Letters

Control Strategy Using Vision for the Stabilization of an Experimental PVTOL Aircraft Setup

A. Palomino, P. Castillo, I. Fantoni, R. Lozano, and C. Pégard

***Abstract*—In this letter, we stabilize the planar vertical takeoff and landing (PVTOL) aircraft using a camera. The camera is used for measuring the position and the orientation of the PVTOL moving on an inclined plane. We have used a simple control strategy to stabilize the system in order to facilitate the real experiments. The proposed control law ensures convergence of the state to the origin.**

***Index Terms*—Aircraft control, camera sensor, nonlinear control systems, stabilization, vision.**

I. Introduction

The planar vertical takeoff and landing (PVTOL) aircraft system is based on a simplified aircraft model with a minimal number of states and inputs. In the last few years, numerous control designs for the stabilization and the trajectory tracking have been proposed for the PVTOL aircraft model. The proposed control techniques include the approximate I-O linearization procedure in [1], the stabilization algorithm for nonlinear systems in so-called feedforward form in [2], the output tracking of nonminimum phase flat systems in [3], the linear high gain approximation of backstepping proposed in [4], the robust hovering control of the PVTOL using nonlinear state feedback based on optimal control in [5]. Furthermore, a paper on an internal-model based approach for the autonomous vertical landing on an oscillating platform has been proposed by Marconi *et al.* [6]. Olfati-Saber [7] proposed a global configuration stabilization for the VTOL aircraft with a strong input coupling using a smooth static state feedback. Recently, control methodologies using embedded saturation functions have been proposed for the stabilization of the PVTOL aircraft. Indeed, Zavala *et al.* [8] developed a new control strategy which coped with (arbitrarily) bounded inputs and which provided global convergence to the origin. Lozano *et al.* [9] presented a simple control algorithm for stabilizing the PVTOL aircraft, using Lyapunov convergence analysis. Experimental results have been provided using a four-rotor mini-helicopter.

The PVTOL system dynamics commonly used are quite simple and constitute a great challenging nonlinear control problem. Moreover, the PVTOL problem is important because it retains the main features that must be considered when designing control laws for a real aircraft. It then represents a good test-bed for researchers, teachers and students working on flying vehicles. Due to the difficulties in building an experimental platform of the PVTOL, there are very few experimental tests published in the literature. Note that, as far as we are aware, only Saeki *et al.* [10] carried out a real experiment of the PVTOL aircraft. Indeed, they offered a new design method, making use of the center of oscillation and a two-step linearization, and they provided some experimental results for a twin rotor helicopter model.

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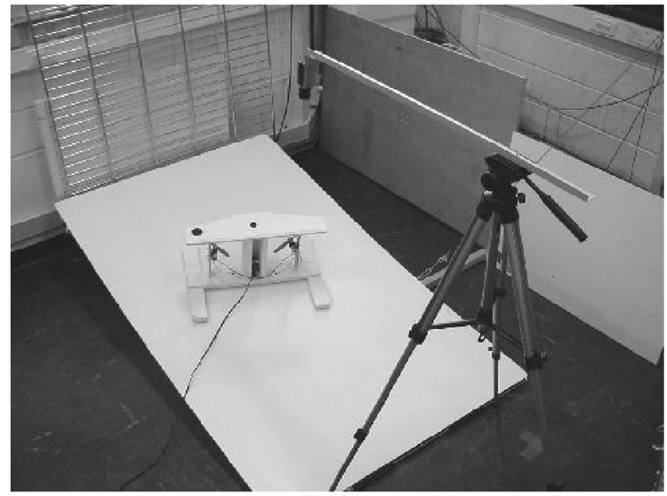

Fig. 1. Experimental setup.

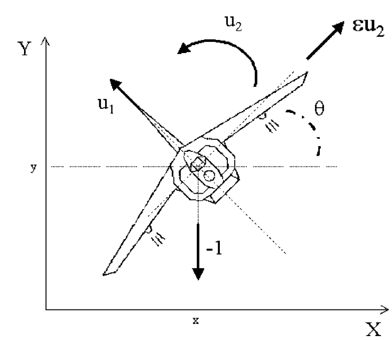

Fig. 2. PVTOL aircraft (front view).

In this letter, we both present a simple control strategy and experimental results on the stabilization of the PVTOL aircraft, by using a camera for measuring the position and the orientation of the aircraft. We have developed an experimental setup for the PVTOL system. The platform is composed of a two-rotor radio-controlled object moving on an inclined plane (see Fig. 1). The control strategy that have been used comes from [11] and [12]. The methodology is relatively simple and gives a satisfactory behavior.

The simplified PVTOL aircraft dynamics, depicted in Fig. 2, are given by the following equations:

$$\begin{aligned} \ddot{x} &= -u_1 \sin\theta \\ \ddot{y} &= u_1 \cos\theta - 1 \\ \ddot{\theta} &= u_2 \end{aligned} \tag{1}$$

where x, y denote the center of mass horizontal and vertical positions and θ is the roll angle. The control inputs u_1 and u_2 are, respectively, the thrust and the angular acceleration. The constant "-1" is the normalized gravitational acceleration. Note that the term due to the small coefficient ε present in the complete model [1] and characterizing the coupling between the rolling moment and the lateral acceleration of the

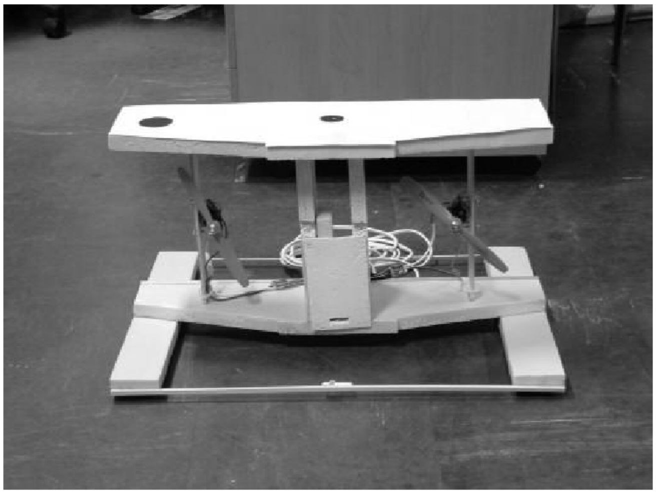

Fig. 3. Photo of the PVTOL prototype.

aircraft has been here neglected or the simplified model (1) is a result of an appropriate coordinate transformation [7]. The main contribution of this letter is the validation of a simple stabilizing control algorithm in real experiments using a camera as a position/orientation measuring device. The letter is organized as follows. In Section II, we describe the environment that we use for our experiments. Section III describes the methodology used in the vision program to detect the position and the orientation of the PVTOL. In Section IV, the control approach is presented. Experimental results are shown in Section V and conclusions are finally given in Section VI.

II. Description of the Experimental Setup

The PVTOL prototype that we have built is shown in Fig. 3. The rotors are driven separately by two electric Speed 400 motors, with a gear reduction of 1.85:1. One motor rotates clockwise while the second one rotates counter-clockwise. The main thrust is the sum of the thrusts of each motor. The rolling moment is obtained by increasing (decreasing) the speed of one motor while decreasing (increasing) the speed of the second motor. Each motor is linked to a speed variator which is itself linked to a gyroscope. The two gyroscopes which improve the manoeuvrability and the stability of the object, are connected to the receiver of the radio. The radio sends the signals through the transmitter to the receiver located on the PVTOL. The size of each propeller is 10-cm long. The mass of the PVTOL is 0.7 kg, while the inertia has been neglected. In order to provide additional information on the experimental setup, Table I describes correspondences between voltage of one motor, rpm (rotations per minutes) of one propeller, speed of the wind and thrust measured in the middle of the motors. Since the maximal voltage of each motor is 10.8 V and since the weight of the PVTOL aircraft is 0.7 kg, we can foresee that it would be difficult that our prototype could take off vertically. The PVTOL prototype is rather designed to move on an inclined plane. The general view of our experimental setup is depicted in Fig. 1. The PVTOL moves on an inclined plane, which defines our two-dimensional (2-D) workspace. The size of the PVTOL prototype is 60 cm (L) $\times$ 20 cm (W) $\times$ 32 cm (H), while the size of the inclined plane is 200 cm (L) $\times$ 122 cm (W) and the size of the camera field of vision on the plane is 128 cm (L) $\times$ 106 cm (W). The inclination of the plane is 15 deg. The PVTOL platform in Fig. 1 is an experimental setup designed to study the problems currently found in navigation at low altitude of small flying objects. At low altitude, GPS and even inertial navigation systems are not enough to stabilize the mini-flying objects. Indeed, inertial navigation systems are devices

TABLE I
Additional Information of the PVTOL Prototype

Volts (V)	RPM (x10)	Anemometer (km/h)	Thrust (kg)
5.24	140	29.0	0.20
6.37	190	32.4	0.22
6.74	250	33.0	0.25
7.40	290	35.0	0.31
7.98	300	36.7	0.34

mainly constructed with accelerometers and gyros. These systems measure accelerations and angular velocities. They are very sensitive to electromagnetic noise generated for instance by motors. Some experimental tests we performed with a four rotor mini-flying object using a 3DM-G inertial navigation unit of Microstrain Company have shown that inertial navigation unit measurements are perturbed by vibrations during takeoff of the flying object. This phenomenon makes the state measurement more difficult, even when we add numerical filters. On the other hand, GPS which provides the position of an object, is not accurate enough for takeoff and landing. Next to natural obstacles or buildings or hills, GPS can be defective. Vision using cameras should provide additional information to make autonomous flights near the ground possible. We have therefore chosen to use a camera for measuring position and orientation of the mini-helicopter. For simplicity, at a first stage, we have placed the camera outside the aircraft. In the future, the camera will be located at the base of the mini-helicopter pointing downwards or upwards. Note that even when the camera is located outside the flying object, we still have to deal with the problems of object localization computation using cameras and delays in the closed-loop system.

In the platform, a charge coupled device (CCD) camera Pulnix is located perpendicular to the plane at a fixed altitude and provides an image of the whole workspace. We have used an acquisition card PCI-1409 of National Instruments Company. The camera is linked to the PC computer dedicated to the vision part (which will be referred as Vision PC). From the image provided by the camera, the program calculates the position (x, y) and the orientation θ of the PVTOL with respect to a given origin. Then, the Vision PC sends these information to an other PC computer dedicated to the control part (which we call Control PC), via a RS232 connection, transmitting at 115 200 bauds. The two control inputs are therefore calculated according to the proposed strategy and sent to the PVTOL via the radio. In order to simplify the implementation of the control law we have designed the platform in such a way that each of the two control inputs can independently work either in automatic or in manual mode. The Vision PC calculates the position and the orientation every 40 ms, while the Control PC requires these information every 2 ms. Therefore, the minimum sampling period we are able to obtain in the experimental platform is 40 ms. This includes the computation of the control law, image processing, localization computation and analog-to-digital (A/D) and digital-to-analog (D/A) conversion in the radio-PC interface. Fig. 4 shows a diagram of the radio-PC interface.

III. Position and Orientation of the PVTOL Aircraft Using Vision

We have placed two black points on the colored white PVTOL experiment in order to obtain a contrasted image (see Fig. 1). One of these black points is larger than the other one. The smallest point corresponds

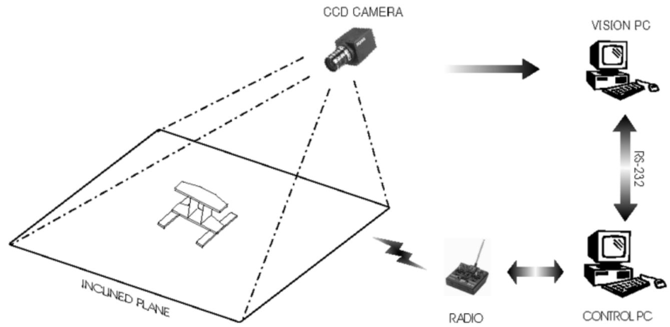

Fig. 4. Diagram of the system interface.

to the position of the PVTOL system. Its orientation is determined by the angle between the line linked up the two points and the horizontal axis in the image plane. From the scene, we obtain a 2-D image by using the camera as described in Section II. This image is saved in a computer via an acquisition card PCI-1409 of National Instruments Company. The acquired image is a black and white image (given the real conditions of the scene) that does not need a binarization process. We detect the black points on the white background in the following way. Starting at the top of the image, we skim through all the pixels, line by line, considering the gray level of each pixel. We save the position of all the pixels having a gray level whose value is 255 or having a "black" gray level, ignoring those having a gray level whose value is 0 or having a "white" gray level. The program classifies all the pixels having a high gray level and being in the same neighborhood. Then, it calculates the barycentre of these pixels which gives the position of each black point in the image plane. The orientation angle of the PVTOL aircraft is then obtained with the help of the straight line linked up the two black points and the horizontal of the reference system in the image plane. The program computing the capture and the image processing was made in language C.

IV. Stabilizing Control Law

In this section, we present the control law that will be applied to the experimental setup. The control strategy follows the controller synthesis approach developed in [11] and [12]. The controller is obtained by defining the following desired linear behavior for the position x and the altitude y. Let us, therefore, define the following functions r_1 and r_2 as:

$$\ddot{x} \triangleq r_1(x, \dot{x}) = -2\dot{x} - x \tag{2}$$

$$\ddot{y} \triangleq r_2(y, \dot{y}) = -2\dot{y} - y. \tag{3}$$

From (1) and (3) it follows:

$$u_1 = \frac{1}{\cos\theta}(1 + r_2) \tag{4}$$

which will not have any singularity provided $\tan\theta$ is bounded. Introducing (4) into the second equation of system (1) gives $\ddot{y} = r_2$. It follows that $y^{(i)} \to 0$ for $i = 0, 1, \ldots$. It means that the altitude is stabilized around the origin. $y^{(i)} \in L_2$ and $r_2 \in L_2$. Using (4), let us rewrite the first equation of system (1) as follows:

$$\ddot{x} = r_1(1 + r_2) - (\tan\theta + r_1)(1 + r_2). \tag{5}$$

Since r_1 will tend to zero, we also would like that $(\tan\theta + r_1)$ would converge to zero. Therefore, by introducing the error variable

$$\nu_1 \triangleq \tan\theta + r_1 \tag{6}$$

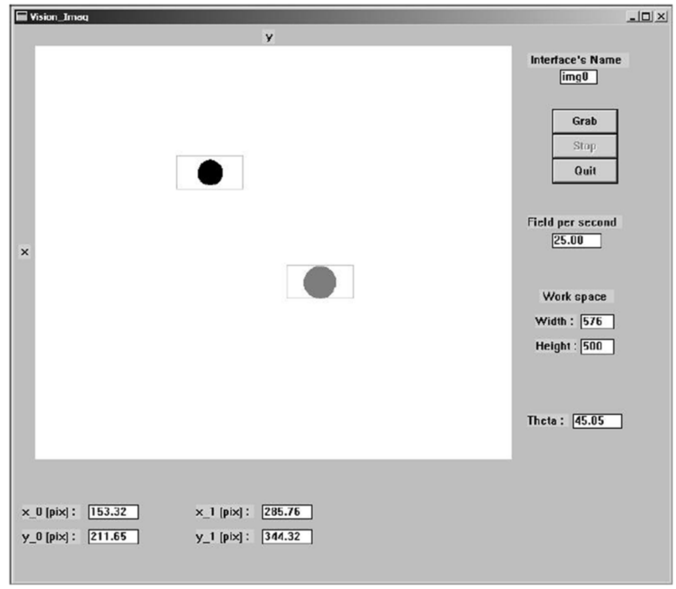

Fig. 5. Screen of the vision interface.

we choose a control input u_2, so that the previous closed-loop system is given by $\ddot{\nu_1} = -2\dot{\nu_1} - \nu_1$ where $s^2 + 2s + 1$ is a stable polynomial. Therefore, $\nu_1 \to 0$. The controller u_2 is then given by

$$u_2 = \frac{1}{1 + \tan^2\theta}(-2\dot{\theta}^2 \tan\theta(1 + \tan^2\theta) - \ddot{r}_1 - \tan\theta - r_1 - 2(1 + \tan^2\theta)\dot{\theta} - 2\dot{r}_1) \tag{7}$$

u_2 is a function of $\{\theta, \dot{\theta}, r_1, \dot{r}_1, \ddot{r}_1\}$ and that all these variables can be expressed as a function of $\{x, y, \theta\}$ and their derivatives. The main result is summarized in the following theorem.

Theorem 4.1: Consider the PVTOL aircraft model (1) and the control law in (4) and (7). Then the solution of the closed-loop system converges asymptotically to the origin, provided that $|\theta(0)| < (\pi/2)$.

The stability analysis of the previous result is presented in detail in [11] and [12].

V. Experimental Results

In this section, we present the experimental results when the control law given in Section IV is applied to the PVTOL platform described in Section II where the x, y position and the orientation θ measurements are obtained from the image given by the camera. In the computation of the control law, we also require the time derivatives of x, y and θ. They will be obtained using the following approximation $\dot{q}_t \approx (q_t - q_{t-T})/(T)$ where q represents either x, y or θ and T is the sampling period. The measurement of x, y and θ are expressed in pixels in the image frame, which means that the servoing is done on the basis of image features directly. For the real experiment, we have introduced in the model and in the control law the mass of the PVTOL. In Fig. 5, the results of the image acquisition program are shown. We clearly see the detection of the two points located on the PVTOL prototype. From the measurement of these two points, we compute the position x, y and the angle θ of the system. as explained in Section III. In particular, we started the PVTOL aircraft at the origin and the objective is to stabilize it at the position $(x, \dot{x}, y, \dot{y}, \theta, \dot{\theta}) = (0, 0, 60, 0, 0, 0)$ in pixels during $t \in [30s, 40s]$, then to bring back the aircraft at the origin. The results are shown in Figs. 6–8. In Fig. 6, we can see the difference between the real horizontal position of the PVTOL (along x) and the desired horizontal position. Along the horizontal axis x, 1 cm corresponds to

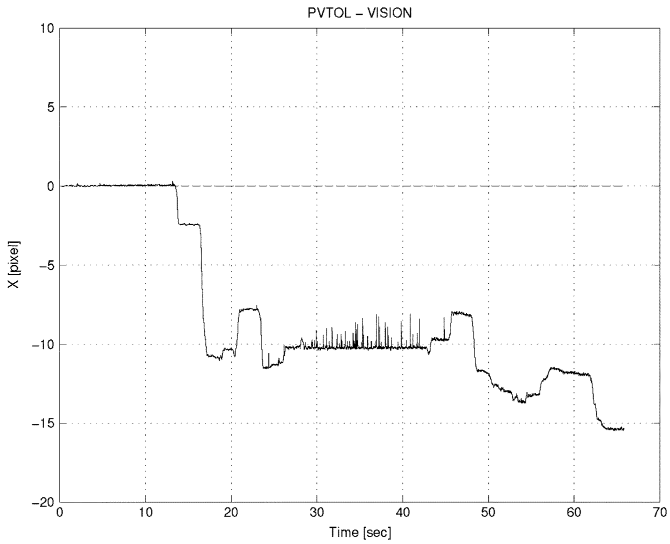

Fig. 6. Position x of the PVTOL system (- - - desired position, —real position).

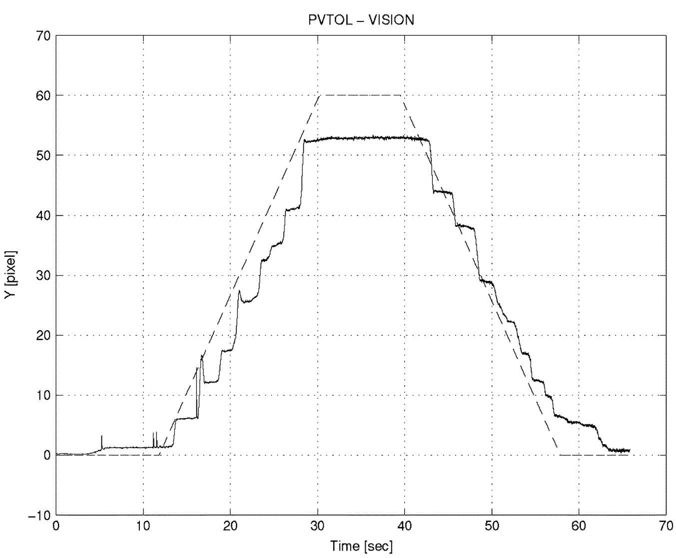

Fig. 7. Position y of the PVTOL system (- - - desired position, —real position).

5 pixels, which means that the position error is about 2 or 3 cm approximately. Fig. 7 describes the difference between the real altitude of the PVTOL (along y) and the desired altitude. We can notice that it follows satisfactorily the desired reference. Along the vertical axis, 1 cm corresponds to 2.5 pixels, which also means that the position error along y is about 2 or 3 cm approximately. Fig. 8 shows the evolution of the angle θ. In this figure, we visualize the effect of the control law which brings back the angle to zero as the PVTOL goes up toward the altitude of 60 pixels. This also explains the variations of the PVTOL along the horizontal axis x. Moreover, the differences between real and desired trajectories and the "staircase" traces appearing in Fig. 7 are also due to small frictions when the object moves on the plane and that we deliberately have not considered. The results are nevertheless very satisfactory. Indeed, experimental results show that the object remains inside the desired workspace and that stability is preserved.

VI. CONCLUSION

We have presented a stabilizing control strategy for the PVTOL and its application in an experimental platform. This platform exhibits the same difficulties found in autonomous flight close to the ground and can

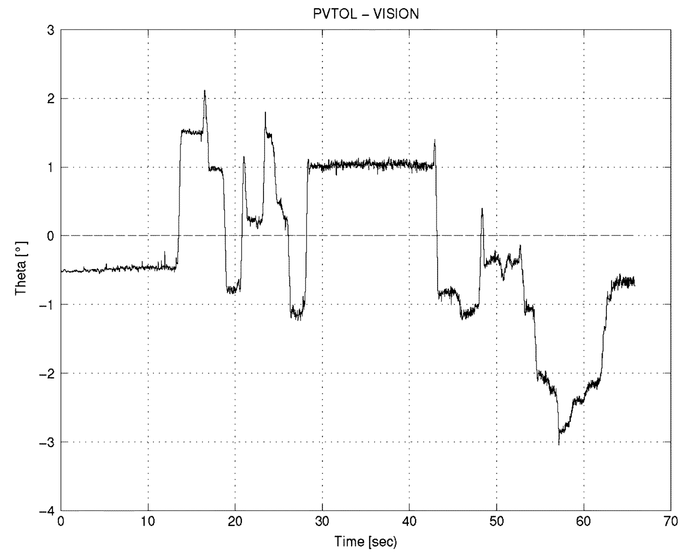

Fig. 8. Angle θ of the PVTOL system (- - - desired position, —real position).

be used as a benchmark for developing controllers for unmanned flying vehicles. The position and orientation of the PVTOL are computed using the image provided by a camera. We have developed a real-time environment to be able to validate the proposed control law. The experimental results showed a satisfactory behavior of the closed-loop system. Future works include visual servoing when the camera is onboard and pointing downwards or upwards to estimate the flying object position and orientation. We also believe that this experimental platform is a good test-bed for educational purposes in the domain of small flying vehicles.

REFERENCES

[1] J. Hauser, S. Sastry, and G. Meyer, "Nonlinear control design for slightly nonminimum phase systems: Application to V/STOL aircraft," *Automatica*, vol. 28, no. 4, pp. 665–679, 1992.

[2] A. R. Teel, "A nonlinear small gain theorem for the analysis of control systems with saturation," *IEEE Trans. Autom. Control*, vol. 41, no. 9, pp. 1256–1270, Sep. 1996.

[3] P. Martin, S. Devasia, and B. Paden, "A different look at output tracking: Control of a VTOL aircraft," *Automatica*, vol. 32, no. 1, pp. 101–107, 1996.

[4] R. Sepulchre, M. Janković, and P. Kokotović, *Constructive Nonlinear Control*, London: Springer-Verlag, 1997.

[5] F. Lin, W. Zhang, and R. D. Brandt, "Robust hovering control of a PVTOL aircraft," *IEEE Trans. Contr. Syst. Technol.*, vol. 7, no. 3, pp. 343–351, May 1999.

[6] L. Marconi, A. Isidori, and A. Serrani, "Autonomous vertical landing on an oscillating platform: An internal-model based approach," *Automatica*, vol. 38, pp. 21–32, 2002.

[7] R. Olfati-Saber, "Global configuration stabilization for the VTOL aircraft with strong input coupling," *IEEE Trans. Autom. Control*, vol. 47, no. 11, pp. 1949–1952, Nov. 2002.

[8] A. Zavala, I. Fantoni, and R. Lozano, "Global stabilization of a PVTOL aircraft with bounded inputs," *Int. J. Control*, vol. 76, no. 18, pp. 1833–1844, 2003.

[9] R. Lozano, P. Castillo, and A. Dzul, "Global stabilization of the PVTOL: Real-time application to a mini-aircraft," *Int. J. Control*, vol. 77, no. 18, pp. 735–740, 2004.

[10] M. Saeki and Y. Sakaue, "Flight control design for a nonlinear nonminimum phase VTOL aircraft via two-step linearization," in *Proc. 40th IEEE Conf. Decision and Control (CDC'01)*, Orlando, FL, pp. 217–222.

[11] I. Fantoni, R. Lozano, and P. Castillo, "A simple stabilization algorithm for the PVTOL aircraft," in *Proc. 15th IFAC World Congr.*, Barcelona, Spain, 2002, pp. 580–584.

[12] A. Palomino, P. Castillo, I. Fantoni, R. Lozano, and C. Pégard, "Control strategy using vision for the stabilization of an experimental PVTOL aircraft setup," in *Proc. IEEE 42th Conf. Decision and Control*, Maui, HI, 2003, pp. 4487–4492.