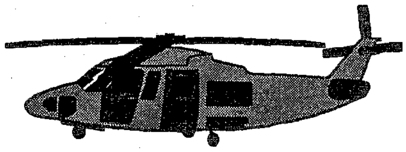
FUZZY CONTROL TO MULTIVARIABLE SYSTEMS CASE STUDY: HELICOPTER MODEL



W. GHARIEB*, *Member, IEEE*, G. NAGIB**

* Assistant Professor, Computer and Systems Engineering Dept.,
Faculty of Engineering - Ain Shams University,
1 El-Sarayat st., 11517 Abbassia, Cairo EGYPT
E-mail: wahied@shams.eun.eg, Fax: (202) 2850617
Tel: (202) 4820959, Tel: (202) 2855582

** Assistant Professor, Electrical Engineering Dept.,
Faculty of Engineering - Cairo University - Fayoum Branch, EGYPT
Fax: (202) 084- 334031, Tel: (202) 084 - 334816
Tel: (202) 084 - 334016, Tel: (202) 084 - 334031

Abstract

This paper presents a general hierarchical fuzzy control design for multivariable systems. The control structure consists of two levels. The first one generates the basic control signals as the system is decoupled. The second one behaves as a fuzzy decoupler to anticipate and to compensate the coupling effect on the system outputs. This level is achieved using simple and reduced number of fuzzy rules. These rules can be driven from the open loop system's response. Therefore, the second level generates the control signals applied to the physical system. A Simulation study is performed on a real multivariable helicopter model to manipulate the elevation and azimuth angles with significant cross coupling between these controlled variables. The obtained results showed the potential of the proposed design approach and its promise to manipulate multivariable systems.

1. Introduction

During the past decade, fuzzy logic has found a variety of applications in various fields ranging from industrial process control to medical diagnosis and decision making [1-4]. Fuzzy controller (FC) bases its decision on inputs such: (error, variation of error, ..., etc.) in the form of linguistic variables derived from membership functions which are used to determine the fuzzy set to which a value belongs and its degree in that set. The variables are then matched with the IF-THEN rules, and the response of each rule is obtained through fuzzy inference, the response of each rule is weighted according to the confidence or degree of membership of its inputs, and the centroid of the responses is calculated to generate the appropriate controller output [3].

In the analysis and design of fuzzy expert control systems, most of applications are found to be single-input single-output (SISO) systems. There is no systematic

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procedure for design of multivariable systems. Most of proposed methods try to decouple perfectly the system in order to use a simple fuzzy controller such as SISO systems. Kumer and Dutta showed that after decoupling the non-linear system, it reduced to a set of SISO subsystems. Hence, the design problem can be easily treated. However, it is not easy to decouple the physical system without perfect modelling. They are applied the proposed algorithm to a non-linear multivariable steam generating unit [5]. Other techniques are based on structural analysis of fuzzy systems to obtain a decomposed fuzzy rules [6]. Kiszka *et al.* have investigated the upper bounds for a multivariable fuzzy logic controller under Gődel's implication [7]. Linkens and Junhong have proposed a multivarible fuzzy control algorithm by constructing rule bases using self learning [8]. They have applied this approach to the problem of multivariable control of blood pressure, which is characterized by strong interactions and pure time delays in controls [8]. Chafouk *et al.* have proposed a fuzzy control design using a fuzzy supervision to manipulate two-inputs two-outputs systems. They have applied this approach to regulate the temperature and water level of a tank [9].

This paper is organized as follows: Section 2 is devoted to the development of a fuzzy control algorithm for multivariable systems. In section 3, the helicopter model is described and some open loop responses are given to investigate the anticipation rules. Also, closed loop simulation results are presented and emphasized the potential of the proposed algorithm. Some concluding remarks given in section 4 end this paper.

2. Fuzzy Control Algorithm

2.1 MIMO systems

The matrix of fuzzy control rules for SISO systems has a dimension of F^2, where F is the number of used fuzzy sets. The direct fuzzy control design for MIMO arises the following problems (direct design means one controller for the overall system as illustrated in Fig.1) :

- The quantity of fuzzy rules increases exponentially as the system's inputs increase.
- The cross coupling exists between inputs and outputs of a physical system. In ideal case, it can be assumed that each input manipulates only one output. However, it is a special case to find in practice a decoupled system which requires an equal number of inputs and outputs.

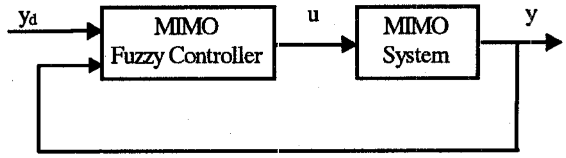


Fig.1. Direct synthesis of fuzzy control.

In this design approach, the maximum possible (upper bound) number of rules N_R is given by:

$$N_R = r * F^{(m.n)} \tag{1}$$

Where:

r	is the dimension of input vector u.
m	is the dimension of output vector y.
F	is the number of fuzzy sets.
n	is the number of input variables in the fuzzy rule (e.g. error, error variation, ...).

From equation (1) N_R has a linear relation for increasing r while m is constant. But, it has an exponential relation for increasing m while r is constant. Therefore, if N_R is very large, this leads to speed down the inference mechanism of fuzzy controller and much storage memory is required. The above discussion affirm that the direct synthesis of fuzzy controller for a multivariable system is not practical. Thus, it is preferred to develop an alternative design methodology to overcome this problem.

2.2 Design algorithm

In this section, a hierarchical fuzzy control is proposed to overcome the challenge of MIMO systems. The proposed algorithm is illustrated in Fig.2. where the control structure consists of two levels:

- The first one receives the outputs y and their desired values y_d and generates the basic control vector V of dimension m to manipulate the system outputs as they are decoupled. That means, this level contains m fuzzy controllers, each one consists of two inputs and one output. In this level, the difference between the fuzzy controllers depends on the dynamic characteristics of system outputs. The structure of each fuzzy controller (FC) consists of main four steps: ***Fuzzification interface, control rules, inference engine*** and ***defuzzification interface.*** More details for fuzzy controller synthesis can be found in [2].

- The second level takes into account the effect of the cross coupling and tries to compensate it using anticipation rules (AR). These rules behave as a fuzzy decoupler and can be driven from the open loop response.

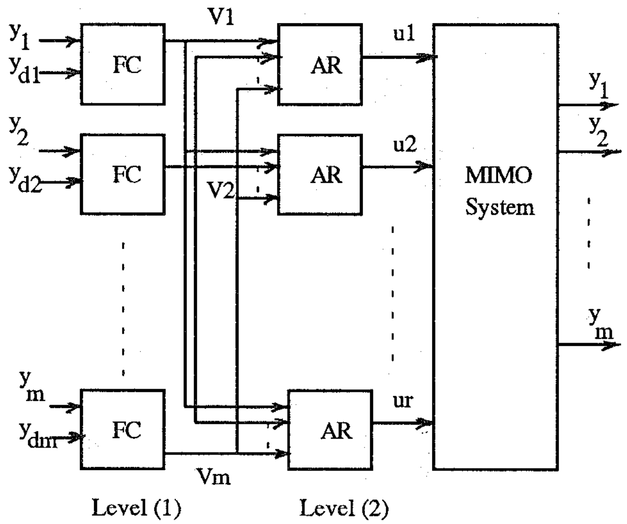


Fig.2. Hierarchical Fuzzy Control

Hence, the final control synthesis (u) is a non-linear function of all the available basic control signals (V) from the first level as in the following equation:

$$u_i = f_i\,(v_1, v_2, \ldots, v_m) \quad ; \qquad i=1, 2, \ldots .r \qquad (2)$$

In this control structure, the N_R is the sum of basic control rules in the first level ($m_* F^n$) and the anticipation rules ($r_* F^m$) in second one. Thus, N_R is given by:

$$N_R = m_* F^n + r_* F^m \qquad (3)$$

Comparing the above equation with equation (1), the proposed hierarchical fuzzy control in Fig.2 reduces the total number of rules N_R. The number of anticipation rules could be less than the upper limit defined by the second term in equation 3 [10].

3. Simulation Work

We have tested the proposed hierarchical fuzzy control algorithm on a real multivariable helicopter model through intensive simulation studies.

3.1 Helicopter model

The system is naturally unstable with two manipulated inputs and two measured outputs with significant cross coupling. The system consists of a body carrying two propellers driven by DC motors and a massive support. The body has two degrees of freedom. Both body position angles (in horizontal and vertical plane) are influenced by DC motor torques. The axes of a body rotation are perpendicular. The model inputs are analogue signals for driving DC motors power amplifiers. The systems outputs are elevation and azimuth angles. The mathematical model of the helicopter is typical MIMO 2x2 system with significant cross coupling. The attempt to model the system dynamics in detail leads to extremely complicated, not readable and non-linear model. The aim of model is to investigate the system dynamics with respect to control task. The system operates in some working conditions and not all of properties will be invoked. Thus, to simplify the control design, the electromechanical system can be described by linear six-order model when operating near the steady state. The real model is developed in Prague and more details can be found in [11]. Hence, the identified state space model in discrete form (sampling time is 100ms) is given by

$$\begin{aligned} x_{k+1} &= A\, x_k + B\, u_k \\ y_k &= C\, x_k \end{aligned} \qquad (4)$$

Where

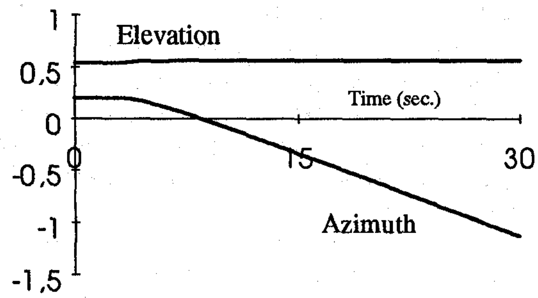
$$A = \begin{bmatrix} 0.8642 & -0.7346 & 0.5534 & 0 & 0 & 0 \\ 0.0937 & 0.9624 & 0.0287 & 0 & 0 & 0 \\ 0 & 0 & 0.9277 & 0 & 0 & 0 \\ 0 & 0 & 0.0283 & 0.098 & 0 & 0.0255 \\ 0 & 0 & 0.0014 & 0 & 1 & 0.0013 \\ 0 & 0 & 0 & 0 & 0 & 0.7468 \end{bmatrix}$$

$$B = \begin{bmatrix} 0.0063 & 0 \\ 0.0002 & 0 \\ 0.0212 & 0 \\ -0.0291 & 0.0139 \\ -0.0015 & 0.0005 \\ 0 & 0.8958 \end{bmatrix} \qquad C = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

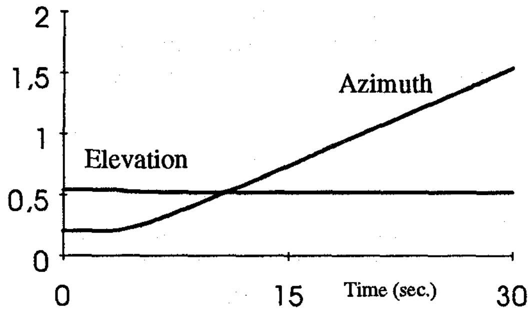
The significant discrepancy between the linear model and reality is due to omitting coulomb friction.

3.2 Open loop simulation

The above model is simulated on a PC microcomputer using MATLAB software package. The operating condition was selected as Elevation angle = 0.54, Azimuth angle =0.2, u1 (main propeller input voltage) = -0.1 and u2 (side propeller input voltage) = 0.4 units.



(a) Positive step change



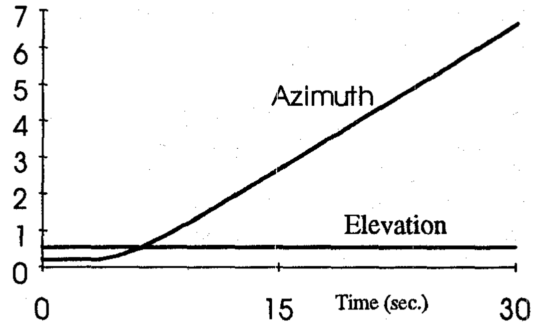
(b) Negative step change

Fig.3. Step change in u1 while u2 is constant

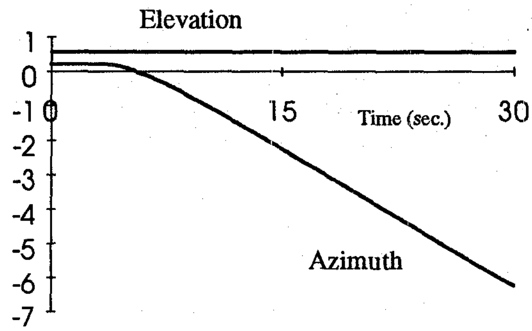
All these variables are in machine units using ADDA card to interface the real helicopter model with the computer system. All the simulation results are obtained during 30 seconds and the step change in system inputs are applied after 3 seconds from the starting simulation instant.

Fig.3 shows the simulation test by applying a step change on the main propeller input (u1) while the second input (side propeller input) is fixed at a constant value. We observe that the elevation angle has a small proportional gain with u1 while the azimuth angle has a high inverse gain with the same input.

Fig.4 shows a similar simulation test by applying a step change on the side propeller input (u2) while the other input (main propeller) is constant. We observe that azimuth angle has a high proportional gain with u2 while elevation angle is insensitive to the variations in this input. These results show that elevation angle is affected only by main propeller input voltage while azimuth angle is affected by both inputs main propeller and side propeller voltage. Therefore, the cross coupling exists in one direction due to the influence of u1 (main propeller input voltage) on azimuth angle.



(a) Positive step change



(b) Negative step change

Fig.4. Step change in u2 while u1 is constant

3.3 Closed loop simulation

From the intensive simulation study in open loop, the applied control to the helicopter model yields the following equation (see Fig.2).

$$\begin{aligned} u_1(k+1) &= u_1(k) + V_1(k) \\ u_2(k) &= V_2(k) + \Delta(V_1(k)) \end{aligned} \tag{5}$$

Where k is the sampling instant.

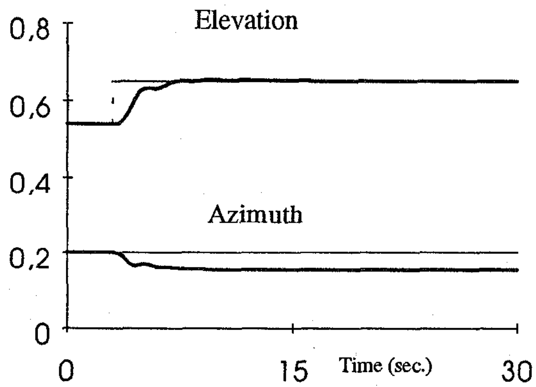
Δ is a function of V1 and to compute its value the following anticipation rules are used.

IF	V_1 is Positive	THEN	Δ is Positive
IF	V_1 is Negative	THEN	Δ is Negative

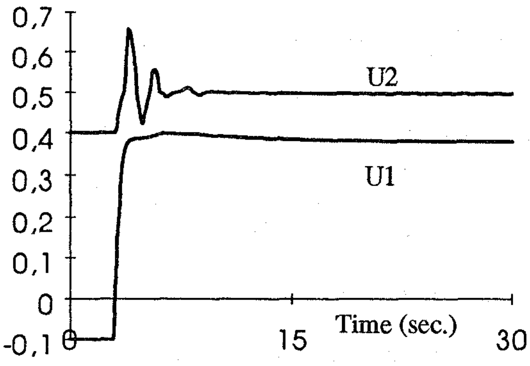
Where Positive and Negative are two fuzzy sets.

From equation (5), the fuzzy controller to produce V1 is an incremental that means it is equivalent to a non-linear PI controller. While, the other one to produce V2 is equivalent to a non-linear PD controller. The control synthesis is proposed as above, because the azimuth angle has a high gain and sensitive to system inputs. If an incremental fuzzy controller is used for this variable, it will introduces time delays and subsequently leads to unstable response (this case has been tested in simulation). While, the elevation angle has a low sensitive gain to main propeller input and the incremental fuzzy controller not violate the stability. Each fuzzy controller in level (1) uses seven fuzzy sets labelled as (NB, NM, NS, ZE, PS, PM, PB). As the simulated system is an electromechanical with fast response (few seconds), we used the proposed fuzzy rules by Mic-Vicar [12].

Fig.5 shows the output responses as a step change in desired elevation angle is demanded. These results are obtained without using the anticipation rules in level (2). We observe that the elevation angle tracks well its reference. While the azimuth angle is deviated from its reference due to cross coupling. The main propeller input voltage u1 is more smooth due to its incremental synthesis.



(a) Output responses

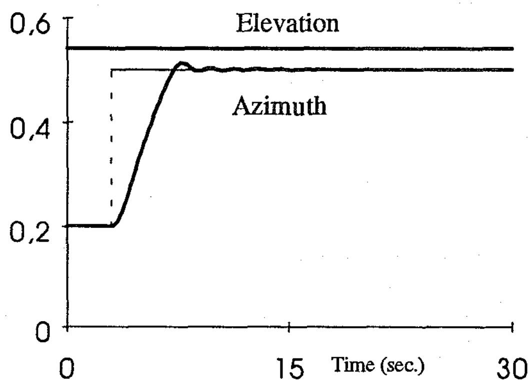


(b) Input controls

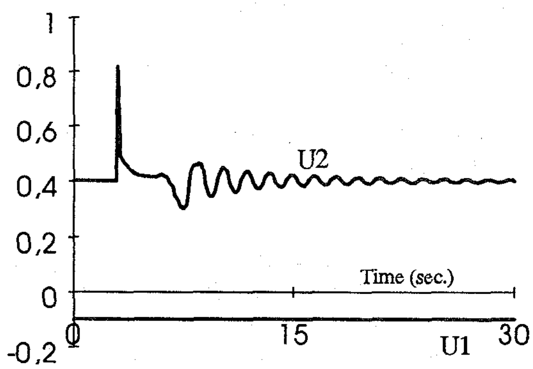
Fig.5. Step demand in Elevation angle without anticipation

Fig.6 shows the output responses as a step change in azimuth angle is demanded while the desired elevation is fixed. We observe that the azimuth angle tracks well its desired while the elevation is fixed at its desired value (coupling not exists). The control synthesis of u2 is not smooth because it is not incremental and azimuth response is very sensitive with high gain to that input.

Fig.7 shows the output responses as a step demanded in elevation. These results are obtained using the anticipation rules in second level (see Fig.2). We observe that elevation angle tracks well its desired reference while the azimuth angle is less sensitive to main propeller input. That means the anticipation rules adapted the side propeller input to compensate the cross coupling (compare these results with Fig.5).

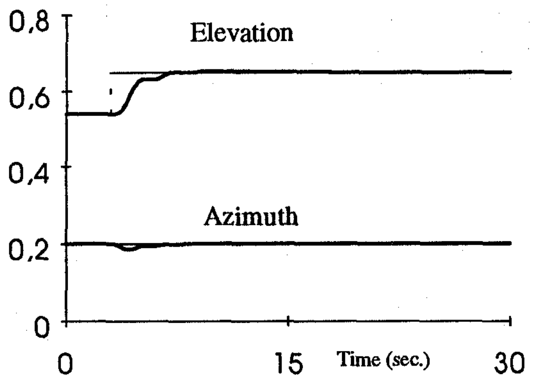


(a) Output responses

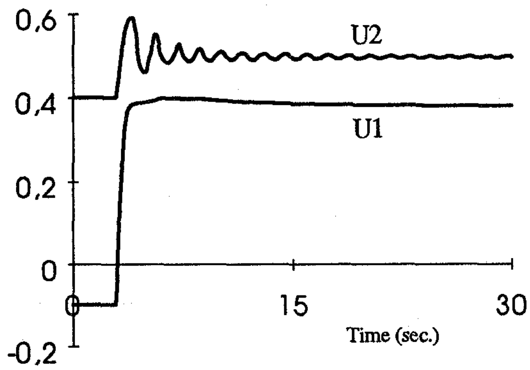


(b) Input controls

Fig.6. Step demand in Azimuth angle without anticipation



(a) Output responses



(b) Input controls

Fig.7. Step demand in Elevation angle with anticipation

4. Conclusion

The proposed hierarchical fuzzy control algorithm is a promising approach for multivariable systems. This algorithm with anticipation reduces the dimension of fuzzy rules and compensates the cross coupling effect. Parallel computation could be the ideal support for its real time application. The intensive simulation studies on a helicopter model showed that the proposed algorithm gives a good tracking response and a good compensation for cross coupling. Future work is planned to apply this design approach on a real multivariable system.

5. References

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