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FOUR ROTOR HELICOPTER CONTROL LABORATORY PLANT

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Abstract: In this paper, a test-bed for teaching in multivariable system is presented. Firstly, the different aspects of the prototype construction will be described, making a special emphasis in the mechanics, the design of the sensorial and actuation systems and the prototype control. Next, the real time control software will be explained. The mathematical model of the plant is presented in order to design a control strategy, test it in simulation and validate in the real system

Keywords: Multifrequency systems, Multivariable systems, Helicopter dynamics, Helicopter control, real time control.

1 INTRODUCTION

Some multivariable laboratory processes are commercially available, for example from Feedback instruments, Alecop or Gunt and their principal multivariable plants are the double rotor and the double tank. However, these plants have a low degree of interaction between input and output and a control strategy can be designed as two independent controllers.

In this paper, a laboratory pilot plant with the characteristics described above is presented. The setup was initially developed as a test-bed for applied research in the field of nonlinear multivariable control, and it was extended at the laboratory experiment to the last year of undergraduate course on control engineer.

The development of real time hardware and software is more accessible thanks to the advance of computer science; in this case the real time software is integrated with standard design software like Matlab/Simulink, played a very important role in the design of the control strategy.

The outline of the paper is as follow. The plant is described in Section 2, including the sensorial and actuation subsystem. The movements and prototype comportment is presented in section 3. The mathematical model is explained in section 4. The real time software and hardware platform is exposed in section 5. A Control example in section 6.

2 PLANT DESCRIPTION

2.1 Introduction

Helicopters have the capacity of keeping flying in a fixed place (hovering). In addition to this ability, any movement of six degrees of freedom is allowed (Austin, 1997), (Simons, 1987). This marks the helicopter as one of the few flying systems with the capability of making these actions. So a helicopter as a laboratory plant has six output to control, the position in the space (x,y,z) and its orientation expressed in Euler angles.

The prototype that has been constructed corresponds to a helicopter with a four rotor tandem. This type of model has the advantage of having a very simple mechanical part. The main component of a standard helicopter is the rotor, which is a very complex mechanical system which directs the propeller in the appropriate way to move the helicopter in the correct direction. To achieve this objective, the angle of attack (collective grip) and the inclination (cyclic pitch) of the blades are varied. In this prototype the rotor consists of a motor and a reduction gear. In a standard helicopter each output variable have a principal input variable to control, in a four rotor one the inputs have a high degree of interaction, so a multivariable control system should be designed to manage the prototype.

In a four rotor helicopter all the movements are exclusively controlled by using the angular velocities of each rotor. Concretely, combinations of rotation speeds of the four rotors are used with this purpose. Thus, the mechanical problems related with the rotors construction are greatly simplified. Another important feature is the absence of anti-torque rotor, because the torque of each propeller is cancelled by its neighbour's. In Fig.1 it can be seen the prototype in the test place.

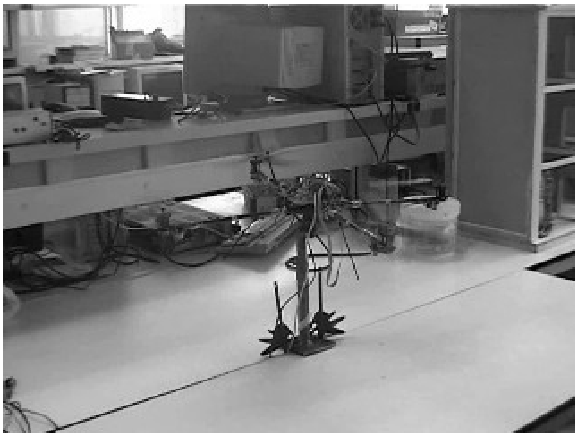

Fig. 1. Overview of helicopter plant.

2.2 Mechanical aspects

The main components of the external structure of the prototype are the following:

· Two cross-shaped tubes.
· Four engines, each one of them provided with two blades.
· An ultrasounds sensor under each rotor.
·A board containing all the other electronic components.

The blades of the rotor are 18 cm long. In order to avoid turbulence, it is necessary to leave a certain distance between each one of the rotors of at least 10cm. This avoids that the movement of one of the rotors affect the others. The material chosen for the construction of the helicopter is carbon fibre, due to the fact that it is essential that the prototype is as light as possible. Concretely for the chassis, a tube of carbon of 8mm of outer diameter has been used. With the purpose of the two cross-shaped tubes of 65cm are at an angle of 90 degrees, a piece used in the construction of kites has been also used in this prototype.

A very important part of the chassis is the joint with the engines. The pieces constructed with this purpose are made of carbon fibre.

The paws of the helicopter are also incorporated to the chassis. Due to the peculiarities of this prototype, these paws do not look like the ones of a conventional helicopter. Concretely, in the prototype presented in this paper, the paws have a dual function: apart from being the support in the take-off and landing, they also keep the helicopter chassis in a certain altitude.

The blades of the rotors are also made of carbon fibre and had to be made-to-measure for this prototype.

2.3 The sensorial system of the prototype

The sensorial system of the prototype is composed of four different types of sensors: gyroscopes, accelerometers, ultrasounds and compass.

2.3.1 The ultrasounds

With the aim of measuring the distance from the prototype to the floor and its inclination with respect to it, the SRF08 ultrasounds have been used. Two of the most relevant characteristics of these modules are the possibility of connecting them through a I2C bus and their low consume. Although due to the prototype symmetry it incorporates four ultrasounds, (one ultrasound device in each one of the helicopter propellers), only the information provided by three of them is really used in order to determine the plane in which the prototype is with respect to the floor.

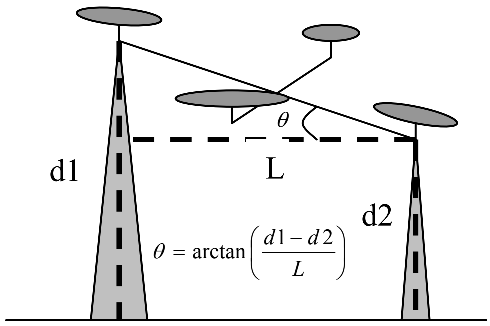

Fig.2. Schematic representation of prototype inclination angle using the ultrasound sensors.

As it can be seen in Fig. 2, the angles defining the prototype inclination can be determined if the distance from each propeller to the floor is known. Due to the ultrasound devices characteristics, the fact that the prototype is inclined with respect to the horizontal plane is not a problem from the point of view of the measurements the make. This is because the ultrasound aperture angle will be always larger than the prototype inclination angle and, consequently, the distance the ultrasound measure will be the same as if it was in the horizontal plane. The ultrasound measurement system is an absolute positioning system. This is the reason why the information provided by these sensors is more accurate than the integration of the gyroscopes and accelerometers rotational speeds.

2.3.2 The gyroscopes

The prototype is provided with three gyroscopes, one for each rotation axis. The model used is ENC-03J of Murata. It size is quite small: 26-27-11,3mm and it only weights 4,8g.

2.3.3 The accelerometers

Two accelerometers of two axes are available and, consequently, there exists redundancy in one of the axis. The model chosen is ADXL202E of Analog Devices. The ADXL202E is a low-cost accelerometer capable of measuring accelerations in two axis giving digital outputs. It measures accelerations up to 2g and can measure both dynamic acceleration (for example, the vibrations) and static acceleration (gravity).

2.3.4 Electronic compass

In order to sense the absolute orientation of the prototype, a electronic compass of Honneywell (HMC-1002) is included in the main board. This compass gets the yaw Euler angle that can not be derived from the ultrasound device.

The maximum sampling frequency of both gyroscopes and accelerometers is 100 Hz. In the case of the ultrasound sensor, this maximum frequency is 15,3 Hz for one device. Since the prototype is equipped with four ultrasound sensors, the effective maximum sampling frequency is 3,84 Hz in order to avoid interference between the sensors.

2.4 The actuation system of the prototype

The actuation system of the four rotor helicopter whose prototype is presented in this paper is composed of four DC engines. They are specifically designed for aero modelling and correspond to the IPS-DX-EXC model. Each engine is provided with a 10.7:1 reduction gear coupled to it and to the propeller. The most important characteristics that make these engines to be specially suitable for aero modelling are their low weight (only 29,92g) and the high rotation speed they allow to reach. A transverse perspective of the prototype in which the engines can be clearly observed is shown in Fig.3.

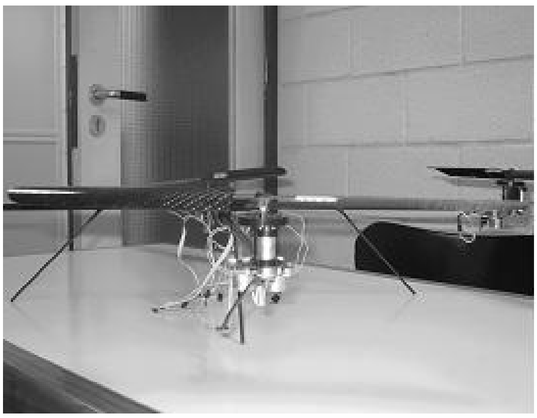

Fig.3. Photograph showing the engines of the prototype.

2.5 Helicopter bench

The last component necessary in the prototype is the fixation and stabilization component. In order to make the tests, the prototype is placed in a test bench based on a low friction joint that let the prototype move freely with three degrees of freedom, these degrees correspond to the three Euler angles.

The bench is used to test the control strategies, the sensors and all the functionalities of the prototype. The experiments can be made in the prototype testing three degrees of freedom, leaving the height fixed to the bench. In Fig. 4 a schema of the Helicopter bench can be seen.

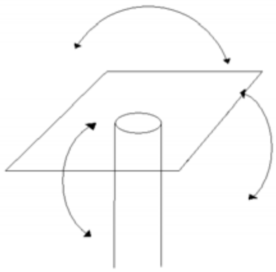

Fig. 4 Helicopter bench functional schema

3 PROTOTYPE MOVEMENTS

In contrast to what happens in the one-rotor conventional helicopters, in the four rotor ones the tail rotor is not necessary because the forces of the engines are balanced ones with the others. Since the prototype has four rotors, it is enough that two of them rotate in one sense and the other two in the opposite one, as shown in Fig.5.

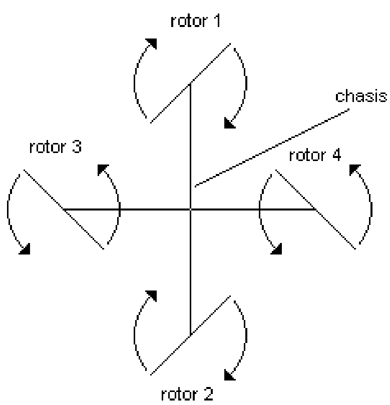

Fig.5. Schematic representation of the rotors movements.

In the four rotor helicopters it is only necessary to act over the rotation speeds of each rotor in order to keep the stability of the device, or to carry out any kind of operation. This is another important characteristic of this type of helicopters.

There exist three rotation axes that define the different movements of a four rotor helicopter, called pitch, roll and yaw. These axes are represented in Fig.6.

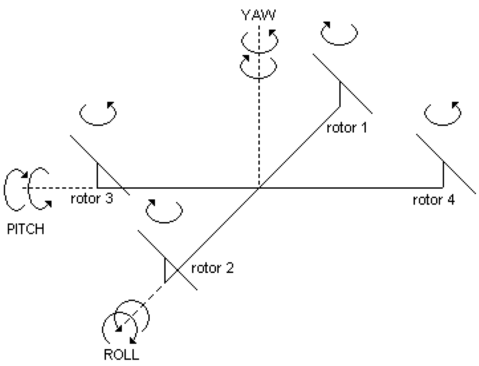

Fig.6. Rotation axis: pitch, roll and yaw.

The different combinations of angles in each one of these axis, define the state and the movements of the helicopter in flight. Due to the symmetry of the prototype, the decision of making one of the rotors (for example, the rotor 1) to coincide with the head of the prototype must be taken. In order to maintain the helicopter stable, the controller should actuate over the motors to set pitch, roll and yaw.

If the sensor detects an angle deviation in the pitch axis, the velocity of two motors should be modified. In the case of a positive pitch angle, the velocity of motor 2 should be increased and motor 1 should be decreased in order to no modify the yaw angle. The control of roll angle is similar to yaw, modifying the velocity of motor 3 and 4.

A complex situation is presented when a positive angle is detected in the yaw angle. In this case the velocity of the four motors should be modified, the velocity of motors 3 and 4 should be increase and motors 1 and 2 should be decrease. The main force change and the structure tend to spin in the momentum conservation principle. The global force made by the rotors should maintain to avoid a change in height.

The position in Cartesian coordinates (x,y,z) is set using the same technique. The height changes with the force of the four motors, changing the global sustentation force of the prototype. The x, y position varies proportional to the pith, roll angle, but the sustentation force varies and the force in each propeller should be increased.

In general terms, the problem of keeping the helicopter stability (hovering) must be solved by means of carrying out the control of the pitch, the roll and the yaw, in addition to the control of the elevation (throttle) and the displacement.

3.1 Multivariable input/output interaction

In the previous section the helicopter movements are explained. In an input/output view, the helicopter has four inputs the voltage of each motor, and six outputs Euler angles and position in Cartesian axis. In the bench the output is reduced to the Euler angles, so the helicopter has four inputs and three outputs.

The blades of the rotors had to be made-to-measure for this prototype, so its efficiency changes in each blade. If the controller try to correct an angle in the pitch axis changing the relation between motor 1 and 2, the difference between these rotors efficiency made a change in the yaw angle, so the controller correct it and prompt a change in roll angle. So a change in one output turns into a change in all output. This made that the prototype have a high degree of interaction between input and outputs (Skogestad et al, 1996).

4 PROTOTYPE DYNAMICS

In order to carry out the analytical study of the closed-loop system stability it is essential to have a dynamic model of the prototype (Baraff 1989), (Baraff 1992). Such model is described in the eq. 1:

where the system state vector Y(t) is composed of the following variables:

$$\frac{d}{dt}X(t)=\frac{d}{dt}\begin{pmatrix} x_x \\ x_y \\ x_z \\ r_{xx} \\ r_{xy} \\ r_{xz} \\ r_{yx} \\ r_{yy} \\ r_{yz} \\ r_{zx} \\ r_{zy} \\ r_{zz} \\ p_x \\ p_y \\ p_z \\ L_x \\ L_y \\ L_z \end{pmatrix} \quad \begin{array}{l} \frac{dp_x}{dt}=\left(R\left(F_1+F_2+F_3+F_4-k_x\dot{x}\right)_a\right)_x \\ \frac{dp_y}{dt}=\left(R\left(F_1+F_2+F_3+F_4-k_y\dot{y}\right)_a\right)_y \\ \frac{dp_z}{dt}=\left(R\left(F_1+F_2+F_3+F_4-k_z\dot{z}\right)_a\right)_z-mg \\ \frac{dL_x}{dt}=\left(R\left(L\left(F_4-F_2\right)\right)_o\right)_x \\ \frac{dL_y}{dt}=\left(R\left(L\left(F_1-F_3\right)\right)_n\right)_y \\ \frac{dL_z}{dt}=\left(R\left(F_{d1}+F_{d3}-F_{d2}-F_{d4}\right)\right) \\ \frac{dx_x}{dt}=v_x=\frac{p_x}{m} \\ \frac{dx_z}{dt}=v_z=\frac{p_z}{m} \\ \frac{dR}{dt}=\omega(t)*R(t)=I^{-1}(t)L(t) \end{array} \tag{1}$$

$$F_{ti}=K_t\omega_i^2; \quad F_{di}=K_{di}\omega_i^2; \quad \omega_i=\frac{K_{mi}}{T_{mi}s+1}v \tag{2}$$

·(xx, xy, xz) are the Cartesian coordinates of the centre of mass of the prototype,

·(px, py, pz) are the components of the linear momentum,
·(Lx, Ly, Lz) are the components of the angular momentum,
·rij are the components of the 3x3 rotation matrix R.

R allows transforming the coordinates expressed on the prototype reference system into the earth reference system.

As usual, w(t) represents the angular speed, I(t) the inertia moment, m the mass and g the gravity acceleration.

F1, F2, F3 and F4 represent the forces developed by the prototype propellers. The force generated by a propeller is not linear; it depends in square form of the voltage applied to the motor eq. 2. Kt represents the propeller efficiency in thrust sense, w is the angular velocity of the motor and Km and Tm are the motor constant. The same is applied to Kd in drag sense who tend to rotate the prototype. Due to the construction of the blades, each rotor is different of the others. The voltages applied to the motors are the system inputs, so the system is non-linear multivariable with four inputs (each voltage) and six outputs (position in Cartesian coordinates x,y,z and Euler angles representing in a rotation matrix).

In order to design a control strategy the model is linearised around a working set and a linear space state model is obtained. Using this model, students can test the controllers in simulation before using the control strategy in the real plant.

5 REAL TIME PLATFORM

The main board of the prototype is equipped with a PIC microcontroller connected with a PC using a RS-232 link. Using this link, the prototype sends to the PC the sensors reading and receives from the control strategy implemented in the PC the reference value of each motor. In the board is installed the power electronic to convert the reference calculated by the controller in the real voltage applied to each motor.

In the PC a real time software able to read the sensor, calculate the control action and send the reference to the motors, has been developed. The solution employed is a combination between Matlab and JAVA (Teng 2000). This solution joins the facilities included in Matlab for control design, and simulation with the capabilities of JAVA to access the hardware and read real time data. Matlab since version 6 is a JAVA based software that run over a JAVA virtual machine. In Matlab virtual machine is possible to run another process, with high priority that manages data in real time. This is the software to read the sensors and to act over the prototype. The control algorithm is implemented in Matlab, using the JAVA software to access to the data in the prototype, this can be made calling the java code as a Matlab function.

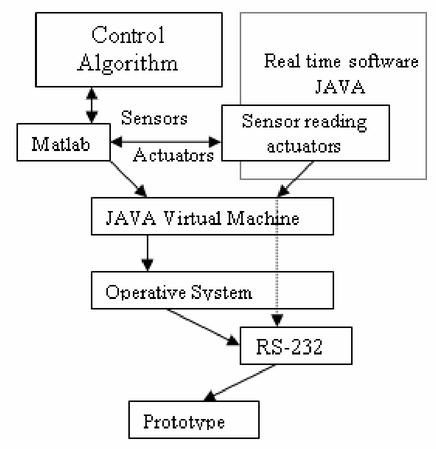

Fig 7: Real time software schematic.

In Fig. 7 control schematic is presented, the access to the prototype is done using a RS-232 link. The JAVA real time software read the sensors and applies the control actions, using the JAVA virtual machine and the operative system. A high level control is made in Matlab software and use the information give by the JAVA software to design the real time control.

The main advantage of this software structure is that the capacity and easy to program of Matlab is combined with the velocity of JAVA code getting the advantage of the two platforms.

6 EXAMPLE

In order to illustrate the operation of this laboratory plant and after established the transfer function for our system in open loop, several types of controller will be tested in simulation. The results obtained in each case should be discussed and the goodness estimated. The Simulink model is given to the students in order to test the controllers. In Fig 8 the Simulink model is presented.

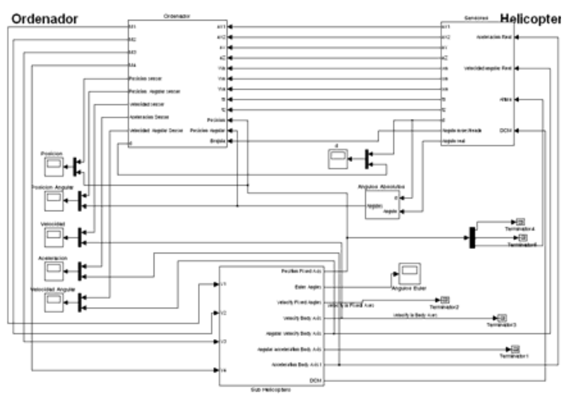

Fig 8: Simulink model of the plant

In Fig. 9 the control structure can be seen, where three standard controllers are used, and a K Matrix connect inputs and outputs. Parameters should set to obtain an acceptable response for the prototype.

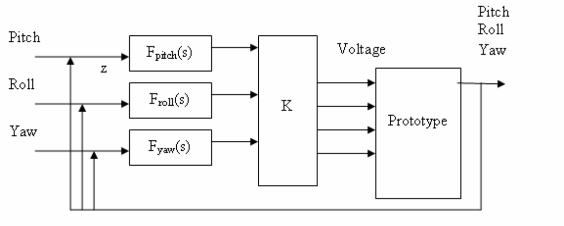

Fig. 9 Control structure

The control key is the Matrix to connect the controller's outputs to Motors. This Matrix is presented in eq. 3 that simply implements the control rules indicated in section 4. The command calculated by each controller is applied to the correct combination of motors.

$$K = \begin{bmatrix} 1 & 0 & 1 \\ -1 & 0 & 1 \\ 0 & -1 & -1 \\ 0 & 1 & -1 \end{bmatrix}; \begin{matrix} M_1 = ePitch + eYaw \\ M_2 = -ePitch + eYaw \\ M_3 = eRoll - eYaw \\ M_4 = -eRoll - eYaw \end{matrix} \quad (3)$$

Using this model and the control structure the students try different controllers to get a stable system. The controllers tested are:

Proportional: The first step in the control design is to use a proportional controller. With proportional control students get an unstable system, and discover PID: The classical PID controller have a better behaviour than PID, but the system will be unstable too.

Finally, a modified PD controller is used to regulate the angles of the prototype to get the helicopter stable.

The students not only have to design, and adjust a control strategy, the reading of the sensors should be combined to get the state of the prototype in each moment. The reconstruction of the four rotor helicopter state is made using the data received from the sensors. The slow data is suppose to be correct, so the position is actualized when a fast sensor is read, the position calculated from the slow sensor is modified relatively to these sensors. With This strategy the angular position of the prototype is calculated in real time.

When the students have a good control strategy tested in simulation and a good acquisition method to calculated the prototype position the full control strategy is tested in the real plant. In this case the parameters should be adjusted to get the best performance and to get the helicopter flying stable.

If a good control strategy is presented and the sensorial information is correctly joined, the prototype would fly stable in the bench.

The experimental setup described in this paper has actually been implemented in the laboratory during the last year on control engineering course. It provided a good opportunity for the students to experiment with controller design on real multivariable systems.

7 CONCLUSION

In this paper, a four rotor helicopter is presented. This prototype has been constructed with the aim of designing a control strategy to get the best control. The prototype is provided with four different types of sensors: gyroscopes, accelerometers ultrasounds and compass. The system is nonlinear multivariable, and a model linearised in a working point is presented. The purpose of the laboratory plant is to evaluate multivariable algorithms in real plants. A laboratory example with different activities for the students is presented. The final objective of the plant is to get the structure stable applying the control strategy over the information getting from the sensorial device and acting over the actuation system.

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