# Pedro Castillo García

Contents

# Pedro Castillo García

**Ph.D. in Automatic Control,**

**MSc. in Electrical engineering,**

**B.S. in Electromechanical engineering.**

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**Date and place of birth** : January 8, 1975 in Puente de Ixtla, Morelos, México.


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## Awards

- Award to the best thesis in Automatic control of the Club EEA 2005, (http ://www.clubeea.org/), France.

## Position

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|---|---|
| May 05 – | Post-doc Polytechnic University of Valencia, Spain.<br>Prof. P. Albertos. |
| January 05 - April 05 | Post-doc Massachusetts Institute of Technology – MIT,<br>Department of Mechanics, Cambridge, MA, USA.<br>Prof. A. Annaswamy |

## Education

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|---|---|
| August 05 - Sept. 05 | Post-doc CINVESTAV-IPN, Department of Automatic Control<br>Project : Control of a crane to 3 degrees of freedom.<br>Mexico. |
| April 04 - June 04 | Post-doc University of Sydney, Department of Aeronautics<br>Project : T-Wing. Responsible : Prof. H. Stone<br>Sydney, Australia. |
| 2003 – 2005 | ATER (Research and Teaching Associate) HeuDiaSyC Laboratory<br>UMR CNRS 6599, France. |
| April 2003 | Training to the Polytechnic University of Valencia, Spain.<br>Project : NACO2 |

## Education

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|---|---|
| 2000 – 2004 | University of Technology of Compiègne (UTC), France<br>Ph.D. in Control System, March, 2004<br>Ph.D. thesis :<br>MODELING AND CONTROL OF A FOUR ROTOR MINI ROTORCRAFT<br>Advisor : R. Lozano, CNRS director of research. |
| 1997 – 2000 | National Polytechnic Institute - CINVESTAV, México, México<br>Master of Science (MSc) in Electrical engineering<br>MSc. thesis : A VISUAL SERVOING ARCHITECTURE FOR CONTROLLING ELECTROMECHANICAL SYSTEMS. |
| 1992 – 1996 | Zacatepec Institute of Technology (ITZ), Morelos, México<br>B.S. in Electromechanical engineering |

## Domain of interest :

- Non linear dynamics and control
- Underactuated mechanical systems
- Aircrafts and manipulating robots
- Visual servoing
- Real time control applications

## Research projects :

1. European Network NACO2 (2001-2004).
2. LAFMAA – French-Mexican laboratory of applied control (2002-2004)
3. Pre-project ROBEA (2001)
   - *Automatic control of mini helicopters* (2001).
4. Regional Project DIVA :
   - *UAVs* (2001-2004).
   - *Localization and control of UAVs* (2004-2007).
5. Project DGA-ONERA :
   - *BIROTAN* (2003-2005).
6. Project French-Australian (2004)

**European Network NACO2**

**[http ://www.eee.ic.ac.uk/naco2/]**

The purpose of the project NACO2 (Nonlinear and Adaptative Control Network) is to improve the results and theoretical methods in the field of nonlinear control and adaptative control. The European network provides training and mobility for researchers between the 8 nodes of the network. A node is located at the University of Technology of Compiègne supervised by Professor R. Lozano. Throughout my Ph.D. studies I collaborated with a node at the Polytechnic University of Valencia (Spain).

**French-Mexican laboratory of applied control (LAFMAA)**

**[http ://www.hds.utc.fr/LAFMAA/]**

The French-Mexican laboratory of applied control was founded in order to group, develop and coordinate high level educational and research activities related to the social and economical needs of both countries. We are designing experimental platforms to develop the control of a PVTOL aircraft (Planar Vertical Take-Off and Landing), the positioning of a flying object in 3 dimensions, the nonlinear control of a four rotor rotorcraft and the nonlinear control of a mini helicopter with a combustion motor.

**Pre-project ROBEA / Regional Project DIVA**

**[http ://www.hds.utc.fr/UAV] / [http ://www.hds.utc.fr/diva]**

The purpose of this research is to realize an autonomous flight of a helicopter. The work realized is both theoretical and practical. The theoretical part focuses on the modelling and control of aerial vehicles, it takes into account nonlinear phenomena, positioning problems caused by sensor capability limits, aerodynamics forces and delay effects generated by computing time.
Throughout my Ph. D. studies I have been involved in the development of control algorithms, in the design of embedded electronics and in the real time programming of the system. The control algorithms have to be efficient with respect to disturbances encountered in real applications.

**Project French-Australian**

The research project is part of a cooperation between the CNRS in France and the ARC in Australia. The project entitled "*Modeling and control of bi-rotor aerial vehicles to vertical takeoff and cooperation between terrestrial and aerial autonomous robots*" was accepted this year and its number is 16 076 (French reference). Professor H. Stone is the leader of the project in Australia and Professor R. Lozano is the leader of the project in France. This project has the objective to develop an airplane with the ability to vertically take off and land. At the moment we work with the aircraft T-Wing developed by the University of Sydney and an Australian company, Sonacom Pty Ltd. We are working in the phase of transition maneuvers between vertical and horizontal flight of this aircraft.

**Project BIROTAN**

**[http ://www.hds.utc.fr/birotan]**

The objective of the project is to develop a bi-rotor with tilting propellers in tandem capable of performing various tasks autonomously. Three Universities participate in the project : UTC at Compiègne, UPJV at Amiens and UTT at Troyes. This project is financed by the ONERA and the DGA in France.

**Design of experimental platforms :**

I have been involved in the design of experimental platforms. My participation started with the design of a mechanical platform to make a helicopter hover. We have also designed a new platform to evaluate the modelling and the control algorithms which have been used for a four rotor rotorcraft. This platform enabled us to realize the first autonomous flight of a four rotor rotorcraft. In this platform, we use a sensor of position and orientation of the helicopter based on the electromagnetic field. Then, we designed another platform to evaluate the control algorithms for a PVTOL aircraft. This platform was developed to do some vision-based control ; the vision was used as a sensor of position. Currently, I am involved in the design of a new Planar Vertical Take-Off and Landing aircraft.

## Teaching

– LO01 : Computer Science basis (2003-2004), UTC, Compiègne, France.
– NF16 : Data Structures, Algorithms (2003-2004), UTC, Compiègne, France.

# 2.- Research activities

## Nonlinear control of mini flying vehicles

### Research activities

I developed nonlinear control laws to make a helicopter hover. I have mainly focused on the following topics :

- Control approach based on nested saturations and Lyapunov analysis.

Using saturations function properties and Lyapunov theory, I developed control laws for two types of flying vehicles, the PVTOL aircraft and the four rotor rotorcraft. A dynamic model on Euler-Lagrange approach was developed for the four rotor rotorcraft. An algorithm was developed to control the system with delay. We have proposed an analysis of stability of a hybrid control algorithm, i.e. the system representation is given in continuous time while the controller is given in discrete time.

- Application to flying vehicles

Many control strategies based on Lyapunov theory have been developed to stabilize the PVTOL aircraft and the four rotor rotorcraft. To test these control algorithms we designed several experimental platforms.

### Theoretical development

Nonlinear control of a PVTOL aircraft

The system of the PVTOL (Planar Vertical Take-Off and Landing) aircraft is based on a mathematical model of simplified plane having a minimal number of states and inputs, which is involved in a vertical plane. It also represents the longitudinal mode of the helicopter. The PVTOL aircraft is a topic of interest to the automatic community for these applications and its nonlinear behavior. We developed many relatively simple control laws based on nested saturation techniques.

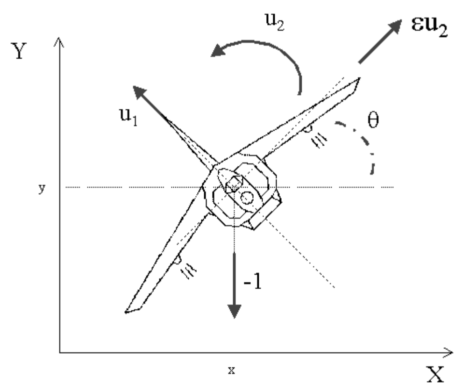


Fig. 1 – The PVTOL aircraft.

### Development of a model for the four rotor rotorcraft

The four rotor rotorcraft has some similarities with PVTOL (Planar Vertical Take Off and Landing) aircraft problem. This rotorcraft can be seen as two PVTOL connected such that their axes are orthogonal. The four rotor rotorcraft does not have a swashplate. In fact it does not need any blade pitch control. The collective input (or throttle input) is the sum of the thrusts of each motor. We developed a dynamical model for the four rotor rotorcraft obtained via a Lagrange approach.

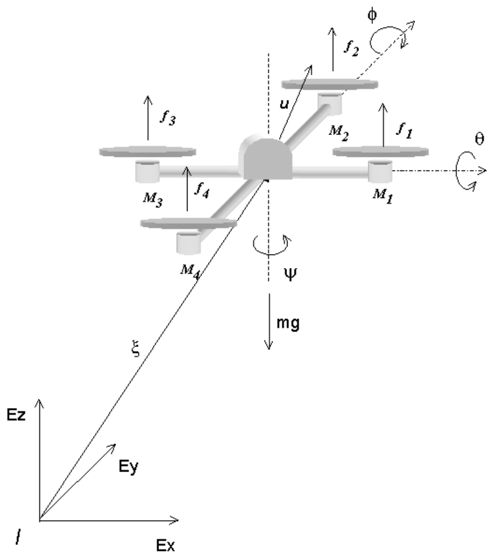


Fig. 2 – Schema of the four rotor rotorcraft.

### Control of a four rotor rotorcraft

We developed a control strategy for the PVTOL based on nested saturations. We generalized this idea for the case of the four rotor aircraft ; the stability analysis was done using Lyapunov theory. The method is relatively simple compared to the one based on back stepping. Simulations demonstrated good performances of the control law. This control algorithm was also tested in real time experiences.

Fig. 3 – Real-time control of the rotorcraft.

Control of yaw angular displacement of a four rotor rotorcraft taking into account delays

We have studied a control scheme for continuous-time systems with delay. We have proposed a discrete-time controller based on state feedback using the prediction of the state. We have presented a convergence analysis that shows that the state converges to the origin in spite of uncertainties in the knowledge of the plant parameters, the system delay and even variations of the sampling period. The proposed control scheme has been implemented to control the yaw displacement of a real four rotor mini-helicopter. Real-time experiments have shown a satisfactory performance of the proposed control scheme.

## Design of the experimental platforms

### Helicopter on the vertical platform

The system is composed of a small-scale helicopter which is mounted on a vertical platform. The model is based on Lagrange formulation and the controller is obtained by classical pole-placement techniques for the yaw dynamics and adaptive pole-placement for the altitude dynamics.

In order to minimize the probability of accidents, we designed a vertical platform which enables a vertical displacement with a range of 1.5 m and a free spinning around the vertical axis. The radio-controlled helicopter used is a VARIO 1.8 m diameter rotor with a 23 cm3 gasoline internal combustion engine. The vertical displacement is measured by a linear optical encoder and the yaw angle is obtained through a standard angular encoder. The radio and the PC are connected using data acquisition cards. In order to simplify the experiments, the control inputs can be independently switched between the automatic and the manual control modes. The connection in the radio is directly made to the joystick potentiometers for the gas and yaw controls.

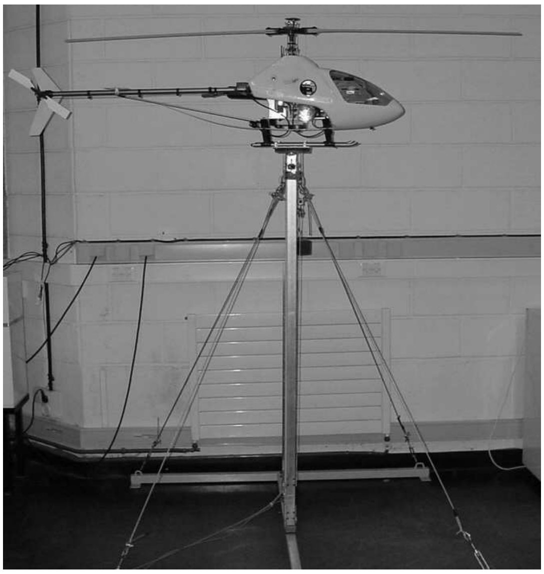

Fig. 4 – Helicopter on the vertical platform

Platform to control a four rotor rotorcraft

We worked with a mini helicopter with four electrical motors. The diameter of the rotors is 20 cm and the size of the rotorcraft is about 70 by 70 cm. The total weight is about 500 grams including the 12V battery. The radio transmission works at 72Hz and the helicopter has three embedded gyrometers used to stabilize the angular velocity of the rotorcraft in the 3 orthogonal axes.

We use the 3D tracker system (POLHEMUS) for measuring the position and orientation of the helicopter. The Polhemus is connected via RS232 to the PC.

In the real application we used a control algorithm based on nested saturations. The parameters of the control law were adjusted to get a satisfying response of the four rotor helicopter. The control law developed gave very good experimental results ; it enabled stationary flight at 30 cm above the ground. It also enables slow flight along a straight line in the horizontal plane. We made the vehicle undergo large perturbations by pulling it manually with a string to move it away from the origin. We realized that the control law works well with respect to this kind of perturbations.

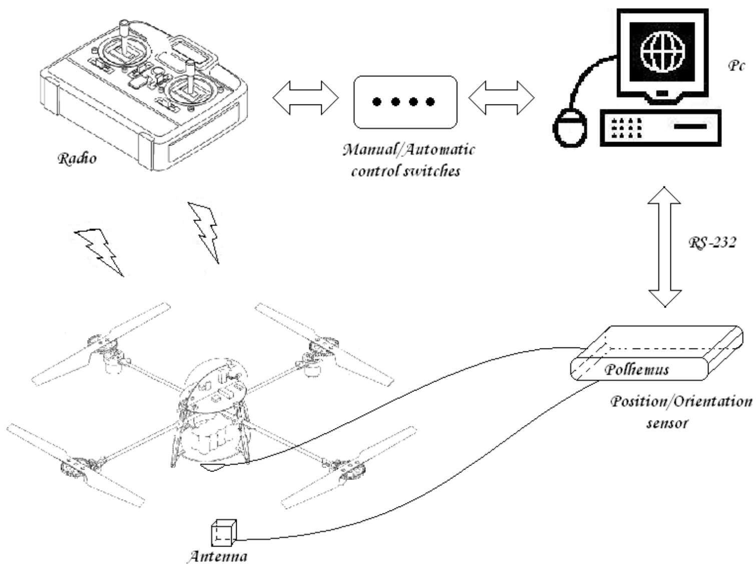


Fig. 5 – Real-time computer architecture of the platform.

Vision based stabilization of the PVTOL aircraft

We developed a control strategy to stabilize the PVTOL aircraft using vision and its application on an experimental platform. The PVTOL aircraft moves over an inclined plan which defines our space work in 2D. The PVTOL platform is designed to study problems commonly encountered in the low altitude navigation of small flying objects. At low altitude, GPS and even inertial systems are not sufficient to stabilize mini flying objects. The vision, by using cameras, should give additional data to make autonomous flight near the ground possible.

Therefore, we have chosen to use a camera to measure the position and orientation of the mini helicopter. We set the camera outside the helicopter but in the future it will be set pointing downwards at the bottom part of the mini helicopter. Unless the camera is set outside the helicopter, problems of computation of space positioning and delays in the system loop have to be taken into account. In the platform, a CCD Pulnix camera is set at a given altitude and gives an image of the whole work space. Position and orientation of the PVTOL are computed using the image given by the camera. We have developed a real time environment to be able to test our control law. Experimental results of the system in closed loop are satisfactory. Future work will take into consideration the visual information when the camera onboard is oriented downwards, in order to estimate the position and the orientation of the flying object.

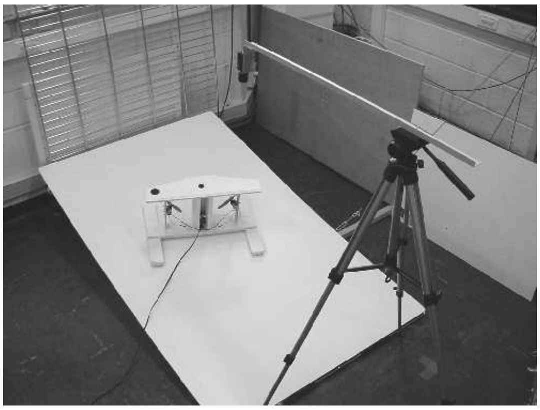

FIG. 6 – Platform of the PVTOL

### DESIGN OF A FLYING MACHINE

I have been involved in the design of a vertical take-off vehicle propelled by a single electrical motor. Our purpose is to study different configurations to understand the maneuverability and the flight capacity of different types of helicopters. It turned out that this configuration is more difficult to control than the four rotor rotorcraft.

FIG. 7 – Single rotor rotorcraft.

# 3.- Ph.D. Thesis

**Thesis name :**

Modelling and control of a mini helicopter having four rotors

Date of dissertation : March 8, 2004

**Key words :**

Aircraft dynamics, Lyapunov Methods, Quad-rotor rotorcraft, Saturation function, Delay systems, Aircraft control, Helicopters, Recursive control algorithms.

**Abstract :**

This report presents the non linear control laws for stationary autonomous flight. Control laws for the stabilization of two different kinds of aircraft were realized by using the properties of the saturation function and the Lyapunov Theory : the PVTOL (Planar Vertical Take Off and Landing) and the four-rotor mini rotorcraft.

A mathematical model including the dynamics of the motors for a four-rotor mini rotorcraft has been developed. This model enables us to explain how this type of helicopter works and, in particular, how forces and torques applied on the aircraft are generated.

A control law, based on a prediction of the state has been developed, in order to study a hybrid system (the system is considered to be continuous while the control law is discrete). The stability is shown to be robust with respect to uncertainties in the knowledge on the plant parameters, the system delay and the sampling period.

A theoretical analysis of control algorithms and experiments is realized to show the achievements of these developments. Experimental platforms have been created to verify the proposed control laws.

Finally, a study of the different sensors commonly used in the field of autonomous aircraft was completed in order to understand the functioning of an inertial navigation unit.

**Supervised by :**

R. Lozano, CNRS Research Director, Heudiasyc−UTC, France.

**Jury :**

- Raja CHATILA, CNRS Research Director−LAAS, France
- Bernard BROGLIATO, INRIA Research Director − Rhônes Alpes, France
- Claude PEGARD, Professor − UPJV, France
- Isabelle FANTONI, CNRS Research Heudiasyc − UTC, France

# 4.- Publications

## Book

– P. Castillo, R. Lozano & A. Dzul, **Modelling and control of mini flying machines**, to appear at Springer-Verlag, 2005.

## Thesis

[T1 ] **P. Castillo**, "Modélisation et commande d'un mini-hélicoptère à quatre rotors", Ph.D. Thesis, Heudiasyc-UTC, France, March 2004.

[T2 ] **P. Castillo**, "A visual servoing architecture for controlling electromechanical systems", MSc. thesis, CINVESTAV-IPN, Mexico, August 2000.

## Book chapters

[Ch1 ] **P. Castillo**, R. Lozano, P. Garcia, P. Albertos. "Nonlinear control of a small four-rotor rotorcraft : Theory and real-time application". *Nonlinear and adaptive control : theory and algorithms for the user*, **Imperial College Press**, London, 2005.

[Ch2 ] R. Lozano, P. Garcia, **P. Castillo**, A. Dzul, "Robust prediction-based control for unstable delay systems". *Proceedings of the Workshop on Advances in Time-Delay Systems*, Paris-France 2004, **Springer-Verlag**, London.

[Ch3 ] I. Fantoni, A. Palomino, **P. Castillo**, R. Lozano and C. Pégard, "Control Strategy using vision for the stabilization of the PVTOL aircraft". *Current trends in nonlinear systems and control*, **Birkhauser**, 2005.

## Journal papers

[R1 ] **P. Castillo**, A. Dzul and R. Lozano, "Real-time stabilization and tracking of a four rotor mini rotorcraft", **IEEE Transactions on Control Systems Technology**, Vol. 12, No. 4, pp. 510-516, July 2004.

[R2 ] **P. Castillo**, R. Lozano, A. Dzul, "Stabilization of a Quadrotor : Theory and Practice", to appear in **Advanced Robotics** (Special Issue on "Selected Papers from IROS 2004"), 2005.

[R3 ] R. Lozano, **P. Castillo**, P. Garcia, A. Dzul, "Robust prediction-based control for unstable delay systems : Application to the control yaw of a mini helicopter ", **Automatica**, Vol. 40, No. 4, pp 603-612, April 2004.

[R4 ] R. Lozano, **P. Castillo** et A. Dzul, "Global stabilization of the PVTOL : Real- time application to a mini aircraft", **Int. Journal of Control**, Vol. 77, No. 8, pp 735-740, May 2004.

[R5 ] A. Palomino, **P. Castillo**, I. Fantoni, R. Lozano, C. Pégard, "Control strategy using vision for the stabilization of an experimental PVTOL aircraft setup", to appear in **IEEE Transactions on Control Systems Technology**, 2005.

[R6 ] A. Dzul, R. Lozano et **P. Castillo**, "Adaptive altitude control for a small helicopter in a vertical flying stand", **Int. J. of Adaptive Control and Signal Processing**, Vol. 18, Issue 5, pp. 473-485, June 2004.

## Journal Paper submission

- **P. Castillo**, R. Lozano et A. Dzul, "Stabilization of a mini rotorcraft having four rotors", 3rd revision at **IEEE Control Systems Magazine**, February 2005. Regular Paper.

## Conference papers

[C1 ] **P. Castillo**, A. Dzul & R. Lozano, "Stabilization of a mini-rotorcraft having four rotors", Proceedings de l'IROS (International Conference on Intelligent Robots and Systems), September 28 - October 2, 2004, Sendai, Japan.

[C2 **P. Castillo**, A. Dzul & R. Lozano, "Real-time stabilization and tracking of a four rotor mini rotorcraft", European Control Conference ECC'03, Cambridge, U.K., 1-4 September 2003.

[C3 ] **P. Castillo**, R. Lozano, I. Fantoni, A. Dzul, "Control design for the PVTOL aircraft with arbitrary bounds on the acceleration", IEEE 2002 Conference on Decision and Control CDC'02, 10-13 December 2002, Las Vegas, Nevada, EUA.

[C42 ] A. Palomino, **P. Castillo**, I. Fantoni, R. Lozano, "Control Strategy using vision for the stabilization of the PVTOL aircraft", CDC'03, Hawaii, USA, December 2003.

[C5 ] R. Lozano, **P. Castillo**, P. Garcia, A. Dzul, "Robust prediction-based control for unstable delay systems : Application to the yaw control of a mini helicopter", CDC'03, Hawaii, USA, December 2003.

[C6 ] A. Palomino, **P. Castillo**, I. Fantoni, R. Lozano, "Stratégie de commande utilisant la vision pour la stabilisation de l'avion à décollage vertical PVTOL", JDA'03, Valenciennes, France, June 2003.

[C7 ] R. Lozano, **P. Castillo**, A. Dzul, "Global stabilization of the PVTOL : real-time application to a mini-aircraft", IFAC Symposium on System, Structure and Control (SSS'04), 8-10 December 2004, Oaxaca, Mexico.

[C8 ] A. Dzul, R. Lozano et **P. Castillo**, "Adaptive altitude control for a small helicopter in a vertical flying stand", CDC'03, Hawaii, USA, December 2003.

[C9 ] P. Garcia, A. Crespo, **P. Castillo**, R. Lozano, A. Dzul, P. Albertos, "Real-time applications for a unstable delay system", Proceedings du Workshop on Real Time Programming WRTP'03, Poland, 14-17 May 2003.

[C10 ] I. Fantoni, R. Lozano, **P. Castillo**, "Stabilisation of the PVTOL aircraft", IFAC World Congress, 12-26 July 2002, Barcelona, Spain.

[C11 ] A. Dzul, R. Lozano, **P. Castillo**, "Adaptive altitude control of a small helicopter in a vertical flying stand", CLCA'02-IFAC, Guadalajara, Mexico, 4-6 December 2002.

[C12 ] R. Garrido, A. Soria, **P. Castillo**, I. Vasquez, "A visual servoing architecture for controlling electromechanical systems", Workshop AAPR 2000, Advances in Artificial Perception and Robotics, 23-25 October 2000, Guanajuato, Mexico.

[4]P. CASTILLO GARCIA – Publications