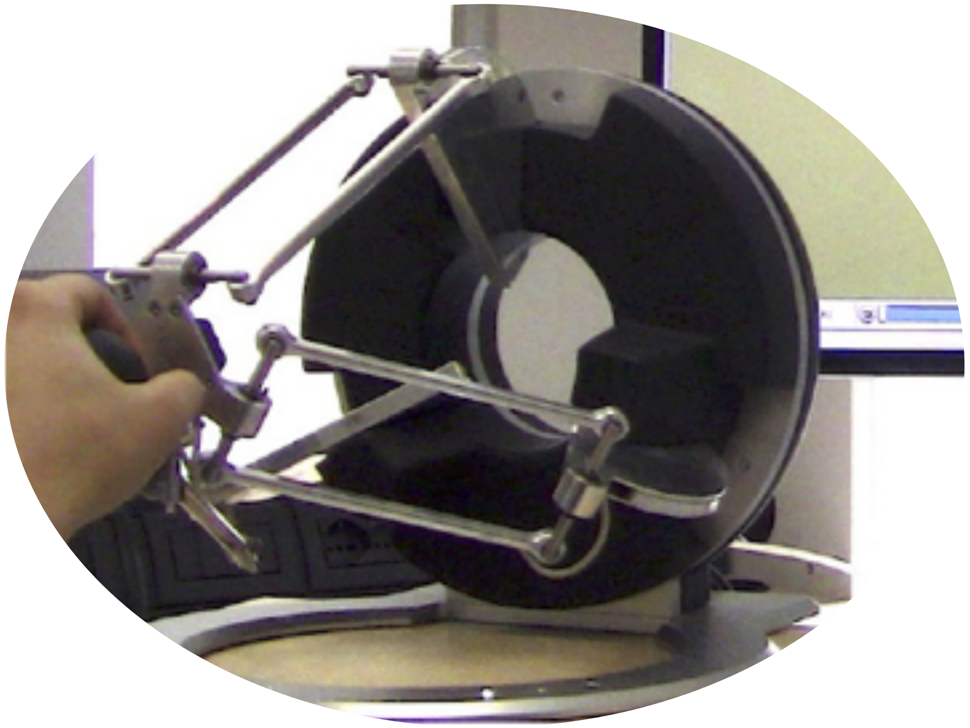
The flying hand

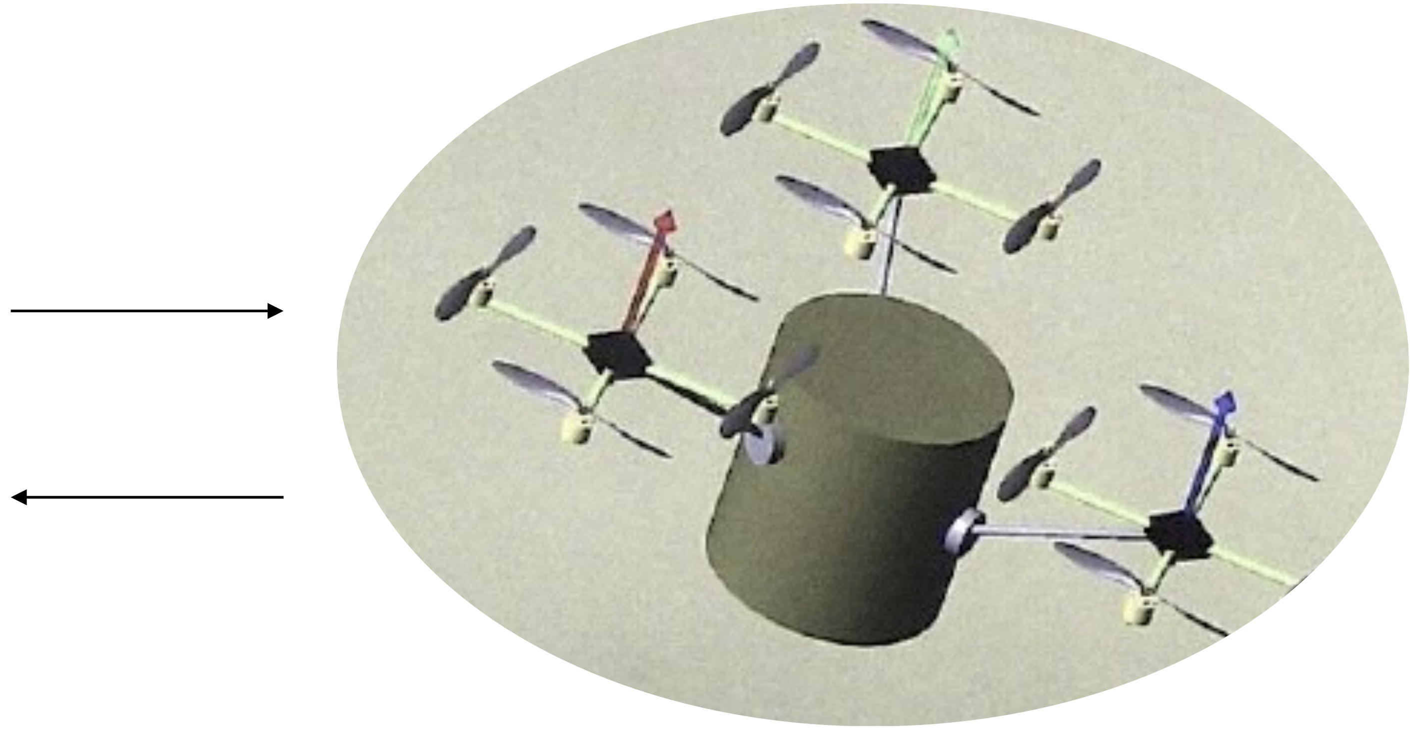


Gioioso G, Franchi A, Salvietti G, Scheggi S, Prattichizzo D. The Flying Hand: a Formation of UAVs for Cooperative Aerial Tele-Manipulation. In 2014 IEEE Int. Conf. on Robotics and Automation. Hong Kong, China; 2014. pp. 4335-4341.

Focus of the talk

Flying finger



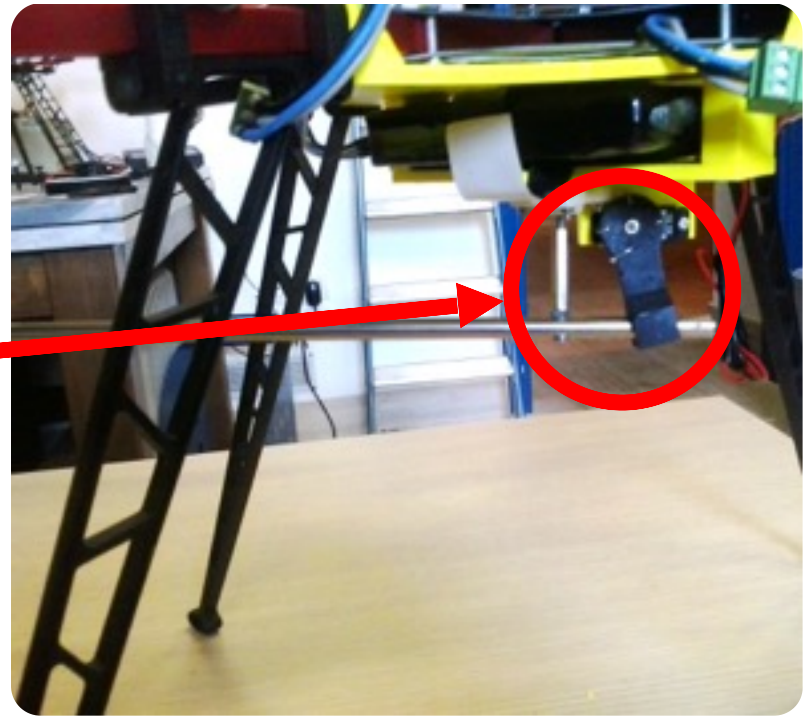


Flying hand/grasp

Contact mechanism

Unilateral contact augmented with magnetic adhesive forces

Rigid link and spherical joint



- Lightweight bar

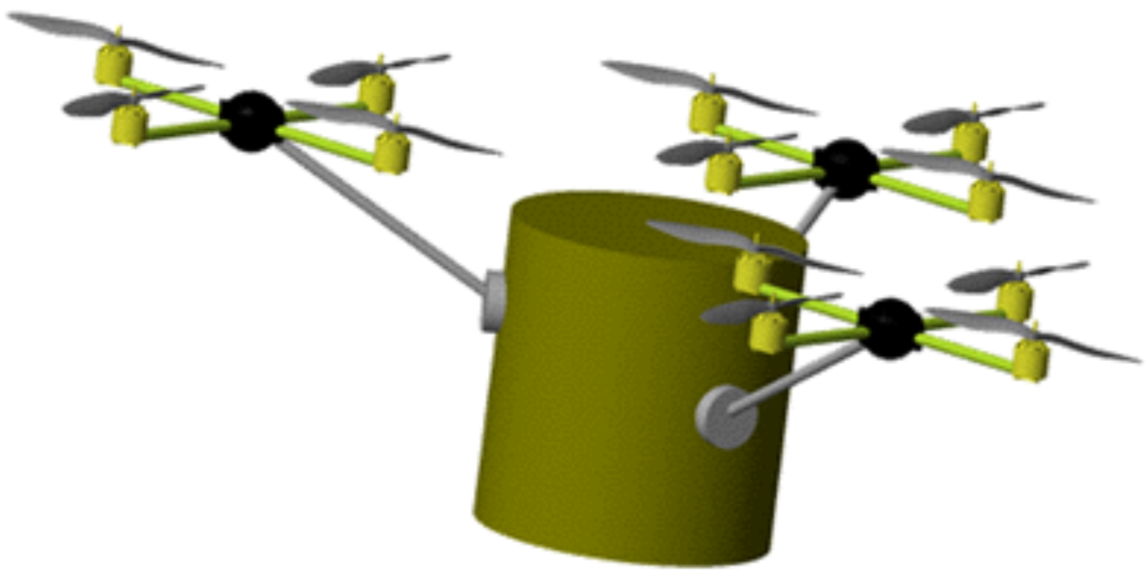
Simple release mechanism:

- Free flight: **no DoFs**
- Contact flight: **3 DoFs**
  - Micro-switch and servo-motor set free the spherical joint
  - Rotational freedom thanks to the spherical joint

Spherical joint inspired by Hai-Nguyen Nguyen, Sangyul Park and Dongjun Lee (IROS 2015)

Constraints on the VTOL force vector

1. Ultimate goal:
   control the motion of the grasped **object**
2. The flying hand controls the object through **contact forces**
3. Forces must satisfy **contact constraints**

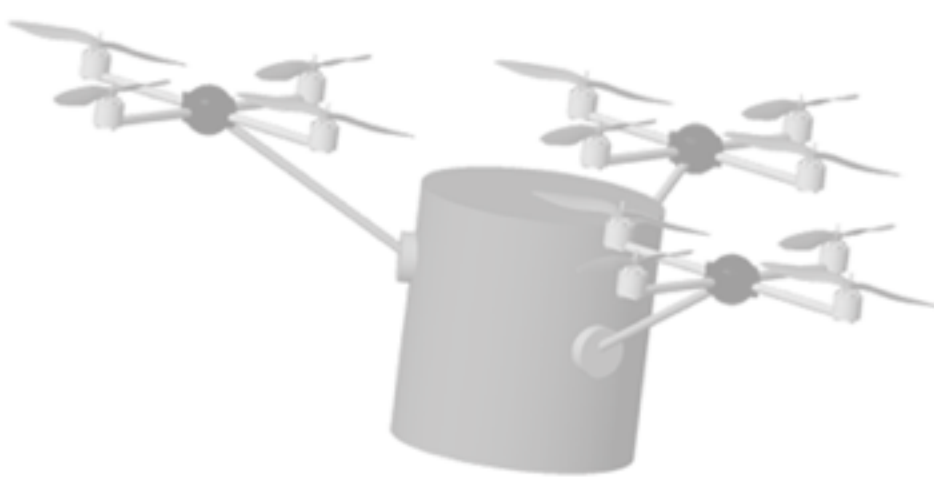


D. Prattichizzo, and J. Trinkle “Grasping.’' Springer Handbook of Robotics. Siciliano and Kathib Eds. 2016.

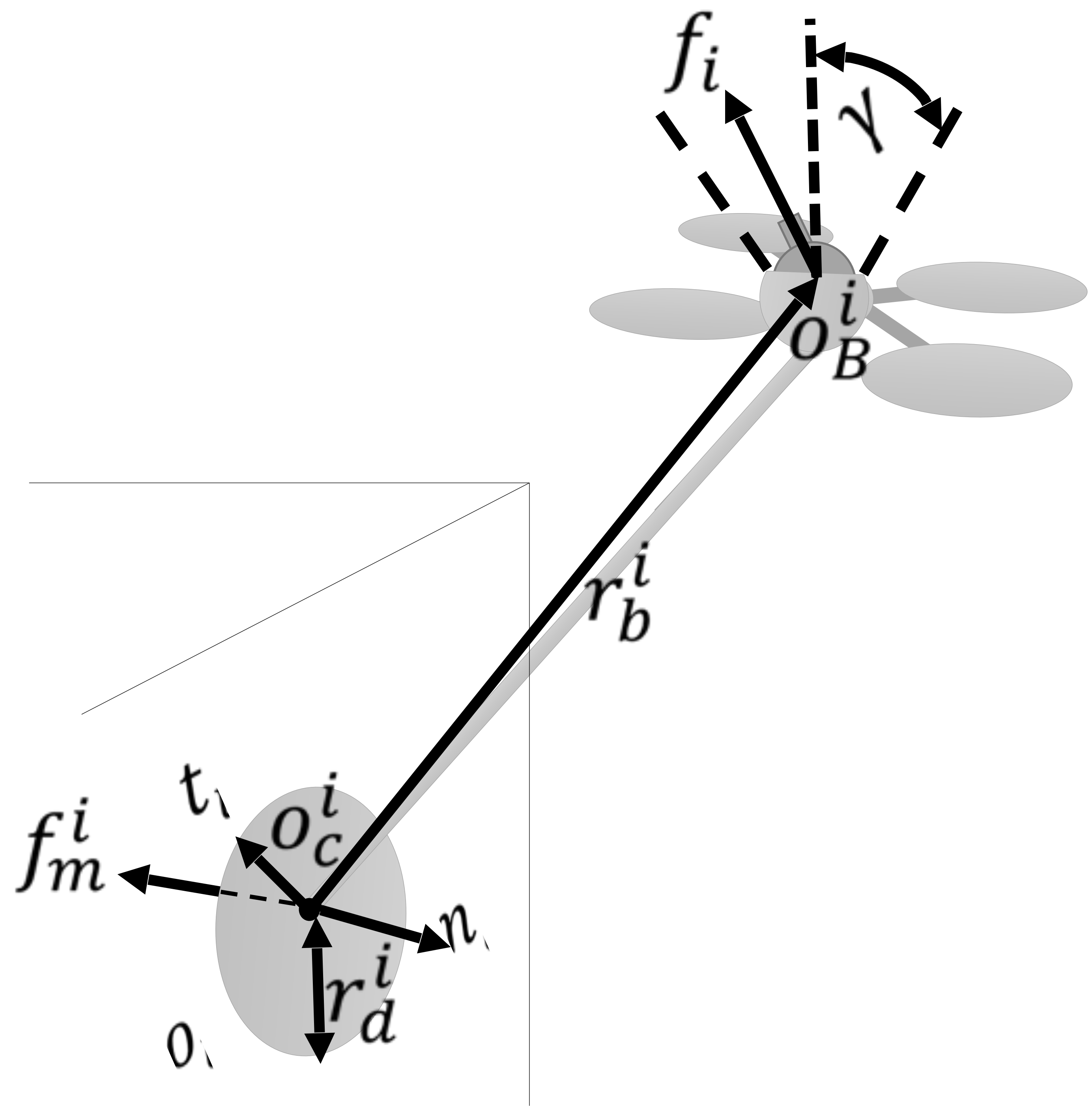
D. Prattichizzo, M. Malvezzi, M. Gabiccini, A. Bicchi. On Motion and Force Controllability of Precision Grasps with Hands Actuated by Soft Synergies. IEEE Transactions on Robotics, 29(6):1440-1456, 2013

Constraints on the VTOL force vector

- **Limited thrust** actuation
- Spherical **joint limits**
- **Contact constraints**
  - handle object **fragility**
  - **maintain** the contact



VTOL force vector



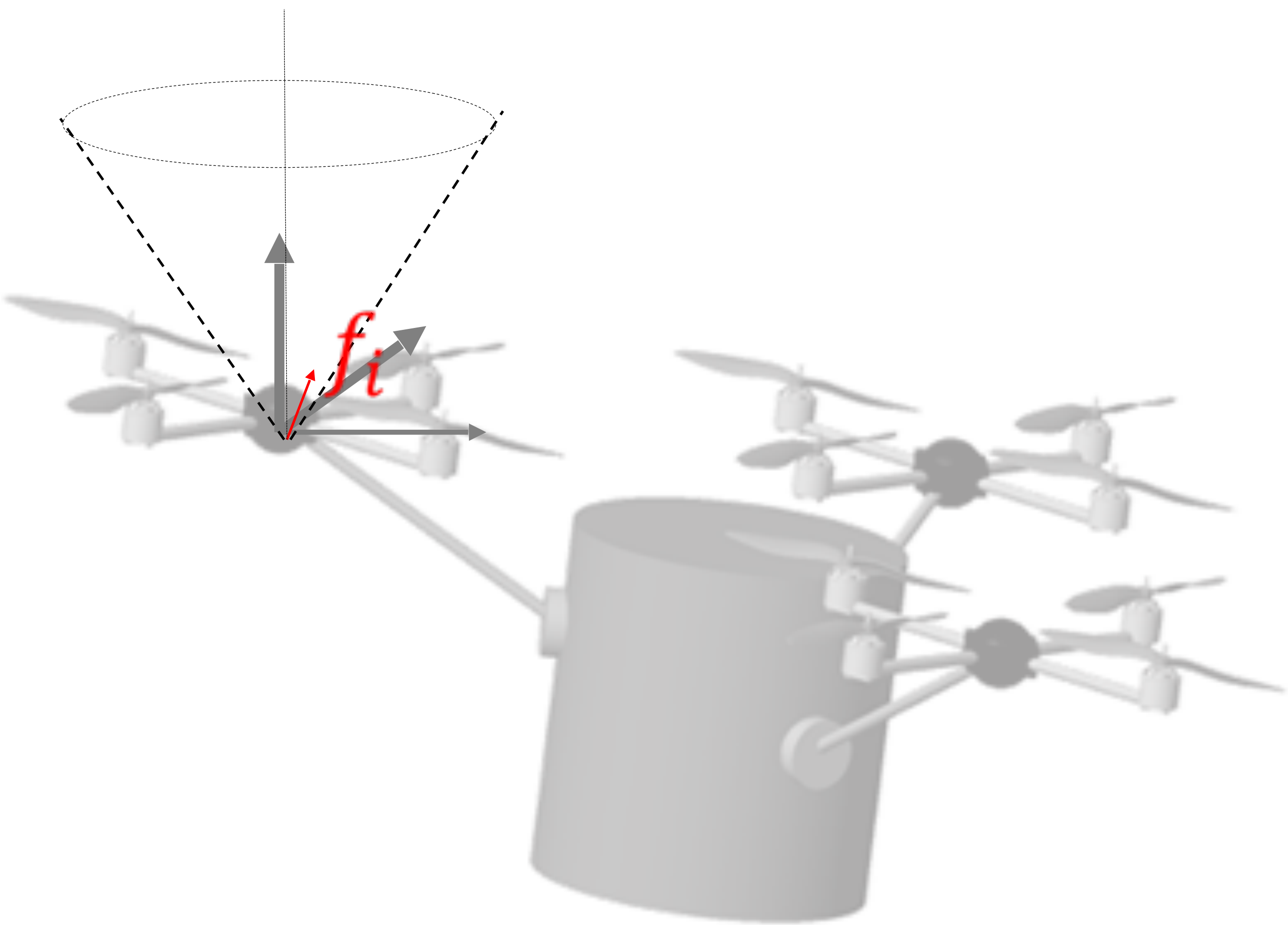
Limited thrust

$$f_p^{min} \leq \|f_i\| \leq f_p^{max}$$

Minimum thrust:
keep the motors functional

Maximum thrust:
motor power is limited

$$f_i = \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix}$$

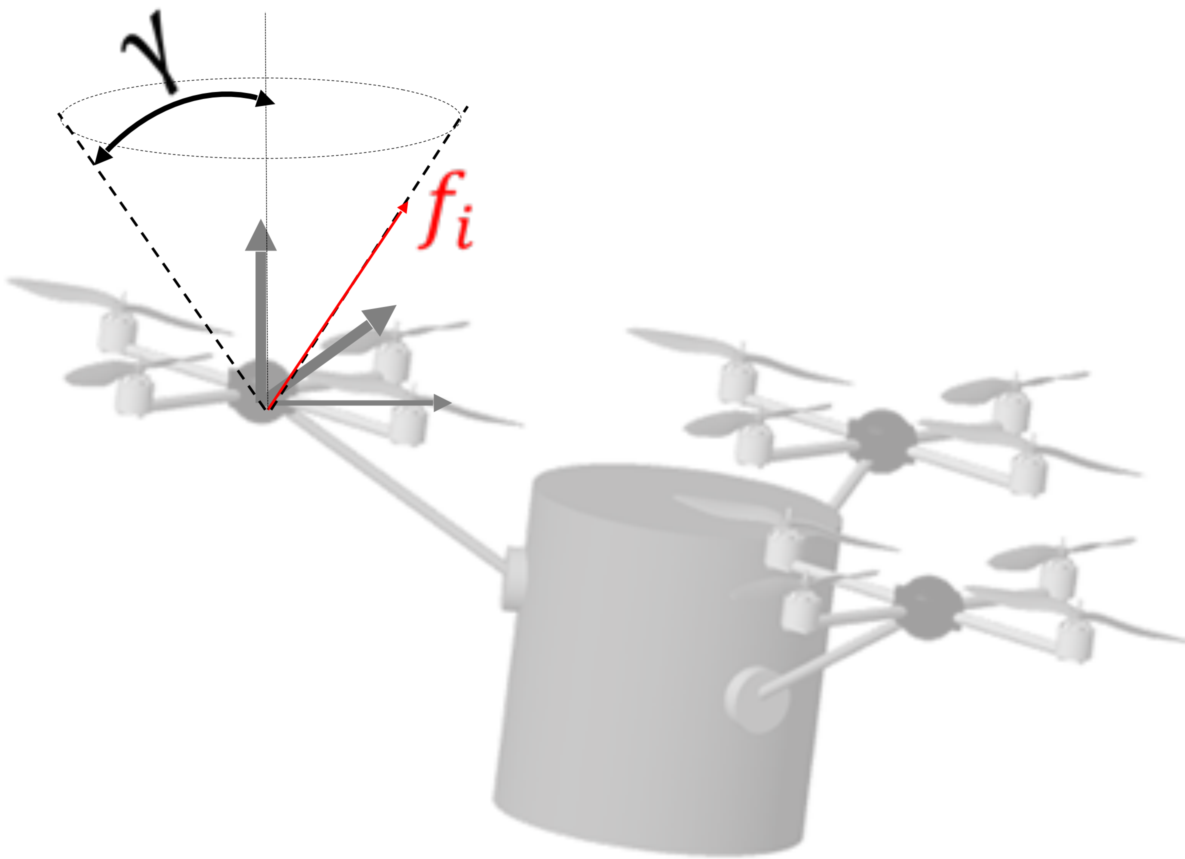


Spherical joint limits

$$\|f_i\| \leq \beta f_z$$

VTOL force constraints: structural limit of the spherical joint

$$f_i = \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix}$$



$$f_{i,b}^{z} > \vartheta \sqrt{(f_{i,b}^{x})^2 + (f_{i,b}^{y})^2}$$

$$\vartheta = tan(\gamma)$$

$$\beta = \frac{\sqrt{1+\vartheta^2}}{\vartheta}$$

The force vector must be inside the cone defined by the mechanically limited spherical joint

Contact constraints

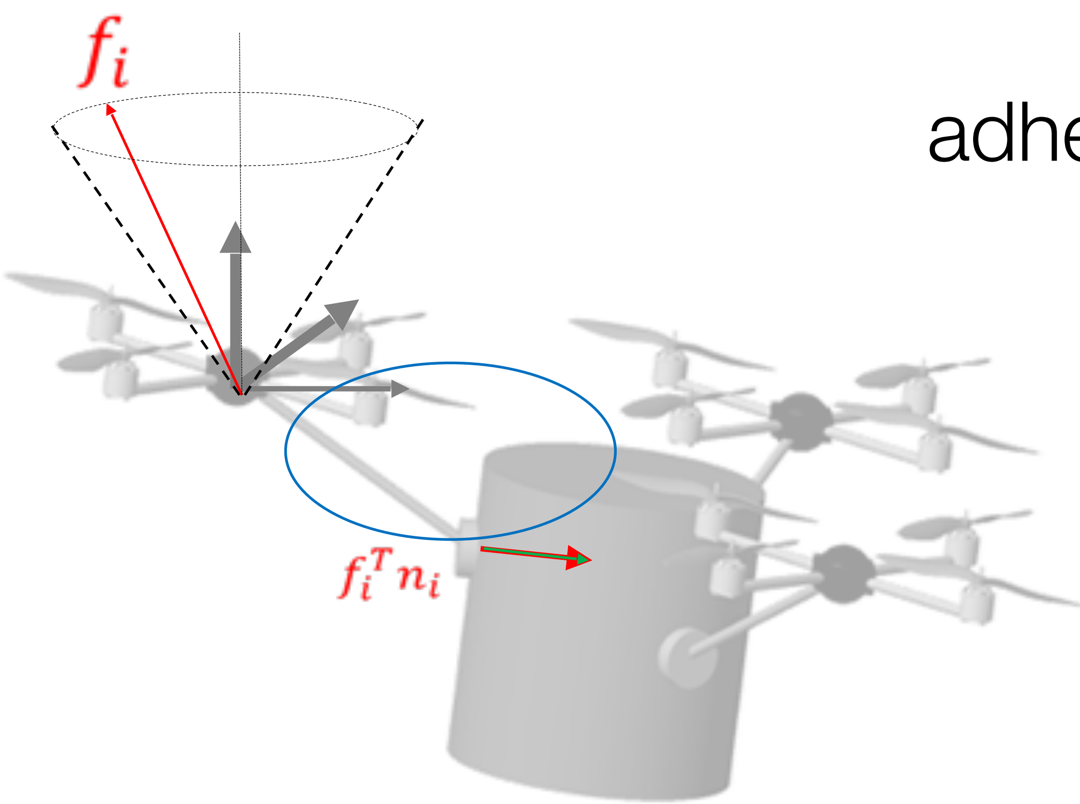
Two opposing goals:
not to break contact and **not to damage the object**

- object fragility
- adhesive (magnetic) force

$$-k_m \leq f_i^T n_i \leq f_n$$

adhesive force | penetration force

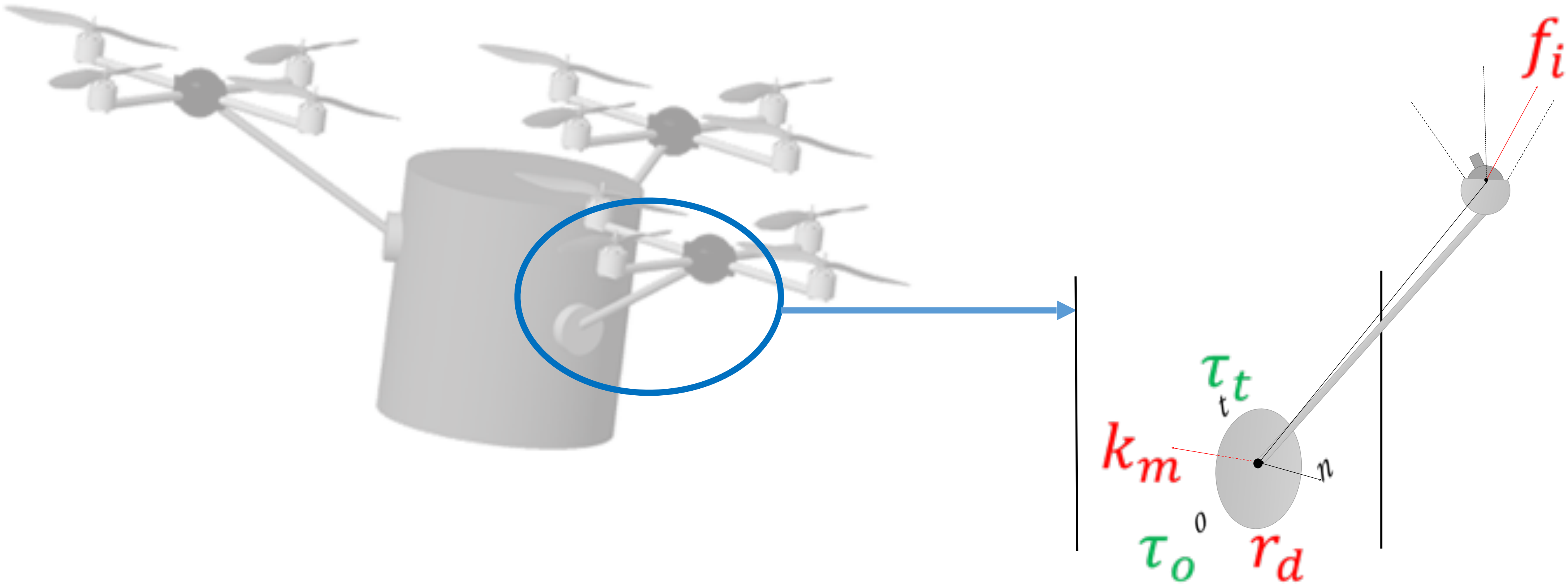
$$f_i = \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix}$$



Normal component of the force must not cancel out adhesive (magnetic) force which is small

Contact constraints (con't)

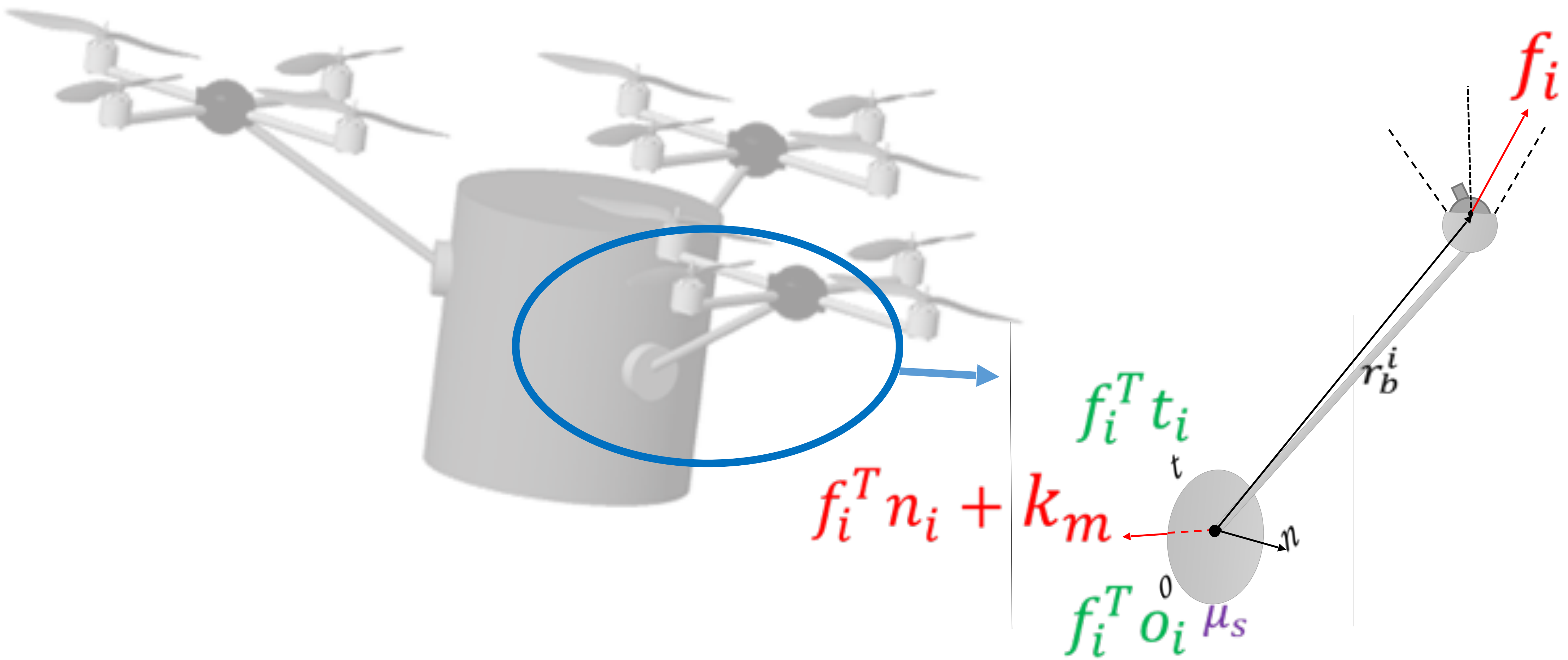
- torques must not break the contact $\sqrt{(\boldsymbol{\tau}_i^t)^2 + (\boldsymbol{\tau}_i^o)^2} \leq r_d k_m$



The resultant torque of f_i must not uplift the disk from any side

Contact constraints (con't)

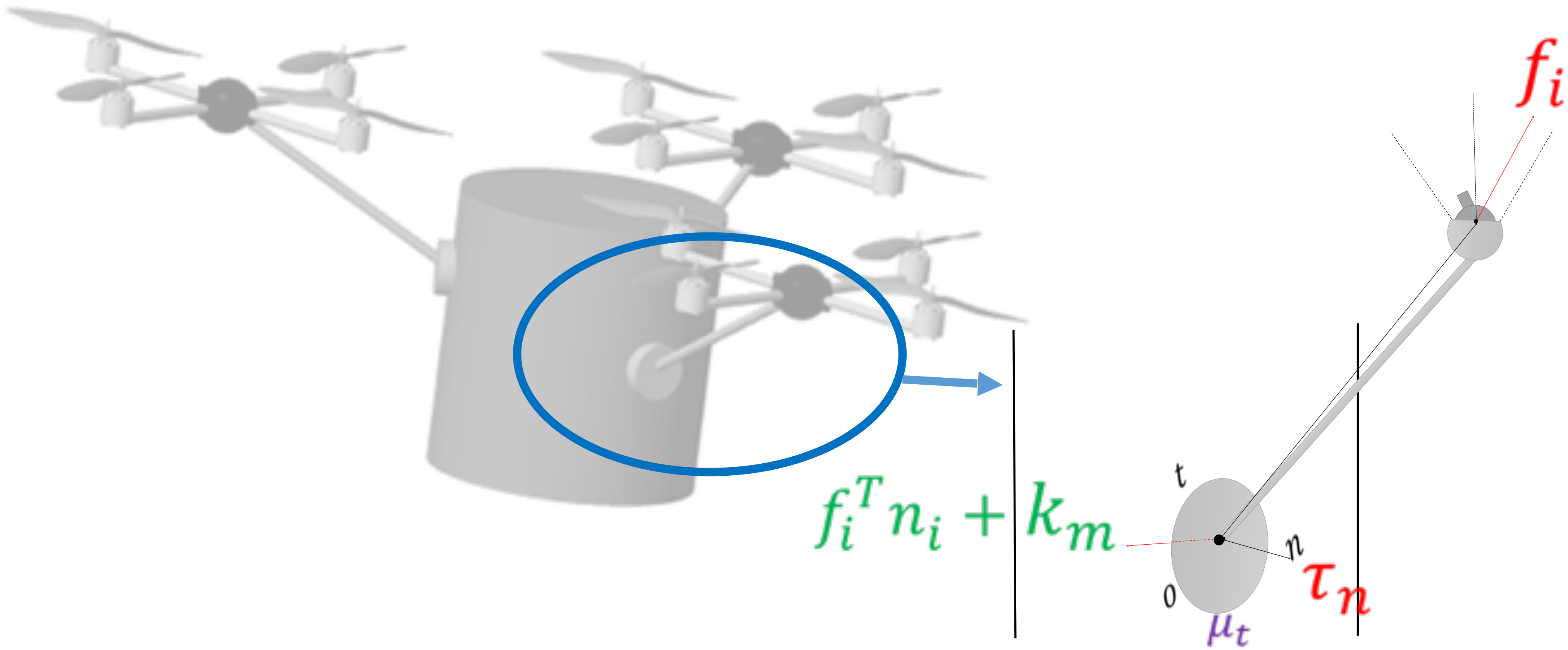
linear slippage $\sqrt{(\boldsymbol{f}_i^\top \boldsymbol{t}_i)^2 + (\boldsymbol{f}_i^\top \boldsymbol{o}_i)^2} \leq \mu_s | k_m \ + (\boldsymbol{f}_i^\top \boldsymbol{n}_i)|$



The force tangential components should stay in the friction cone defined by normal component of force plus magnetic force

Contact constraints (con't)

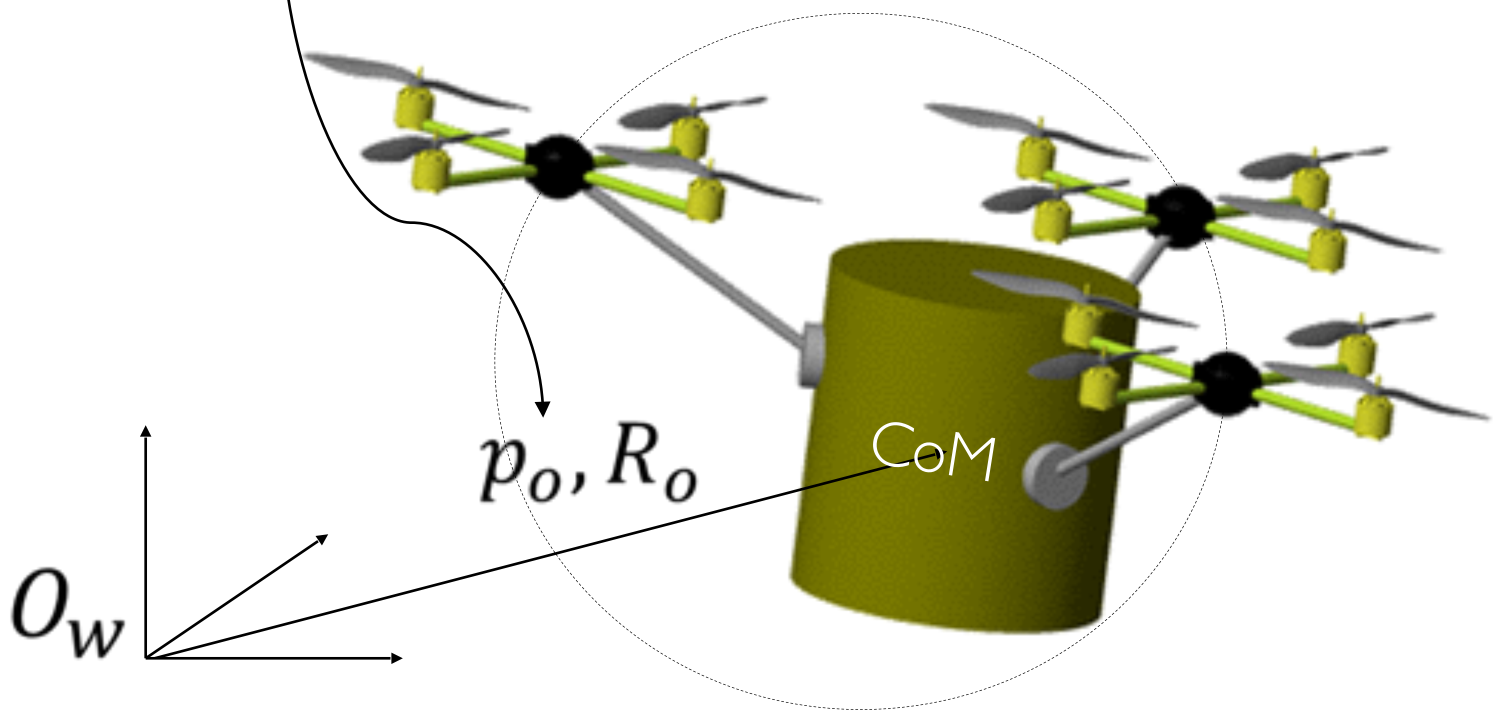
angular slippage $$\|\boldsymbol{\tau}_i^n\| \leq \boldsymbol{\mu}_t |(k_m + (\boldsymbol{f}_i^\top \boldsymbol{n}_i)|$$



The resultant normal component of torque must not be able to rotate the disk around the normal axis plus magnetic force

Modeling comes from the grasping literature

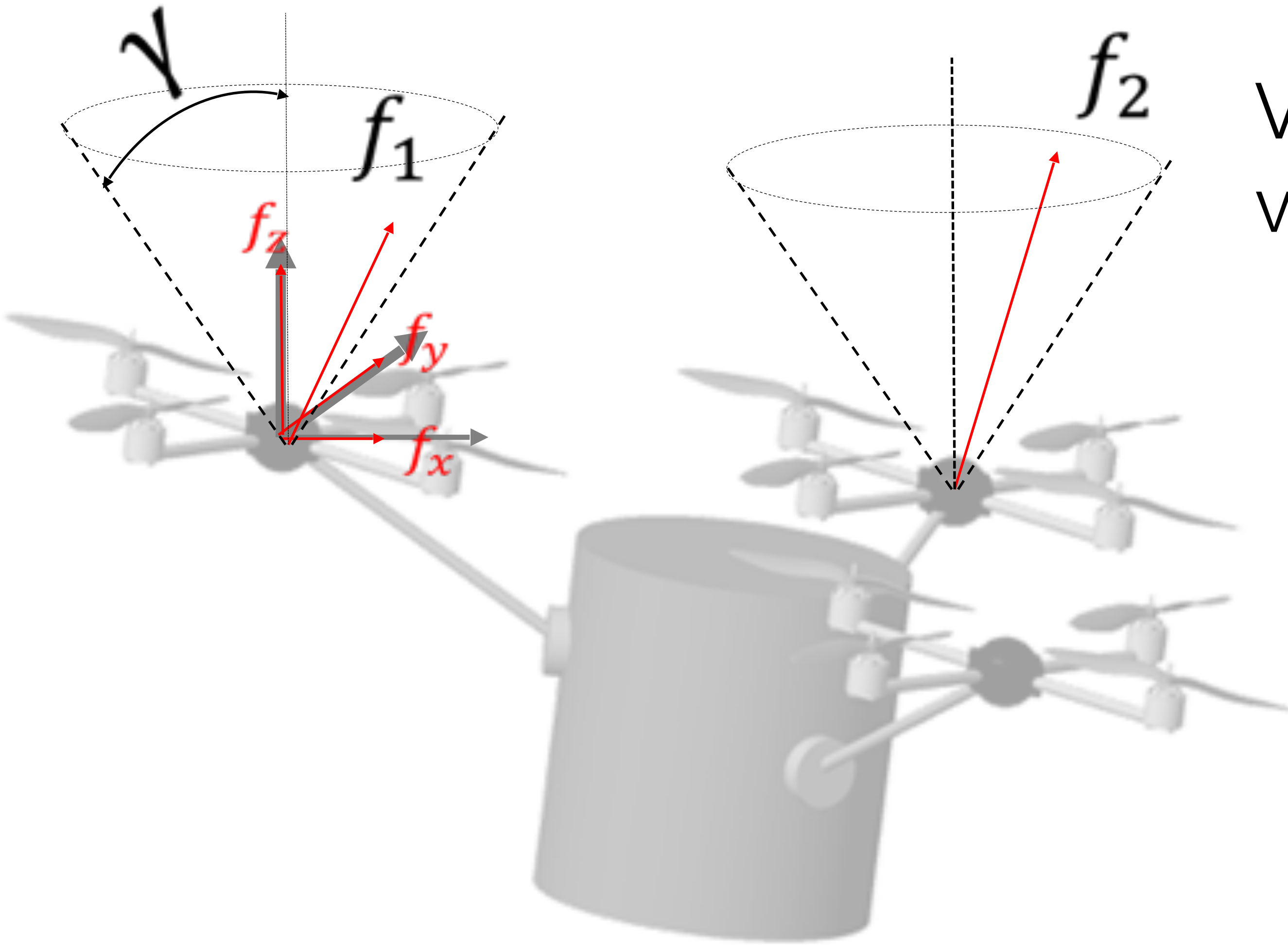
$$M(x)\ddot{x} + b(x,\dot{x}) + g = Gf$$



Prattichizzo, D., and Jeffrey C. T.. "Grasping." Springer handbook of robotics. Siciliano B. and Kathib O. Editors. Springer 2016.

Modeling

$$M(x)\ddot{x} + b(x,\dot{x}) + g = Gf \longrightarrow f = \begin{bmatrix} f_1 \\ \vdots \\ f_n \end{bmatrix} \longrightarrow f_i = \begin{bmatrix} f_x \\ f_y \\ f_z \end{bmatrix}$$



VTOL force vector

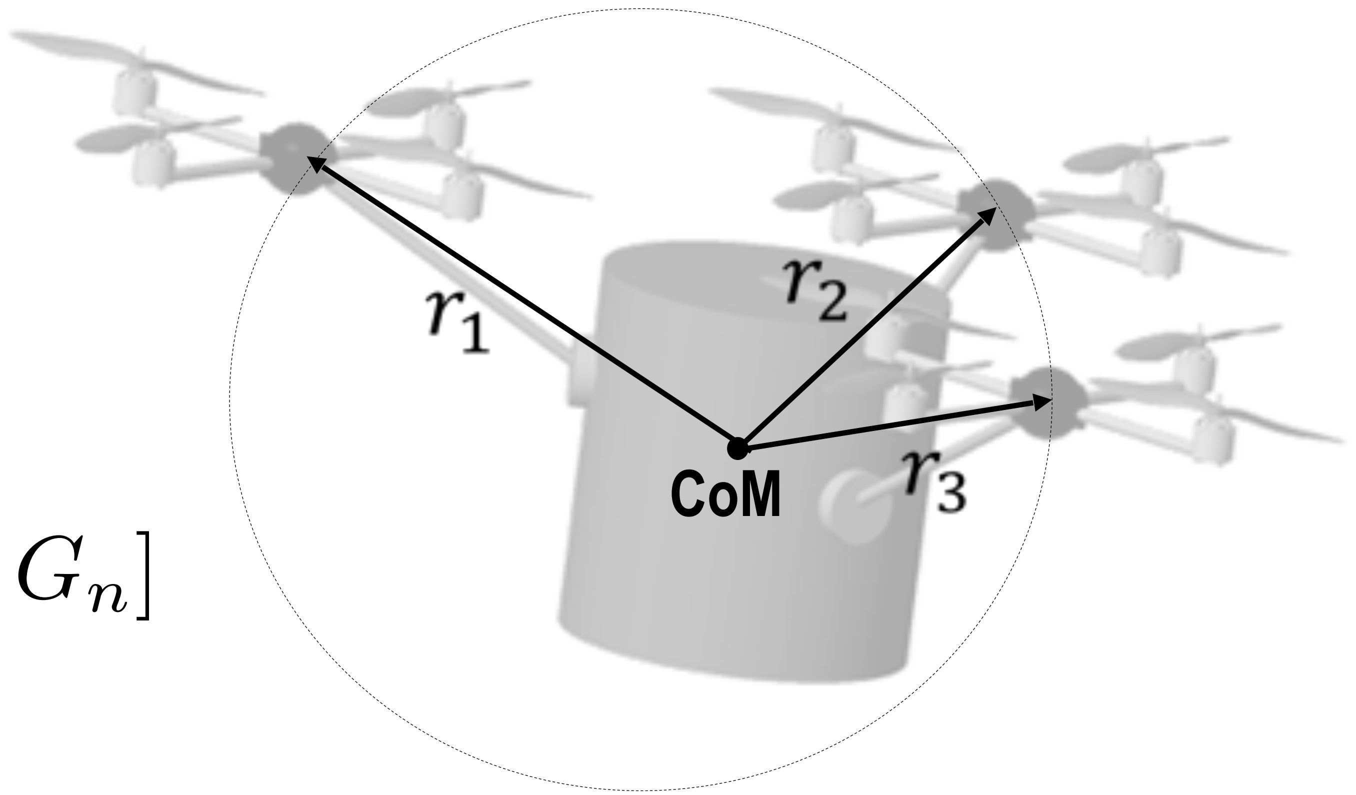
Grasping

$$M(x)\ddot{x} + b(x,\dot{x}) + g = Gf$$

Grasp Matrix

$$G = [G_1, \ldots, G_i, \ldots, G_n]$$

$$G_i = \begin{bmatrix} I_{3\times 3} \\ S(R_o^T r_i) \end{bmatrix}$$

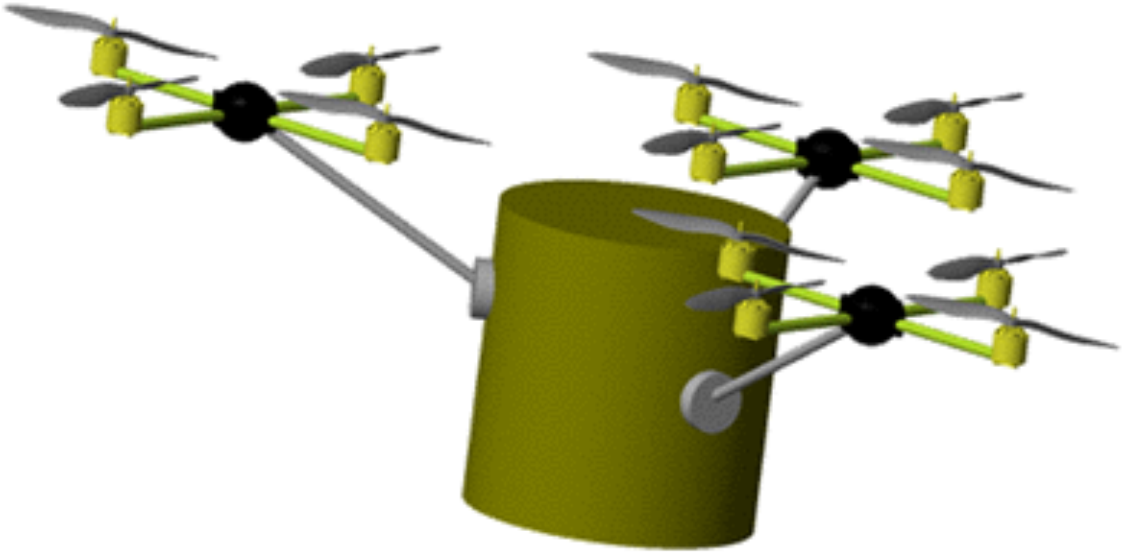


Trajectory controller for the manipulated object

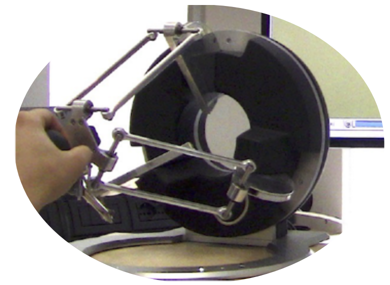
$$M(x)\ddot{x} + b(x,\dot{x}) + g = Gf$$

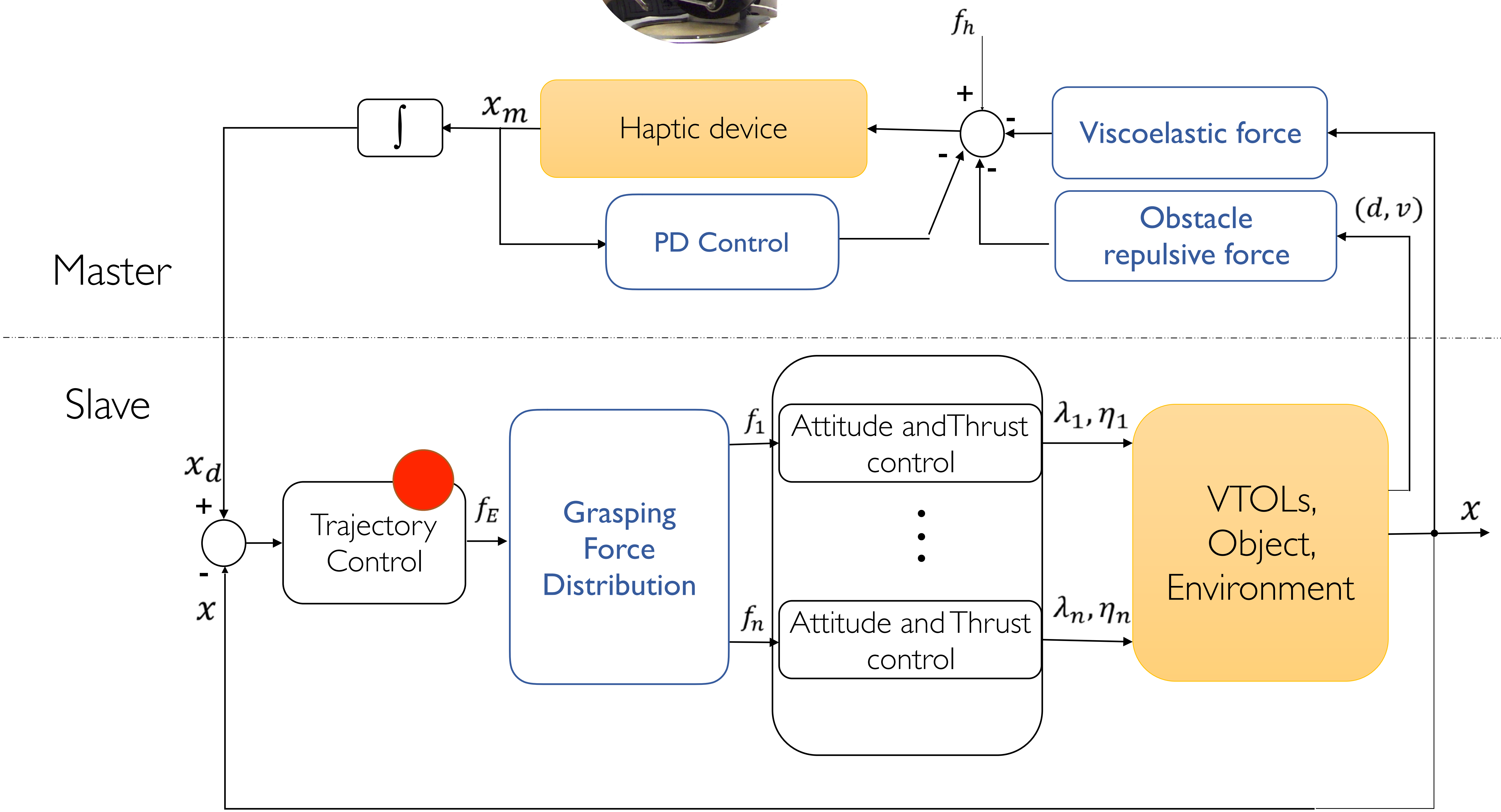
$$\tilde{\boldsymbol{x}} = \boldsymbol{x}_d - \boldsymbol{x}$$

$$\begin{cases} \boldsymbol{f}_E = \hat{\boldsymbol{M}}(\boldsymbol{x})\boldsymbol{\mu} + \hat{\boldsymbol{b}}(\boldsymbol{x},\dot{\boldsymbol{x}}) + \hat{\boldsymbol{g}}(\boldsymbol{x}) \\ \boldsymbol{\mu} = K_P\tilde{\boldsymbol{x}} + K_D\dot{\tilde{\boldsymbol{x}}} \end{cases}$$



- Approximate inverse dynamics
- PD control on object's pose error
- Grasping with unilateral contacts





f_h
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x_m
∫
Haptic device
Viscoelastic force
PD Control
Obstacle repulsive force
(d, v)
Master
Slave
x_d
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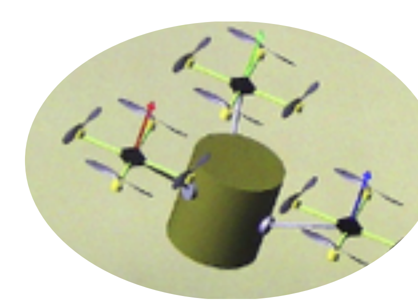
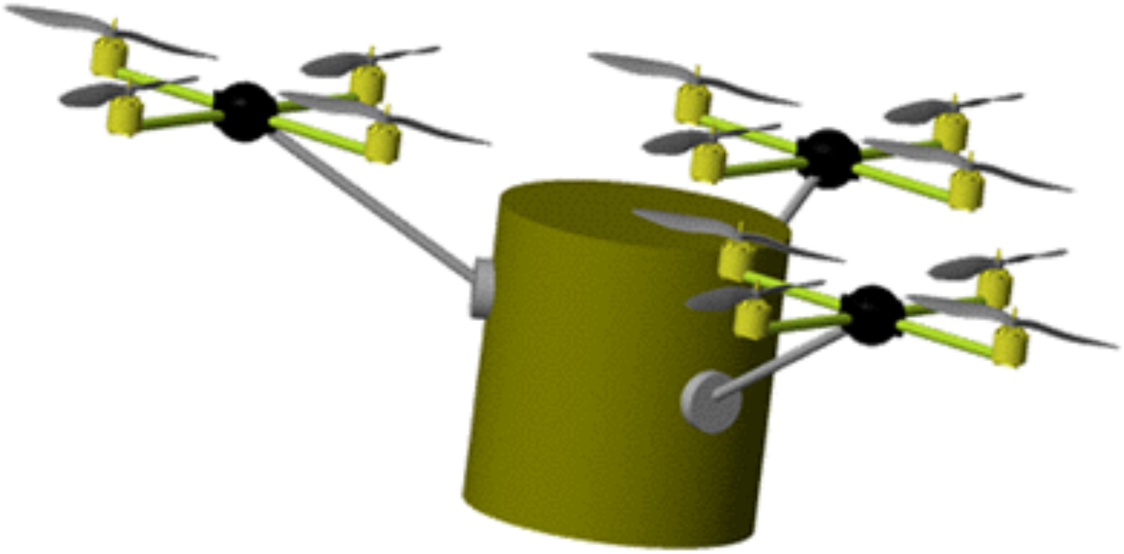


Equality constraints

$$\xi : \mathbb{R}^{3n} \rightarrow \mathbb{R}^6$$

$$\xi(\boldsymbol{f}) = \boldsymbol{G}\boldsymbol{f} - \boldsymbol{f}_{\boldsymbol{E}}$$

Output of the trajectory controller



Inequality constraints

$$\chi(\boldsymbol{f}) = [\chi_1^\top(\boldsymbol{f}_1) \ldots \chi_n^\top(\boldsymbol{f}_n)]^\top \leq 0$$

$$\chi_i(\boldsymbol{f}_i) : \mathbb{R}^3 \rightarrow \mathbb{R}^8$$

$$\chi_i(\boldsymbol{f}_i) = \begin{bmatrix} \|\boldsymbol{f}_i\| - \beta f_{i,b}^z \\ \|\boldsymbol{f}_i\| - f_p^{max} \\ -\|\boldsymbol{f}_i\| + f_p^{min} \\ -\boldsymbol{f}_i^\top \boldsymbol{n}_i - f_m^n \\ \sqrt{(\boldsymbol{f}_i^\top \boldsymbol{t}_i)^2 + (\boldsymbol{f}_i^\top \boldsymbol{o}_i)^2} - \mu_s |(k_i^m + (\boldsymbol{f}_i^\top \boldsymbol{n}_i)| \\ \boldsymbol{f}_i^\top \boldsymbol{n}_i - k_i^m \\ \|\boldsymbol{\tau}_i^n\| - \mu_t |(k_i^m + (\boldsymbol{f}_i^\top \boldsymbol{n}_i)| \\ \sqrt{(\boldsymbol{\tau}_i^t)^2 + (\boldsymbol{\tau}_i^o)^2} - r_d k_i^m \end{bmatrix}$$

Grasping and force distribution

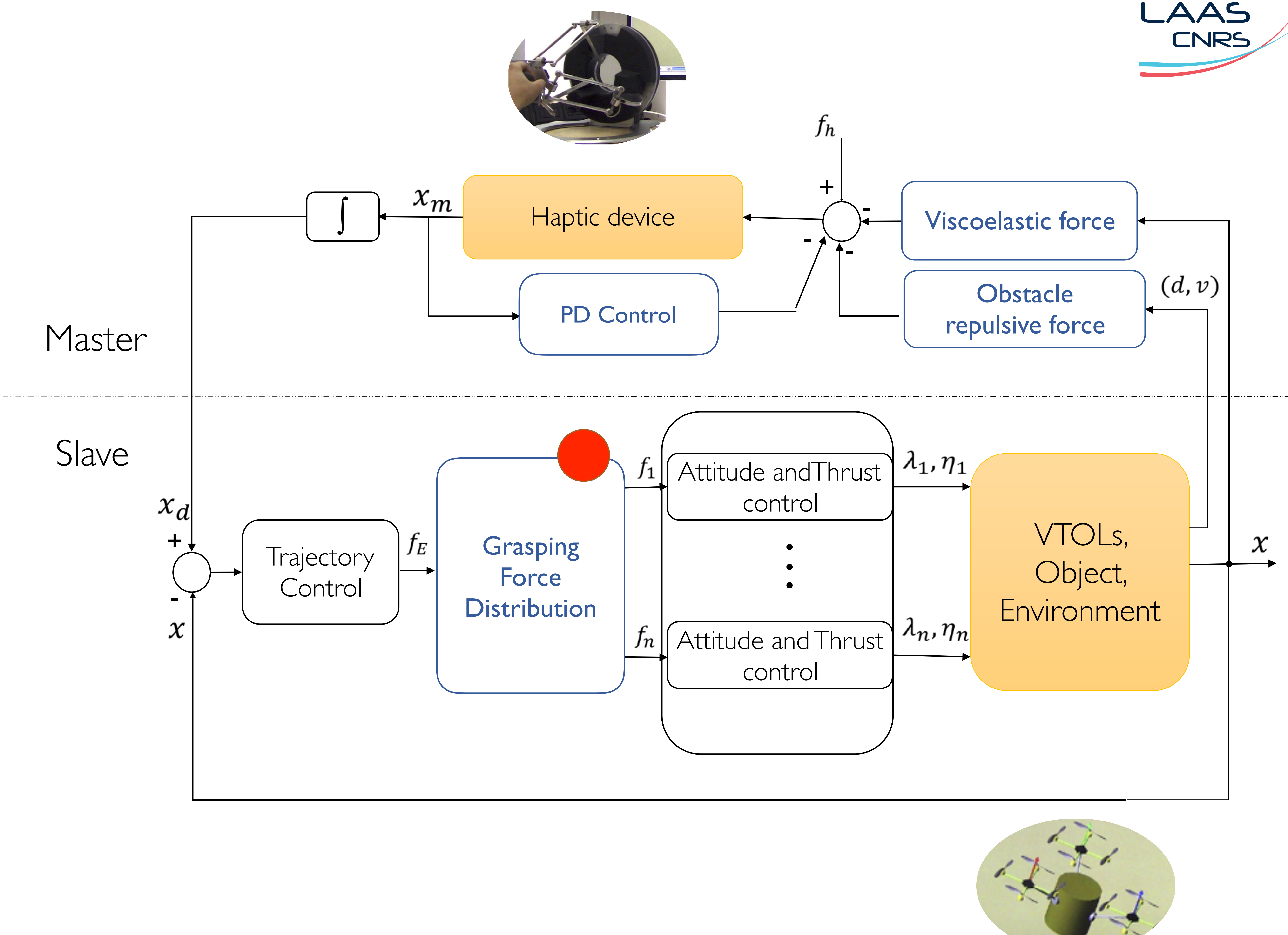
Convex optimization problem

$$
\begin{aligned}
\boldsymbol{f}^* = \arg\min_{\boldsymbol{f}} \quad & J(\boldsymbol{f}) \\
\text{s.t.} \quad & \chi(\boldsymbol{f}) \leq 0 \\
& \xi(\boldsymbol{f}) = 0.
\end{aligned}
$$

$$
J(\boldsymbol{f}) = \frac{1}{2}\boldsymbol{f}^\top \boldsymbol{f} + \varepsilon(\boldsymbol{f} - \boldsymbol{f}_{k-1})^\top(\boldsymbol{f} - \boldsymbol{f}_{k-1})
$$

Small force

Smoothing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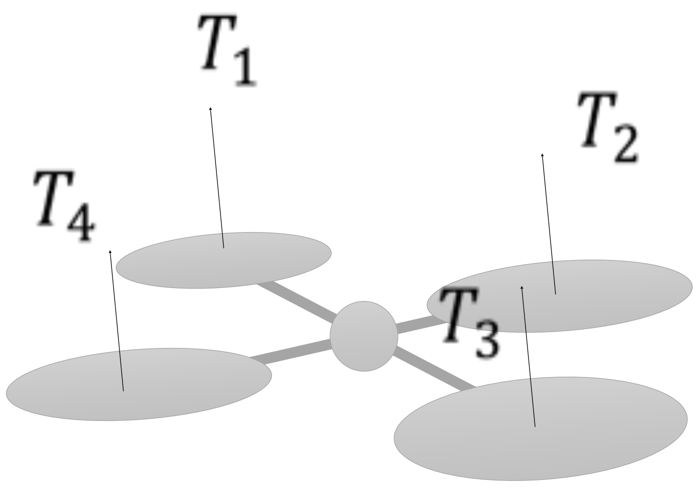
Attitude and thrust controller

$$\begin{cases} \lambda_d^i = \boldsymbol{f}_i^\top R_i [0\ 0\ 1]^\top \\ \frac{\boldsymbol{f}_i}{\|\boldsymbol{f}_i\|} = R_d^i [0\ 0\ 1]^\top. \end{cases}$$

$$\boldsymbol{\tau}_i = -K_R \boldsymbol{e}_R^i - K_\omega \boldsymbol{e}_\omega^i + \boldsymbol{\omega}_i \times J_i \boldsymbol{\omega}_i$$

$$\boldsymbol{e}_R^i = \frac{1}{2} S^-({R_d^i}^\top R_i - R_i^\top R_d^i)$$

$$\boldsymbol{e}_\omega^i = \boldsymbol{\omega}_i - R_i^\top R_d^i \boldsymbol{\omega}_d^i$$



$$\tau_i = \begin{bmatrix} \tau_\phi \\ \tau_\theta \\ \tau_\psi \end{bmatrix}$$

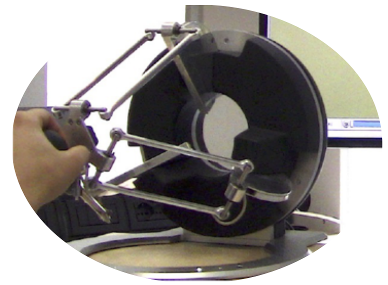
$$\lambda = T_1 + T_2 + T_3 + T_4$$

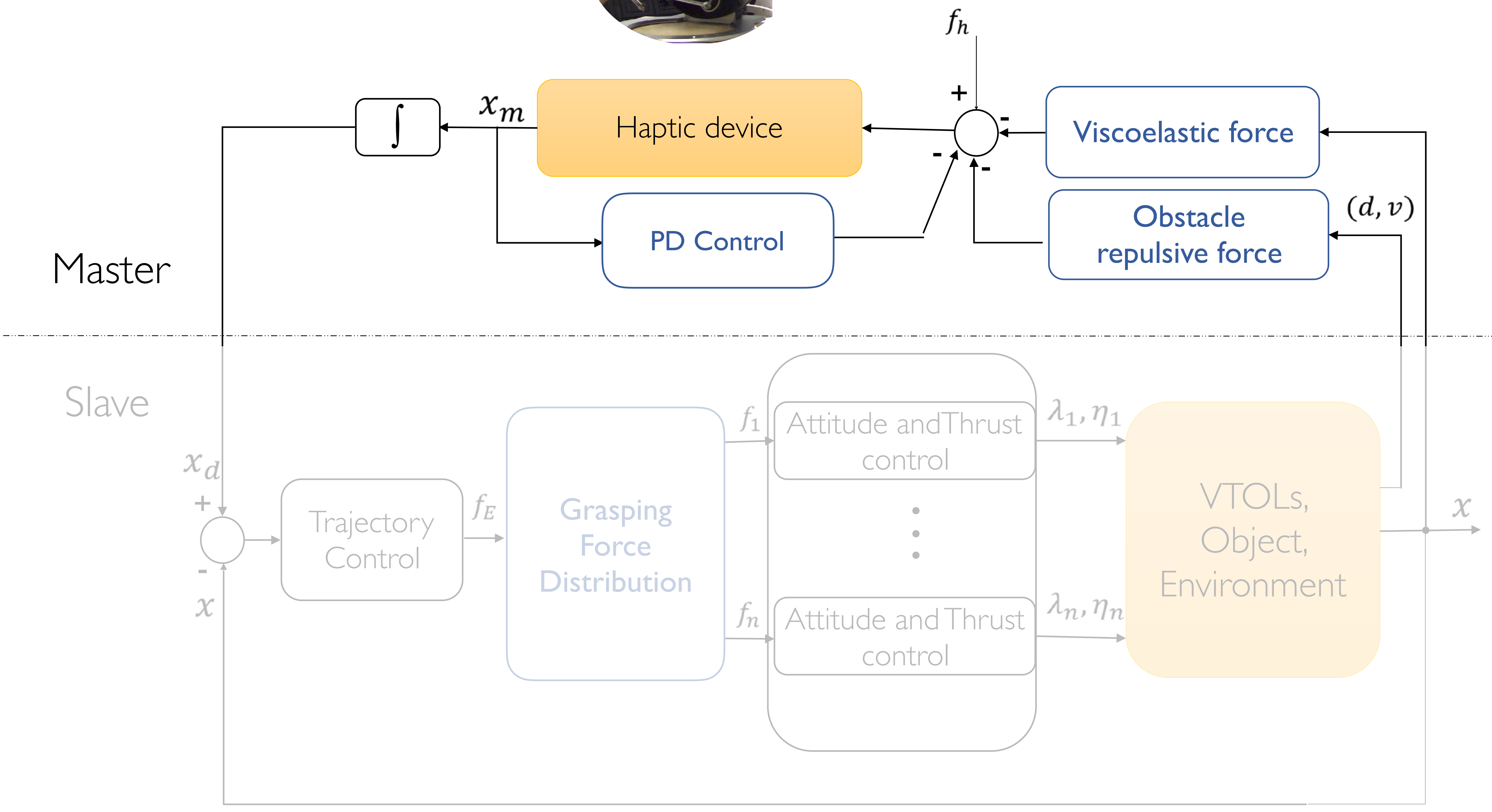
$$\tau_\phi = T_1 - T_3$$

$$\tau_\theta = T_2 - T_4$$

$$\tau_\psi = (T_1 + T_3) - (T_2 + T_4)$$

T. Lee, M. Leoky, and N. H. McClamroch, "Geometric tracking control of a quadrotor uav on SE(3)," in Decision and Control (CDC), 2010 49th IEEE Conference on. IEEE, 2010, pp. 5420–5425





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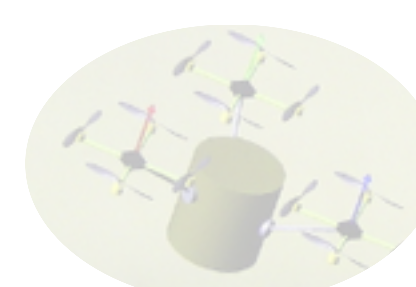


Human in the loop and haptic feedback

Haptics can be used to interact with swarms

A. Franchi, C. Secchi, H. I. Son, H. H. Bulthoff, and P. R. Giordano.
Bilateral teleoperation of groups of mobile robots with time-varying topology.
(TRO 2012)

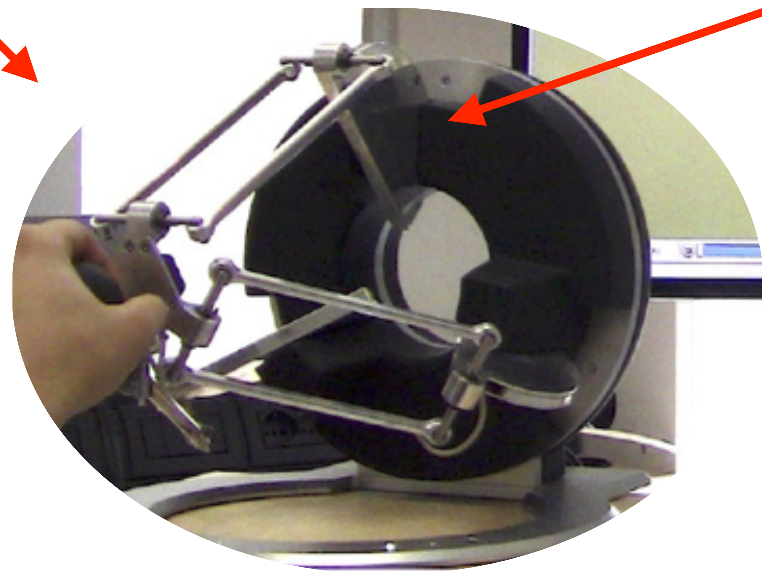
Haptics improves the performance of human operator in disaster recovery

G.-J. M. Kruijff, M. Janicek, S. Keshavdas, B. Larochelle, H. Zender, N. J. Smets, T. Mioch, M. A. Neerincx, J. Diggelen, F. Colas et al., “Experience in system design for human-robot teaming in urban search and rescue,” in Field and Service Robotics. Springer, 2014, pp. 111–125.

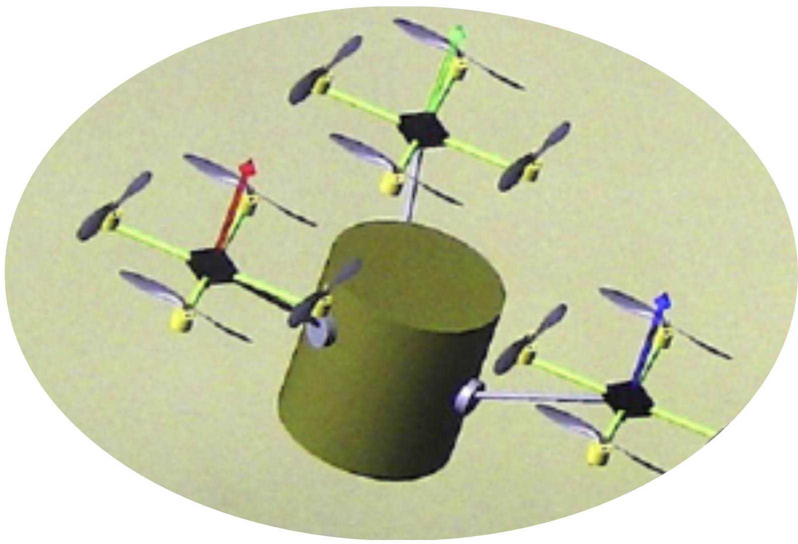
L. D. Dole, D. M. Sirkin, R. R. Murphy, and C. I. Nass, “Robots need humans in the loop to improve the hopefulness of disaster survivors,” in Robot and Human Interactive Communication (RO-MAN), 2015 24th IEEE International Symposium on. IEEE, 2015, pp. 707–714.

Bilateral control and haptics

$$M_m(x_m)\ddot{x}_m + b(x_m, \dot{x}_m)(+g) = f_h - f_c$$



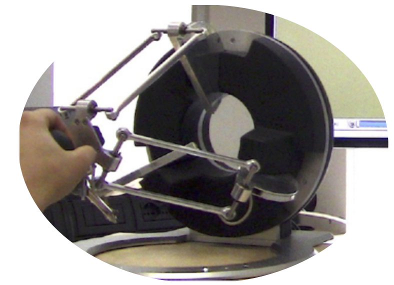
Master

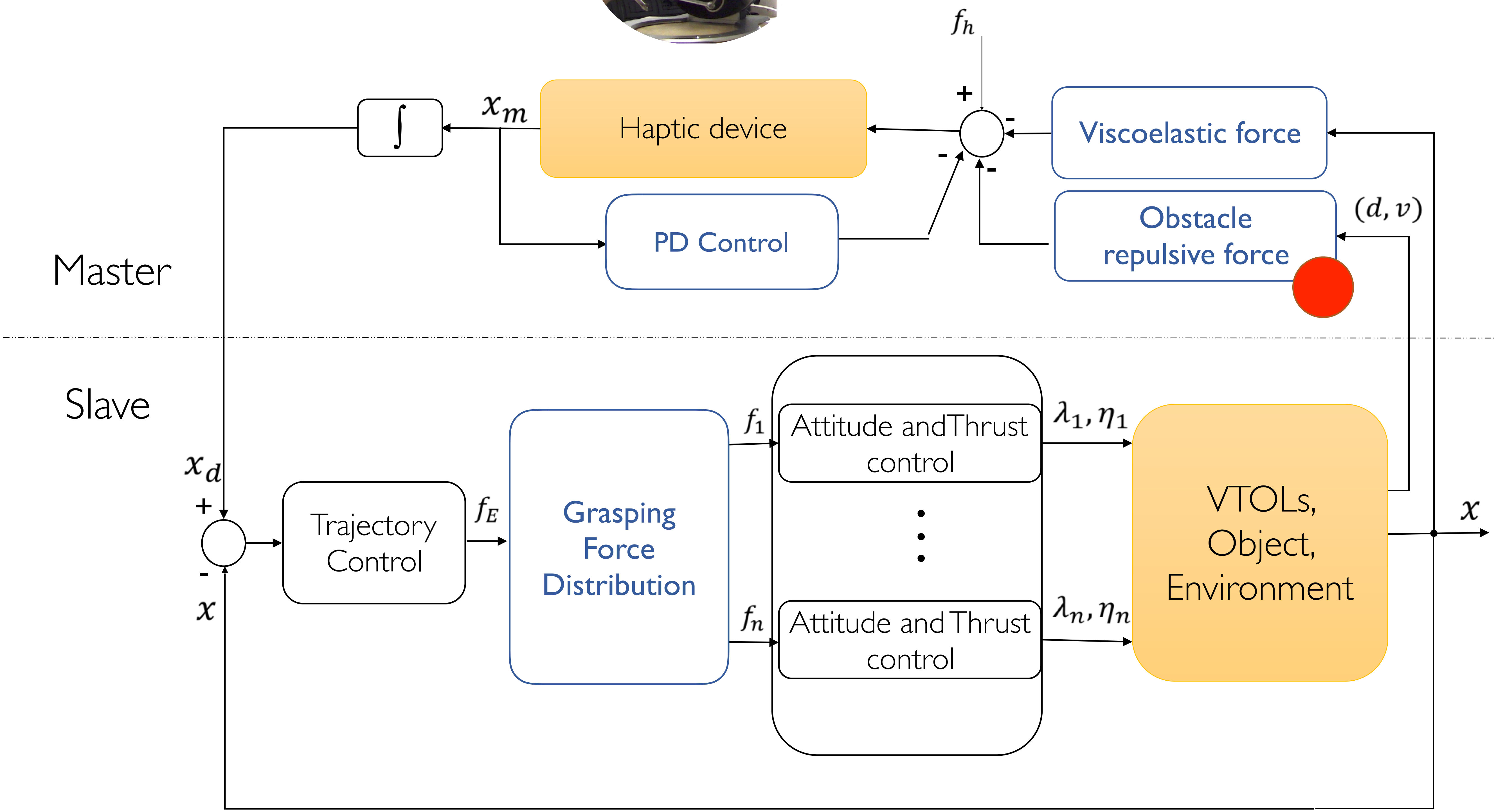


Slave

Impedance type interaction

- Human applies forces to the haptic device
- Haptic device position provides reference to transported object
- Haptic feedback f_c depends on the system states (both master and slave)





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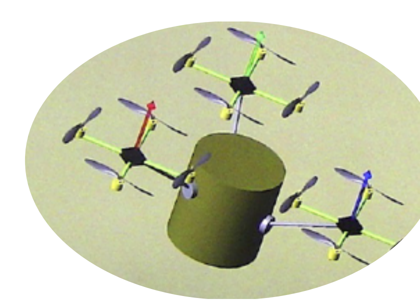
VTOLs, Object, Environment
x



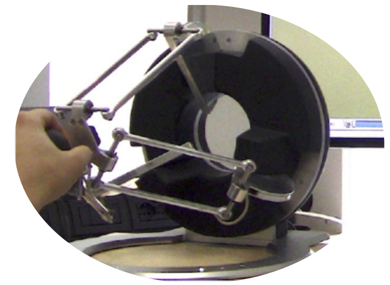
Obstacle repulsive force

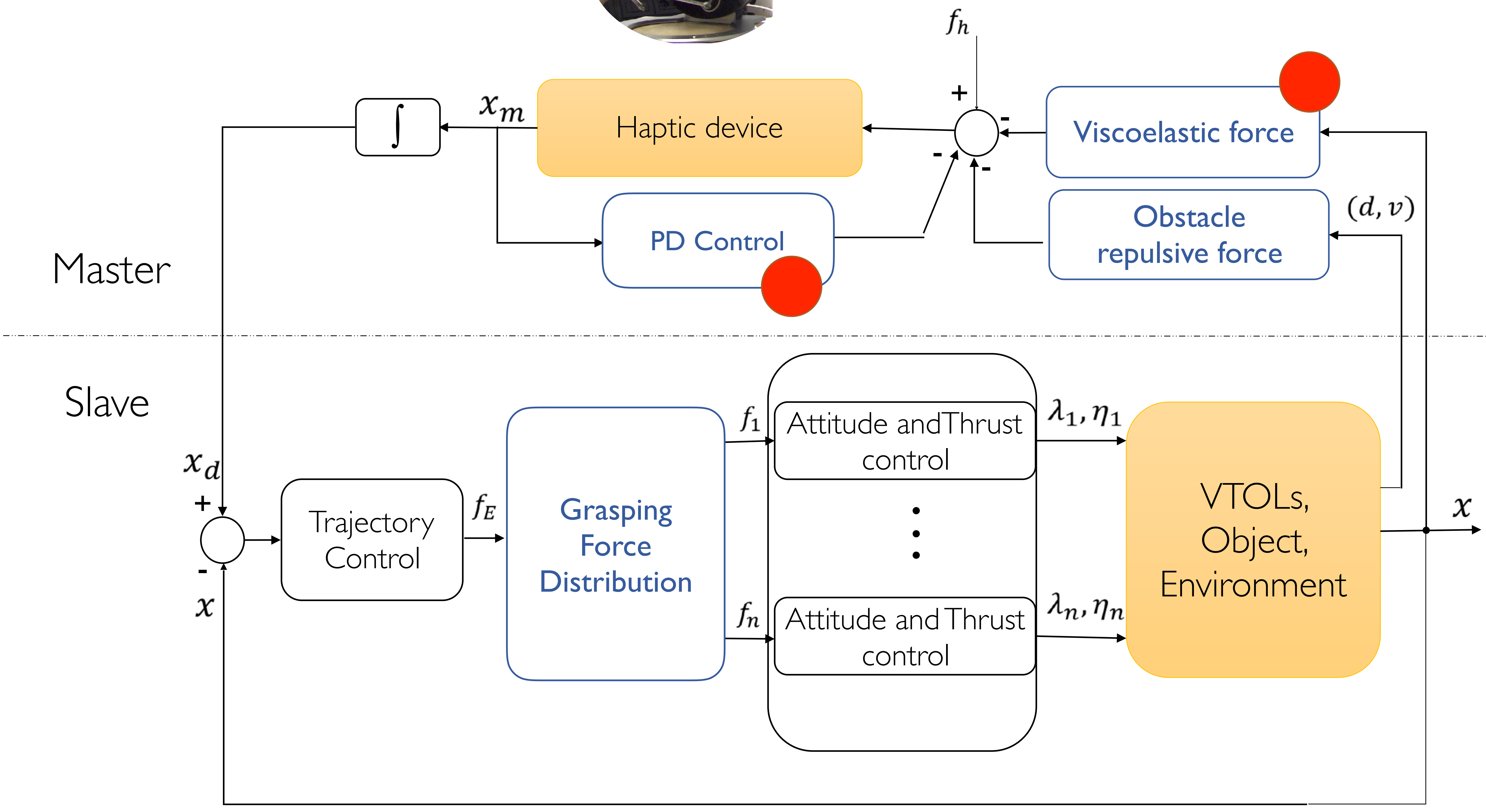
$$
\boldsymbol{f_o} = \begin{cases} 0 & \text{if} \quad \frac{1+v}{d_{res}(d,v)} \leq 0 \\ f_o^{max} \boldsymbol{n_o} & \text{if} \quad \begin{cases} d_{res}(d,v) \leq 0 \\ \frac{1+v}{d_{res}(d,v)} \geq \frac{1}{k_o} \end{cases} \\ k_o \frac{1+v}{d_{res}(d,v)} \boldsymbol{n_o} & \text{otherwise} \end{cases}
$$

$$
d_{res}(d,v) = \begin{cases} \frac{2a_{max}d+v^2}{2a_{max}} & \text{if} \quad v \leq 0 \\ \frac{2a_{max}d-v^2}{2a_{max}} & \text{if} \quad v > 0 \end{cases}
$$

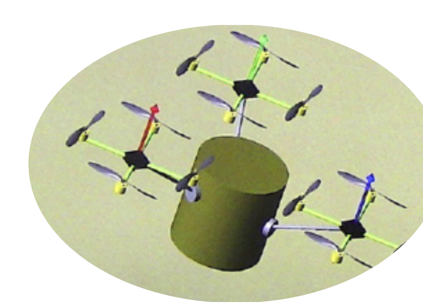
reserve avoidance distance:
dist. from obstacle
+
dist. needed to stop

T. M. Lam, H. W. Boschloo, M. Mulder, and M. M. Van Paassen, "Artificial force field for haptic feedback in uav teleoperation," Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on, vol. 39, no. 6, pp. 1316–1330, 2009.





Master
Slave
x_m
Haptic device
f_h
+
-
-
-
Viscoelastic force
PD Control
Obstacle repulsive force
(d, v)
x_d
+
-
x
Trajectory Control
f_E
Grasping Force Distribution
f_1
f_n
Attitude and Thrust control
Attitude and Thrust control
λ_1, η_1
λ_n, η_n
VTOLs, Object, Environment
x



Viscoelastic forces

LAAS CNRS

$$f_e = K_1 \tilde{x} + K_2 \dot{\tilde{x}}$$

$$\tilde{x} = x_d - x$$

$$\dot{\tilde{x}} = \dot{x}_d - \dot{x}$$

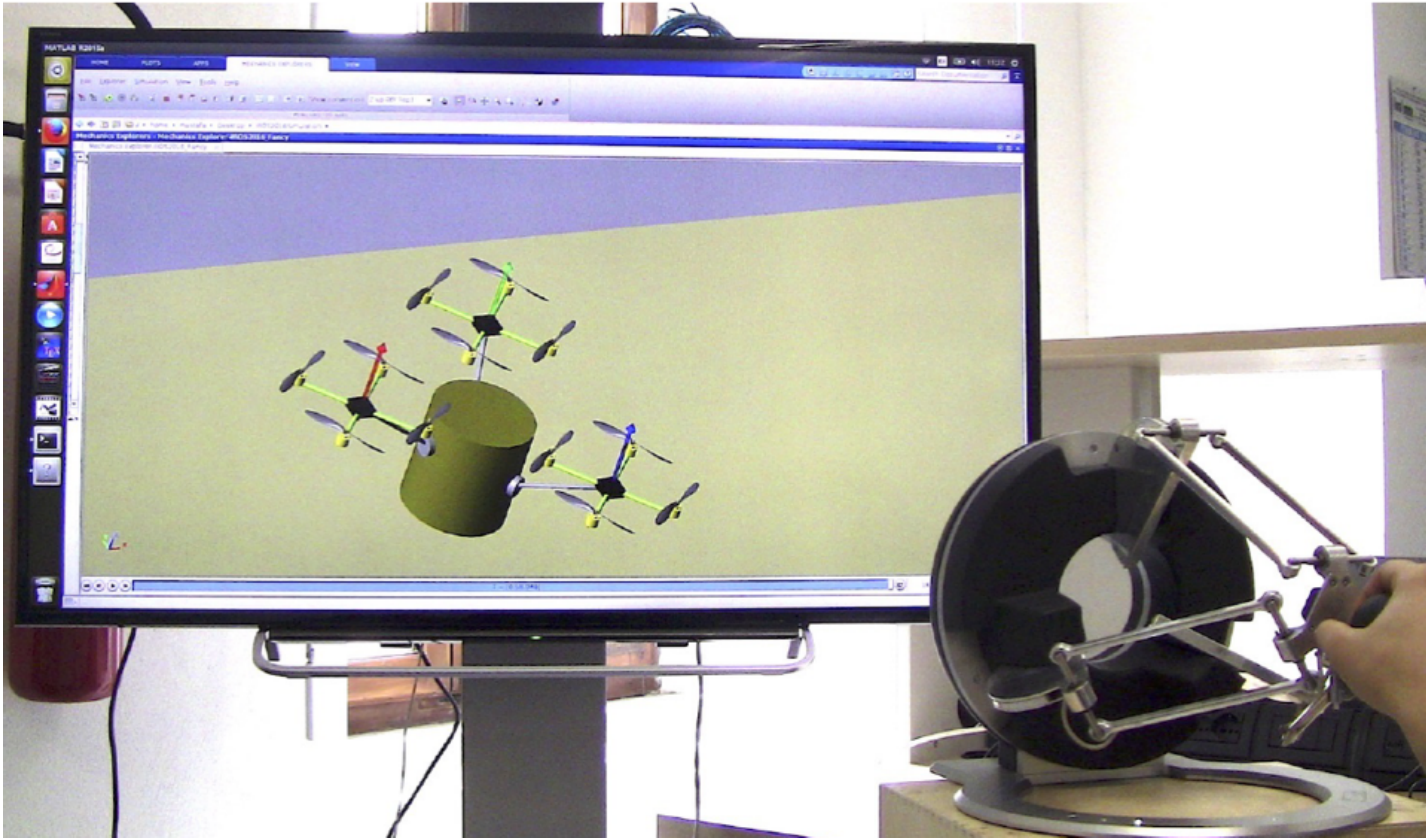
Improves the performance of position tracking by pushing back the human operator in the direction of error

$$f_m = K_h sat(x_m, x_m^{max}) + B_h \dot{x}_m$$

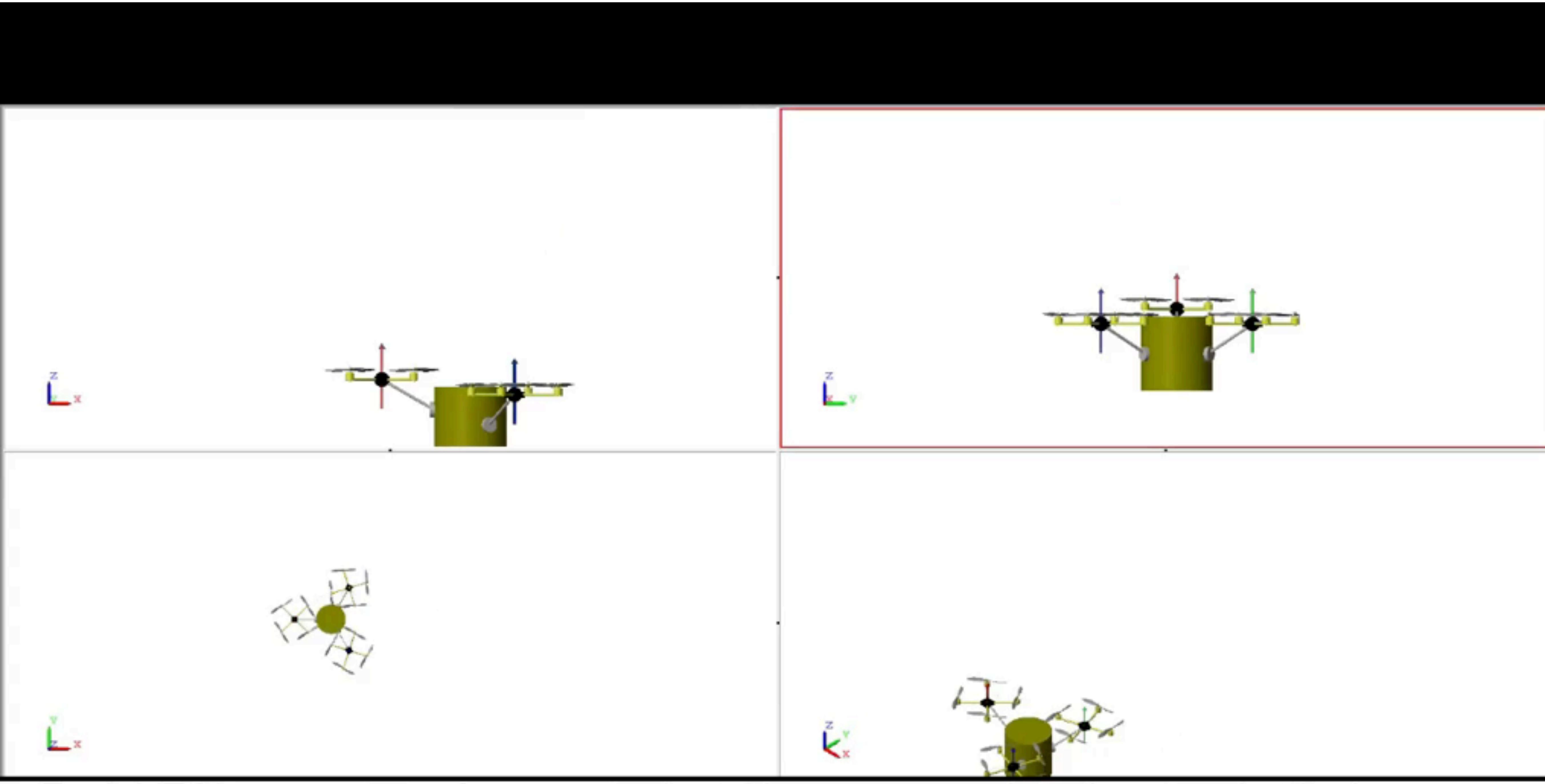
$$sat(x_m, x_m^{max}) = \begin{cases} x_m & \text{if} \|x_m\| \leq x_m^{max} \\ \frac{x_m}{\|x_m\|} x_m^{max} & \text{otherwise} \end{cases}$$

Brings back the master device handle to the center whenever the user leave it, thus the VTOL team and the object will keep the position when the master device is left by the human operator

Human/Hardware In the Loop Simulation

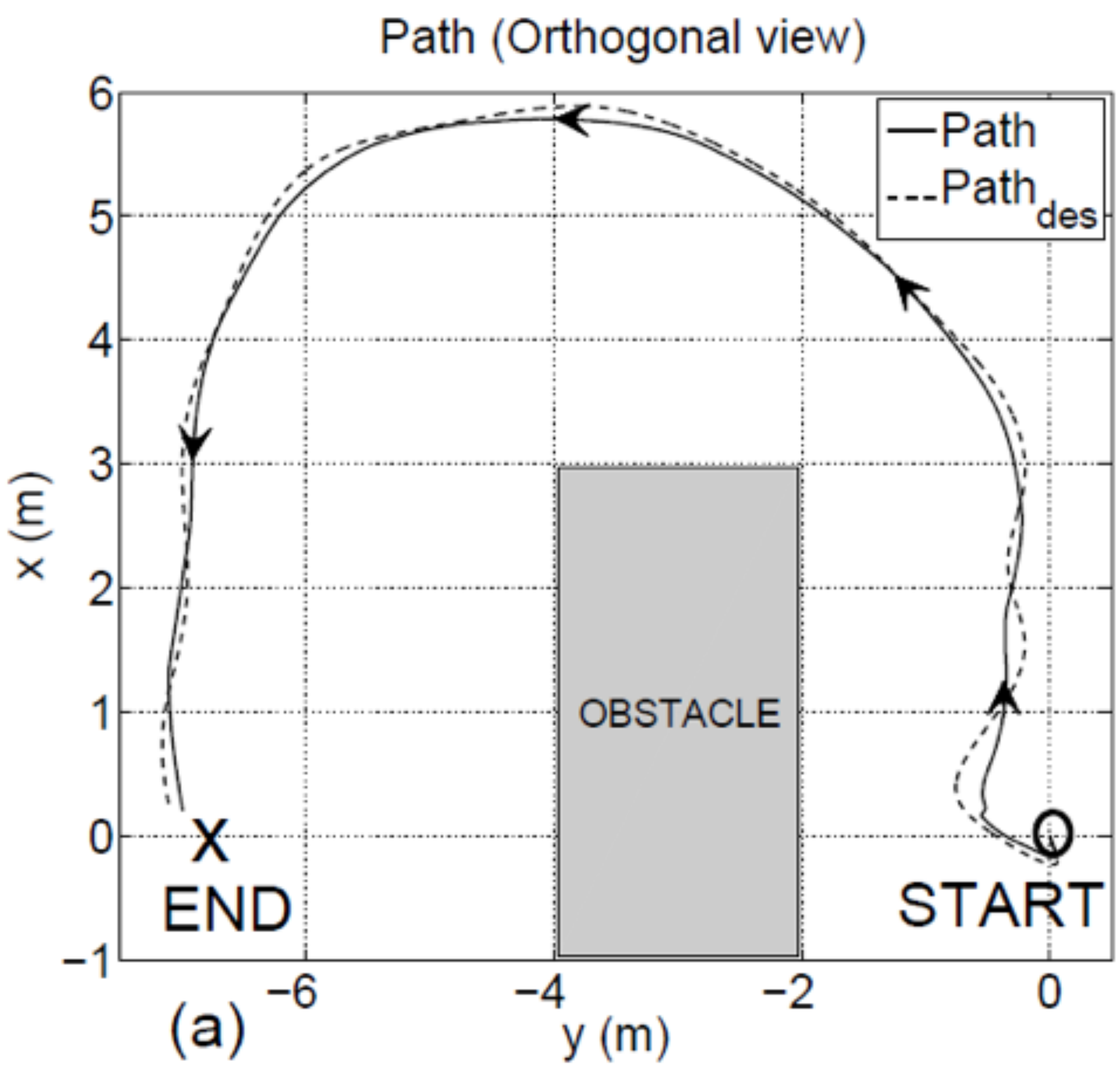


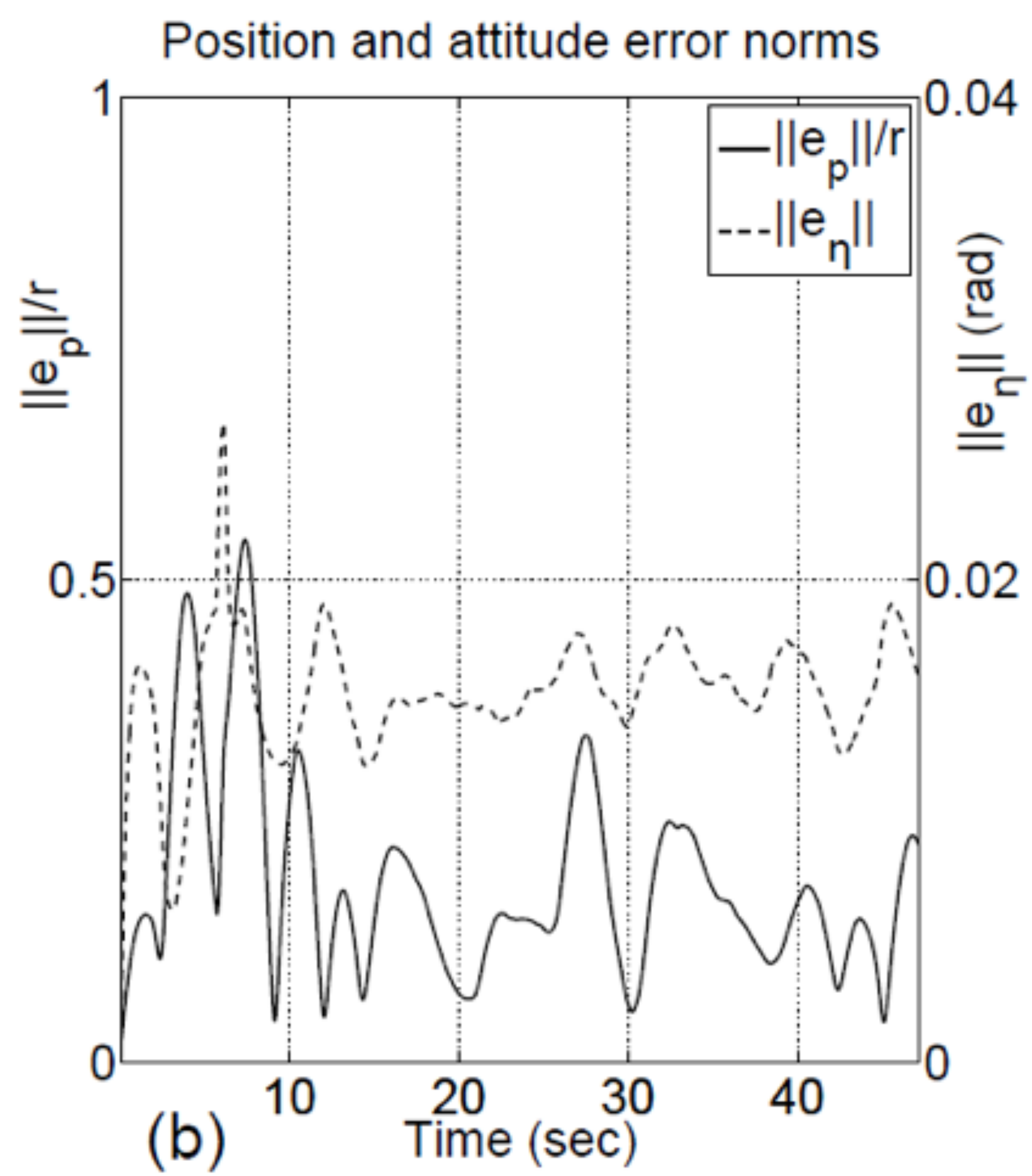
Human/Hardware In the Loop Simulation



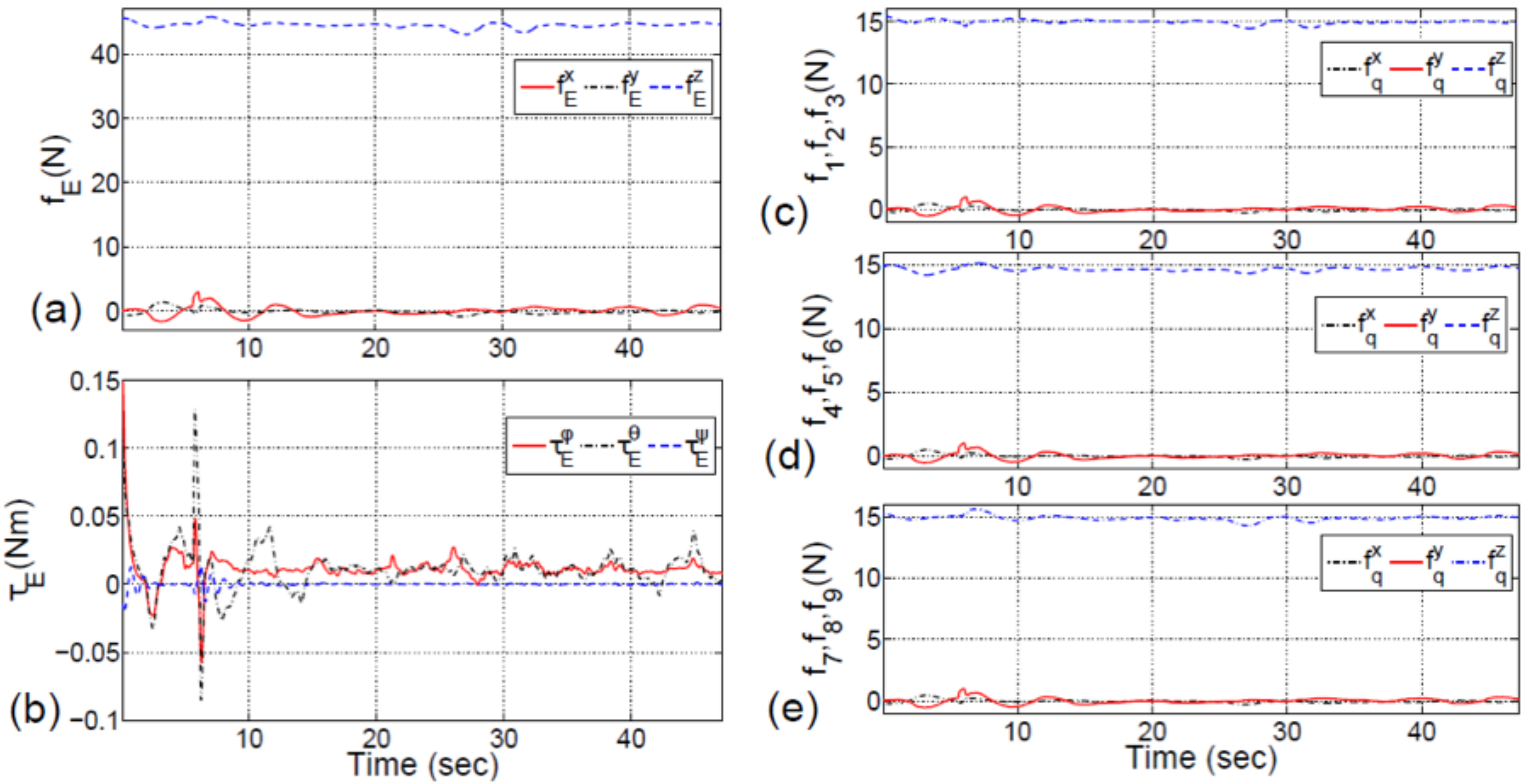
- Each VTOL generates a force vector by taking an appropriate thrust and attitude
- Extra DOFs allow to find the minimum smooth force while satisfying the system constraints

Human/Hardware In the Loop Simulation: Results





Human/Hardware In the Loop Simulation: Results



Haptic feedback preliminary tests

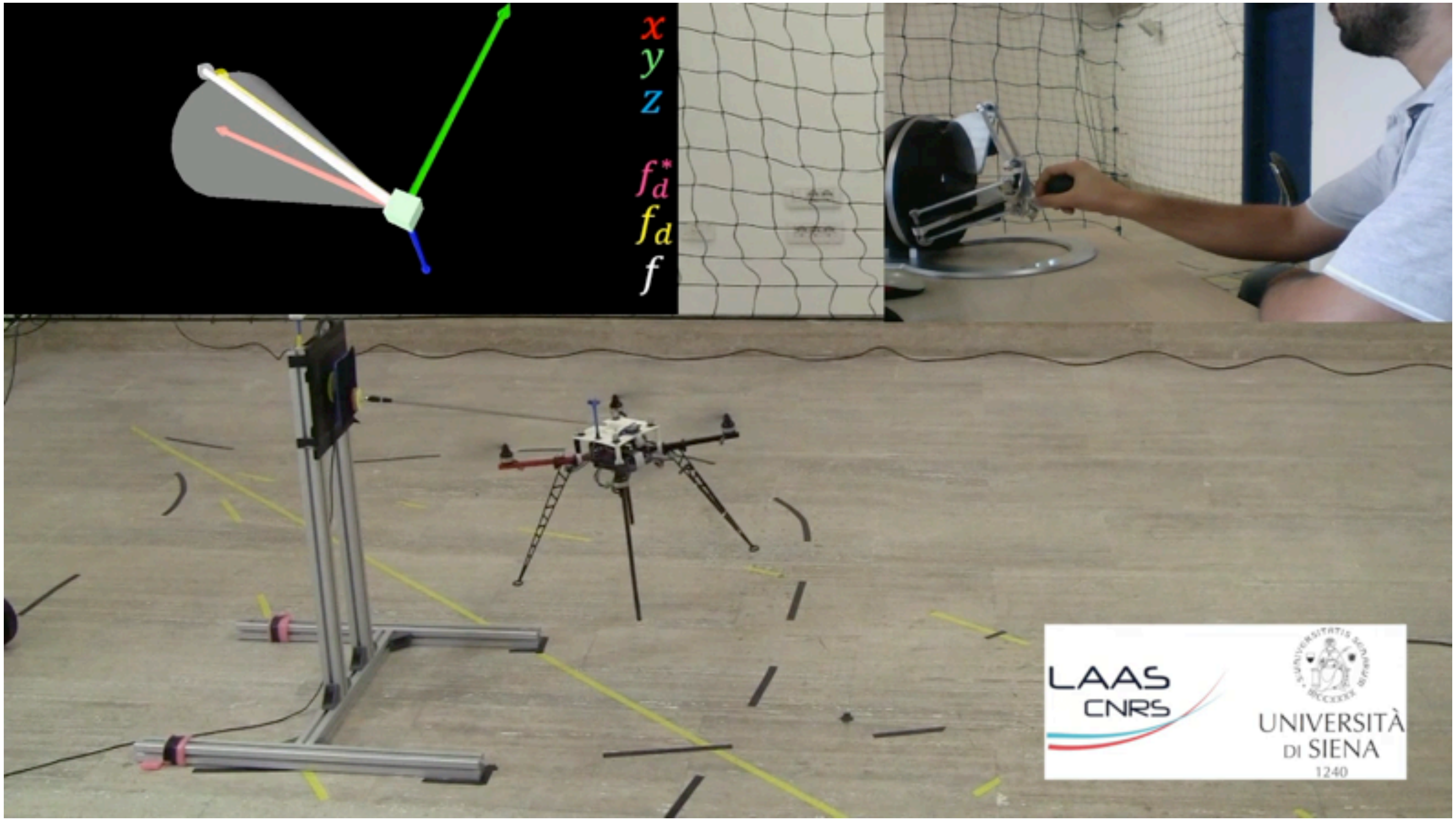
Time to complete the task and tracking performance for ten subjects.

	With haptic feedback	Without haptic feedback
Tracking performance $Avg.(Std.)$ m	0.134 (0.038)	0.172 (0.038)

$$\frac{1}{t_f}\int_0^{t_f} \|\tilde{x}\| dt$$

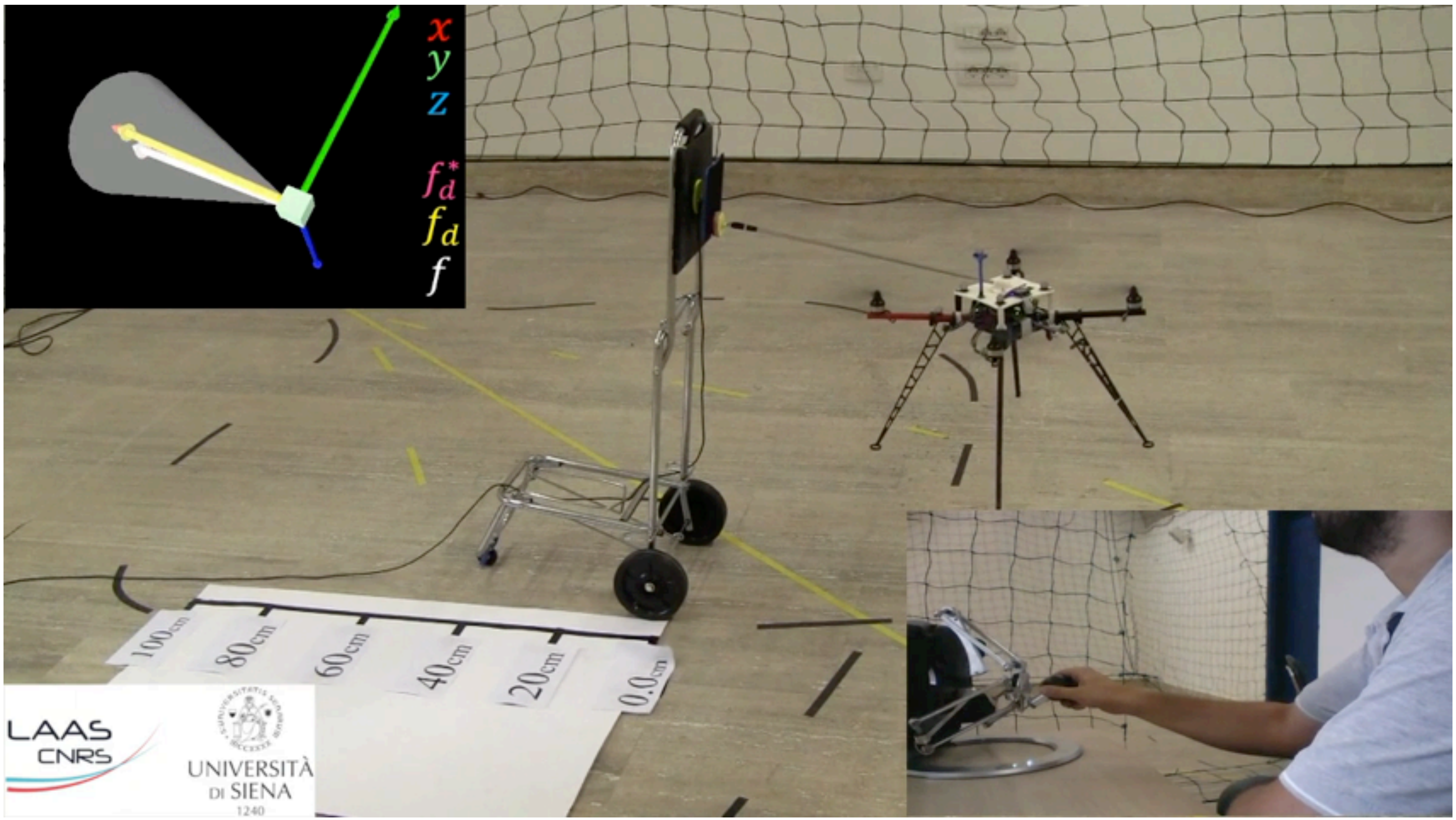
Preliminary experiments

- One finger
- No magnet
- Pushing against **static wall**



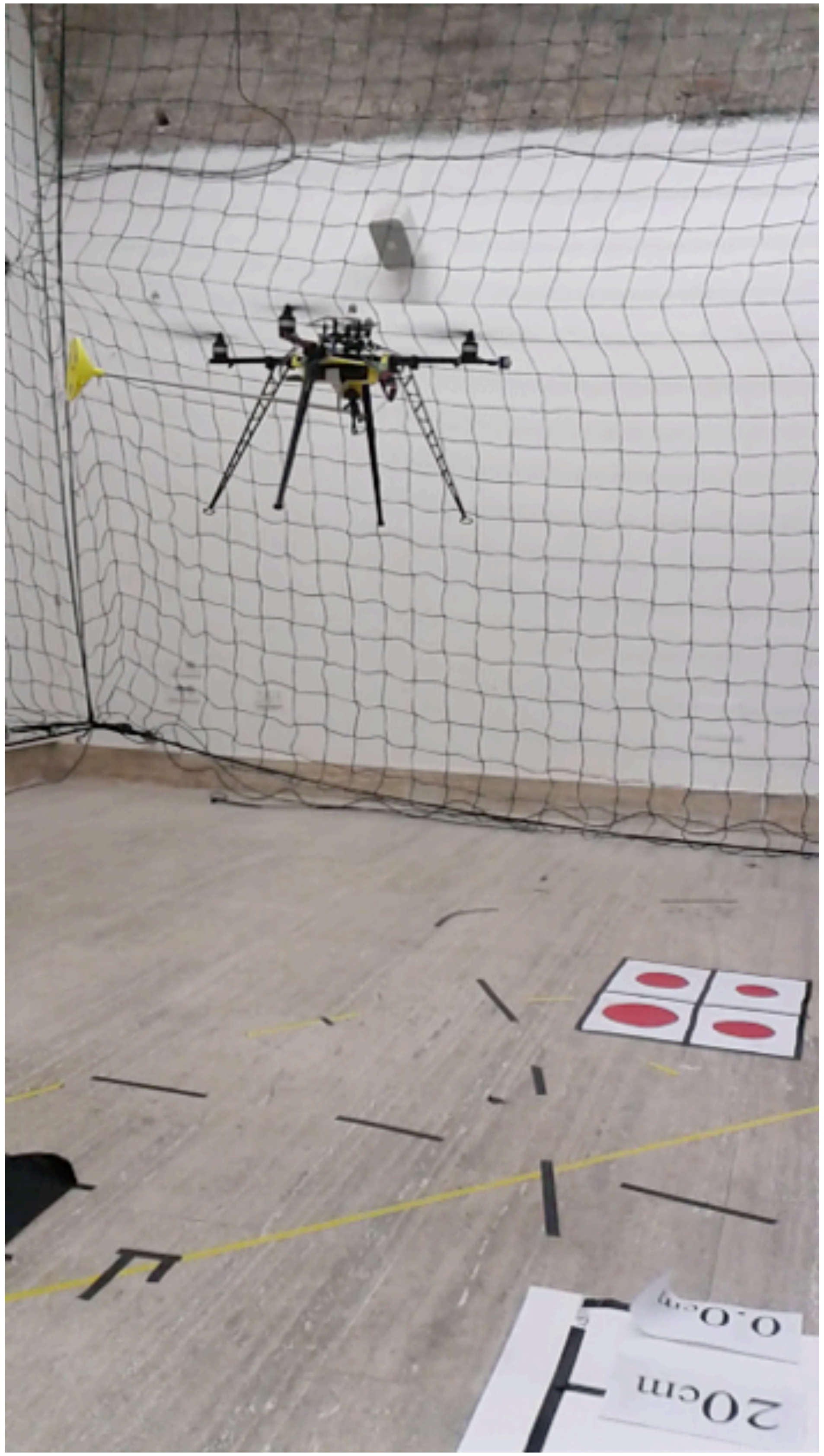
Preliminary experiments

- One finger
- No magnet
- Pushing against **moving object**



First experiment with magnetic finger

- One finger
- Magnet
- **Contact-free** flight



Conclusion

- Novel flying fingers/hand and unilateral contact mechanism for aerial multi-grasping
- Optimization used to distribute among aerial vehicles the forces to track object pose reference
- A human/hardware in the loop simulation study showed the efficiency of the proposed scheme
- Importance of haptic feedback in reducing the time to complete the task and also enhancing the tracking performance

Future Work

- Complete the real experiment
- Grasp planning
- Passivity layer
- Evaluate other haptic feedback policies
- Improve design of contact mechanism

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For more information:

Mohammadi M, Franchi A, Barcelli D, Prattichizzo D. Bilateral Parallel Position/Force Teleoperation of a Quadrotor UAV Equipped with a Lightweight Tool. (submitted)

Mohammadi M, Franchi A, Barcelli D, Prattichizzo D. Cooperative Aerial Tele-Manipulation with Haptic Feedback. In 2016 IEEE/RSJ Int. Conf. on Intelligent Robots and System. Daejeon, South Korea; 2016. pp. 5092-5098.

Gioioso G, Franchi A, Salvietti G, Scheggi S, Prattichizzo D. The Flying Hand: a Formation of UAVs for Cooperative Aerial Tele-Manipulation. In 2014 IEEE Int. Conf. on Robotics and Automation. Hong Kong, China; 2014. pp. 4335-4341.