Quadrotor Modeling and Control for DLO Transportation

Thesis dissertation

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Abstract

- The **contributions** of the thesis deal with:
  - proposal of **DLO and quadrotor model**
  - new **transport configuration**
  - **offline/online control** strategy

Outline

Outline

Motivation

The growing availability of cheap and robust drones widens drone possibilities and pose new challenges:

- Turn up of new drone applications
- Better performance of cooperative quadrotor systems
- Necessity of autonomy and minimum human intervention

Motivation

A recently proposed challenging task for Unmanned Aerial Vehicles (UAV) is the transportation of deformable linear objects (DLO), i.e. cables, by a team of quadrotors, which can be extremely useful in emergency situations.

Motivation

Current tasks developed with drone teams and DLO transport:

- Tethered quadrotors
- Industrial applications (high-voltage renewal with drones)
- ETH (Zurich): Rope bridge building with quadrotors

Motivation

The physical configuration of an instance of the system with three quadrotors is represented next, where three drones are sustaining a DLO hanging freely in the space in stationary state.

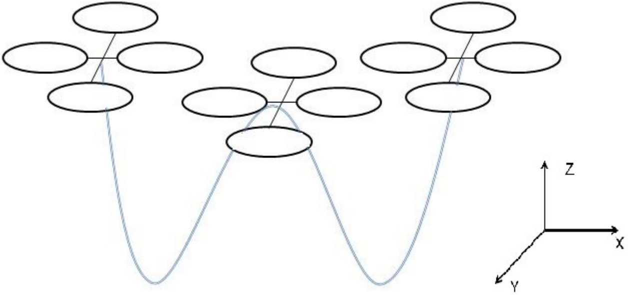


Figure: *Stylized physical representation of three drones carrying a DLO*

- This thesis has been carried out in a **simulated environment**.
- As a consequence, **dynamic modeling of different elements becomes necessary**.

Objectives

1. Building an accurate dynamic simulation model of the DLO + quadrotor team
2. Define a spatial configuration of the quadrotors in which the energy consumption is the same for all
3. Propose robust drone control that carries out the desired task under the load and perturbations induced by the DLO and external perturbations

Outline

Introduction

Deformable Linear Objects (DLO)

- Ropes, cables, and sutures
- Dynamics, graphic representation, material behaviour and deformation
- Some DLO properties are finely represented while sacrificing other ones
- Cosserat rods; splines; Geometric Exact Dynamic Splines
- **This work uses catenaries**

Advantages

The advantages of using **catenaries** as our DLO model to transport are stated next:

- Perform a good analysis of effects of joints, both in 2D and 3D
- Low computation cost at simulations
- Stablished static formulas
- Catenaries usage is an innovation

Parameters

Geometric parameters of the catenary:

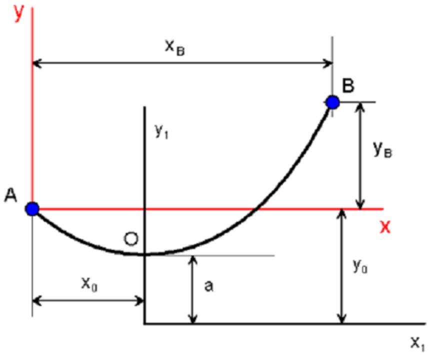
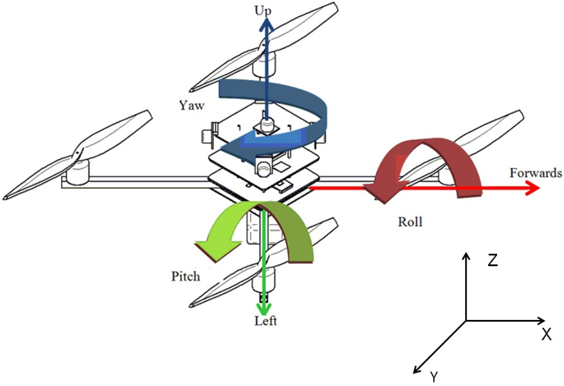


Figure: *Catenary curve modeling a DLO holding between robots A and B*

Outline

Degrees of freedom

- A quadrotor has **6 dofs and 4 inputs**: nonlinear interactions.
- Cross-configuration



Quadrotor equations

- **Angular accelerations**

$$\left\{ \begin{array}{l} \ddot{\phi} = \frac{U_2}{I_{xx}} \\ \ddot{\theta} = \frac{U_3}{I_{yy}} \\ \ddot{\psi} = \frac{U_4}{I_{zz}} \end{array} \right\}, \tag{1}$$

- **Linear accelerations**

$$\left\{ \begin{array}{c} \ddot{x} = \frac{(-\cos\phi\sin\theta\cos\psi - \sin\phi\sin\psi)}{m} U_1 \\ \ddot{y} = \frac{(-\cos\phi\sin\theta\sin\psi - \sin\phi\cos\psi)}{m} U_1 \\ \ddot{z} = \frac{(\cos\phi\cos\theta)U_1}{m} - g \end{array} \right\}, \tag{2}$$

Quadrotor equations

- **Torques and Thrust**

$$\left\{ \begin{array}{c} U_1 = b\left(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2\right), \\ U_2 = l \cdot b\left(-\Omega_2^2 + \Omega_4^2\right), \\ U_3 = l \cdot b\left(-\Omega_1^2 - \Omega_3^2\right), \\ U_4 = d\left(-\Omega_1^2 + \Omega_2^2 - \Omega_3^2 + \Omega_4^2\right) \end{array} \right\}, \tag{3}$$

Outline

Quadrotor control system

Quadrotor translation is ruled by two feedback cascade circuits: **inner-loop and outer-loop control circuits**.

- **Inner-loop:** in charge of reaching the desired altitude and attitude. The controller acts on different torques and thrust of the quadrotor (**attitude control**).
- **Outer-loop:** controls the navigation to a specific point in space (**translational control**), so that it calculates the desired quadrotor angles in order to move horizontally.

Quadrotor control system

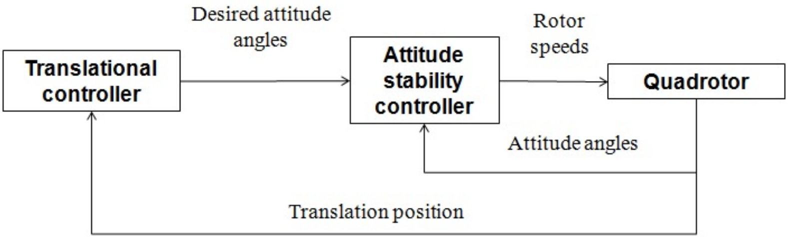


Figure: Each quadrotor equips same structure

Inner-loop control circuit

Inner-loop control circuit

- We use four **independent** PID controllers for the roll, pitch, yaw and height, respectively, which are the degrees of freedom of each quadrotor.
- K_P, K_I and K_D are the three parameters of the controllers to be tuned.
- All the quadrotors in the team equip the same PID values.

Inner-loop control circuit

A PID circuit for each degree of freedom

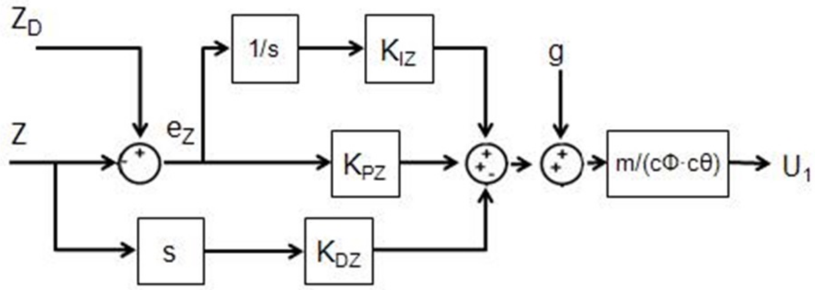


Figure: PID Z controller

Outer-loop control circuit

Outer-loop control circuit

- In charge of adjusting desired angles depending on the position in the space to move.
- Control **is decentralized**.
- The circuit is divided in two parts, each one for a direction on the plane.
- PD controllers were used.

Outer-loop control circuit

- θ for X direction; ϕ for Y direction

$$\begin{cases} \phi_d = -\arcsin\left(\frac{u_y \cdot m}{U_1}\right) \\ \theta_d = \arcsin\left(\frac{u_x m}{U_1 \cos\phi}\right) \end{cases}, \tag{4}$$

$$\begin{cases} u_x = \ddot{x}_d + K_{dx}(\dot{x}_d - \dot{x}) + K_{px}(x_d - x) \\ u_y = \ddot{y}_d + K_{dy}(\dot{y}_d - \dot{y}) + K_{py}(y_d - y) \end{cases}. \tag{5}$$

Outline

Formation constraints

- A **leader-following strategy** is implemented.
- Considering this aspect and DLO transport, a series of constraints turn up.

Formation constraints

Quadrotor formation constraints. It stablishes the condition of relative movement among drones:

- Column formation
- Distance among drones must be maintained
- Follower quadrotor must tend to maintain 180 degrees of the leader heading direction

Quadrotors formation

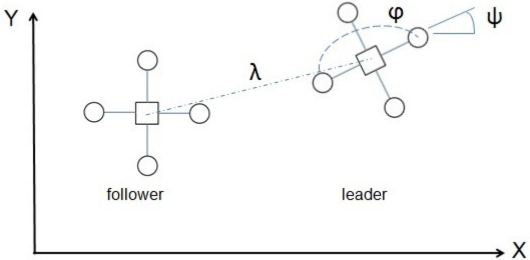


Figure: Follow-the-leader behavior parameters: distance (λ) between quadrotors positions, and heading angular difference (φ) parameters

Quadrotors formation

- The desired position of a follower robot related to the leader robot is given by:

$$\begin{cases} x_F = x_L + \lambda_X \cos(\psi_L) - \lambda_Y \sin(\psi_L) \\ y_F = y_L + \lambda_X \sin(\psi_L) + \lambda_Y \cos(\psi_L) \end{cases}, \tag{6}$$

$$\begin{cases} \lambda_X = \lambda \cos(\varphi) \\ \lambda_Y = \lambda \sin(\varphi) \end{cases}, \tag{7}$$

Outline

Characteristics

Characteristics of the equi-load configuration:

- Goal: Equal energy expenditure for all the drones
- Identical vertical forces exerted by the DLO on all quadrotors.
- Equi-load configuration is obtained by catenary nodes height adaption
- Valid for different lengths, non-symmetric catenaries, weights per unit and distances of catenary.

Characteristics

Catenary strength parameters:

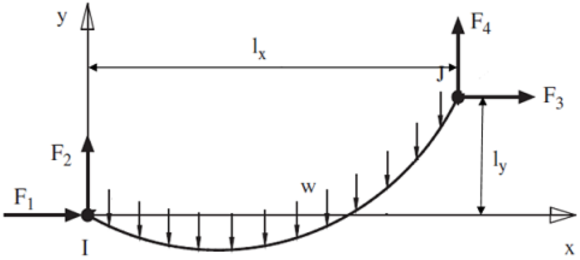


Figure: Catenary static parameters

Characteristics

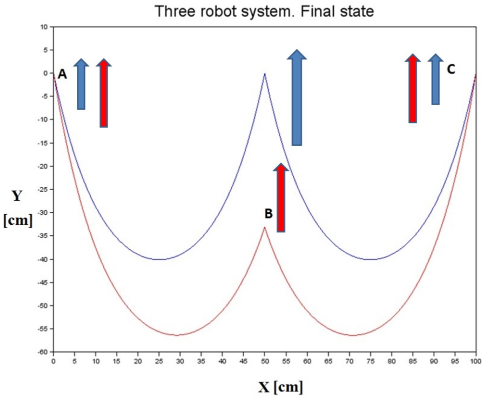
Catenary strength parameters:

$$\begin{cases} F_1 = -\frac{w \cdot l_x}{2 \cdot \lambda_0} \\ F_2 = \frac{w}{2}\left(-l_y \coth\left(\lambda_0\right) + L_0\right) \\ F_3 = -F_1 \\ F_4 = w \cdot L_0 - F_2 \end{cases}, \qquad (8)$$

$$\lambda_0 = \left\{ \begin{array}{ccc} 10^6 & \text{if} & (l_x^2 + l_y^2) = 0 \\ 0.2 & \text{if} & (L_0^2 \leq l_x^2 + l_y^2 + l_z^2) \\ \sqrt{3\left(\frac{L_0^2 - y^2}{l_x^2} - 1\right)} & \text{if} & (L_0^2 \geq l_x^2 + l_y^2 + l_z^2) \end{array} \right\}, \qquad (9)$$

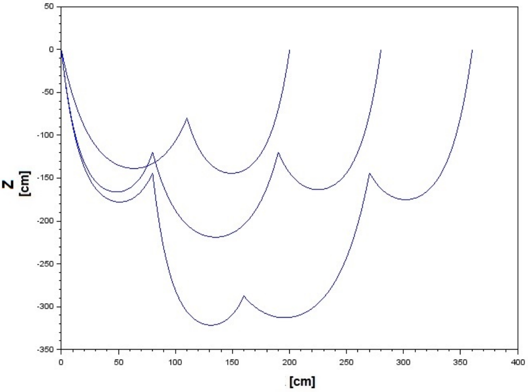
Characteristics

Three robots, symmetric system



Characteristics

The system is scalable:



Control Challenges

Problems to solve:

- Control structure is introduced. However, specific tuning is necessary in order to achieve a **stable and robust** transport system.
- The system must be able to **compensate external and variable perturbations**.
- **Inner and outer loop control circuits** must be tuned.
- Little bibliography deals with control of quadrotor manipulating DLO.

Outline

Challenges. Inner-loop control tuning

Inner-loop control circuit tuning:

Two experiments were carried out to tune PIDs:

- A comparison between Ziegler-Nichols and Particle Swarm Optimization.
- Check equi-load configuration adaptability during DLO transport.

Challenges. Inner-loop control tuning

Experiment 1a: Vertical descend

- Two symmetric catenaries measuring 200cm long each
- $\Delta y = 66.54cm$
- Time increment used to compute simulation steps is 0.1 seconds
- Quadrotor angles maintain to 0

Challenges. Inner-loop control tuning

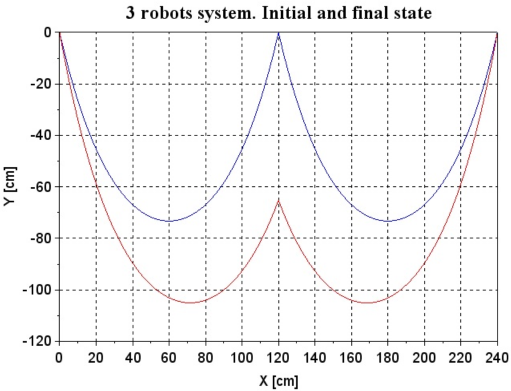
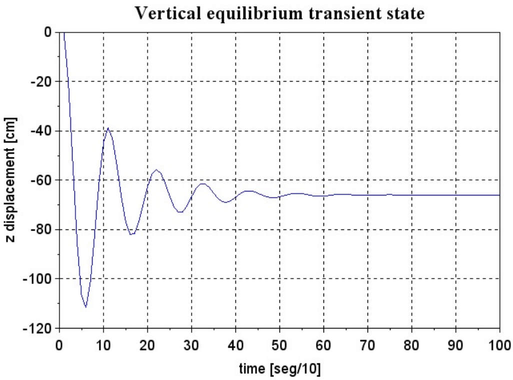


Figure: Catenary and three robots system for *Experiment 1a*

Challenges. Inner-loop control tuning

Experiment 1a: Vertical descend

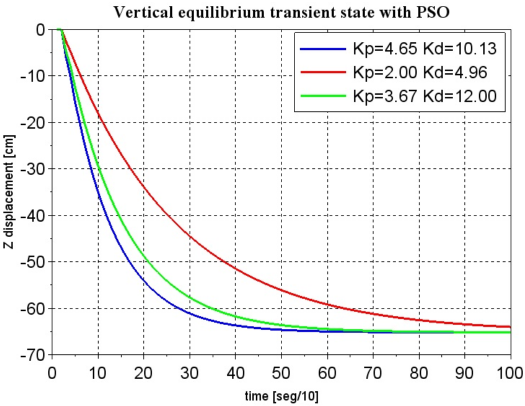
- Ziegler-Nichols



Challenges. Inner-loop control tuning

Experiment 1a: Vertical descend

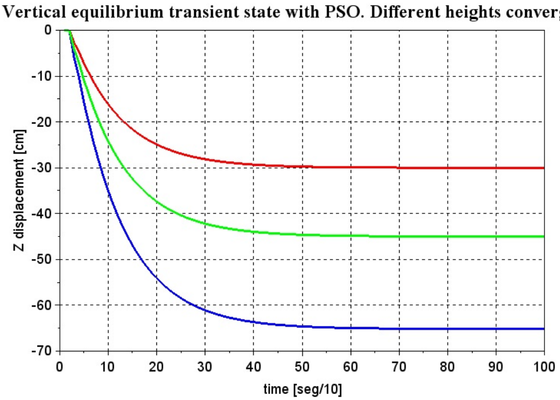
- Particle Swarm Optimization. Only Proportional-Derivative



Challenges. Inner-loop control tuning

Experiment 1a: Vertical descend

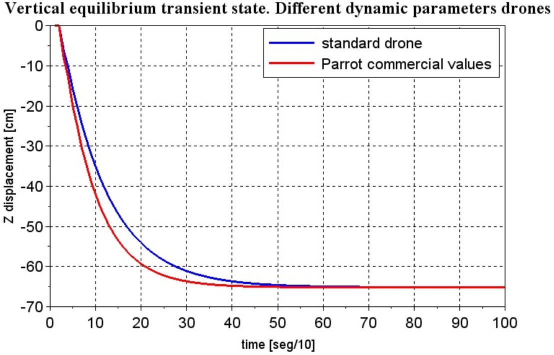
- Particle Swarm Optimization for different height objectives



Challenges. Inner-loop control tuning

Experiment 1a: Vertical descend

- Particle Swarm Optimization for different quadrotor dynamic parameters



Challenges. Inner-loop control tuning

Experiment 1b: Height adaption

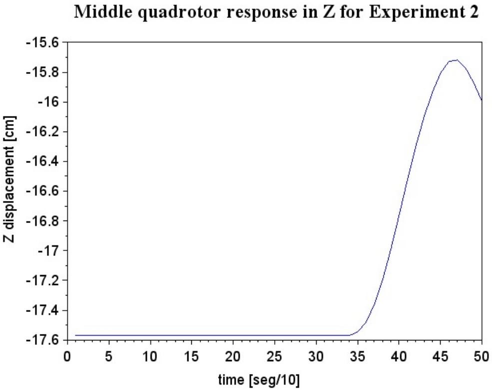
Experiment consists in checking whether a sudden misfunction of any drone in the system is compensated by the rest.

- Two symmetric catenaries measuring 70cm long each
- Horizontal distance among the nodes of 50cm
- At t=3.6" till t=4.5", leader quadrotor in the column accelerates for a short period

Challenges. Inner-loop control tuning

Experiment 1b: Height adaption

- PDs tuned by Particle Swarm Optimization



Outline

Challenges. Outer-loop control tuning

- **Inner-loop control circuit** has been tuned with offline PSO algorithm.
  - These values remain constant for coming experiments
- **Outer-loop control circuit**, in charge of calculating the desired angles to move to a point in space, is going to be tuned with:
  - Basic offline tuning (PSO)
  - Fuzzy based adaptive modulation + improved quadrotor formation

Challenges. Outer-loop control tuning

Outer-loop control circuit:

Experiment: Two cost-functions for PSO tuning

- **CF1:** Optimize the PD parameters to minimize the overshoot of the quadrotor in X direction
- **CF2:** Optimize the PD parameters to minimize the overshoot in $(X; Y)$ plane.

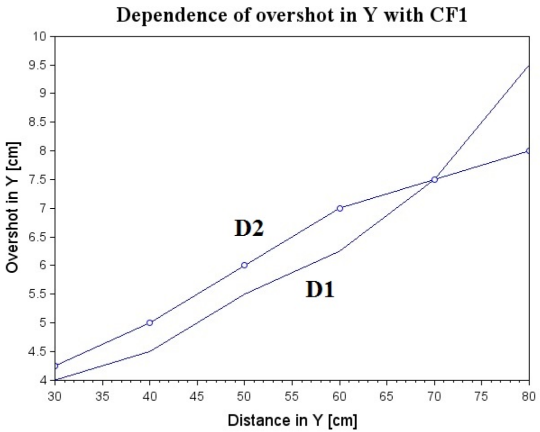
Challenges. Outer-loop control tuning

Experiment: Horizontal motion with simmetry

- Three quadrotors must reach the $(x_{0,i} + \Delta x, y_{0,i} + \Delta y)$
  - Catenary section of $L_0 = 300cm$ and horizontal distance between drones is $120cm$
  - $\Delta y = 99.9cm$
  - Initial state for the simulation is set in its energy balanced configuration
  - Horizontal motion with no wind disturbances

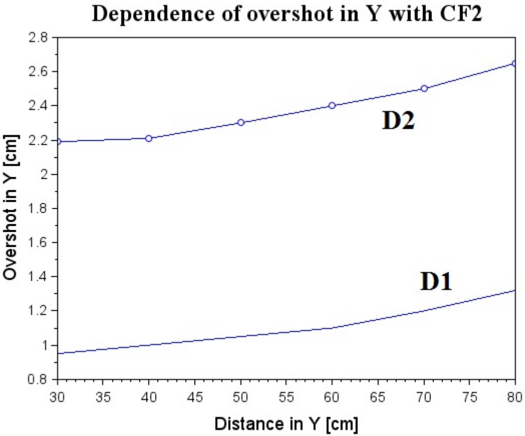
Challenges. Outer-loop control tuning

Results for different ($\Delta x; \Delta y$) with CF1:



Challenges. Outer-loop control tuning

Results for different ($\Delta x; \Delta y$) with CF2:



Challenges. Outer-loop control tuning

Thus, previous experiments show that in order to move in $X - Y$ plane a quadrotor system:

- Offline tuning system requires two directions cost function (CF2)
- Overshot still is big

Challenges. Outer-loop control tuning

Fuzzy based online adaptive tuning:

- Adaptive nature is based on the constant adaption of outer-loop PD values based on the angle errors.
- K_p and K_d adaptive law:

$$K_p\left(t+1\right)=K_p\left(t\right)+\alpha e(t)\left(\mu_1\left(Pe\left(t\right)\right)+\mu_4\left(Pe\left(t\right)\right)\right) \quad (10)$$

$$K_d(t+1)=K_d\left(t\right)+\alpha e(t)\left(\mu_2\left(Pe\left(t\right)\right)+\mu_3\left(Pe\left(t\right)\right)\right) \quad (11)$$

Challenges. Outer-loop control tuning

- Two error measuring variables:

$$\begin{cases} e_{\phi}(t) = \phi_d - \phi\,(t) \\ e_{\theta}(t) = \theta_d - \theta\,(t) \end{cases}, \tag{12}$$

$$Pe = \frac{Y_{ref} - Y_{real}}{Y_{ref}} \cdot 100, \tag{13}$$

Challenges. Outer-loop control tuning

- **Fuzzy membership functions:**

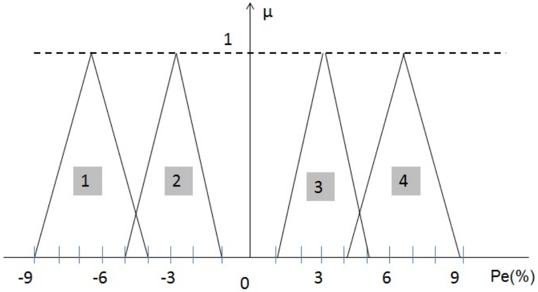


Figure: Membership functions of the fuzzy adaption rules of the PD control parameters

Challenges. Outer-loop control tuning

There is no guarantee that all the robots will fly at the same speed, so **two extra quadrotor formation conditions** are introduced for online tuning:

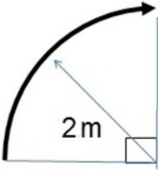
- If distance between drones overcomes a threshold, the leader's desired angles turn to 0.
- If distance between drones is shorter than a threshold, the follower's desired angles turn to 0

$$\varphi = \pi - \frac{(\psi_L - \psi_F)}{2}, \tag{14}$$

Challenges. Outer-loop control tuning

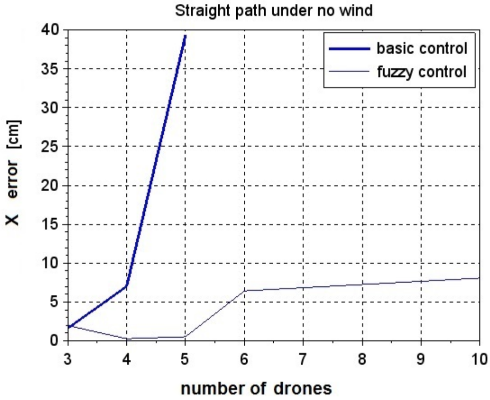
Two computational experiments have been carried out in order to test the efficiency and robustness of the adaptive fuzzy modulated tuning of the PD controllers, taking into account scalability.

- *Experiments:* Basic offline tunning vs online fuzzy tuning:
  - along a straight line, with and without perturbations
  - along a constant radius curve, with and without perturbations



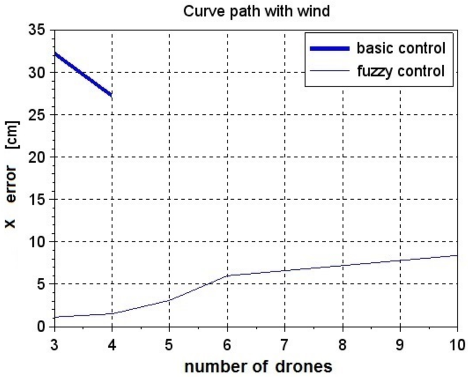
Challenges. Outer-loop control tuning

Under the softest conditions, fuzzy control shows a much better performance



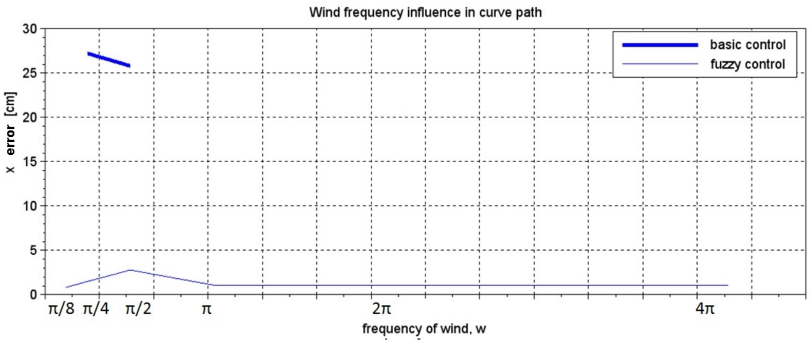
Challenges. Outer-loop control tuning

Under most exigent conditions, fuzzy control turns up to be the only alternative.



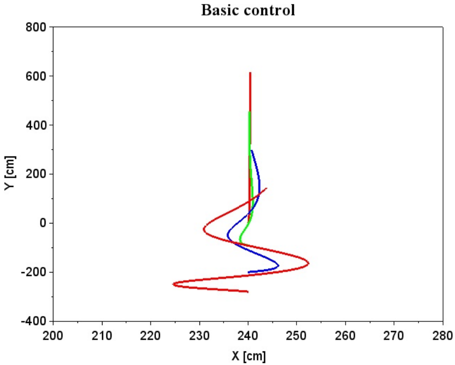
Challenges. Outer-loop control tuning

Fuzzy tuning compensates much better than basic offline tuning the different natural frequency for the perturbations.



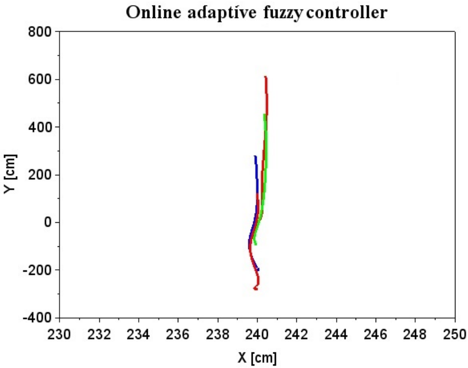
Challenges. Outer-loop control tuning

Next picture shows the performance of a four-drone system under a straight path without disturbances.



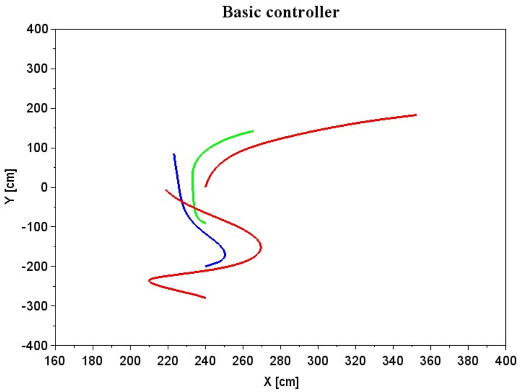
Challenges. Outer-loop control tuning

And next, the online adaptive tuning:



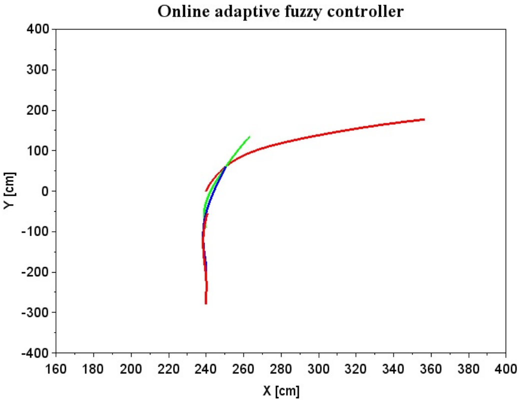
Challenges. Outer-loop control tuning

The other test shows the performance of a four-drone system under a curve path with disturbances. First, basic PSO tuning:



Challenges. Outer-loop control tuning

And next, the online adaptive tuning:



Outline

Conclusions

- Aerial robots modeling for cooperative transportation of DLOs
  - a novel model of a system to transport DLO solids such as wires and ropes with some aerial robots has been proposed and validated.
- Offline control strategy
  - We have compared two PID/PD offline tuning methods to adapt the quadrotor system for a smooth, fast and reliable behaviour.
- Online adaptive control strategy
  - Adaptive online tuning was proofed to be better than offline tuning, taking into account curve/straight path, perturbances and scalability.

Future work

- System modeling
  - Experimental validation
  - Further research on alternative DLO models who take into account dynamic effects
- Control strategy
  - Implementation of Machine Learning Techniques

Publications achieved

- 4 JCR articles among submitted and published
- Two international congresses
- A book chapter
- Science popularization articles

Related activities

- Teaching duties:
  - 5 different subjects
  - 85 credits
- Scientific Quadrotor sessions for children: primary schools, hospitals, non profit associations
- Europython and PySS volunteer (first congress with more than 1,200 participants)

Questions

QUESTIONS