Takagi-Sugeno Fuzzy Controller for a 3-DOF Stabilized Platform with Adaptive Decoupling Scheme

S. Leghmizi, S. Liu and F. Naeim

***Abstract*—**This paper presents a fuzzy control system for a three degree of freedom (3-DOF) stabilized platform with explicit decoupling scheme. The system under consideration is a system with strong interactions between three channels. By using the concept of decentralized control, a control structure is developed that is composed of three control loops, each of which is associated with a single-variable fuzzy controller and a decoupling unit. Takagi-Sugeno (TS) fuzzy control algorithm is used to implement the fuzzy controller. The decoupling units design is based on the adaptive theory reasoning. Simulation tests were established using Simulink of Matlab. The obtained results have demonstrated the feasibility and effectiveness of the proposed approach. Simulation results are represented in this paper.

***Keywords*—**3-DOF platform of a ship carried antenna; the concept of decentralized control; Takagi-Sugeno (TS) fuzzy control algorithm; Simulink**.**

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I. Introduction

THE stabilized platform is the object which can isolate motion of the vehicle, and can measure the change of platform’s motion and position incessantly. It can make the equipment which is fixed on the platform aim at and track object fastly and exactly. In the stabilized platform systems, the basic requirements are to maintain stable operation even when there are changes in the system dynamics and to have very good disturbance rejection capability.Since they began to be utilized about 100 years ago, stabilized platforms have been used on every type of moving vehicle, from satellites to submarines, and are even used on some handheld and ground-mounted devices [1, 2]. Its application is quite abroad and it becomes investigative hotspot in most counties all the time.The considered platform is a class of multivariable servomechanisms with multiple axes. The control of such multivariable servomechanisms is, in general, not a simple problem, as there exist cross-couplings, or interactions, between the different channels. In addition, this system is required to maintain stable operation even when there are changes in the system dynamics. In the stabilized platform systems, the basic requirement is to have very good disturbance rejection capability. Presence of inherent nonlinearities such as stiction, friction, saturation of actuators, etc. is also must be taken into account. Many approaches have been proposed to control such a complex interconnected system for example the decomposition-coordination approach, the aggregation approach, the multitime-scale approach, and the decentralized control approach [3]–[4]. Since the decentralized control approach is reliable and practical in view of the implementation, it is the most popular method that attempts to design control schemes, where each subsystem is controlled independently based on local information. However, the decentralized approaches are restricted to stabilization, and the dynamics of each subsystem and the interconnection terms are assumed to be known [5], [6]. In practice, the model of the considered platform contains vast unknown uncertainties. Since fuzzy logic control has been considered as an alternative to traditional control schemes to deal with system dynamics uncertainty and obtain the best performance of the system. Fuzzy control is adopted as the subject of this work [7].Fuzzy control has gained many interests in recent years [8], [9]. A number of successful applications have been reported in literature and these applications of fuzzy control to industrial processes have often produced results superior to those of classical control [10].However considerable difficulty was encountered when applied to multivariable nonlinear systems. The difficulty stems not from the development of control algorithm, but from the construction of the rule-base, a key factor for the implementation of a fuzzy controller. Due to the presence of interactions between control channels, it might be a very hard task for domain operators to express their control strategies in the form of relating multi-situations to multi-actions, even though they may be able to manually control the process satisfactorily [5]. One of the methods for handling the problem is to use a decentralized control structure. The input–output variables of the process are appropriately paired and each channel is controlled by an independent fuzzy controller.This paper considers a 3-DOF stabilization platform consisting of three channels. By using the decentralized control concept, we developed a control structure composed of three separate control channels, each of which is associated with a single variable fuzzy controller and a feedback decoupling unit based on the adaptive theory reasoning. The simulation results in applying the proposed fuzzy controller to a 3-DOF stabilization system are presented which demonstrates the effectiveness of the adaptive controller.

II. 3-DOF Platform Stabilization System

The considered system in this paper is composed of the platform, inner gimbal, outer gimbal, and the case (Fig. 1); each member is assumed to be rigid and has one degree of freedom [11].

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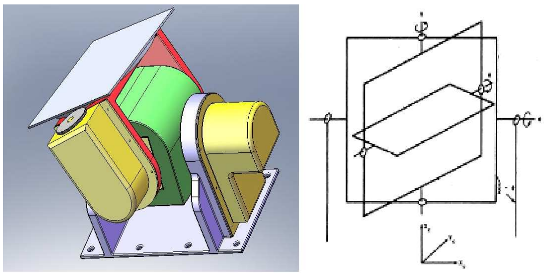

Fig. 1 An illustrative diagram of the 3-DOF platform

The mathematical modeling was established using Euler theory. The Euler's moment equations are

$$\overrightarrow{M} = i\dot{\overrightarrow{H}} \tag{1}$$

The net torque $\overrightarrow{M}$ consists of driving torque applied by the adjacent outer member and reaction torque applied by the adjacent inner member.

$$i\dot{\overrightarrow{H}} = \frac{dH}{dt} = m\dot{\overrightarrow{H}} + \overrightarrow{\omega_m} \times \overrightarrow{H} \tag{2}$$

$i\dot{\overrightarrow{H}}$: Inertial derivative of the vector $\overrightarrow{H}$;

$m\dot{\overrightarrow{H}}$: Derivative of H calculated in a rotating frame of reference;

$\overrightarrow{\omega_m}$: Absolute rotational rate of the moving reference frame;

$\overrightarrow{H}$: Inertial angular momentum;

$\overrightarrow{M}$: External torque applied to the body.

By applying equation (2) on the different parts of the platform system, the system may be expressed as a set of second-order differential equations in the state variables. Solving this system of equations we obtain:

$$\ddot{\phi} = \frac{C_i B_o - C_o B_i}{A_i B_o - A_o B_i} \tag{3}$$

$$\ddot{\psi} = \frac{C_o A_i - C_i A_o}{A_i B_o - A_o B_i} \tag{4}$$

$$\ddot{\theta} = \frac{C_p}{B_p} - \frac{A_p}{B_p} * \frac{C_i B_o - C_o B_i}{A_i B_o - A_o B_i} \tag{5}$$

Where

$A_p = \sin\psi$

$B_p = 1$

$C_p = \dfrac{M^*_{Ipy} - MPY}{I_{py}}$

$A_i = \cos\psi \cos\theta \sin\theta \left[\dfrac{I_{px} - I_{pz}}{I_{iz}}\right]$

$B_i = \left[1 + \sin^2\theta \dfrac{I_{px}}{I_{iz}} + \cos^2\theta \dfrac{I_{px}}{I_{iz}}\right]$

$C_i = \dfrac{M^*_{oiz} - MIZ}{I_{iz}}$

$A_o = 1 + \cos^2\psi \left[\dfrac{I_{ix} + I_{px}\cos^2\theta + I_{pz}\sin^2\theta}{I_{ox}}\right] + \sin^2\psi \left[\dfrac{I_{iy}}{I_{ox}}\right]$

$B_o = \cos\theta \sin\theta \cos\psi \left[\dfrac{I_{px} - I_{pz}}{I_{ox}}\right]$

$C_o = \dfrac{M^*_{cox} - MCX}{I_{ox}}$

Detailed equations computation is presented in the paper [12].

III. Fuzzy Controller for the Stabilized Platform

A. Control System Description

As mentioned in the Introduction, we are interested in adopting a decentralized control structure to cope with multivariable control problems. The design process following this idea consists of two steps: decomposition and anti-interaction. First, with reference to some physical insight into the system under consideration, a multivariable system is decomposed into several input–output paired channels, thereby enabling each channel to be treated independently without taking coupling effects into account. Next, the coupling effects between channels are explicitly compensated by designing an anti-interaction mechanism for each channel. The decoupling scheme does not aim at eliminating interaction completely since the exact decoupling would require complete and accurate knowledge about the controlled process, this being clearly contrary to the design philosophy of fuzzy control. Rather, it is indented to reduce interactions to some acceptable level by using as little process knowledge as possible. It is also expected that the coupling effect, if viewed as a perturbation, can be partly compensated by the robust property of the fuzzy controller.

Fig. 2 shows the overall architecture for the 3-DOF stabilized platform control system described in the last section. For obvious reasons, (τ_1, θ) , (τ_2, ψ) and (τ_3, ϕ) are chosen to be three control pairs, each of which is associated with a fuzzy controller and a decoupling unit. Thus, the applied actuator torques are given by

$$\tau_1 = u_{f1} + u_{d1} \tag{6}$$

$$\tau_2 = u_{f2} + u_{d2} \tag{7}$$

$$\tau_3 = u_{f3} + u_{d3} \tag{8}$$

where u_{f1} , u_{f2} and u_{f3} denote the outputs due to the fuzzy controllers, u_{d1} , u_{d2} and u_{d3} denote the decoupling units.

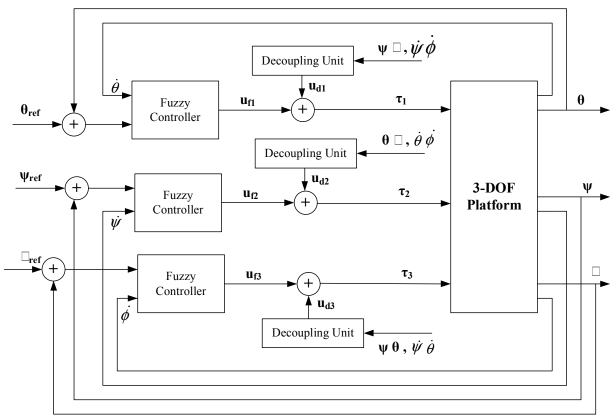

Fig. 2 Multivariable fuzzy control for the 3-DOF platform

B. The Fuzzy Controller Design

The applied decentralized control structure transforms the system to three separate SISO systems as shown in fig. 2. At each subsystem we applied a Takagi-Sugeno (TS) fuzzy PD controller. The objective of this controller is to minimize the tracking error of each subsystem to a zero state. Thus, the control input must be a function of the tracking error and the change rate of tracking error, which represents the difference between the desired and actual tracking velocity. The structure of a complete fuzzy control system is composed from the following blocs: Fuzzification, Knowledge base, Inference engine, Defuzzification as shown in fig. 3 [9]. There are two major types of fuzzy systems: Mamdani fuzzy systems and Takagi-Sugeno (TS) fuzzy systems. The main difference between the two lies in the consequent of fuzzy rules. Mamdani fuzzy systems use fuzzy sets as rule consequent whereas TS fuzzy systems employ linear functions of input variables as rule consequent [13]. Both types of fuzzy systems have been used widely as effective tools in various practical applications, especially in the areas of control and modeling [14].

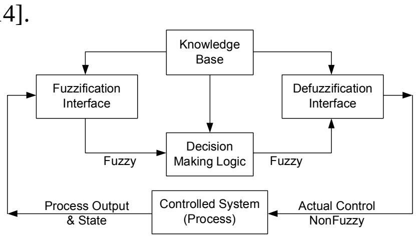

Fig. 3 Basic configuration of fuzzy logic controller (FLC)

C. Fuzzifier and Rule-Base formation

The fuzzifier transforms the measured crisp input X to the fuzzy sets defines in V_x, where V_x is characterized by a membership function $\mu_f : V_x \rightarrow [0,1]$, and is labeled by a linguistic term such as "negative big (NB)," "negative medium (NM)," "negative small (NS)," "zero (ZR)," "positive small (PS)," "positive medium (PM)," and "positive big (PB)."

The general TS fuzzy systems in this study use 2 input variables. e_θ, e_ψ, e_ϕ and $\dot{\theta}, \dot{\psi}, \dot{\phi}$ are selected as input variables of each subsystem respectively and defined as two variables representing the situation. c_i^j is selected as output of the j^{th} subsystem and defined as a variable representing the action. Notice that variables for θ , ψ , ϕ , $\dot{\theta}$, $\dot{\psi}$ and $\dot{\phi}$ assume linguistic terms as their values such as positive-big, negative-small, and zero, etc.

Using the Takagi-Sugeno model [34], the fuzzy system is characterized by a set of **p If-Then** rules stored in a rule-base and expressed as

R_i: IF e_θ is A_i and $\dot{\theta}$ is B_i THEN $c_i^j = p_0 + p_1 e_\theta + p_2 \dot{\theta}$

where A_i and B_i are linguistic terms which in this study can be NL, NM, NS, ZR, PS, PL and PB.

The output level c_i of each rule is weighted by the firing strength μ_i of the rule. For example, for an AND rule with Input 1 = e_θ and Input 2 = $\dot{\theta}$, the firing strength is

$$\mu_i = AndMethod(F_1(e_\theta), F_2(\dot{\theta})) \tag{9}$$

where $F_{1,2}$ (.) are the membership functions for e_θ and $\dot{\theta}$.

The Sugeno rule operates as shown in the diagram of the fig. 4.The idea to construct the rule base of this controller from common control experience is justified by the two following principles:

- If the error is zero, the speed is also.
- If the error is not zero, turn very quickly to eliminate this error.

So based on these principles, a set of rules have been derived and are summarized in Table I.

TABLE I
RULE BASE OF THE FUZZY LOGIC CONTROLLER

$e_\theta \backslash \dot{\theta}$	NB	NM	NS	ZR	PS	PM	PB
PB	ZR	PS	PM	PB	PB	PB	PB
PM	NS	ZR	PS	PM	PB	PB	PB
PS	NM	NS	ZR	PS	PM	PB	PB
ZR	NB	NM	NS	ZR	PS	PM	PB
NS	NB	NB	NM	NS	ZR	PS	PM
NM	NB	NB	NB	NM	NS	ZR	PS
NB	NB	NB	NB	NB	NM	NS	ZR

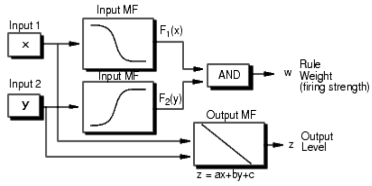

Fig. 4 TS fuzzifier

For simplicity, the same universe of discourse and the same fuzzy set are adopted for fuzzy input variables. The membership functions of isosceles triangles are used as the fuzzification function. For the output the coefficients p_i are defined in the simulation part.

D. Fuzzy Inference Engine and Defuzzifier

In a fuzzy inference engine, fuzzy logic principles are used to synthesize the fuzzy IF–THEN rules in the rule base into a mapping from the family of fuzzy subsets in $V \times V$ to the family of fuzzy subsets in W. The defuzzifier performs a mapping from fuzzy subsets in W to a crisp point $y \in W$. The Sugeno type fuzzy controller employ linear functions of input variables as rule consequent, so the steps of aggregation and defuzzification of fuzzy rules are simultaneously and the final output of the system is the weighted average of all rule outputs, computed as

$$T_l = \frac{\sum_{i=1}^{N} c_i^j \mu_i}{\sum_{i=1}^{N} \mu_i} \tag{10}$$

IV. DECOUPLING SCHEMES

The procedures of designing a SISO fuzzy controller described above indicate that only little qualitative knowledge about the process being controlled is required for deriving the rule base and the fuzzy control algorithm itself is, in fact, independent of the controlled process. It is not surprising that such designed controller will not perform well, in general, when applied to multivariable systems with the presence of strong interactions between channels. To achieve better performance, it necessary to take coupling effects into account.

For the 3-DOF stabilized platform considered in this paper, by exploring physical and mechanical properties of the system and the obtained dynamic equations we may conclude that the dominant source of interaction lies in the direct interconnection of the different parts of the platform and the rotation of each one. The position of each channel also affects the position of the others. We also assume that these interaction sources are transmitted mainly through angular velocities. Therefore, we can define three interaction components as

d_{123} the interaction component existing in the platform channel due to the inner and the outer gimbal channels.

d_{231} the interaction component existing in the inner gimbal channel due to the outer gimbal and the platform channels.

d_{312} the interaction component existing in the outer gimbal channel due to the platform and the inner gimbal channels.

The task is now to design three decoupling units to compensate for the effects d_{123} , d_{231} and d_{312}.

For the sake of simplicity, we assume that these interactions can be approximately expressed linearly with respect to $\dot{\theta}$, $\dot{\psi}$ and $\dot{\phi}$ by

$$d_{123} = k_{a1}(\psi,\phi)\dot{\psi}.\dot{\phi} \tag{11}$$

$$d_{231} = k_{a2}(\theta,\phi)\dot{\theta}.\dot{\phi} \tag{12}$$

$$d_{312} = k_{a3}(\theta,\psi)\dot{\theta}.\dot{\psi} \tag{13}$$

where k_{a1} , k_{a2} and k_{a3} are unknown.

Suppose that the input torque of the 3-DOF platform for each channel comprises two components, u_f and u_d, as indicated in (9), (10) and (11). Recall that the fuzzy controller output u_f acts as a principal controller whereas the decoupling output u_d is responsible for reducing interactive effects. For adaptive decoupling, we propose the following algorithm to obtain u_{d1}, u_{d2} and u_{d3} :

$$u_{d1} = \hat{k}_{a1}(\psi,\phi)\dot{\psi}.\dot{\phi} \tag{14}$$

$$u_{d2} = \hat{k}_{a2}(\theta,\phi)\dot{\theta}.\dot{\phi} \tag{15}$$

$$u_{d3} = \hat{k}_{a3}(\theta,\psi)\dot{\theta}.\dot{\psi} \tag{16}$$

Then, we are required to design three decoupling units $\hat{k}_{a1}$, $\hat{k}_{a2}$ and $\hat{k}_{a3}$, which are approximations of k_{a1}, k_{a2} and k_{a3}, such that the addition of the input torques u_{d1}, u_{d2} and u_{d3} to each channel given by the equations (14), (15) and (16) would compensate to some degree for coupling effects due to d_{123} , d_{231} and d_{312}

To obtain the adaptive laws a complete analysis of the closed control system containing decoupling units is very difficult due to the introduction of scaled nonlinear fuzzy controllers and time-varying adaptive units. Thus, a simple but less mathematically rigorous analysis will be described below to prove that the obtained adaptive scheme is justified. In what follows, only the platform channel is discussed since the generalization of the results to the other channel is straightforward.

Let us suppose that initially no dominant interactive term $d_{123} = k_{a1}(\psi,\phi)\dot{\psi}.\dot{\phi}$ is presented. For a specified reference command, the closed system employing the fuzzy controller only may be represented by

$$y_p(\theta,\psi,\phi,\dot{\theta},\dot{\psi},\dot{\phi}) = u^i_{f1} \tag{17}$$

where y_p represents all dynamic terms for the platform channel and u^i_{f1} is the corresponding fuzzy control effort.

Next, a dominant interactive term d_{123} is added to the system. Without the introduction of any decoupling mechanism, the closed system in response to the same reference command would be

$$y_p(\theta,\psi,\phi,\dot{\theta},\dot{\psi},\dot{\phi}) + d_{123} = u_{f1} \tag{18}$$

where u_{f1} is the fuzzy control effort when $\bar{d}_{123}$ is presented. We assume that

$$u_{f1} = u^i_{f1} + \delta u_{f1} \cong (1+\alpha_1)u^i_{f1} \tag{19}$$

where $\alpha_1 > 0$.

Now we want to use an additional control effort u_{d1} to reduce the interactive effect produced by d_{123}, leading to

$$y_p(\theta,\psi,\phi,\dot{\theta},\dot{\psi},\dot{\phi}) + d_{123} = (1+\alpha_1)u^i_{f1} + u_{d1} \tag{20}$$

By identification with (18), we have

$$d_{123} = \alpha_1 u^i_{f1} + u_{d1} \tag{21}$$

By using the linear relationship of u^i_{f1} and u_{f1}, (21) becomes

$$d_{123} = \mu_1 u_{f1} + u_{d1} \tag{22}$$

where

$$\mu_1 = \frac{\alpha_1}{1+\alpha_1} \tag{23}$$

Using (11), we have

$$k_{a1}(\psi,\phi)\dot{\psi}.\dot{\phi} = \mu_1 u_{f1} + u_{d1} \tag{24}$$

Or

$$\mu_1 u_{f1} = k_{a1}(\psi,\phi)\dot{\psi}.\dot{\phi} - u_{d1} \tag{26}$$

The above equation indicates that u_{d1} at time t may be constructed by

$$u_{d1}(t) = \hat{k}_{a1}(t)\dot{\psi}(t).\dot{\phi}(t) \tag{27}$$

Thus, we have

$$\mu_1 u_{f1}(t) = k_{a1}(\psi(t),\phi(t))\dot{\psi}(t).\dot{\phi}(t) - \hat{k}_{a1}(t)\dot{\psi}(t).\dot{\phi}(t) \tag{28}$$

Let

$$J_{f1}(\hat{k}_{a1}) = \frac{1}{2}(\mu_1 u_{f1})^2 \tag{29}$$

The gradient of J_{f1} with respect to $\hat{k}_{a1}$ is given by

$$\frac{\partial J_{f1}}{\partial \hat{k}_{a1}} = -\mu_1 \dot{\psi}.\dot{\phi} u_{f1} \tag{30}$$

Finally, the adaptive law is given by

$$\frac{d\hat{k}_{a1}}{dt} = -\lambda_1 \frac{\partial J_{f1}}{\partial \hat{k}_{a1}} = \lambda_1 \mu_1 \dot{\psi}.\dot{\phi} u_{f1} \tag{31}$$

In the form

$$\frac{d\hat{k}_{a1}}{dt} = \eta_1 \dot{\psi}.\dot{\phi} u_{f1} \tag{32}$$

where $\eta_1 = \lambda_1 \mu_1$

To prevent from possible drifting to infinity with time, it is advised to use some projection algorithms to project into given bounded sets [9]. The simplest algorithm might be

It can be seen that adaptive units (33) and (34) have linear structures and adaptive laws (35) and (36) utilize fuzzy controller outputs and as their basis for adaptation.

V. Simulation Results

Designing a simulation for the system based on the complete nonlinear dynamics developed in (3), (4) and (5) is extremely difficult. It is thus necessary to reduce the complexity of the problem by considering the linearized dynamics [15]. This can be done by noting that the gimbal angles variations are effectively negligible and that the ship velocities effect is insignificant. Applying the above assumptions to the nonlinear dynamics, the following equations are obtained.

$$\ddot{\phi} = \frac{D_{co}}{I_{px}+I_{ix}+I_{ox}}\dot{\phi} - \frac{1}{I_{px}+I_{ix}+I_{ox}}F_{co}(\text{sgn}\dot{\phi}) - \frac{I_{pz}-I_{py}+I_{px}}{I_{px}+I_{ix}+I_{ox}}\dot{\psi}\dot{\theta} - T_{oo} \tag{33}$$

$$\ddot{\psi} = \frac{D_{oi}}{I_{pz}+I_{iz}}\dot{\psi} - \frac{1}{I_{pz}+I_{iz}}F_{oi}(\text{sgn}\dot{\psi}) - \frac{I_{py}-I_{px}+I_{pz}}{I_{pz}+I_{iz}}\dot{\theta}\dot{\phi} - T_{mm} \tag{34}$$

$$\ddot{\theta} = \frac{D_{ip}}{I_{py}}\dot{\theta} - \frac{1}{I_{py}}F_{ip}(\text{sgn}\,\dot{\theta}) - \frac{I_{px}-I_{pz}+I_{py}}{I_{py}}\dot{\psi}\dot{\phi} - T_{II} \tag{35}$$

It can be seen from the dynamic equations that this system exhibits strong interactions between three channels. In each channel we can see the interaction term of the two others channels. The overall control objectives are to achieve good transient and steady state performances with respect to step-like input command despite coupling effects and to exhibit good disturbance rejection capability.

The parameters of the platform model were estimated from the 3D model in Solid works.

A. Fuzzy Controller Simulation

The platform is controlled by three independent and identical control loops. The state variables are position and speed. The output from the controller is the change in platform angle, which is used to calculate the control signals to the servos. The controller used in this paper is a fuzzy PD controller as shown in fig. 5. The scaling factors K_e, K_{de} and K_u are approximated in order to give good performance for the controller.

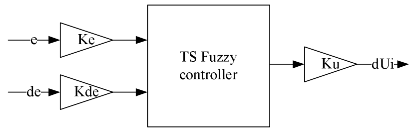

Fig. 4 TS fuzzy PD controller structure

In this simulation, we investigate the performance of TS fuzzy controller with the adaptive compensation schema. We will apply two kind of TS fuzzy system. The first one is Sugeno-type fuzzy controller of order 1 and the second one is of order 0.

In the zero-order Sugeno model, the output level z is a constant ($p_1 = p_2 = 0$). The value of p_0 depends on the linguistic term of the output. For example if the output is NB (according to the rule base) so $p_0 = -1$.

In the order-1 Sugeno model, the output level z is a linear function of input variables. The value of p_0 depends on the linguistic term of the output and the value of p_1 , p_2 are constant($p_1 = p_2 = 1$). For example if the output is PM (according to the rule base) so $p_0 = 0.666$ and $p_1 = p_2 = 1$.

The simulation of the fuzzy logic controller employs the Simulink Fuzzy Logic Block set. It is able to read files written in Matlab Fuzzy Logic Toolbox™. FLT files contain the membership functions and the rules used in the fuzzy logic system.

To perceive the performance of the adaptive decoupling schema, a comparison between the step response of the platform using TS fuzzy controller with decoupling and without decoupling scheme was done and the disturbance rejection was also treated. The results are shown and discussed in the section below.

B. Results and Discussions

The results of the simulation investigating positioning performance comparison of platform system are shown in Fig. 6 and Fig. 7.

Fig. 6 (dashed lines) shows step responses of the stabilized platform system when controlled by three separated order-0 TS fuzzy controllers. For the same fuzzy controller parameters as used above, three adaptive decoupling units were added. As shown in Fig 6, the responses (solid lines) were significantly improved with smaller overshoot, shorter rising time.

In the fig. 7 for the order-1 TS fuzzy PD controller these step responses performances for the platform, inner gimbal and outer gimbal axes, respectively, show insignificant overshoots, and the ameliorations are fairly marked.

Fig. 8 illustrates the position tracking responses using TS fuzzy PD controller with adaptive decoupling units. It can be seen that this controller present good tracking performance with minor rise time.

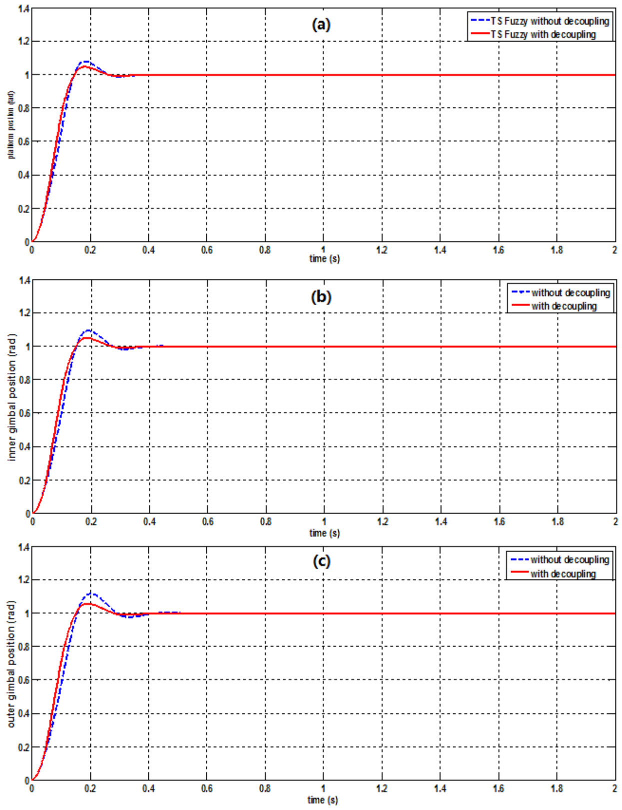

Fig. 5 Order-0 TS fuzzy controller step responses of the platform system with and without decoupling scheme, (a) platform, (b) inner gimbal, (c) outer gimbal

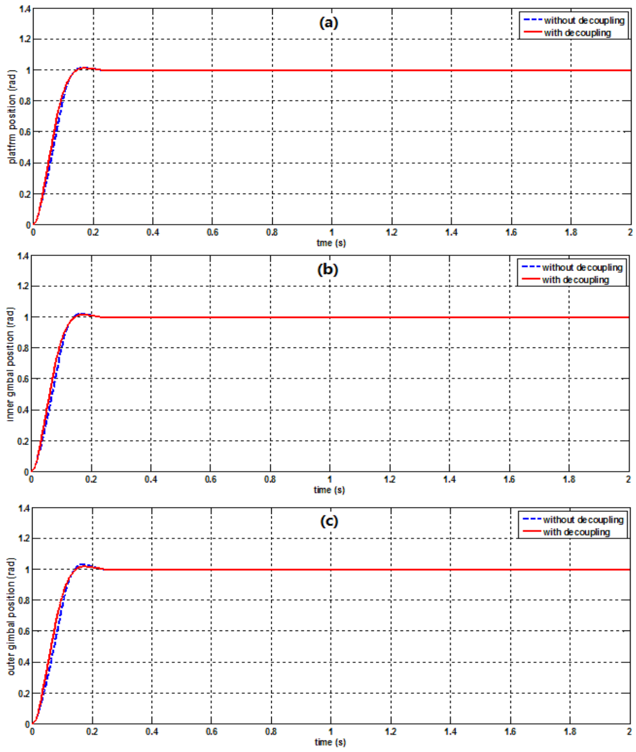

Fig. 6 Order-1 TS fuzzy PD controller step responses of the platform system with and without decoupling scheme (a) platform, (b) inner gimbal, (c) outer gimbal

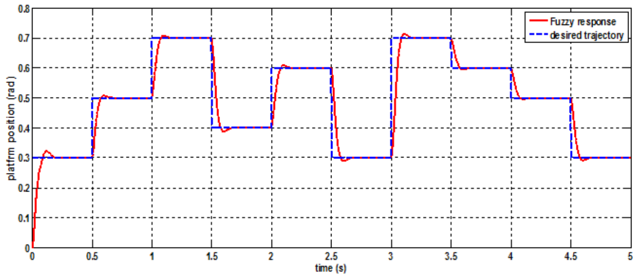

Fig. 7 Tracking performance using TS fuzzy controller with adaptive decoupling scheme

In order to see the disturbance rejection aptitude of the proposed controller, small disturbance $\Delta\tau$ was introduced. The injected disturbance was a pulse of $\Delta\tau = 0.05rad$ amplitude and adds to the system input at time instant 1s.

The disturbance rejection capability of each part of the stabilized platform using proposed controller with adaptive decoupling unit is plotted in Fig. 9. They show that the controller is capable of dealing with this situation.

In summary, the simulation results show that the proposed adaptive decoupling scheme is able to compensate the interaction between the platform elements. The obtained controller is also stable and it results in a satisfactory tracking performance.

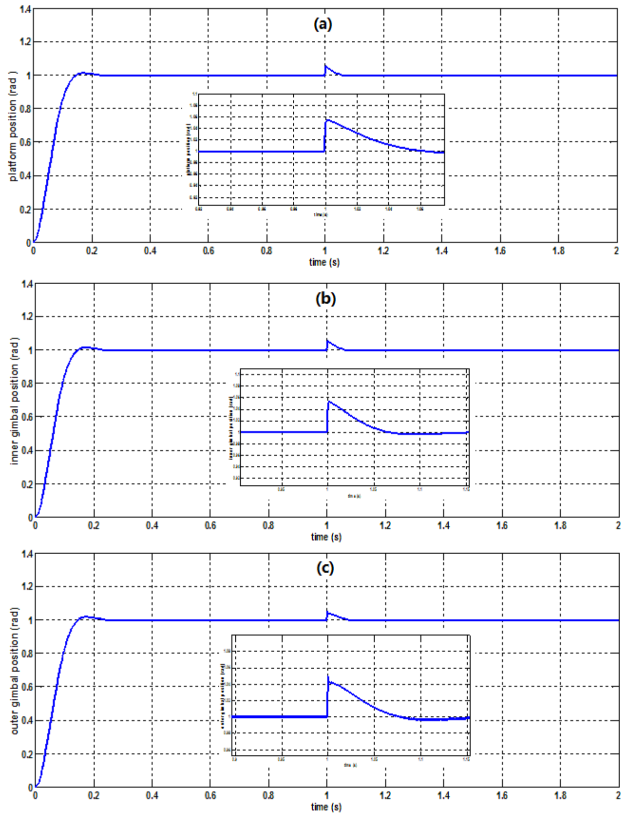

Fig. 8 An example of disturbance rejection, (a) platform, (b) inner gimbal, (c) outer gimbal

V. Conclusion

This paper has considered the problem of controlling multivariable servomechanisms where there exist cross-couplings between the channels. A fuzzy PD control strategy using a Takagi-Sugeno fuzzy model has been proposed, and an adaptive decoupling unit was added, it has been shown in the paper that uniformly stable operation is achieved together with asymptotic tracking of the reference command signals.

In the paper, simulation results in applying the proposed TS fuzzy PD controller with adaptive decoupling unit to a 3-Dof stabilization system have been presented which demonstrates the effectiveness of the fuzzy controller and the decoupling system. Future work is directed to the fuzzy decoupling scheme.

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