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DEVELOPMENT OF THE CROSS-COUPLING PHENOMENA OF MIMO FLIGHT SYSTEM USING FUZZY LOGIC CONTROLLER

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Abstract

This paper describes the performance of a simplified dynamic controller with fuzzy logic controllers. The six degree-of-freedom simulation study focuses on the results with and without fuzzy logic controller. One area of interest is the performance of a simulated the cross coupling effect. The controller uses explicit models to produce the desired commands. In this paper the effect of the cross-coupling between channels on the overall performance of the flight system has been considered. Two fuzzy controllers have been added to the system to improve its performance. This paper presents the development and simulation of a modified system is presented using MatLab Simulink. Also it focuses on the use of fuzzy logic controller in model-based control of multiple-input, multiple-output systems. Here, we address the question of how the overall performance of the system is affected when both fuzzy logic controllers are applied at the same time. Simulation and experimental results of a flight system , as an illustrative example, are presented.

Keywords*:* Cross Coupling, Fuzzy Logic Controllers, DOF, Pitch channel,
Yaw channel, Roll rate.

1. Introduction

In daily life, it often confronts with various forms of decision-making situations under which more than one goal must be fulfilled. Difficulty arises when some of the objectives are conflicting with each other. In this case, inconsistency and lack

Nomenclatures

A, B, C	Moments of inertia about axis, kgm^2
D, E, F	Products of inertia, kgm^2
L, M, N	Moments acting on vehicle about the three axes, Nm
p, q, r	Angular rates, rad/s
u,v, w	Components of vehicle velocity along the three axes, m/s
X, Y, Z	Components of force on vehicle along the three axes, N

Greek symbols

γ, θ, ψ	Angles of incidence, rad

Abbreviations

B	Big
DOF	Degree of Freedom
FLC	Fuzzy Logic Controller
M	Medium
MIMO	Multiple-Input, Multiple-Output systems
N	Negative
P	Positive
S	Small
Z	Positive

of coherence among the objectives may prevent us from getting an optimal decision, and sometimes invoke sacrifice of at least one objective among them [1,2]. Thus, it is considered a challenging issue to investigate decision-making problems with multiple objectives for efficient and satisfactory solutions. The demand for increased efficiency in various branches of industry, such as manufacturing, aerospace, process and energy production industry leads to an increased degree of automation of the production process. Extensive research in fuzzy control has been devoted to single-input single-output processes, including modeling and control design aspects, analysis of stability, robustness, and adaptive control [3].

Fuzzy control provides effective solutions for nonlinear and partially unknown processes, mainly because of its ability to combine information from different sources, such as available mathematical models, experience of operators, process measurements, etc. Multi-variable processes, however, have received considerably less attention, despite strong practical needs for multivariable control solutions, indicated among others from process industry, (waste) water treatment, or aerospace engineering. Yet, theoretical foundations and methodological aspects of multivariable control are not well developed. For these multi-objective control problems, any control strategy based on a single-objective optimization technique can hardly provide a desired performance.

It is noted that most typical optimization methods, used for optimal control, such as linear/nonlinear programming and dynamic programming techniques are not effective when the uncertainty about the plant is significant and there are more than one performance criteria [4]. The main idea of a cross-coupling control module is to use feedback to minimize the contour error instead of the individual axis errors, since that is more important from a performance standpoint. The cross-coupling control strategy was first proposed by Koren, 1980 [5]. The typical procedure for implementing a cross-coupling control module is to first build a contour error model in real time, based on the feedback information from all the axes as well as the interpolator. Then, an optimal compensating law is found which will minimize the contour error based on the error model.

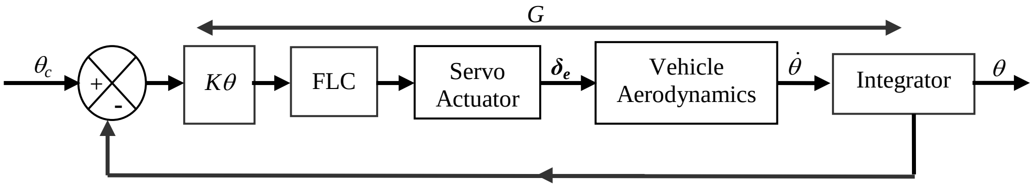
Finally, a feedback correction signal is sent to the individual axes. Thus, a cross-coupling control module includes two major components: the contour error model and the control law. In a conventional multi-axis machine tool system, each axis is controlled by a separate servo loop, which is designed to minimize the axial position error [6]. Even with well designed servo algorithms, these types of conventional decoupled control strategies cannot control a machine tool with enough accuracy to meet the increasing precision requirements for newly designed parts.

Many different types of auxiliary control modules for machine tool control have been proposed, and researchers in academia have shown how these additional control modules can increase the performance of a vehicle system [7]. The variable-gain cross-coupling controller, recently proposed by Koren [8], demonstrated excellent tracking ability on an experimental system. In addition, a variety of gains were used in both the friction compensation and cross-coupling control.

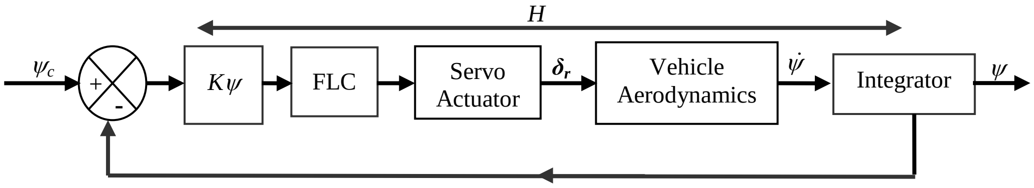
The problem considered in this paper is how the cross-coupling of channels affects the overall performance of the vehicle system. We also address the question of how the overall performance of the system is affected when two fuzzy controllers are applied to the machining system simultaneously.

2. Description of the Overall Vehicle Control System

The conventional vehicle control design, which has uncoupled pitch, yaw and roll channels ideally suited for a non-rolling vehicle. The roll effect can be getting by use the cross-coupling phenomena assuming that the roll rate is very small. If the roll rate is large, some performance and even system stability; may lost in rolling the vehicle. Thus low roll rate assumption allows the system designer to negligent the roll rate, separates the pitch and yaws channels and then deals with them independently [9]. Figures 1 (a) and (b) show the schematic block diagram of the system used to control pitch and yaw in the non-rolling vehicle since the vehicle does not spin. The pitch and yaw channels are identical and uncoupled.



(a) Pitch Control System



(b) Yaw Control System

Fig. 1. Non-Rolling Pitch and Yaw Control System.

The system consists of fuzzy logic controller (FLC), servo actuator, vehicle aerodynamics and integrator. All system constants, physical parameters, and other values, which are used for analysis and simulation, will be taken from non-rolling vehicle. When the non-rolling pitch-yaw control system just designed is forced to roll, the system becomes cross-coupled as shown in Fig. 2.

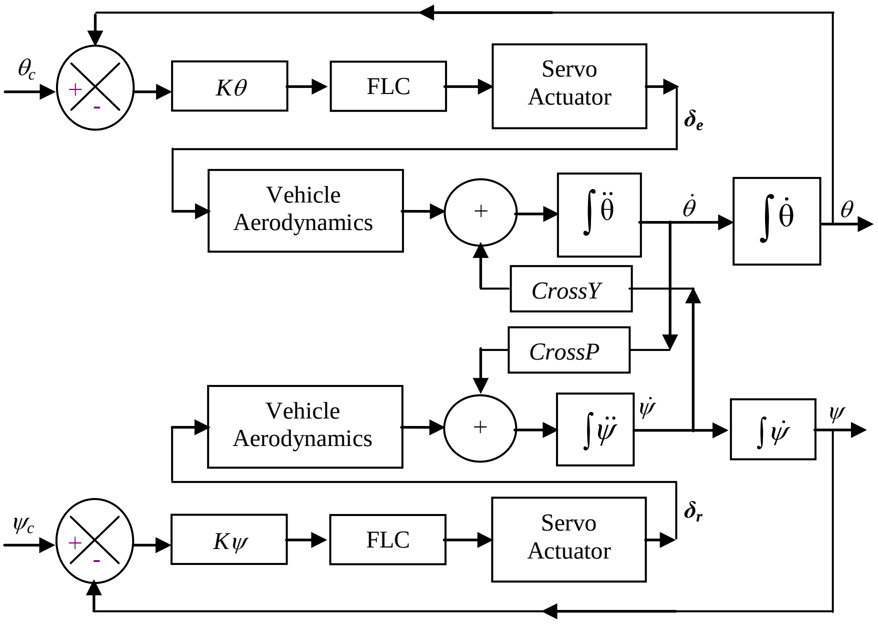


Fig. 2. The Block Diagram of Rolling, Pitch, and Yaw Channels.

The equations of motion for a body with six-degrees of freedom and a mass, m, are summarized below:

$$m(\dot{u}+qw-rv)=X \tag{1}$$

$$m(\dot{v}+ru-pw)=Y \tag{2}$$

$$m(\dot{w}+pv-qu)=Z \tag{3}$$

$$A\dot{p}-(B-C)qr+D(r^2-q^2)-E(pq+\dot{r})+F(rp-\dot{q})=L \tag{4}$$

$$B\dot{q}-(C-A)rp+E(p^2-r^2)-F(qr+\dot{p})+D(pq-\dot{r})=M \tag{5}$$

$$C\dot{r}-(A-B)pq+F(q^2-p^2)-D(rp+\dot{q})+E(qr-\dot{p})=N \tag{6}$$

Furthermore, it is assumed that the role rate, *p*, can be measured during flight or estimated from measured parameters with reasonable accuracy. Since the parameters ($K\theta$) and ($K\Psi$) will be selected so that the system will exhibit minimal overshoot to step inputs and has a short settling time [10]. The Laplace transformations of the linearized non-rolling system's governing differential equations can be written as two separate equations: One for the pitch channel and one for the yaw channel. In order to begin to analysis the effect of cross-coupling phenomena on the non-rolling pitch-yaw control system, take the equations, which describe this phenomenon briefly.

$$S^2\theta + G\theta = G\theta_c \tag{7}$$

$$S^2\psi + H\psi = H\psi_c \tag{8}$$

where, *G* and *H* represent the overall transfer function of the system as shown in the Fig. 1. Equations (7) and (8) can be rearranged and put into matrix form as in Eq. (9). Note that the equation has only diagonal non-zero elements and is therefore uncoupled [10].

$$\begin{bmatrix} S^2+G & 0 \\ 0 & S^2+H \end{bmatrix}\begin{bmatrix} \theta \\ \psi \end{bmatrix} = \begin{bmatrix} G & 0 \\ 0 & H \end{bmatrix}\begin{bmatrix} \theta_c \\ \psi_c \end{bmatrix} \tag{9}$$

Rolling the vehicle leads to the addition of cross-coupling terms between the equation governing pitch and yaw response. The transformed differential equations governing the responses of the rolling system are:

$$S^2\theta + G\theta + S\psi \cdot CrossY = G\theta_c \tag{10}$$

$$S^2\psi + H\psi + S\psi \cdot CrossP = H\psi_c \tag{11}$$

where *CrossY* and *CrossP* are defined below:

$$CrossY = \frac{(A-C)p}{B} \tag{12}$$

$$CrossP = \frac{(B-A)p}{C} \tag{13}$$

Rearrange Eqs. (10) and (11) into matrix form as before leads to the coupled form:

$$\begin{bmatrix} S^2+G & S\cdot CrossY \\ S\cdot CrossP & S^2+H \end{bmatrix}\begin{bmatrix} \theta \\ \psi \end{bmatrix} = \begin{bmatrix} G & 0 \\ 0 & H \end{bmatrix}\begin{bmatrix} \theta_c \\ \psi_c \end{bmatrix} \tag{14}$$

Equation (14) shows that the introduction of roll has affected the transfer functions, which determine the input-to-output relationships of the system in two ways.

3. Design of a Fuzzy Controller for Multi-objective System

To incorporate a priori knowledge into data-driven identification of dynamic fuzzy models; the model parameters are based on knowledge about the process stability, minimal or maximal gain, and the settling time. When no a priori knowledge about the local dynamic behavior of the process is available, information about the steady-state characteristic could be extremely useful [11].

The purpose of any plant controller is to relate state variables to action variables i.e., to periodically look at the values of the state variables and from the expressed relationship to compute the value of the action variable. The control action which results from evaluating the rules is deterministic. The heuristic rules could be applied directly by assigning values to process states as illustrated in Fig. 3 below. The aim of the heuristic is to obtain a non-linear relationship between system states and control action which gives a better control system than a linear alternative. The fuzzy control was much less sensitive to process parameter changes and give good control at all operating points in many cases control was better than with the conventional control system. This largely is attributed to the non-linear nature of the heuristic rules which could be used to give a rapid response and a small amount of overshoot.

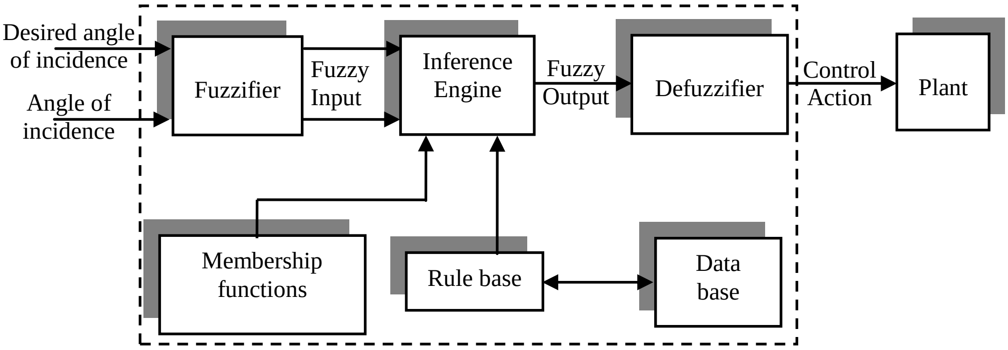


Fig. 3. Block Diagram of Fuzzy Controller.

The selection of rule base of FLS is based on the user knowledge and experience. To define the linguistic rules of a fuzzy variable, Gaussian, triangular or trapezoidal shaped membership functions are used [12]. It has been select triangular shaped membership function for offering more computational simplicity. However, the tuning of fuzzy rules is intuitive, and can be related in simple linguistic terms with user experience. There are two measurements used as input values for pitch channel (θ, θ_c).These two values are given to the FLC at each running of the system. The output of controller has intended to keep the vehicle in balance. The controller design diagram (as simulated in Simulink-MatLab) and its layout are shown in Fig. 4. While the look-up table for this controller is given in Table 1 which contained 49-rules.

In Table 2, P stands for Positive, N for Negative, B for Big, M for Medium, S for Small, and Z for Zero."

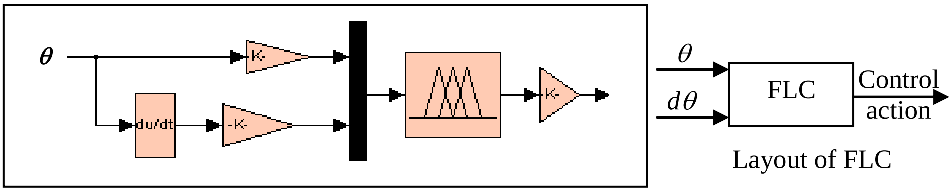
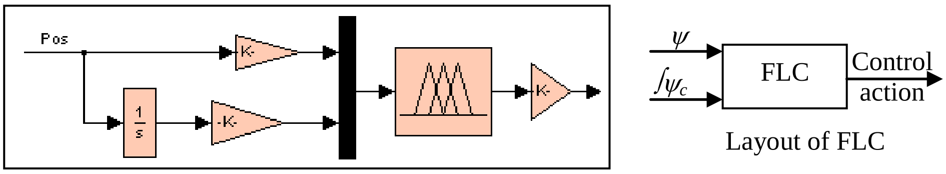


Fig. 4. Pitch Fuzzy Controller.

Table 1. Look-up for Pitch Channel Controller with Rule No. = 49.

θ $d\theta/dt$	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	PB	PB	PB	PB	PM	PS	Z
NM	PB	PB	PB	PM	PS	Z	NS
NS	PB	PB	PM	PS	Z	NS	NM
Z	PB	PM	PS	Z	NS	NM	NB
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	Z	NS	NM	NB	NB	NB
PB	Z	NS	NM	NB	NB	NB	NB

While, the second fuzzy controller (of the raw channel) has been used two measurements (ψ, ψ_c) are used as inputs values to this controller. The controller design diagram Yaw channel (as simulated in Simulink-Matlab) and its layout is shown in Fig. 5 and the look-up table for this controller is given in Table 2 which contained 49-rules.



Layout of FLC

Fig. 5. Yaw Fuzzy Controller.

Table 2. Look-up for Yaw Channel Controller with Rule No. = 49.

ψ_c ψ	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NM	PS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

4. Simulation and Experimental Results of the Vehicle System

A simulation is performed for a 6-DOF rigid-body dynamics. The 6-DOF equation of motion block from MatLab-Simulink Aerospace Blockset is used for the simulation. In this paper, we propose a control scheme for the formation control for a multi-objective vehicle system by utilizing a FLC. By canceling out the cross-coupling between two channels, these channels become decoupled each other and also have dynamics of usual mechanical systems. The research will be required to determine the maximum amount of coupling a vehicle may possess and still be rated, an amount that is estimated to be between the zero and 50% cases evaluated in this simulation. Figures 6 and 7 give the control surface of both channels (Pitch and Yaw). While Figs. 8 and 9 illustrate the transient response of the vehicle with and without FLCs respectively, when the roll rate (p = 3). The same experiment has been done but when roll rate (p = 7), the results are shown in Figs. 10 and 11.

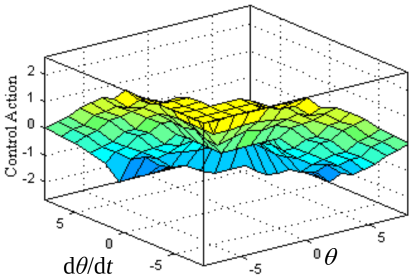


Fig. 6. The Control Surface of the Pitch FLC.

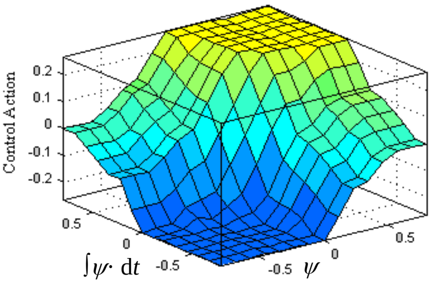


Fig. 7. The Control Surface of the Yaw FLC.

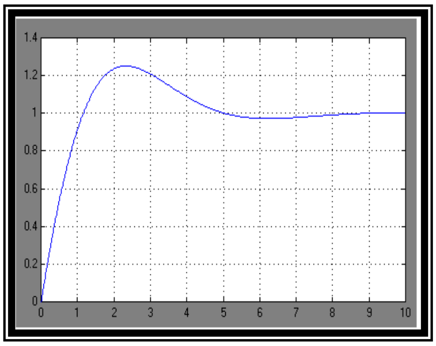


Fig. 8. The Transient Response with FLCs when (p=3).

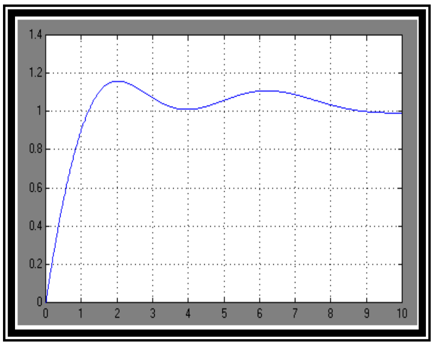


Fig. 9. The Transient Response without FLCs when (p=3).

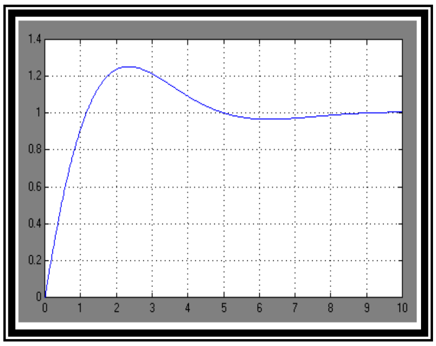


Fig. 10. The Transient Response with FLCs

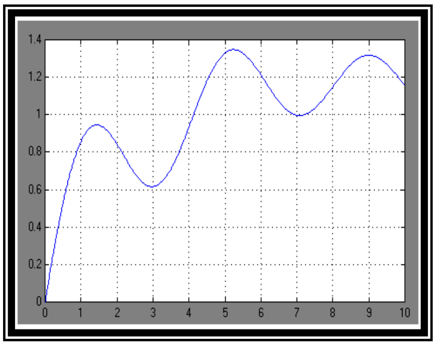


Fig. 11. The Transient Response without FLCs when (p=7).

5. Conclusions

The proposed Fuzzy controller improves partially to some extent the pre-roll performance of the vehicle. For comparison purposes, the peak overshoot, the settling time, and the steady state error were observed as shown in Table 3. Simulation tests were performed with and without fuzzy controllers under pitch and yaw step inputs and for different values of roll rate. One can notice that in the case of reasonable small role rate (up to 3 rad/s), a dramatically improvement is achieved. However, for large values of roll rate (up to 7 rad/s), the proposed fuzzy controller increase the stability degree of the system and a satisfactory steady state error is achieved.

Table 3. The Performance of Rolling Control System with and without Fuzzy Controllers.

Roll Rate (p) (rad/s)	**Cross coupling without FLCs**			**Cross coupling with FLCs**		
	Peak Overshoot (Volts)	**Settling Time (s)**	**Steady state error**	**Peak Overshoot (Volts)**	**Settling Time (s)**	**Steady state error**
3.0	1. 185	9.0	0.07	1.25	5.5	0.003
7.0	Unstable	Unstable	0.15	1.25	5.5	0.04

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