

# From Biology to Robotics: The Role of Mathematics in Imitating Behavior.

## De la biologie à la robotique : le rôle des mathématiques dans l'imitation du comportement [1].

José Castillo<sup>1</sup>

<sup>1</sup> Aix-Marseille Université, ISM CNRS

November 23, 2023

# About patterns in nature

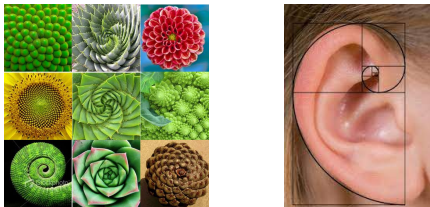


Figure: Fibonacci's sequence in nature

The Fibonacci sequence:

$$F_n = \begin{cases} 0 & n = 0 \\ 1 & n = 1 \\ F_{n-1} + F_{n-2} & n \geq 2 \end{cases} \quad (1)$$

# On the motion of bees...

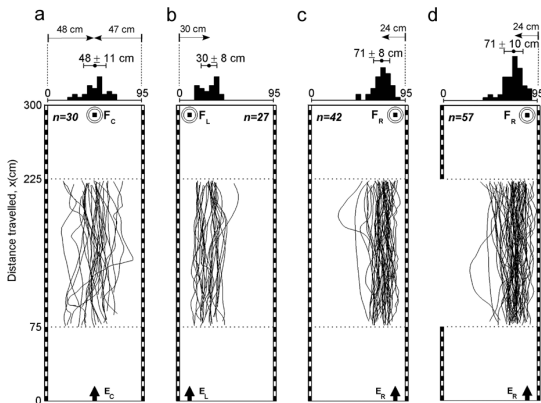


Figure: Bees in a corridor[2]

# On the motion of flies...

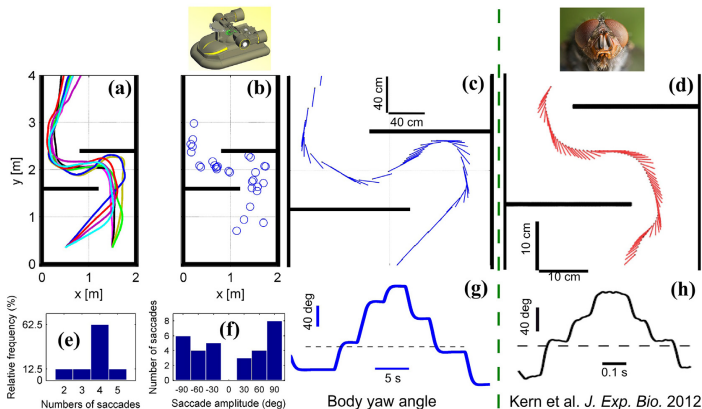


Figure: Robot vs Fly in a challenging environment [3]

# Optic Flow Based Navigation

Optic flow is the pattern of apparent motion of objects, surfaces, and edges in a visual scene caused by the relative motion between an observer and a scene:

$$\omega = \frac{v_x}{d_{y,z}} \quad (2)$$

The condition to follow:

$$\begin{bmatrix} \max(\omega_u + \omega_d, \omega_l + \omega_r) \\ \max(\omega_l, \omega_r) \\ \max(\omega_u, \omega_d) \end{bmatrix} = \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \quad (3)$$

$l = \text{left}$ ,  $r = \text{right}$ ,  $u = \text{upwards}$  and  $d = \text{downwards}$

# Outline

- 1 Introduction
- 2 Fully-Actuated Hexarotor (FAH) Model
  - FAH Dynamics
  - Unit Quaternion Representation
  - Under-Actuated Hexarotor (UAH) Dynamics
- 3 Optic Flow-Based Navigation Strategy
  - Attitude Stabilization
  - Triple Optic Flow Regulation
- 4 Results
  - Simulation Parameters
  - Simulation Results
- 5 Concluding Remarks

# Introduction

# Introduction

## Problem Statement

- Co-planar multirotors need bulky gimbal systems to stabilize their vision.
- *The usage of Fully-Actuated Multi-rotors may improve Optic Flow-based tasks, improving its own navigation capabilities.*

## Proposal

- Development of Adaptive Integral Sliding Mode Controllers (AI-SMCs) for a Fully-Actuated Hexarotor and the Optic Flow regulation in a 3D environment.
- Bio-inspired corridor navigation strategy, granting the hexarotor a bee-like behavior.



## Fully-Actuated Hexarotor (FAH) Model

# Outline

- 1 Introduction
- 2 Fully-Actuated Hexarotor (FAH) Model
  - FAH Dynamics
  - Unit Quaternion Representation
  - Under-Actuated Hexarotor (UAH) Dynamics
- 3 Optic Flow-Based Navigation Strategy
  - Attitude Stabilization
  - Triple Optic Flow Regulation
- 4 Results
  - Simulation Parameters
  - Simulation Results
- 5 Concluding Remarks

## Fully-Actuated Hexarotor (FAH) Model

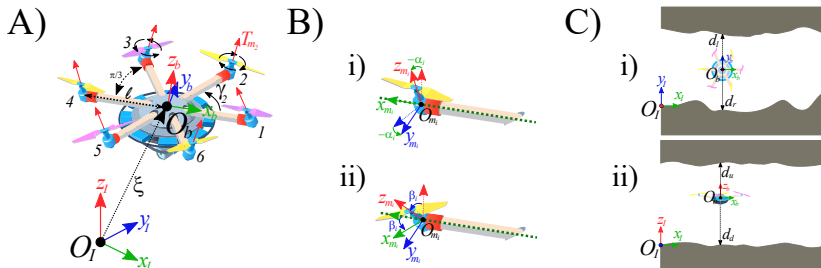


Figure: A) FAH geometrical description. B) Angles of the fixed tilted rotors. C) FAH in a corridor.

# Fully-Actuated Hexarotor (FAH) Model

## Newton-Euler Equations

$$m\ddot{\xi} + m\mathbf{g} = \boldsymbol{\tau}_{\xi} + \boldsymbol{\rho}_{\xi} \quad (4)$$

$$I\dot{\Omega} + \Omega \times (I\Omega) = \boldsymbol{\tau}_{\Omega} + \boldsymbol{\rho}_{\Omega} \quad (5)$$

$m > 0$  is the mass,  $I = \text{diag}(I_x, I_y, I_z) \in \mathfrak{R}^{3 \times 3}$  is the inertia matrix.  $\mathbf{g} = [0 \ 0 \ g]^T$  and  $\boldsymbol{\rho}_{\xi}$ ,  $\boldsymbol{\rho}_{\Omega} \in \mathfrak{R}^3$  represent external disturbances.

$\xi = [x \ y \ z]^T \in \mathfrak{R}^3$  denotes the position.  $\boldsymbol{\tau}_{\xi}, \boldsymbol{\tau}_{\Omega} \in \mathfrak{R}^3$  are the vector of external forces and moments.

The attitude of the vehicle is defined by the Euler angles  $\boldsymbol{\eta} = [\phi \ \theta \ \psi]^T \in \mathfrak{R}^3$ . The angular velocity  $\Omega = [p \ q \ r]^T \in \mathfrak{R}^3$  is related to the Euler rates  $\dot{\boldsymbol{\eta}}$ :

$$\Omega = W_{\boldsymbol{\eta}} \dot{\boldsymbol{\eta}} ; W_{\boldsymbol{\eta}} = \begin{bmatrix} 1 & 0 & -S_{\theta} \\ 0 & C_{\phi} & S_{\phi}C_{\theta} \\ 0 & -S_{\phi} & C_{\phi}C_{\theta} \end{bmatrix} \in \mathfrak{R}^{3 \times 3} \quad (6)$$

# Fully-Actuated Hexarotor (FAH) Model

## Translational Actuation

$$\boldsymbol{\tau}_{\xi} = \begin{bmatrix} \tau_x \\ \tau_y \\ \tau_z \end{bmatrix} = R_{\eta} \sum_{i=1}^6 R_{\eta_{m_i}} \begin{bmatrix} 0 \\ 0 \\ T_{m_i} \end{bmatrix} \quad (7)$$

Forces of the rotors:  $T_m^u \geq T_{m_i} \geq 0$  (with  $i = 1, 2, \dots, 6$  and  $T_m^u$  an upper bound).

$\boldsymbol{\eta}_{m_i} = [\alpha_i \ \beta_i \ \gamma_i]^T \in \mathfrak{R}^3$  comprises the fixed tilted angles  $\alpha_i$  and  $\beta_i$ , and  $\gamma_i = (i-1)\pi/3$ .

# Fully-Actuated Hexarotor (FAH) Model

## Rotational Actuation

$$\boldsymbol{\tau}_{\Omega} = \begin{bmatrix} \tau_{\phi} \\ \tau_{\theta} \\ \tau_{\psi} \end{bmatrix} = \sum_{i=1}^6 T_{m_i} \left\{ \zeta R_{\eta_{m_i}} \begin{bmatrix} 0 \\ 0 \\ (-1)^{i-1} \end{bmatrix} + \ell \left( R_{3,\gamma_i} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \right) \times \left( R_{\eta_{m_i}} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \right) \right\} \quad (8)$$

$\ell > 0$  is the arm length and  $\zeta > 0$  is a proportionality constant such that  $\tau_{m_i} = \zeta T_{m_i}$ .

# Outline

- 1 Introduction
- 2 Fully-Actuated Hexarotor (FAH) Model
  - FAH Dynamics
  - Unit Quaternion Representation
  - Under-Actuated Hexarotor (UAH) Dynamics
- 3 Optic Flow-Based Navigation Strategy
  - Attitude Stabilization
  - Triple Optic Flow Regulation
- 4 Results
  - Simulation Parameters
  - Simulation Results
- 5 Concluding Remarks

# Fully-Actuated Hexarotor (FAH) Model

## Rotation Matrix

$$R_{\mathbf{v}} = R_{3,v_3} R_{2,v_2} R_{1,v_1} = \begin{bmatrix} C_{v_3} & -S_{v_3} & 0 \\ S_{v_3} & C_{v_3} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} C_{v_2} & 0 & S_{v_2} \\ 0 & 1 & 0 \\ -S_{v_2} & 0 & C_{v_2} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & C_{v_1} & -S_{v_1} \\ 0 & S_{v_1} & C_{v_1} \end{bmatrix} \quad (9)$$

The rotation matrix can be rewritten in terms of the unit quaternion  $\mathbf{q} = [q_0 \mathbf{q}_v^T]^T \in \mathbb{R}^4$ :

$$R_{\mathbf{q}} = I_{3 \times 3} + 2 \left( q_0 [\mathbf{q}_v^\times] + [\mathbf{q}_v^\times]^2 \right) \quad (10)$$



# Fully-Actuated Hexarotor (FAH) Model

## Unit Quaternion Representation

The rotation of  $O_b$  w.r.t.  $O_I$  can be parameterized in terms of a rotation  $\vartheta \in \mathbb{R}$  about a fixed axis  $\mathbf{e}_v \in \mathbb{S}^2$  by the mapping  $\mathcal{U}(\vartheta, \mathbf{e}_v) = I_{3 \times 3} + S_\vartheta[\mathbf{e}_v^\times] + (1 - C_\vartheta)[\mathbf{e}_v^\times]^2$ . Hence,  $\mathbf{q} = [C_{\vartheta/2} \ S_{\vartheta/2} \mathbf{e}_v^T]^T$  and:

$$\dot{\mathbf{q}} = \begin{bmatrix} \dot{q}_0 \\ \dot{\mathbf{q}}_v \end{bmatrix} = \frac{1}{2} \begin{bmatrix} -\mathbf{q}_v^T \\ I_{3 \times 3} q_0 + [\mathbf{q}_v^\times] \end{bmatrix} \Omega = \frac{1}{2} \Xi \mathbf{q} \Omega \quad (11)$$

# Outline

- 1 Introduction
- 2 Fully-Actuated Hexarotor (FAH) Model
  - FAH Dynamics
  - Unit Quaternion Representation
  - Under-Actuated Hexarotor (UAH) Dynamics
- 3 Optic Flow-Based Navigation Strategy
  - Attitude Stabilization
  - Triple Optic Flow Regulation
- 4 Results
  - Simulation Parameters
  - Simulation Results
- 5 Concluding Remarks

# Fully-Actuated Hexarotor (FAH) Dynamics

## UAH Dynamics

Two different hexarotors for comparison:

- 1 a FAH
- 2 an UAH

The UAH dynamics can be derived from Eqs. (4) - (8) considering  $\alpha_i = \beta_i = 0^\circ$ .

## Underactuation

$$\phi_d = \text{atan} \left( \frac{\tau_x S_\psi - \tau_y C_\psi}{\sqrt{\tau_z^2 + (\tau_x C_\psi + \tau_y S_\psi)^2}} \right) \quad (12)$$

$$\theta_d = \text{atan} \left( (\tau_x C_\psi + \tau_y S_\psi) / \tau_z \right) \quad (13)$$

# Optic Flow-Based Navigation Strategy

# Outline

- 1 Introduction
- 2 Fully-Actuated Hexarotor (FAH) Model
  - FAH Dynamics
  - Unit Quaternion Representation
  - Under-Actuated Hexarotor (UAH) Dynamics
- 3 Optic Flow-Based Navigation Strategy
  - Attitude Stabilization
  - Triple Optic Flow Regulation
- 4 Results
  - Simulation Parameters
  - Simulation Results
- 5 Concluding Remarks

# Optic Flow-Based Navigation Strategy

## Translational Optic Flow

It is assumed that the vehicle attitude is stabilized at  $\mathbf{q}_s = [1 \ 0 \ 0 \ 0]^T$  such the vehicle receive a purely translational OF:

$$\omega_j = \dot{x}/d_j \quad \text{with } j \in \{r, l, u, d\} \quad (14)$$

where  $\dot{x}$  is the forward speed if  $\mathbf{q} \approx \mathbf{q}_s$ , and  $d_j$  denotes the distance to the corresponding surface.

# Optic Flow-Based Navigation Strategy

## Attitude Stabilization: Quaternion Error

The hexarotor is meant to hold a constant attitude  $\mathbf{q}_d = [q_{0_d} \mathbf{q}_{v_d}^T]^T$ . The quaternion error and its derivative are:

$$\mathbf{q}_e = \mathbf{q}_d^{-1} \otimes \mathbf{q} = \begin{bmatrix} \mathbf{q}_d^T \\ \equiv \\ \mathbf{q}_d \end{bmatrix} \mathbf{q} = [q_{0_e} \mathbf{q}_{v_e}^T]^T \quad (15)$$

$$\dot{\mathbf{q}}_e = \frac{1}{2} \mathbf{q}_d^{-1} \otimes \dot{\mathbf{q}} = \frac{1}{2} \begin{bmatrix} \mathbf{q}_d^T \\ \equiv \\ \mathbf{q}_d \end{bmatrix} \equiv \mathbf{q} \Omega = [\dot{q}_{0_e} \dot{\mathbf{q}}_{v_e}^T]^T \quad (16)$$

# Optic Flow-Based Navigation Strategy

## Attitude Stabilization: Adaptive Integral Sliding Mode Controller

- The sliding surfaces read as:

$$\boldsymbol{\sigma}_\eta = \begin{bmatrix} \sigma_\phi & \sigma_\theta & \sigma_\psi \end{bmatrix}^T = \Upsilon_\eta \dot{\mathbf{q}}_{v_e} + \Lambda_\eta \mathbf{q}_{v_e} + \boldsymbol{\varepsilon}_{q_v} \quad (17)$$

$$\dot{\boldsymbol{\sigma}}_\eta = \Upsilon_\eta \ddot{\mathbf{q}}_{v_e} + \Lambda_\eta \dot{\mathbf{q}}_{v_e} + \mathbf{q}_{v_e} = 0 \quad (18)$$

with  $\Upsilon_\eta = \text{diag}(v_\phi, v_\theta, v_\psi)$ ,  $\Lambda_\eta = \text{diag}(\lambda_\phi, \lambda_\theta, \lambda_\psi) \in \mathbb{R}^{3 \times 3}$  diagonal matrices containing the control gains  $v, \lambda > 0$ , and  $\boldsymbol{\varepsilon}_{q_v} = \int \mathbf{q}_{v_e} dt$ .

- The control input is defined by  $\mathbf{U}_\eta = \mathbf{u}_{\eta_o} + \mathbf{u}_{\eta_w} = [U_\phi \ U_\theta \ U_\psi]^T \in \mathbb{R}^3$ .
- To mitigate the nominal dynamics:

$$\mathbf{u}_{\eta_o} = -I \boldsymbol{\Xi}^T \left[ \boldsymbol{\Xi} \dot{\mathbf{q}} \boldsymbol{\Omega} + 2 \boldsymbol{\Xi} \mathbf{q}_d \Upsilon_\eta^{-1} (\Lambda_\eta \dot{\mathbf{q}}_{v_e} + \mathbf{q}_{v_e}) \right] + \boldsymbol{\Omega} \times (I \boldsymbol{\Omega})$$



# Optic Flow-Based Navigation Strategy

## Attitude Stabilization: Adaptive Integral Sliding Mode Controller

- To mitigate the external disturbances  $\rho_\Omega$ :

$$\mathbf{u}_{\eta_w} = -\Delta_\eta \tanh(\boldsymbol{\sigma}_\eta / \rho_\eta) \quad (19)$$

with  $\Delta_\eta = \text{diag}(\delta_\phi, \delta_\theta, \delta_\psi)$  a matrix of adjustable control gains  $\delta > 0$  and  $\rho_\eta > 0$  being a small real constant.

- $\Delta_\eta$  dynamics::

$$\dot{\Delta}_\eta = K_\eta^{-1} \mathfrak{A} \boldsymbol{\sigma}_\eta \quad (20)$$

with  $K_\eta = \text{diag}(\kappa_\phi, \kappa_\theta, \kappa_\psi) \in \mathbb{R}^{3 \times 3}$  ( $\kappa > 0$ ) and  $\mathfrak{A} \boldsymbol{\sigma}_\eta = \text{diag}(|\sigma_\phi|, |\sigma_\theta|, |\sigma_\psi|) \in \mathbb{R}^{3 \times 3}$ .

# Optic Flow-Based Navigation Strategy

## Attitude Stabilization: Stability Analysis

- Lyapunov candidate function  $V_\eta \in \mathbb{R}$ :

$$V_\eta = \frac{1}{2} \boldsymbol{\sigma}_\eta^T \boldsymbol{\sigma}_\eta + \frac{1}{2} \mathbf{l}_3^T (\Delta_\eta - \Delta_{\eta_d})^T K_\eta (\Delta_\eta - \Delta_{\eta_d}) \mathbf{l}_3 \quad (21)$$

where  $\mathbf{l}_3 \in \mathbb{R}^3$  is a vector of ones and  $|\Delta_{\eta_d}| > |\boldsymbol{\rho}_\Omega|$  the unknown terminal value reached by  $\Delta_\eta$ , such that  $\Delta_\eta \rightarrow \Delta_{\eta_d}$  as  $t \rightarrow \infty$ .

- Lyapunov candidate function derivative:

$$\dot{V}_\eta = \boldsymbol{\sigma}_\eta^T \dot{\boldsymbol{\sigma}}_\eta + \mathbf{l}_3^T (\Delta_\eta - \Delta_{\eta_d})^T \mathfrak{A} \boldsymbol{\sigma}_\eta \mathbf{l}_3 \quad (22)$$

It is evident that  $V_\eta \geq 0$ . Additionally,  $\dot{V}_\eta \leq 0$  since  $\boldsymbol{\sigma}_\eta^T \dot{\boldsymbol{\sigma}}_\eta \leq 0$  by definition,  $\Delta_\eta \leq \Delta_{\eta_d}$ ,  $|\Delta_{\eta_d}| > |\boldsymbol{\rho}_\eta|$  and  $\mathfrak{A} \boldsymbol{\sigma}_\eta \geq 0$ . Thus, asymptotic local stability is guaranteed.

# Outline

- 1 Introduction
- 2 Fully-Actuated Hexarotor (FAH) Model
  - FAH Dynamics
  - Unit Quaternion Representation
  - Under-Actuated Hexarotor (UAH) Dynamics
- 3 Optic Flow-Based Navigation Strategy
  - Attitude Stabilization
  - Triple Optic Flow Regulation
- 4 Results
  - Simulation Parameters
  - Simulation Results
- 5 Concluding Remarks

# Optic Flow-Based Navigation Strategy

## Triple Optic Flow Regulation: Translational Control

- A forward speed control loop: Regulates  $\dot{x}$  in order to keep the maximum sum of the two diametrically opposed OFs constant and equal to  $\omega_x = 4.57$  rad/s.
- A positioning control loop: Regulates the distance w.r.t. the walls and the ground or the roof such that  $\max(\omega_l, \omega_r) \rightarrow \omega_y = 2.4$  rad/s and  $\max(\omega_u, \omega_d) \rightarrow \omega_z = 2.4$  rad/s.

## Triple Optic Flow Regulation: Optic Flow Errors

The OF errors are defined as:

$$\mathbf{e}_{\omega_{\xi}} = \begin{bmatrix} e_{\omega_x} \\ e_{\omega_y} \\ e_{\omega_z} \end{bmatrix} = \begin{bmatrix} \int (\max(\omega_u + \omega_d, \omega_l + \omega_r) - \omega_x) dt \\ \max(\omega_l, \omega_r) - \omega_y \\ \max(\omega_u, \omega_d) - \omega_z \end{bmatrix} \quad (23)$$

# Optic Flow-Based Navigation Strategy

## Triple Optic Flow Regulation: Adaptive Integral Sliding Mode Controller

The sliding surfaces are:

$$\boldsymbol{\sigma}_\xi = \begin{bmatrix} \sigma_x & \sigma_y & \sigma_z \end{bmatrix}^T = \Upsilon_\xi \dot{\mathbf{e}}_{\omega_\xi} + \Lambda_\xi \mathbf{e}_{\omega_\xi} + \boldsymbol{\varepsilon}_{\omega_\xi} \quad (24)$$

$$\dot{\boldsymbol{\sigma}}_\xi = \Upsilon_\xi \ddot{\mathbf{e}}_{\omega_\xi} + \Lambda_\xi \dot{\mathbf{e}}_{\omega_\xi} + \mathbf{e}_{\omega_\xi} = 0 \quad (25)$$

with  $\Upsilon_\xi = \text{diag}(v_x, v_y, v_z)$ ,  $\Lambda_\xi = \text{diag}(\lambda_x, \lambda_y, \lambda_z) \in \mathbb{R}^{3 \times 3}$  diagonal matrices containing the control gains  $v, \lambda > 0$ , and  $\boldsymbol{\varepsilon}_{\omega_\xi} = \int \mathbf{e}_{\omega_\xi} dt$ .

# Optic Flow-Based Navigation Strategy

## Triple Optic Flow Regulation: Adaptive Integral Sliding Mode Controller

Since  $\omega_j > 0$ , an additional step must be considered to define the control input

$\mathbf{U}_\xi = [U_x \ U_y \ U_z]^T \in \mathbb{R}^3$ . The auxiliary control input  $\mathbf{u}_\xi = [u_x \ u_y \ u_z]^T \in \mathbb{R}^3$  is:

$$\mathbf{u}_\xi = -\Upsilon_\xi^{-1} \left( \Lambda_\xi \dot{\mathbf{e}}_{\omega_\xi} + \mathbf{e}_{\omega_\xi} \right) - \Delta_\xi \tanh \left( \boldsymbol{\sigma}_\xi / \rho_\xi \right) \quad (26)$$

where  $\rho_\xi > 0$  is a small real constant and  $\Delta_\xi = \text{diag} (\delta_x, \delta_y, \delta_z) \in \mathbb{R}^{3 \times 3}$  is an adjustable control gain matrix whose dynamics is defined as:

$$\dot{\Delta}_\xi = K_\xi^{-1} \mathfrak{Q} \boldsymbol{\sigma}_\xi \quad (27)$$

with  $K_\xi = \text{diag} (\kappa_x, \kappa_y, \kappa_z) \in \mathbb{R}^{3 \times 3}$  (such that  $\kappa > 0$ ) and

$\mathfrak{Q} \boldsymbol{\sigma}_\xi = \text{diag} (|\sigma_x|, |\sigma_y|, |\sigma_z|) \in \mathbb{R}^{3 \times 3}$ .

# Optic Flow-Based Navigation Strategy

## Triple Optic Flow Regulation: Adaptive Integral Sliding Mode Controller

According to the largest of the OFs,  $\mathbf{U}_\xi$  is written as:

$$\mathbf{U}_\xi = \begin{bmatrix} U_x \\ U_y \\ U_z \end{bmatrix} \quad \text{with} \quad \begin{cases} U_x = mu_x \\ U_y = \begin{cases} mu_y & \omega_l > \omega_r \\ -mu_y & \text{else} \end{cases} \\ U_z = \begin{cases} m(u_z + g) & \omega_u > \omega_d \\ -m(u_z - g) & \text{else} \end{cases} \end{cases} \quad (28)$$

To compute the forces  $T_{m_j}$ :  $\boldsymbol{\tau}_\xi = \mathbf{U}_\xi$  and  $\boldsymbol{\tau}_\Omega = \mathbf{U}_\eta$ .

# Optic Flow-Based Navigation Strategy

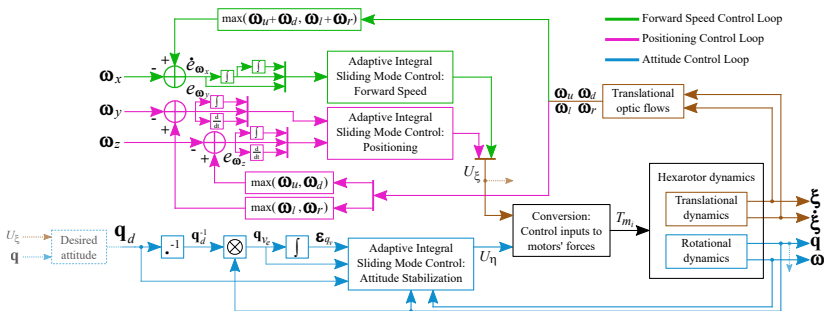


Figure: Control diagram including the triple OF regulation for FAH and UAH (faded elements are necessary for UAH).



# Results

# Outline

- 1 Introduction
- 2 Fully-Actuated Hexarotor (FAH) Model
  - FAH Dynamics
  - Unit Quaternion Representation
  - Under-Actuated Hexarotor (UAH) Dynamics
- 3 Optic Flow-Based Navigation Strategy
  - Attitude Stabilization
  - Triple Optic Flow Regulation
- 4 Results
  - Simulation Parameters
  - Simulation Results
- 5 Concluding Remarks

# Results

Table: Hexacopters parameters

Hexarotor platform		
Property/Parameter	FAH	UAH
$m$ [kg]	0.05	
$I_x, I_y, I_z$ [kg mm <sup>2</sup> ]	140, 197, 250	
$\ell$ [m]	0.04	
$\zeta$ [m]	0.3	
$\alpha_i$ [deg]	$(-1)^i 25$	0
$\beta_i$ [deg]	0	
$T_m^u$ ( $T_{m_i}$ upper bound) [N]	0.015	
$g$ [m/s <sup>2</sup> ]	9.81	

# Results

Table: Controllers parameters

Control gains		
Gains	FAH	UAH
$v_x, \lambda_x, \delta_{x_0}, \kappa_x$	1.1, 2, 0.15, 1000	
$v_y, \lambda_y, \delta_{y_0}, \kappa_y$	0.5, 0.45, 0.05, 1000	
$v_z, \lambda_z, \delta_{z_0}, \kappa_z$	0.5, 0.25, 2, 1000	
$v_\phi, \lambda_\phi, \delta_{\phi_0}, \kappa_\phi$	0.01, 2, 1, 1	0.002, 0.075, 0.01, 1000
$v_\theta, \lambda_\theta, \delta_{\theta_0}, \kappa_\theta$		
$v_\psi, \lambda_\psi, \delta_{\psi_0}, \kappa_\psi$		0.0005, 0.175, 0.01, 1000
$\rho_\xi, \rho_\eta$	0.1, 0.01	

# Outline

- 1 Introduction
- 2 Fully-Actuated Hexarotor (FAH) Model
  - FAH Dynamics
  - Unit Quaternion Representation
  - Under-Actuated Hexarotor (UAH) Dynamics
- 3 Optic Flow-Based Navigation Strategy
  - Attitude Stabilization
  - Triple Optic Flow Regulation
- 4 Results
  - Simulation Parameters
  - Simulation Results
- 5 Concluding Remarks

# Results

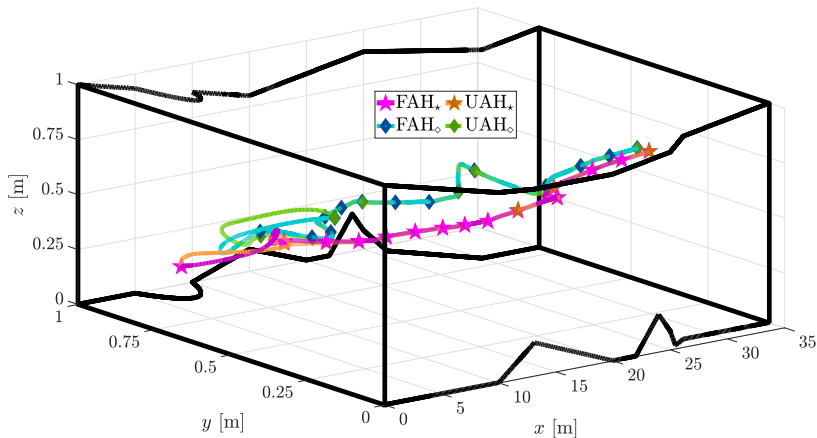


Figure: 3D motion.

## Results

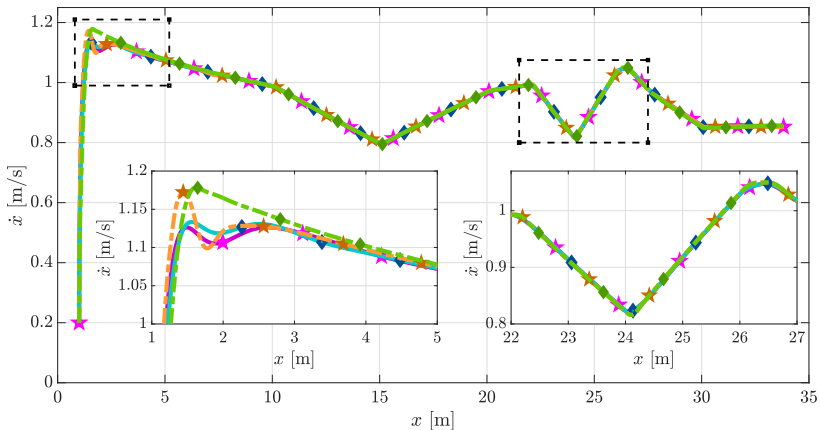
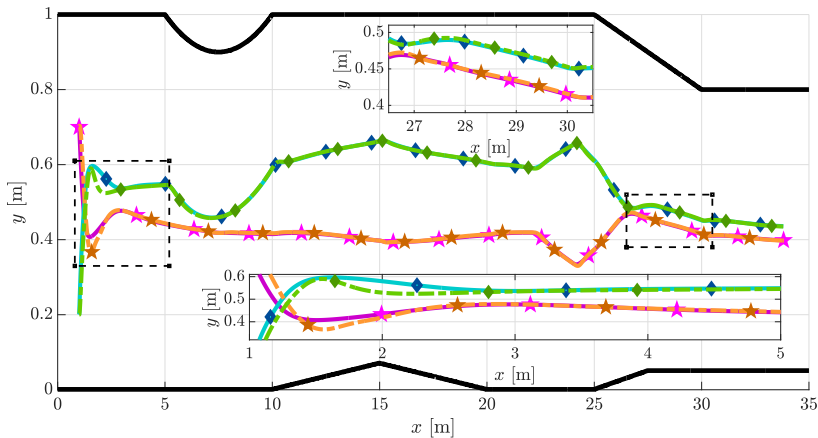


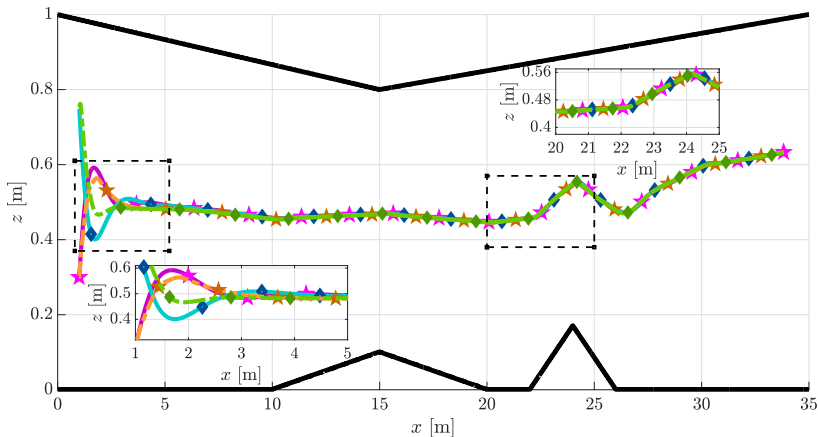
Figure: Forward velocity.

## Results

Figure: Position along  $y_l$ .



## Results

Figure: Position along  $z_l$ .

## Results

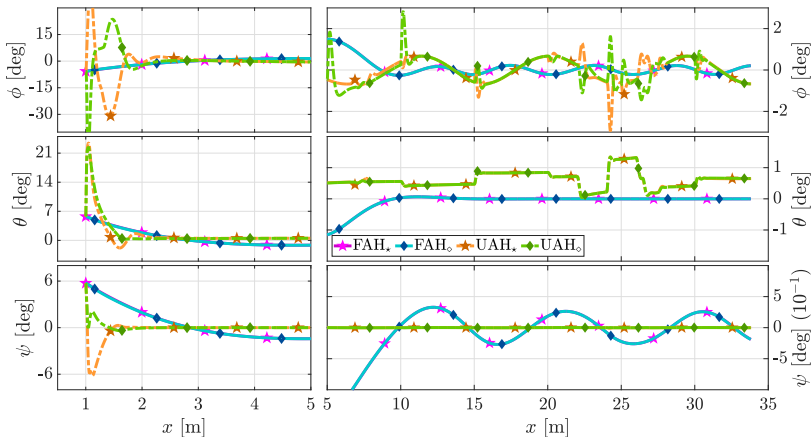


Figure: Attitude.

## Results

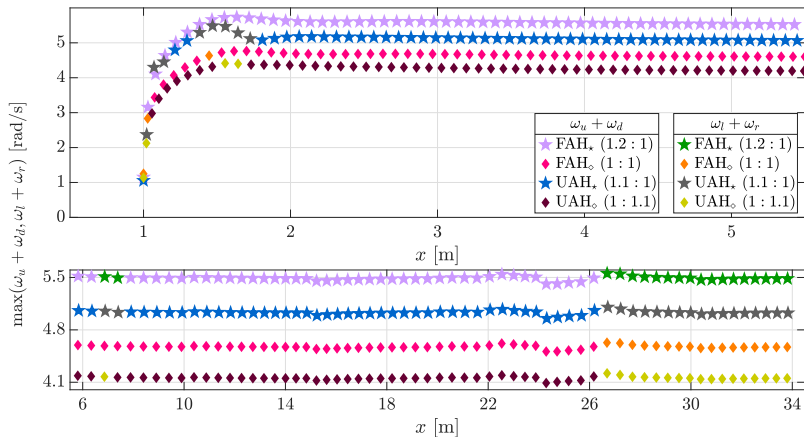


Figure: Maximum sum of the two diametrically opposed OFs (some OFs have been scaled).

## Results

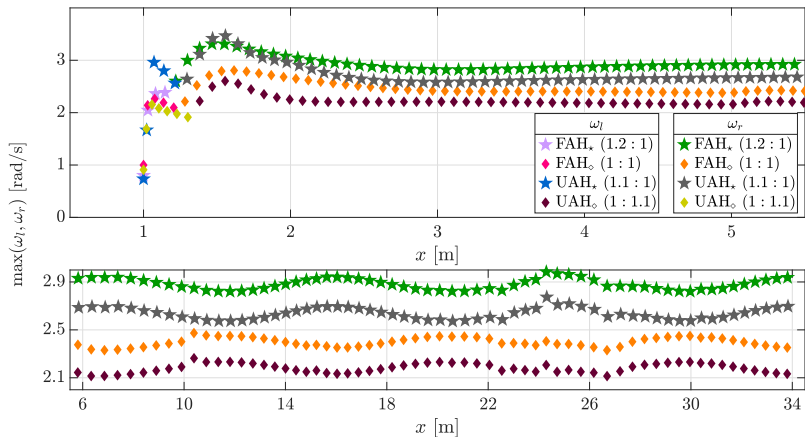


Figure: Maximum lateral OFs (some OFs have been scaled).

## Results

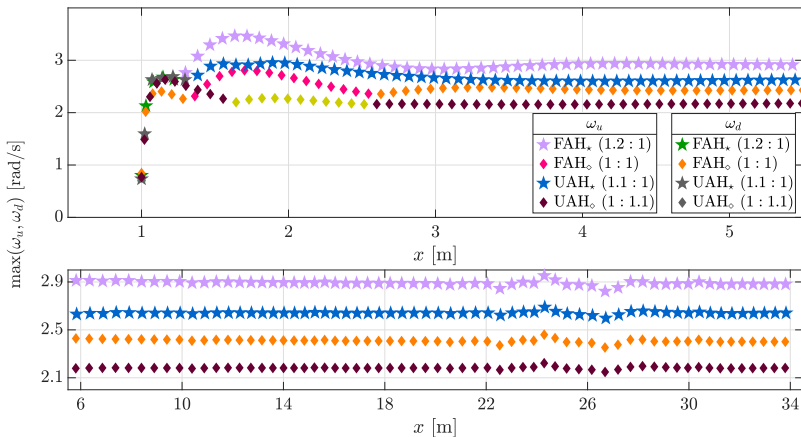


Figure: Maximum vertical OFs (some OFs have been scaled).

# Results

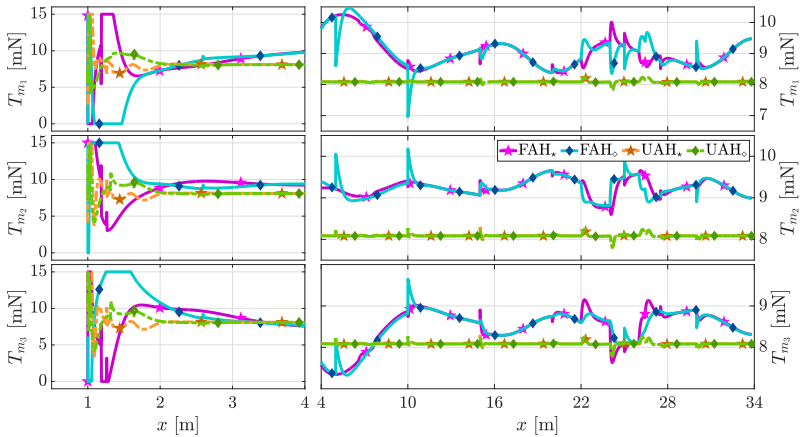


Figure: Forces comparison: Rotors 1, 2 and 3.

## Results

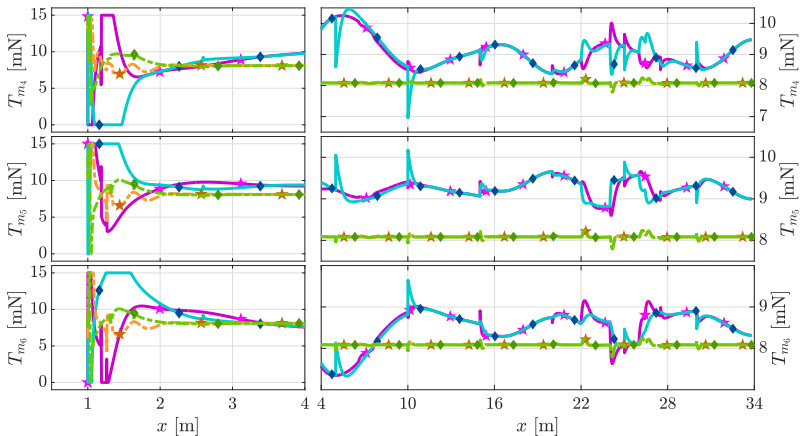


Figure: Forces comparison: Rotors 4, 5 and 6.

## Concluding Remarks



# Concluding Remarks

## Concluding Remarks and Future Work

- A corridor honeybee-inspired navigation strategy based on OF has been adapted to a FAH.
- Vehicles navigate through a straight corridor while reacting actively to the irregularities of the surfaces.
- Future works:
  - Rotational optic flow perturbation
  - Different control techniques
  - Bio-inspired data fusion and odometry
  - Real experimentation in more complex scenarios

# Concluding remarks

# THANK YOU FOR YOUR ATTENTION



# References I



J. J. Castillo-Zamora, L. Bergantin, and F. Ruffier, “Corridor 3d navigation of a fully-actuated multirotor by means of bee-inspired optic flow regulation,” in **2022 26th International Conference on System Theory, Control and Computing (ICSTCC)**. IEEE, 2022, pp. 318–324.



J. R. Serres, G. P. Masson, F. Ruffier, and N. Franceschini, “A bee in the corridor: centering and wall-following,” **Naturwissenschaften**, vol. 95, pp. 1181–1187, 2008.



J. R. Serres and F. Ruffier, “Optic flow-based collision-free strategies: From insects to robots,” **Arthropod structure & development**, vol. 46, no. 5, pp. 703–717, 2017.