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Modelling and Controller Design Methodology for Unmanned Vertical Take Off and Landing (UVTOL) Vehicles

Alexander Martínez, Pedro Gutiérrez, Claudio Rossi,
Antonio Barrientos, Jaime DelCerro and Rodrigo San Martín
Robotics and Cybernetics Group
Universidad Politécnica de Madrid
Calle José Gutiérrez Abascal, 2, Madrid, Spain
E-mail : alexmartinez@etsii.upm.es

Abstract

This paper describes a methodology to parameterize linear, time invariant (LTI) models which represent the dynamics of UVTOLs and that are appropriate for analytical development of controllers. The models' validity was tested against real telemetry from two vehicles, a mini-helicopter and a quadrotor. The experiments show that despite their inherent limitations the LTI models are suitable for modeling the complex dynamics of aerial vehicles. Different LTI models for the mini-helicopter's stationary, lateral and longitudinal flights were obtained. Similarly, given the geometrical and dynamic characteristics of the quadrotor no distinction is made between stationary, lateral and longitudinal flights, and only one LTI model was obtained, which represents the overall dynamic behavior of the vehicle. Because of their relative simplicity these models were used to design analytical controllers and to obtain different controller prototypes in a quick and simple way to evaluate the UVTOL's performance in different flight conditions.

Keywords: UVTOL, modeling, controller prototyping

1. Introduction

The modeling, guidance, navigation and control of Unmanned Vertical Take Off and Landing (UVTOL) vehicles is a research topic with great developments, and has achieved significant progresses in recent years. It is sufficient to mention some work on helicopters modeling as La Civita [2002], Avila et al [2003], Cunha and Silvestre [2003], Bouabdallah [2005, 2006] and Castillo et al [2007] to note the large number of approaches that has been given to this field of engineering.

The UVTOL's complex dynamics and its variations related to flying altitude, weather conditions, changes in the vehicle's configuration (for example: weight, payload and fuel quantity), disrupt the modeling process and, consequently, the systematic development of control systems, resulting in tedious and critical heuristic adjustment procedures. This paper proposes a modeling methodology that leads to a set of linear and time invariant (LTI) models, which allow representations of stationary, lateral and longitudinal phases of flight; these models are then used for the development of analytical controllers and, as a consequence, a systematic synthesis process of them.

2. Description of used VTOL and proposed model

2.1 Description of aerial vehicles

In this section we briefly describe the VTOLs used and give a description of some details about the characteristics, variables and signals involved in their flight dynamics.

VTOLs are considered systems of six degrees of freedom, defined by three degrees to the position or location (X, Y, Z) and three other degrees to attitude (Roll, Pitch, Yaw angles) as described in Figure 1 for the mini-helicopter.

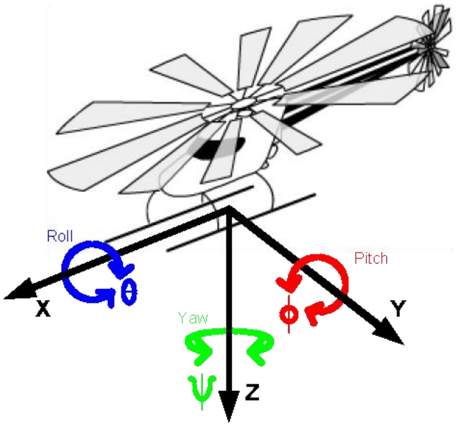

Figure 1. Nomenclature used for the mini-helicopter's variables

The mini-helicopter used is a Benzin Trainer of VARIO. Its main rotor measured 1.5 meters and has a 5 kg payload, thanks to its 26 cc engine.

On the other hand, the quadrotor used is a Draganflyer SAVS, with 0.8 m diameter, a payload of 85 g and energy autonomy for 12 to 15 minutes flights.

Thanks to the instrumentation on board the aircrafts and communications systems available, data from signals involved in the flight can be stored on land. Among the variables that can be obtained, are relevant to the model developed the following signals (as graphically represented in Figure 1):

X, Y, Z: Measured respect to an inertial system and only in the case of mini-helicopter, with a GPS.

Roll, Pitch: Measured with an IMU, with respect to the mobile axis of each VTOL.

Yaw: Measured with magnetic compass in the mini-helicopter and with IMU in Quadrotor.

Vroll, Vpitch, Vyaw: Calculated using a Kalman filter from the signals measured into IMU.

Croll, Cpitch, Cyaw: Control Signals of the respective Roll, Pitch and Yaw angles, sent through of RC transmitter.

2.2 Mini-helicopter's mathematical model

Dynamic features of VTOLs can be represented by complex models, where components such as non-linearities or parameter uncertainty are not easy to determine. In contrast, the majority of controller design procedures require a relatively simple mathematical model to establish some characteristics and adjust the parameters of the controller to design.

A relatively complex mathematical model for the mini-helicopter used in this work was obtained in earlier work (Aguirre [1999] and DelCerro [2007]). This model offers a good input-output representation of the system, but its complexity does not allow to use it in analytical procedures for controllers design. From this model we obtained a structure of a simple mathematical model, which can be represented with linear, time invariant (LTI) state equations and use it to develop a systematic procedure of controllers design.

The mini-helicopter was considered a decoupled system respect to its three main movements: the movement in a horizontal plane, parallel to the ground, with varying angles roll, pitch and the resulting lateral and longitudinal displacement, the Yaw movement and vertical movement or Z variation.

2.2.1 Model structure

The structure of LTI model proposed in this paper for the movement in a horizontal plane, with constant Z and based on zero Yaw angle assumption, is represented by the following state equations:

$$\dot{x} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ a_{21} & a_{22} & a_{23} & a_{24} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ a_{41} & a_{42} & a_{43} & a_{44} & 0 & 0 & 0 & 0 \\ a_{51} & a_{52} & 0 & 0 & a_{55} & 0 & 0 & 0 \\ 0 & 0 & a_{63} & a_{64} & 0 & a_{66} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & a_{76} & 0 & 0 \\ 0 & 0 & 0 & 0 & a_{85} & 0 & 0 & 0 \end{bmatrix} x + \begin{bmatrix} 0 & 0 \\ b_{21} & b_{22} \\ 0 & 0 \\ b_{41} & b_{42} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

Equation (1)

Where:

x_1 : Roll
x_2 : Roll derivative
x_3 : Pitch
x_4 : Pitch derivative
x_5 : Lateral linear speed
x_6 : Longitudinal linear speed
x_7 : Frontal displacement
x_8 : Longitudinal displacement

u_1 : Roll control signal
u_2 : Pitch control signal

This model structure assumes the existence of coupling between the Pitch and Roll angles, and a dependence on the lateral and longitudinal movements only with variations in pitch and roll angles respectively. From various experiments, we were able to verify that this structure model does not depend on the value of Z, or different constant values that can take the angle Yaw.

The model structure represented in Equation 1 is a parametric model whose coefficients a_{ij}, b_{kl}, should be defined for a particular aerial vehicle. For this, we developed an identification process on the real system, using genetic algorithms as computational tool.

During early experiments with the mini-helicopter and after data analysis aimed at obtaining a single model to represent its dynamics, we were able to show that its dynamic behavior when flying in a horizontal plane was sufficiently diverse from stationary, frontal and lateral flight. This raised the need to obtain a specific model for each of these types of flight.

2.2.2 Parameters Identification

A genetic-algorithm-based tool, which has been successfully used to parameterize other models, was used for the a_{ij} and b_{kl} parameter's identification process.

The selection criterion used was the minimization of an objective function given by the difference between real signals measured in the VTOL and signals provided by the model. This difference is represented by the value of the mean square error between those signals.

The implementation of the identification process in the case of mini-helicopter, resulted in the parameters that are detailed in Table 1, for the three different types of flight.

Table 1. Model parameters for mini-helicopter

Parameter	Hover flight	Longitudinal flight	Lateral flight
a_{21}	-0.0897	-4.9522	-9.4286
a_{22}	-1.0211	-0.1898	-2.8422
a_{23}	1.8807	1.5900	6.1920
a_{24}	0.7150	5.0240	-4.6793
a_{41}	-1.0785	-3.6885	-0.0641
a_{42}	-2.6725	-1.8418	0.4656
a_{43}	-1.1095	-4.4536	-8.1002
a_{44}	-2.0666	-3.4587	-5.5487
a_{51}	0.3604	-0.7884	0.2680
a_{52}	0.0213	0.8237	0.5478
a_{55}	-1.1681	-0.1264	-0.9287
a_{63}	1.2946	-0.4601	-1.3005

a_{64}	3.0741	0.5184	0.3482
a_{66}	-4.4571	-0.9718	-0.1548
a_{76}	-0.2156	-1.8407	-0.4067
a_{85}	0.3313	0.0961	1.1147
b_{21}	1.2969	-5.0342	-12.7259
b_{22}	0.8092	2.8049	-0.0557
b_{41}	-3.6516	-4.4360	1.8356
b_{42}	-1.3202	-4.0981	-3.6725

2.3 Quadrotor model

Similarly to mini-helicopter, was considered the quadrotor as a decoupled system respect to its three main movements: the movement in a horizontal plane parallel to the ground, with varying angles roll, pitch and the resulting lateral and longitudinal displacements, the Yaw movement and vertical movement or Z variation. However, given the geometrical and dynamic characteristics of quadrotor no distinction is made between stationary, lateral and longitudinal flights, and only one LTI model was obtained, which represents the overall dynamic behavior of the vehicle.

2.3.1 Quadrotor model structure

Given the physical limitations of quadrotor’s payload and the consequent difficult to obtain reliable measures of variables such as the position (X, Y, Z) a simple model to represent a smaller number of state variables with respect to mini-helicopter was chosen.

We propose a LTI, fourth order model (Equation 2) that will be useful to represent the Pitch and Roll angles, and then develop attitude controllers to provide stability to dynamics of quadrotor.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ a_{21} & a_{22} & a_{23} & a_{24} \\ 0 & 0 & 0 & 1 \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ b_{21} & b_{22} \\ 0 & 0 \\ b_{41} & b_{42} \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix}$$

Equation 2

Where:

x_1 : Roll
x_2 : Roll derivative
x_3 : Pitch
x_4 : Pitch derivative

u_1 : Roll control signal
u_2 : Pitch control signal

2.3.2 Parameters Identification

Using the same computational tools of mini-helicopter case, the parameters of the LTI model for quadrotor were identified, whose values are summarized in Table 2.

Table 2. Parameters model for Quadrotor

Parameter	Value
a_{21}	-1.1132
a_{22}	-0.7118
a_{23}	0.0001
a_{24}	0.0000
a_{41}	7.2721
a_{42}	6.1794
a_{43}	-7.9908
a_{44}	-5.2474
b_{21}	-1.1045
b_{22}	0.0000
b_{41}	-4.5267
b_{42}	-14.4146

3. Models Validation

3.1 Mini-helicopter’s model.

Some graphics are shown to compare the results of the LTI model simulations and the real data obtained in different experimental flights. Figures 2, 4 and 6 show, on the left side, the comparison between the real data (solid lines) and those resulting from the model simulations (dotted lines) with the same set of data used in the parameters identification process. In the right side is reported the same comparison between real and simulated data, but with a different set of data called “control data”.

Figures 2, 4 and 6 compare real values of Pitch and Roll angles, as well as lateral and longitudinal movements of mini-helicopter (which coincide with the X and Y axes, when Yaw angle is zero), with those resulting from the simulation of stationary, lateral and longitudinal flights, obtained from the respective models previously described.

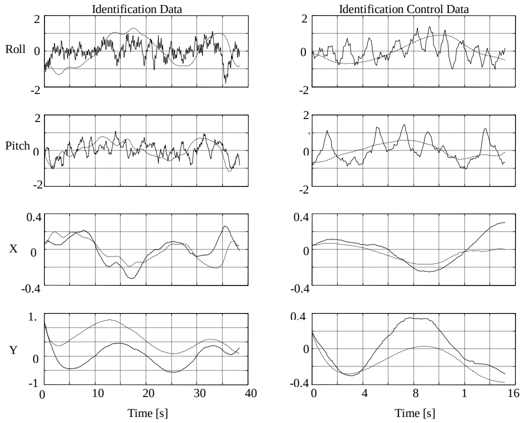

Figure 2. Real and simulated data comparison for hover flight.

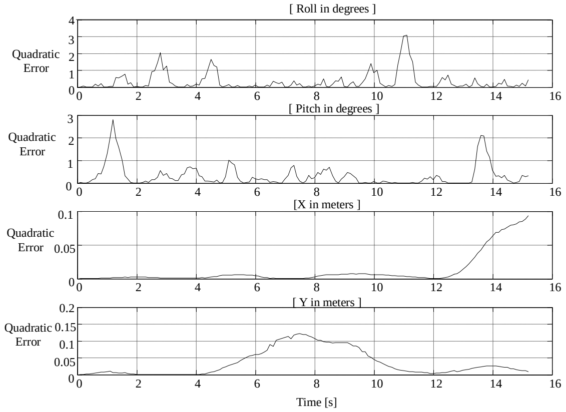

Figure 3. Quadratic error for data control in hover flight

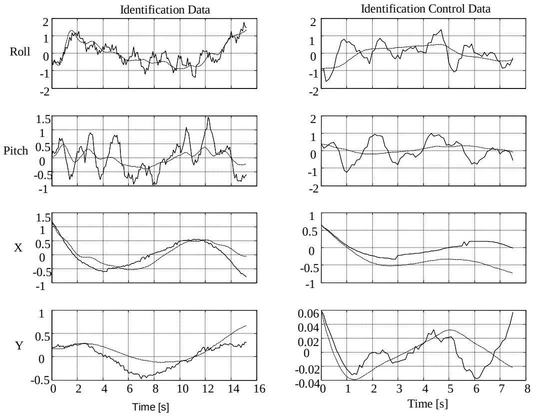

Figure 4. Real and simulated data comparison for longitudinal flight

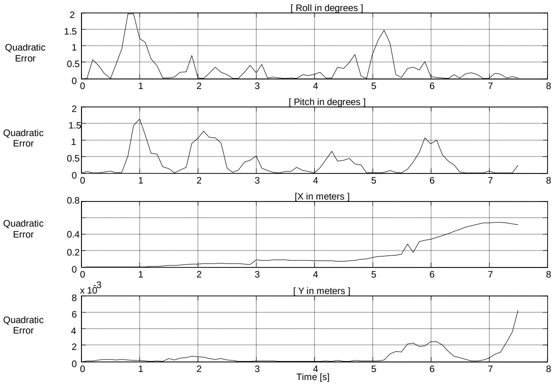

Figure 5. Quadratic error for control data in longitudinal flight

The plots in Figures 2, 4 and 6 shows that real Roll and Pitch signals have a higher frequency component than those obtained from the model simulation. However, frequency analysis of signals measured were performed with the mini-helicopter in flight, with the mini-helicopter on the ground and engine turned on and then with the engine off. Such analysis could determine that these high-frequency signals are due to mechanical vibrations caused by the engine movement.

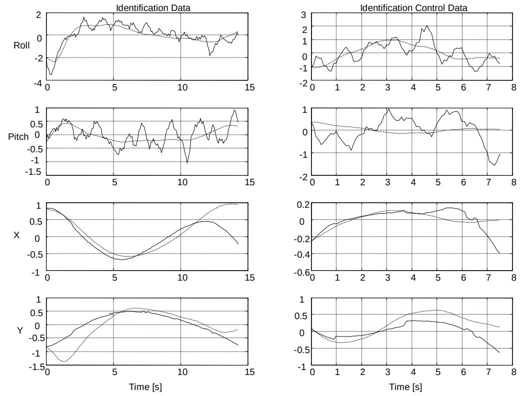

Figure 6. Real and simulated data comparison for lateral flight

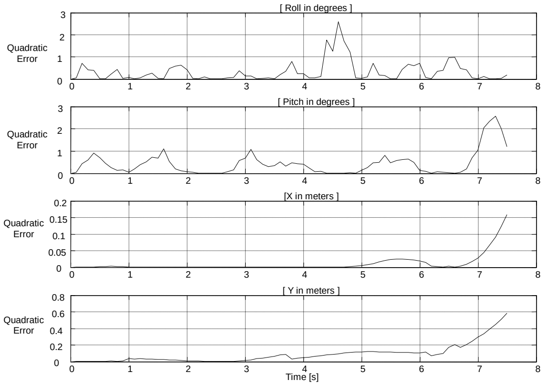

Figure 7. Quadratic error for control data in lateral flight

The quadratic error graphics (Figures 3, 5 and 7) show differences smaller than 0.5 degrees between real and simulated data, in Pitch and Roll angles. The resulting behavior on the position in X and Y also presents a negligible error, except for some specific samples where the error Pitch and Roll is a little higher (in all cases of flight). This error may be attributed to high frequency vibrations commented previously.

It should be noted that the latest samples from each data sets are part of a transition phase between the three different types of flight (stationary, front and side), which explains that towards the end of the quadratic error graphics, this error becomes bigger, because the actual behavior of the helicopter in these transitions does not correspond exactly with any type of flight consideration.

With the above can be concluded that model structure, with the corresponding sets of parameters obtained, is a suitable representation of mini-helicopter dynamic behavior. In other words, the model, with relevant parameters depending on type of flight, allows an approximate representation of mini-helicopter complex dynamic. For this reason, this model can serve as a practical and useful tool for driver design and development procedures, despite the limitations and approaches set out in the model definition

(LTI model with relatively small order).

3.2 Quadrotor model.

Figure 8 shows the same comparisons for the case of the quadrotor. On the left side real data (solid line) is compared to model simulation (dotted line) on the set of data used in the identification process. On the right side the same comparison using a different set of data (control data).

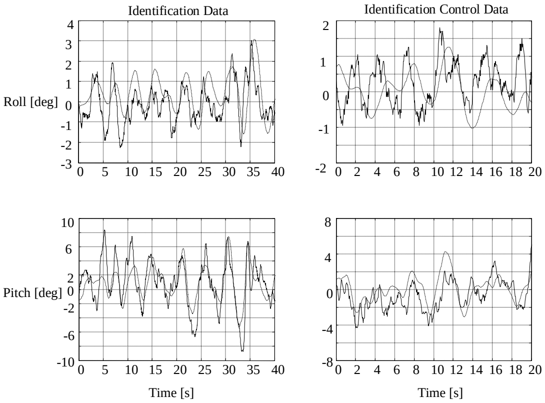

Figure 8. Comparison of real and simulated data for the quadrotor model.

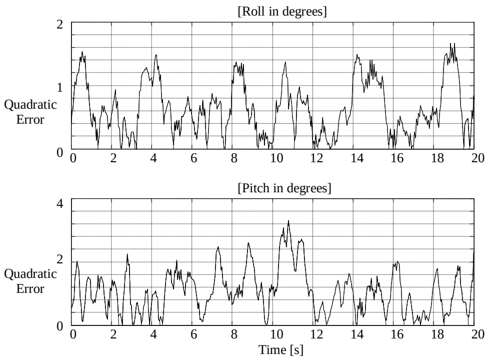

Figure 9. Quadratic error of the control data in the quadrotor model

Figure 9 shows the difference between the measure and simulated Roll and Pitch values, expressed as quadratic error. As it can be noticed, the difference is bigger than in the case of the helicopter. This is due to the fact that in the quadrotor case only one model has been used for the three flight modes. Moreover, due to the limited payload of this vehicle, an IMU with less precision had to be used.

4. Design procedure obtained

Once obtained the models for the two vehicles described above, it was possible to establish a standard procedure for the design of analytical controllers with many proven techniques, such as pole placement, linear quadratic regulators and sliding modes control. This is the main advantage of our modeling methodology, which was validated by the design of various controllers for both UVTOLs.

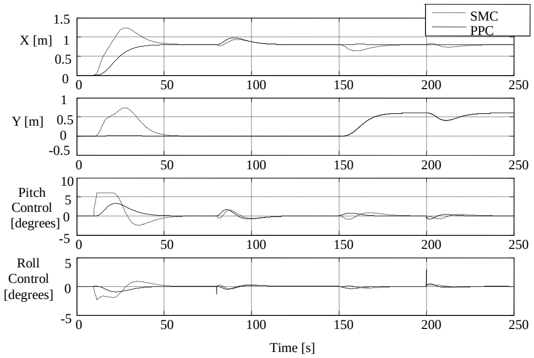

Figure 10. Comparison between two different control techniques for the mini-helicopter.

Figure 10 shows the comparison between X and Y position signals for the mini-helicopter, in response to small changes in the reference for maintaining it in stationary flight, controlled using sliding mode control (SMC) and pole placement control (PPC).

In the same way, Figure 11 shows the comparison between Roll and Pitch simulated signals, using pole placement control (PPC), sliding mode control (SMC) and LQR control.

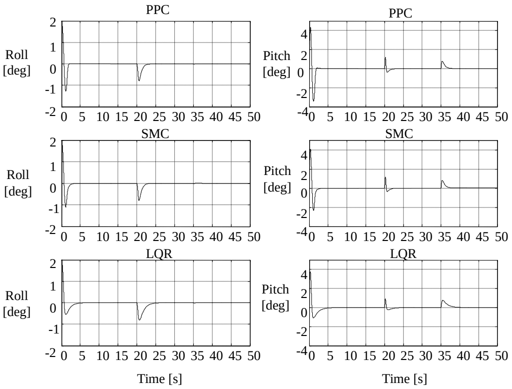

Figure 11. Comparison between three different control techniques for the quadrotor.

Finally, in order to compare the goodness of the controller modelling and design process, we have realized some experimental flight with the quadrotor using the sliding mode controlled for controlling the Roll and Pitch signals, achieving stationary attitude for the vehicle. Figure 12 shows the comparison between manual flight and automatically controlled flight data.

Note that the Roll and pitch values do not reach the value zero due to the position of the position of the IMU that involve an offset for these variables.

In general, the controller designed for this case allow a better behavior, including rejecting the perturbation that can be noticed at t=6 s.

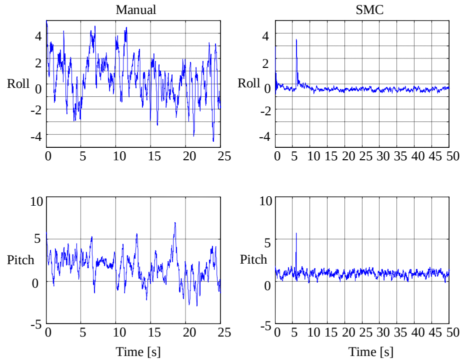

Figure 12. Results obtained for sliding mode control for the quadrotor.

5. Conclusions

The structure of the proposed mathematical model for VTOLs allows a suitable representation for the dynamics of such aerial vehicles, despite its simplicity and approximations.

We have developed and tested a simple methodology that allows obtaining LTI models for small VTOL vehicles, as well as to design implement and test different kinds of controllers for them.

6. Acknowledgment

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