LQG vs PID for attitude control of a for unmanned aerial vehicle in hover

A. Barrientos I. Aguirre J. Del-Cerro P. Portero

Departamento de Automática, Ingeniería Electrónica e Informática Industrial
DISAM -Universidad Politécnica de Madrid
C/ José Gutiérrez Abascal, 2 28006-Madrid, Spain
barrientos@etsii.upm.es

Abstract

Helicopters exhibit highly nonlinear systems with strongly coupled modes. They are very difficult to model and to control. In this paper, a model of the minihelicopter in hovering is proposed and controlled using two types of control strategies: a Linear Quadratic Gaussian (LQG) and a PID one. A test platform is proposed in order to perform tests and avoid helicopter crashes and sensor losses. This paper also describes the architecture of the ELEVA prototype that is being developed by the robotic group of DISAM at the Universidad Politécnica de Madrid for unmanned aerial inspection of electrical power lines. The two controllers are compared using a performance index in order to select the best one.

1. Introduction

The purpose of this work is to compare two control strategies with the objective of maintain a minihelicopter in hovering. Hover is one of the most important helicopter flight modes, because it leaves the craft in stationary flight and keeping the same orientation and altitude of the craft. In hover, roll and pitch angles are close to zero and yaw angle must be constant. These three angles (roll, pitch and yaw) describe how the craft is orientated in space. The adopted expression describes the orientation of the craft.

Helicopters are very difficult to control because they conform highly nonlinear systems with strongly coupled modes. They are complex systems with multiple inputs and multiple outputs (MIMO). Due to the difficulties presented by non linear systems, it is of high interest to study and improve identification and control techniques.

In order to obtain the data, it is necessary to build a system's architecture that allows to know the orientation of the craft at every moment. Once the data are captured, the controller must generates the correct control action in order to maintain the craft in hover.

In the following sections, the system's architecture will be presented. Due to the risk implied in flying a helicopter and considering the possibility of crashes and expensive sensor losses, a test platform is used for initial development experiments. This platform allows to perform experiments with different controllers in a safe space inside DISAM's laboratory.

2. The ELEVA system architecture

The ELEVA project is a three year long project supported by the CICYT (Spanish National Research Program) and by Red Eléctrica de España, that is the owner company of the transmission network within the Spanish electrical system, and it is responsible for operation, maintenance and construction. ELEVA are the initials in spanish of "Exploration of Power Lines with and Unmanned Aerial Vehicle" [1].

Figure 1 shows the system architecture of the ELEVA prototype in which two subsystems can be differentiated. A fixed subsystem and a mobile one which are communicated via radio. The first ELEVA prototype is based on a small commercial radio controlled (RC) helicopter, which uses a gas engine and has a very limited load capability. Due to this, only the minimum weight can be accepted on the craft.

The mobile subsystem is on board the helicopter and it is composed of a computer, two video cameras, several sensors and two radio links. The main sensor to perform the navigation, consists of a strapdown Inertial Measurement Unit (IMU). The IMU allows to determine the attitude and the relative position of the craft. It is composed of three optical fiber gyros and three micro machine accelerometers. Both accelerations and angular rates are measured in a fixed to helicopter frame. Angular rates are integrated in order to get roll, pitch and yaw angles by a navigation module software. Also this module transforms the accelerations into an inertial reference frame and integrates them twice in order to obtain the relative position. The relation between helicopter frame and the position of the power line must be obtained by vision system.

There is also a laser telemeter used as an altimeter so as to measure the distance to the ground. A small size computer has the mission of performing the sensorial fusion, navigation and low level controls. The state of the helicopter is sent to ground station using a radio link as to be displayed to the supervisor. Images of the power lines are captured by a video camera and also are sent to ground via radio to be processed by the vision system.

The ground subsystem is composed of two computers, one of them is in charge of doing the high level control, task scheduling and the path planning of the craft, while the other computer does the image processing and generates the navigation corrections. It is included in Figure1 into the vision system box. The two ground computers are connected via network.

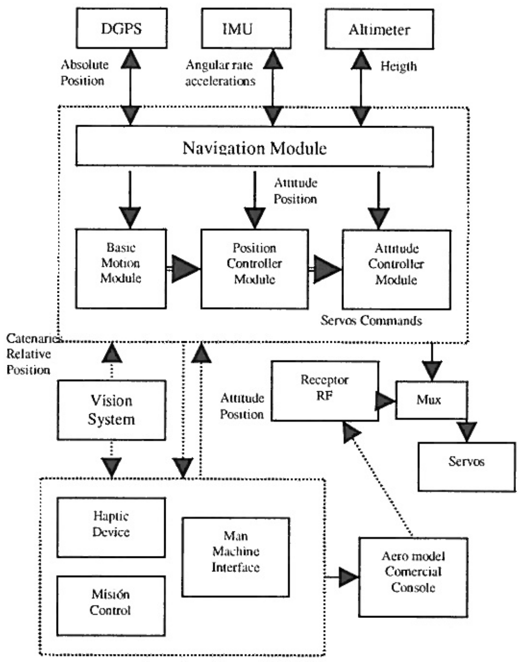

Fig. 1. ELEVA architecture

An operator supervises the operation of the helicopter. Thus, if something unexpected occurs, he/she could take the control of the aircraft using a haptic device. An emergency control exists if something goes wrong. In this case, the selection between automatic and manual control mode can be easily done using a simple switch located in the commercial emitter.

In order to test the different control algorithms without any risk of a human accident or lose of sensors, a test platform has been used. The platform has six freedom degrees and it is constructed in order to allow the craft to freely move in attitude, vertical, lateral and longitudinal traveling. An inertial measurement unit is utilized as principal sensor, to capture the attitude of the vehicle, its acceleration and velocity. See Figure 2.

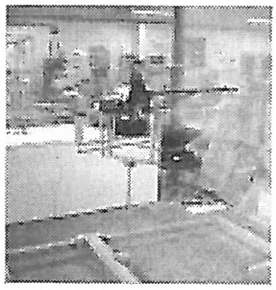

Fig. 2. Helicopter in test platform

3. Minihelicopter Model

The helicopter model is based on other previous works done by [2] and [3]. These studies conclude that the helicopter model may be separated in two parts. The first part represents the main rotor and the second one represents the tail rotor dynamic.

To make this separation, the following assumptions are needed:

- The main rotor is composed of two blades without dragging motion.
- The vehicle mass center is located under the rotor shaft.
- In hover, the rotor angular velocity is constant.
- The tail rotor is composed of two blades and its hub center is located on the fuselage longitudinal axis.

Once the assumptions are made and replacing the hover conditions

$$\ddot{\beta}_S = \ddot{\beta}_C = \dot{\beta}_C = \dot{\beta}_S = u_F = v_F = 0 \qquad (1)$$

and substituting the model variable values from Appendix A, the final reduced model for the roll and pitch movements is obtained: (2)

$$\begin{bmatrix} \dot{\Phi} \\ \Phi \\ \dot{\Theta} \\ \Theta \end{bmatrix} = \begin{bmatrix} 1 & 0.0199 & 0 & 0.0003 \\ 0 & 0.9911 & 0 & 0.0274 \\ 0 & -0.0018 & 1 & 0.0186 \\ 0 & -0.1745 & 0 & 0.8595 \end{bmatrix} \bullet \begin{bmatrix} \dot{\Phi} \\ \Phi \\ \dot{\Theta} \\ \Theta \end{bmatrix} + \begin{bmatrix} 0.0485 & 0.0031 \\ 4.9355 & 0.4557 \\ -0.0104 & 0.2960 \\ -1.1646 & 28.874 \end{bmatrix} \bullet \begin{bmatrix} \theta s \\ \theta c \end{bmatrix} \qquad (3)$$

$$\begin{bmatrix} \Psi \\ \dot{\Psi} \end{bmatrix} = \begin{bmatrix} 1 & 0.0185 \\ 0 & 0.8562 \end{bmatrix} \bullet \begin{bmatrix} \Psi \\ \dot{\Psi} \end{bmatrix} + \begin{bmatrix} 0.008 \\ 0.751 \end{bmatrix} \bullet \begin{bmatrix} \theta t \end{bmatrix} \qquad (4)$$

where:

$\ddot{\Theta}$ = *Pitch angular acceleration* $\dot{\Theta}$ = *Pitch angular velocity*

Θ = *Pitch angle* $\ddot{\Phi}$ = *Roll angular acceleration*

$\dot{\Phi}$ = *Roll angular velocity* Φ = *Roll angle*

$\ddot{\Psi}$ = *Yaw angular acceleration* $\dot{\Psi}$ = *Yaw angular velocity*

Ψ = *Yaw angle* θ_C = *Pitch control (longitudinally cyclic)*

θ_S = *Roll control (laterally cyclic)*

θ_t = *Yaw control (collective of tail rotor)*

β_C = *Pitch flapping angle (longitudinally cyclic)*

β_S = *Roll flapping angle (laterally cyclic)*

4. Identification System

Because of the uncertainty of some model parameters and the fact that some of them are very difficult to measure, they were taken directly from previous works carried out by [2], [4] and [5].

In order to determine how good the helicopter model is, it was identified using experimental data. The proposed model, given by (4), has the same characteristics of the mathematical model. The Matlab System Identification toolbox was used to calculate the parameters. Due to the characteristics of the system (MIMO), the algorithm utilized was the Prediction Error Method (PEM), which permits to handle multiple-inputs multiple- outputs. Once the model was obtained, it was necessary to determine how close it approximates to real. The system identification was done for the pitch and roll movements.

The identification experiment consists of the previous works of acquiring the roll and pitch angle values. A function that establishes the relation between the servo position and the blade angle was constructed. Once the input and output variables were known, the next step was to select an identification model. The data were collected each 20 ms. and store in an input output record file.

The proposed model is described in (4):

$$\begin{bmatrix} \Phi \\ \dot{\Phi} \\ \Theta \\ \dot{\Theta} \end{bmatrix}_{[n+1]} = \begin{bmatrix} P1 & P2 & 0 & P3 \\ 0 & P4 & 0 & P5 \\ 0 & P6 & P7 & P8 \\ 0 & P9 & 0 & P10 \end{bmatrix} \bullet \begin{bmatrix} \Phi \\ \dot{\Phi} \\ \Theta \\ \dot{\Theta} \end{bmatrix}_{[n]} + \begin{bmatrix} P11 & P12 \\ P13 & P14 \\ P15 & P16 \\ P17 & P18 \end{bmatrix} \bullet \begin{bmatrix} \theta_S \\ \theta_C \end{bmatrix} \quad (4)$$

where Pi are the parameters to estimate.

By applying the PEM routine of MATLAB, the final identified model is as follows:

$$\begin{bmatrix} \Phi \\ \dot{\Phi} \\ \Theta \\ \dot{\Theta} \end{bmatrix}_{[n+1]} = \begin{bmatrix} 1 & 0.021 & 0 & 0.0002 \\ 0 & 0.99 & 0 & 0.025 \\ 0 & -0.0013 & 1 & 0.02 \\ 0 & -0.1820 & 0 & 0.848 \end{bmatrix} \bullet \begin{bmatrix} \Phi \\ \dot{\Phi} \\ \Theta \\ \dot{\Theta} \end{bmatrix}_{[n]} + \begin{bmatrix} 0.06 & 0.0032 \\ 4.75 & 0.45 \\ -0.0098 & 0.313 \\ -1.18 & 27.356 \end{bmatrix} \bullet \begin{bmatrix} \theta_S \\ \theta_C \end{bmatrix} \quad (5)$$

The final model was tested with real data collected during the tests, obtaining Figures 3 and 4.

Figures 3 and 4 shows the outputs obtained from the identified system, the outputs taken from measurements of the physical system and the error produced by comparing them. The results obtained demonstrate that the identified model is very close to the real helicopter model.

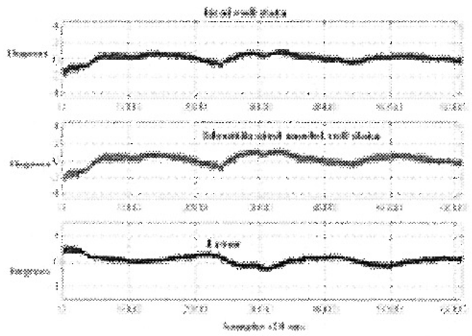

Fig. 3. Roll evolution. Real, identified and error produced

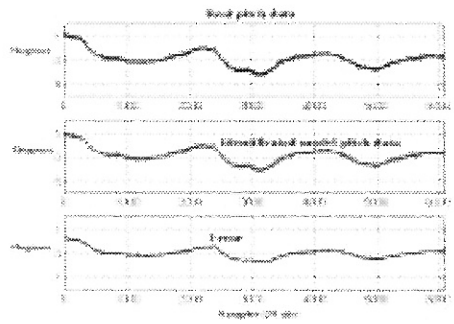

Fig. 4. Pitch evolution. Real, identified and error produced

5. Control System

A helicopter has six degrees of freedom in its motions. There are four control inputs concerning its flight in addition to throttle control for the rotation of rotors. Coordinating these inputs the helicopter can make various flights: forward and backward flight, sideward flight, hovering, hovering turn, vertical climb and descent, etc. The helicopter has several characteristics which makes it difficult to control; it is an unstable and nonlinear system, it has multiple input and cross couplings.

In order to solve this control problem, the ELEVA control system architecture relies on four control layers. The lowest level control is the attitude control. It receives roll, pitch and yaw angles as reference signals and generate the output to the servos. In addition to that, the tail rotor has an inner loop control using a gyroscope. The upper level control is the position control; it receives coordinates as reference and generates the corresponding angles to the low level control so as to reach the desired position. The next layer is the basic movements control. It performs simple movements (forward, backward, vertical climb and descent, sideward, and hovering rotations). A scheduler decomposes every task given to the helicopter control system in a list of these basic movements. The two lowest control layers are implemented into on board computer and the highest ones into the ground control computer. On board system relies on a flight strategy if a long loss of communication appears, thus if this situation happen, the helicopter stop the current task and stay in hovering until the communication is restored.

Robustness is considered as the main requirement of control in minihelicopters. The control action must give a precise answer at any time in such a manner to minimize the risk of a crash. The helicopter has a very particular and complex dynamics due to its couplings and high non linearities. The first control goal is to attempt to control the attitude of the craft (roll, pitch and yaw).

The first step to build a controller is to model the dynamics of the helicopter near the operation point, which in our case is hovering. Once the mathematical model is obtained using the empirical measurements from the craft, the next step is to propose the type of control to be implemented.

5.1 LQG control

Due to the facilities of the mathematical model represented in state space, a Linear Quadratic Gaussian Control (LQG) is selected for controlling the roll and pitch of the craft in hover.

Linear Quadratic Control is utilized to calculate the controller necessary to fulfil the planned objectives. Due to the fact that the only disposed variable is position, it is recommended to estimate the other variables. To estimate variables Kalman Filter is applied. The Linear Quadratic Gaussian Control refers to an optimal control problem for a linear plant model in which Linear Quadratic Control and Kalman Filter are utilized. To calculate the gain matrix, the following quadratic cost function is applied:

where matrices Q and R are positive semi-definite.

$$J = \sum (x' Q x + u' R u)$$

The optimal controller is represented in state model by:

$$u(t) = -K(t)\,\hat{x}(t) \qquad (7)$$

$$\dot{\hat{x}}(t) = \left[A - G(t)\,C_m - B_u\,K(t)\right]\hat{x}(t) + G(t)\,m(t) \qquad (8)$$

Figure 5 shows the block diagram utilized for control of the roll and pitch movements of the craft. After the linearization in hover, the proposed linear model will be composed of four states and two control variables. The use of Kalman filter is required to calculate the velocity, thus Kalman filter performs the estimation of the variables. Once the state variables are obtained, the control action is calculated using the Linear Quadratic Regulator [6].

The function *dlqe* of the control toolbox of Matlab permits to calculate the state estimation. The function *dlqr* is used to calculate de regulator.

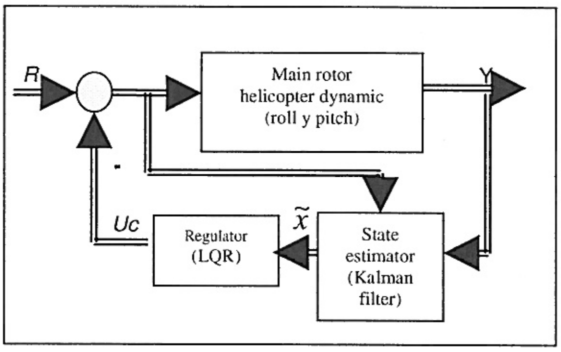

Fig. 5. Control block diagram for pitch and roll

An internal regulation is done using a piezoelectric gyroscope for the yaw. A higher level regulation is obtained using a proportional control. The control scheme for the yaw control could be seen in Figure 6.

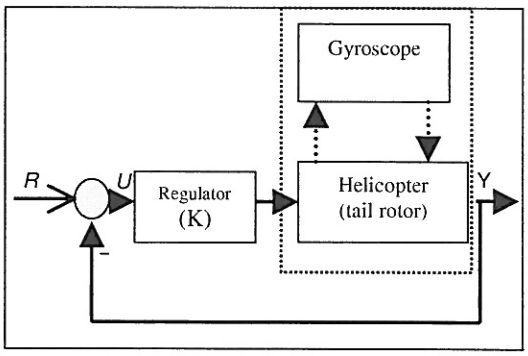

Fig. 6. Control block diagram for the yaw

5.2 LQG control results

Controllers maintain the craft near hovering as shown in Figure 7. The main characteristic of hover is that roll and pitch angles must be close to zero. It can be seen that the three orientation angles, corresponding to roll, pitch and yaw angles of the minihelicopter, maintain their reference values of zero degrees with a small error. The control is obtained for the three angles and keeps the helicopter in hover. The maximum error committed by the pitch and roll value with respect the reference of 0 degrees is of 1 degree but in most of the samples, the error is close to 0. For the yaw figure there are some peaks in short period of time that the error approaches 3.5 degrees and then it maintains the value close to the reference.

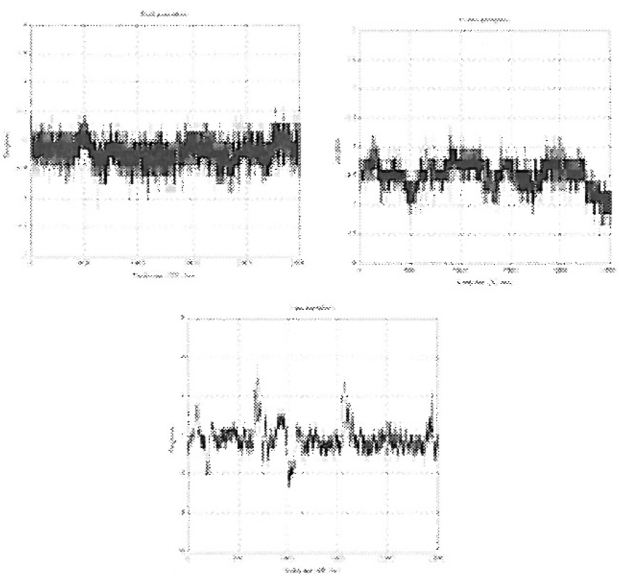

Figure 7. Roll, pitch and yaw evolution

To evaluate the robustness of the controller, a test was carried out by disturbing the helicopter attitude while it was in hover. The disturbances were imposed upon the craft by pulling the helicopter out of the hover position with a cable connected to the test platform. A turbine was also used to disturb the helicopter orientation. As can be seen in Figure 7, the orientation of the helicopter returns to the reference values once the perturbation is compensated by the controls' actions. The disturbances are introduced in sample 0 and in sample 400. The outputs of the system shows that the controller works very well leading the helicopter to a stationary flight. The system delays 4 seconds in returning to the references values after the perturbations were imposed.

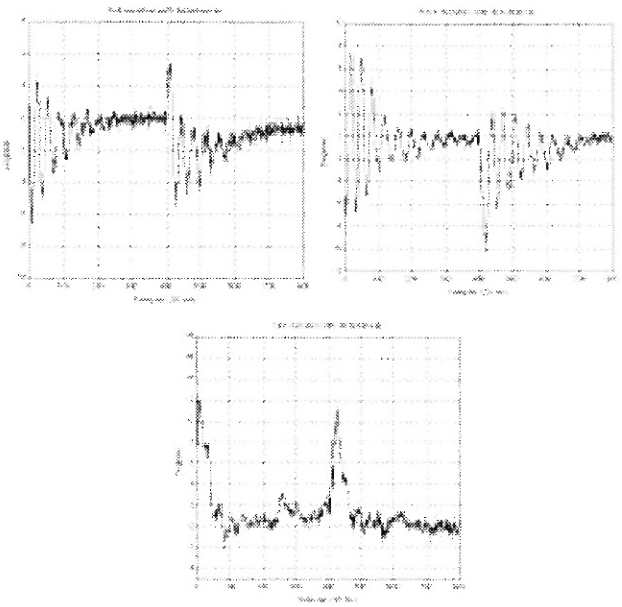

Fig. 8. Roll, pitch and yaw with disturbances

As seen in Figures 7 and 8, the Linear Quadratic Gaussian Regulator calculated for the roll and pitch movements behaves very well and is robust in the presence of external disturbances. The PID control for yaw also works correctly in the presence of external disturbances.

5.3 PID control

Another control strategy is proposed in order to compare the results obtained with the LQG. A PID design was done using the mathematical model. The controller is designed to have a settling time of 2.5 seconds and a maximum overshot of 10%. After the implementation the result are shown in Figure 9. The controller was also tested in order to check the robustness of the system with external disturbances and change of references.

5.4 PID control results

As can be seen in Figure 9, the roll and pitch movements, controlled with the PIDs, respond correctly and conduces the helicopter to the hovering position. The controllers robustness was tested submit to external disturbances. The results obtained are accurate and the systems respond in a short period of time.

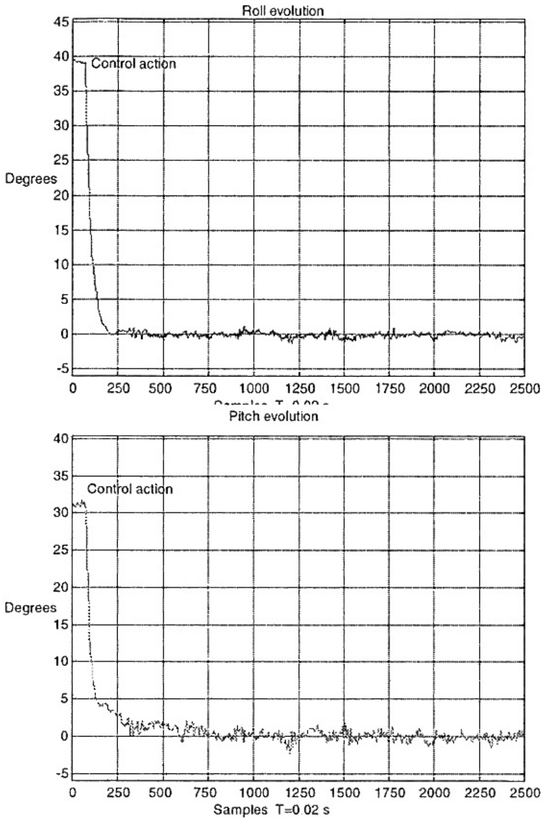

Fig. 9. Roll and pitch evolution with a PID

6. LQG-PID comparition

In order to compare the two control strategies implemented (LQG and PID), a experiment was done. It consists in activating the control action and leaving the helicopter in hover, after a few seconds a change of references were done and the helicopter follows them. A performance index was selected in order to compare the results. The performance index selected was the least square method. After obtaining the performance index for each movement, they can be compare easily. As can be seen in the following table, the system with the LQG controller responds better than with the PID controller.

TABLE 1

Control Strategy	Least square error (%) Roll	Least square error (%) Pitch
LQG	2,98	4,94
PID	4,11	6,61

7. Conclusions

In this paper, a system's architecture has been presented to control a minihelicopter in an autonomous way for inspection of electrical power lines.

A scheme has been proposed and implemented in order to control the minihelicopter attitude. The yaw control is attained with a proportional regulator, which gives a very fast response with no oscillations. The roll and pitch controls are achieved using a Linear Quadratic Gaussian control and a PID, which stabilizes the minihelicopter in hover.

To examine the robustness of the controllers, the helicopter has been subjected to a disturbance. The results show that the controllers are capable of returning the craft orientation to the required hover.

A PID controller was also implemented to compare different control strategies. A performance index was selected and the two regulators were compared. Better results were obtained using the LQG for roll and pitch movements.

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References

[1] Del-Cerro J., Aguirre I., Barrientos A., 2000, "Development of an autonomous minihelicopter for power lines inspection". Proceedings SPIE Vol. 4195, Boston, USA.

[2] Furuta K., Y. Ohyama and O. Yamano, 1984, "Dynamics of RC helicopter and control". Elsevier Science Publishers B. V., Mathematics and computers in simulation. XXVI. Netherland, pp. 148-159.

[3] Johansson H., 1994, "Modellering av en RC-helicopter". Master´s Thesis. Linköping Institute of Technology, Linköping University. Sweden.

[4] Maki E., 1998, "System Identification and Attitude Control of an R/C Helicopter". Honors Thesis for B.S. Department of Mathematics and Computer Science, Central Missouri State University. USA.

[5] Persson M. and R. Klang, 1997, "Autonomous Flying Helicopter: Attitude Control". Master´s Thesis. Center for Computer Architecture, Halmstad University. Sweden.

[6] Barbariol F., 1995, "Implementation of an Autonomous Helicopter Flight Controller". Master´s Thesis. Linköping Institute of Technology, Linköping University, Sweden.