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# A COMPARISON BETWEEN ROBUST AND FUZZY CONTROLLER DESIGN OF A GYRO STABILIZED ELECTRO-OPTICAL SIGHT SYSTEM

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**ABSTRACT**

In modern fire control systems, Line of Sight (LOS) stabilization plays an essential and crucial part. LOS stabilization systems have a wide range of military and civilian applications. Their importance arises from the critical applications that employ these systems. Two techniques are used for the LOS stabilization systems, passive and active. The passive LOS stabilization systems are easy to design and are manufactured at a relatively low cost to be interfaced with different types of electro optical systems. Hence, it can be used to increase the efficiency of many armored vehicles serving in the armed forces, where it may be used for constructing fire control systems. The passive LOS stabilization systems are multi-input multi-output (MIMO) systems that are highly nonlinear and possess a strong coupling effect between their states. It presents a challenging system to control.

In this paper the analysis of the passive LOS stabilization system with the development of its nonlinear mathematical model is derived. Two different types of control algorithms are presented. The first controller is a Linear Quadratic Gaussian controller (LQG). The controller presents a conventional control technique that proves to be stable with high transient and tracking performances. The controller is applied to the LOS stabilization system and the simulation results are introduced. Next, an intelligent fuzzy controller is introduced. The fuzzy control presents a nonlinear control technique that compensates the system's nonlinearity; hence, it is more appropriate to stabilize and control the system under consideration. The fuzzy controller is designed to decouple the relationship between the system state variables. The controller's performance is verified through simulations and results.

Finally, comparative analysis between the two developed controllers is conducted. It discusses the advantages and disadvantages of each control algorithm.

**Keywords:** *Multi input multi output (MIMO), Fuzzy Model reference learning control (FMRLC), LOS stabilized system, non linear control, LQG/LTR..*

## 1. FORMULATION OF SYSTEM EQUATIONS

Figure (1) shows a gyro stabilized platform system [1]. There are generally three main components, a flywheel, motors and mirror system. Two gimbals that provide two-degree of freedom to the flywheel, Inner gimbal provides movement along the yaw axis and outer gimbal provides movement along the pitch axis, two torque motors are used to control the pitch axis and the yaw axis. A mirror that is geared to the inner gimbals through a 2:1 reduction drive mechanism. Figure (2) shows schematic diagram of the gyro-mirror LOS system. The LOS stabilization system consists of four main modules, namely the rotor (R), the inner gimbal (IG), the outer gimbal (OG) and the mirror (Mr). The coordinate frames and the moment of inertia (MI) of each element along the principle axes are defined as follows:

$i$ index of three dimensional axis (1,2,3)., $v_i$ vehicle frame/system frame, assumed fixed
$A$ MI of outer gimbal (OG) about $g_1 - v_1$, $B$, $C$, $D$ MI of inner gimbal (IG) about $r_1$, $r_2$ and $r_3$
$E$, $F$, $G$ MI of mirror about $m_1$, $m_2$ and $m_3$ $g_i$ outer gimbal frame
$r_i$ inner gimbal and rotor frame, $m_i$ mirror frame
$H$ MI of rotor (R) about $r_1$ or $r_2$ , $J$ MI of rotor (R) about $r_3$

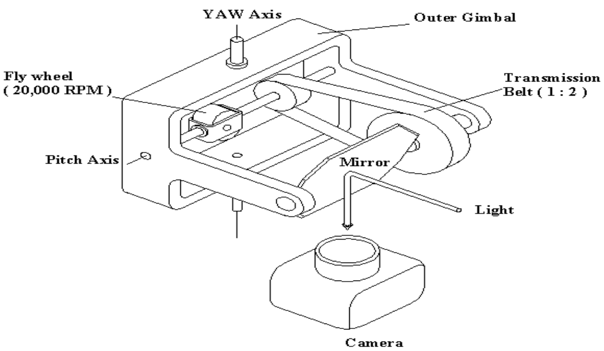


Fig.1 A passive Gyro-stabilized platform

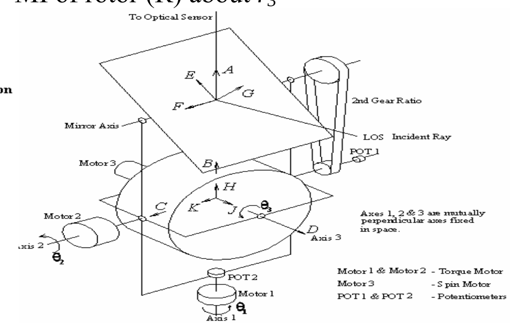


Fig. 2 Schematic of passive LOS stabilization system

As shown in Figure 2, the gyro mirror LOS platform has two coordinate axis (yaw axis and pitch axis), one tracking pointer (mirror) and a flywheel. By defining the coordinate frame. The transformation matrices between the coordinate frames are given by:

$$\begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_1 & \sin\theta_1 \\ 0 & -\sin\theta_1 & \cos\theta_1 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} r_1 \\ r_2 \\ r_3 \end{bmatrix} = \begin{bmatrix} \cos\theta_2 & 0 & -\sin\theta_2 \\ 0 & 1 & \sin\theta_1 \\ \sin\theta_2 & 0 & \cos\theta_2 \end{bmatrix} \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} m_1 \\ m_2 \\ m_3 \end{bmatrix} = \begin{bmatrix} \cos\left(\frac{\theta_2}{2}+\frac{\pi}{4}\right) & 0 & -\sin\left(\frac{\theta_2}{2}+\frac{\pi}{4}\right) \\ 0 & 1 & 0 \\ \sin\left(\frac{\theta_2}{2}+\frac{\pi}{4}\right) & 0 & \cos\left(\frac{\theta_2}{2}+\frac{\pi}{4}\right) \end{bmatrix} \begin{bmatrix} g_1 \\ g_2 \\ g_3 \end{bmatrix} \tag{3}$$

Where $\theta_1$ and $\theta_2$ are angle of rotation about axis 1 and 2 respectively as shown in Figure (1-2). The angular velocities of the mechanical elements are as follows:

$$\Omega_R = \dot{\theta}_1 g_1 + \dot{\theta}_2 r_2 + \dot{\theta}_3 r_3 \tag{4}$$

$$\Omega_{IG} = \dot{\theta}_1 g_1 + \dot{\theta}_2 r_2 \tag{5}$$

$$\Omega_{OG} = \dot{\theta}_1 g_1 \tag{6}$$

$$\Omega_{Mr} = \dot{\theta}_1 g_1 + \frac{1}{2}\dot{\theta}_2 m_2 \tag{7}$$

where $\Omega_R$, $\Omega_{IG}$, $\Omega_{OG}$ and $\Omega_{Mr}$ are the angular velocities of the rotor, inner gimbal, outer gimbal and the mirror respectively. Using the transformation matrices shown above, and its corrseponding own coordinate frame, define the rotational kinetic energy for the system as a rigid body. The kinetic energy simplifies to a sum of three terms that is given by [3-5]:

$$K_e = \sum_{i=1}^{3} \frac{1}{2} I_i \Omega_i^2 \tag{8}$$

where *i*=1,2, 3 are the principle axes of each frame. Therefore, the kinetic energy of the elements are

$$K_e = K_{e_{OG}} + K_{e_{IG}} + K_{e_{Mr}} + K_{e_R}$$
$$= \frac{1}{2}A\dot{\theta}_1^2 + \frac{1}{2}B\dot{\theta}_1^2\cos^2\theta_2 + \frac{1}{2}C\dot{\theta}_2^2 + \frac{1}{2}D\dot{\theta}_1^2\sin^2\theta_2 + \frac{1}{2}E\dot{\theta}_1^2\cos^2 x + \frac{1}{2}\left(\frac{F}{4}\right)\dot{\theta}_2^2 + \tag{9}$$
$$+\frac{1}{2}G\dot{\theta}_1^2\sin^2 x + \frac{1}{2}H\left(\dot{\theta}_1^2\cos\theta_2 + \dot{\theta}_2^2\right) + \frac{1}{2}J\left(\dot{\theta}_1\sin\theta_2 + \dot{\theta}_3\right)^2$$

Assuming that the system is rigid enough such that the strain energies are negligible, the Lagrange's equations thus become [12].

$$\frac{d}{dt}\left(\frac{\partial K_e}{\partial \dot{q}_i}\right) - \frac{\partial K_e}{\partial q_i} = Q_i \tag{10}$$

Where

$K_e$ denotes the kinetic energy, $q_i$ denotes a generalized coordinate ($\theta_1,\theta_2$ and $\theta_3$),and $Q_i$ denotes a generalized force $\tau_1$ and $\tau_2$.

Applying Lagrange's equation (10) to equation (9) we obtain:

$$(A+D)\ddot{\theta}_1 + (B-D+H)\ddot{\theta}_1\cos^2\theta_2 + \frac{1}{2}(E+G)\ddot{\theta}_1 + \frac{1}{2}(G-E)\dot{\theta}_1\dot{\theta}_2\cos\theta_2 + J\omega_s\dot{\theta}_2\cos\theta_2 = \tau_1 \tag{11}$$

$$\left(C+\frac{F}{4}+H\right)\ddot{\theta}_2 + \frac{1}{2}(B-D+H)\dot{\theta}_1^2\sin 2\theta_2 - \frac{1}{4}(G-E)\dot{\theta}_1^2\cos\theta_2 - J\omega_s\dot{\theta}_1\cos\theta_2 = \tau_2 \tag{12}$$

where $\omega_s = \dot{\theta}_3 + \dot{\theta}_1\sin\theta_2$ is the rotor spin velocity. It is a constant angular velocity of the flywheel. Equations (11) and (12) represent the nonlinear model of the LOS stabilization system., the following properties of the LOS system may be inferred as follow [4-5]:

*Property I*: The terms coefficient of $\ddot{\theta}_1$ and $\ddot{\theta}_2$ are positive definite. This is an essential property of the system. This property will be used later in the development of controllers.

*Property II*: The cross-couplings between the axes due to $\theta_2$ terms appearing in equation (11) and θ1 terms appearing in (12). The magnitudes of these values are small, and thus the cross-coupling effects are weak. However, the inclusion of the flywheel introduces strong cross-coupling between the axes of the system as can be seen from the presence of $\theta_3$ in the last terms of equations (11) and (12). $\theta_3$ is usually in the order of thousand rpm. This strong cross-coupling increases the difficulty of the control problem. For the passive LOS stabilization system, the control requirement can be stated as: achieve a sufficient high bandwidth with no steady state error for step inputs and decouple the system such that there is minimal cross-coupling effect in the system. The ability of the proposed control to meet the above requirement will be considered in the following sections. Define the state variable, *X*, control signal, *U*, and the output vector,Y, as follows.

$$X = \begin{bmatrix}\dot{\theta}_1 & \dot{\theta}_2 & \theta_1 & \theta_2\end{bmatrix}^T, U = [\tau_1 \quad \tau_2]^T, \text{ and } Y = [\theta_1 \quad \theta_2]^T$$

## 2. DESIGNING REQUIREMENT

The ultimate requirement to the compensator is, that it works "well" for real system. This requirement can be subdivided into the following four categories:

i. Nominal stability: The compensator must ensure internal stability in the controlled system, provided the model is correct
ii. Nominal Performance: The compensator must minimize the error
iii. Robust Stability: for all models the compensator must ensure internal stability
iv. Robust performance: for all models the compensator must ensure that the error is within a specified bound

## 3. ROBUST CONTROLLER

A popular modern approach to the design of robust controller is linear quadratic Gaussian/loop transfer recovery (LQG/LTR) [8-10]. This approach has been used extensively in the design of advanced multivariable control system. LQG/LTR relies on the separation principle, which involves designing a full state-variable feedback and then an observer to provide the state estimates for feedback purposes. The result is a dynamic compensator that is similar to those resulting from classical control approaches. The importance of separation principle is that compensators can be designed for multivariable systems in straightforward manner by solving matrix equations. Suppose that we have a plant model with state-space representation as:

$$\dot{X} = \mathbf{A}X + \mathbf{B}U + \Gamma w \tag{13}$$

$$Y = \mathbf{C}X + \upsilon \tag{14}$$

$U$ represents the vector of control signals, $y$ is the vector of measured outputs (corrupted by $\upsilon$) and $w$, $\upsilon$ are ‘white noise (namely zero-mean Gaussian stochastic processes). $w$, $\upsilon$ are uncorrelated in time and have covariance:

$$E\{ww^{\mathrm{T}}\} = W \geq 0, \qquad E\{vv^{\mathrm{T}}\} = V > 0 \tag{15}$$

Assume that $w$, $\upsilon$ are uncorrelated with each other, namely that. $E\{wv^{\mathrm{T}}\} = 0$ (16)

The problem is then to design a feedback-control law which minimize the cost function

$$J = \lim_{t\to\infty} E\left\{\int_0^t \left(z^{\mathrm{T}}Q\,z + u^{\mathrm{T}}R\,u\right)dt\right\} \tag{17}$$

Where $z = Mx$ is some linear combination of the states, and $Q=Q^{\mathrm{T}} > 0$ $R=R^{\mathrm{T}}>0$ are weighting matrices. Note that because the states and the control are both random , the cost function will be random, so we minimize it on the average. The solution is given by the following:

The optimal state-feedback matrix $K_c$ is given by

$$K_c = R^{-1}\mathbf{B}^{\mathbf{T}}P_c \tag{18}$$

Where $P_c$ satisfies the algebraic Riccati equation

$$\mathbf{A}^{\mathbf{T}}P_c + P_c\mathbf{A} - P_c\mathbf{B}R^{-1}\mathbf{B}^{\mathbf{T}}P_c + M^{\mathbf{T}}QM = 0 \tag{19}$$

And $P_c = P_c^{\mathrm{T}} \geq 0$ (generally there are many solutions to (19), but only one of them is positive-semi definite.) The Kalman-filter gain matrix $K_f$ is given by:

$$K_{\mathbf{f}} = P_{\mathbf{f}}\mathbf{C}^{\mathbf{T}}V^{-1} \tag{20}$$

Where $P_{\mathrm{f}}$ satisfies another algebraic Riccati equation

$$P_{\mathbf{f}}\mathbf{A}^{\mathbf{T}} + \mathbf{A}P_{\mathbf{f}} - P_{\mathbf{f}}\mathbf{C}^{\mathbf{T}}V^{-1}\mathbf{C}P_{\mathbf{f}} + \Gamma W\Gamma^{\mathrm{T}} = 0 \tag{21}$$

and $P_{\mathbf{f}} = P_{\mathbf{f}}^{\mathrm{T}} \geq 0$

The solution satisfies the separation principle, which states that the problem can be solved in two separate stages. In this case one may still be interested in using the LQG theory as a method for synthesizing controllers but with the matrices W,V,Q and R which appear in the problem formulation considered as "tuning parameters" which are to be adjusted until a satisfactory design is obtained, rather than as representation of aspects of the real problem.

### 3.1 Loop Transfer Recovery (LTR) Method

LQR has excellent stability margins (infinite gain margin and 60 degree phase margin). We know that LQR is usually, considered impractical because it requires that all states be available for feedback. Doyle and Stein[11 ] showed, under certain conditions, that LQG can asymptotically recover the LQR properties. One of the proplems with LQG is that it requires statistical information of the noise processes. In most cases, however , this information is either unavailable or is costly and impractical. Mathematical arguments and simulations had shown that the LQG design parameters ( $\Gamma, Q$ ) have strong influence on the performance of the system. It was suggested that because $\Gamma$ and Q initial values are not usually available, they should be used instead as tuning parameters to improve system performance. Let the transfer function of the LQG compensator shown in
Figure 3 be $K$(s). The return ratio at point 1 is then

$$K(s)G(s) = -K_c(s\mathbf{I} - \mathbf{A} + \mathbf{B}K_c + K_\mathbf{f}\mathbf{C})^{-1}K_\mathbf{f}\mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} \tag{22}$$

Let $\phi(s) = (s\mathbf{I} - \mathbf{A})^{-1}$ and $\Psi(s) = (s\mathbf{I} - \mathbf{A} + \mathbf{B}K_C)^{-1}$ (23)

$$KG = -K_c\Psi K_\mathbf{f}\left[\mathbf{I} + \mathbf{C}\Psi K_\mathbf{f}\right]^{-1}\mathbf{C}\phi\ \mathbf{B} \tag{24}$$

Now suppose that we obtain $K_\mathrm{f}$ by choosing the covariance matrix $W$

$$W = W_o + q\Sigma \tag{25}$$

Where $\Sigma = \Sigma^\mathbf{T} \geq 0$, and q is a real, positive parameter. Here $W_o$ could be an estimate of the true process-noise ($w$) covariance, for example; in order to obtain LTR we shall need to increase $q$ to arbitrarily large values. Substituting for $W$ in (21), we obtain

$$\frac{P_\mathbf{f}\mathbf{A}^\mathbf{T}}{q} + \frac{\mathbf{A}P_\mathbf{f}}{q} - \frac{P_\mathbf{f}\mathbf{C}^\mathbf{T}V^{-1}\mathbf{C}P_\mathbf{f}}{q} + \frac{\Gamma W_o \Gamma^T}{q} + \Gamma\Sigma\Gamma^T = \mathbf{0} \tag{26}$$

As $q$ is increased, so the Kalman filter is being 'told' that an increasing proportion of the variance in the plant output is due to state variations, and a decreasing proportion to measurement errors[8-9]. The preceding suggests the following procedure for design. Choose the LQR parameters such that the LQR loop transfer function (also called the target feedback loop) has desirable time and /or frequency domain properties. Design an observer with parameters specified before. Increase the tuning parameter q until the resulting loop transfer function is as close as possible to the target Because the loop transfer function of LQG approaches that of LQR, it will asymptotically recover it properties.

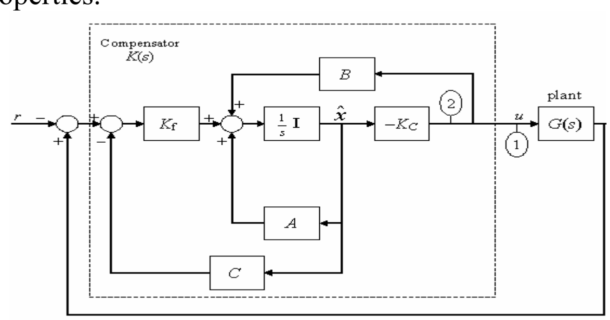

Fig. 3 The LQG Compensator Structure of LOS system

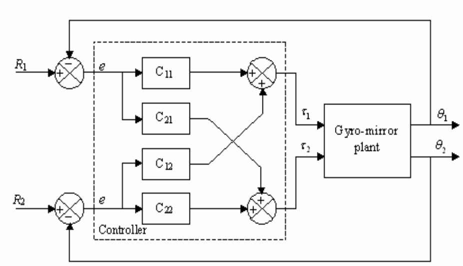

Fig. 4 Fuzzy Controller structure for LOS system

## 4. FUZZY CONTROL

Fuzzy system theory was first introduced to the research community in 1965 by Zadah [13]. Fuzzy set theory can be considered as a development of the classical set theory. In his fuzzy theory, Zadah assumes a gradual transition from one set to another. Accordingly, better presentation of different variable can be obtained with minimal number of sets. Hence classical sets are a simplified case of fuzzy sets where sets the membership level takes only two values, zero or one.

### 4.1 Limitation of Conventional Controllers

Conventional controllers can not used in all applications because it has a lot of restrictions: (1) Plant nonlinearity: Nonlinear models are computational intensive and have complex stability problem. (2) Plant uncertainty: A plant does not have accurate models due to uncertainty and lack of prefect knowledge. (3) Uncertainty in measurements and difficult to model. However Fuzzy Control is used in different research and industrial due to its advantages: ( 1)Ability to translate imprecise /vague knowledge of human experts. (2) Smooth and robust controller behavior.

### 4.2 Fuzzy Control Structure

Fuzzy control theory can be found in many text books a and papers [13,14]. However the controller is composed of four elements as follow:

i. Fuzzyfication interface: it converts the crisp inputs to linguistic values that are easy to manipulate through controller's components.
ii. Rule-base: It is a set of If-then rules that describes the knowledge of the experts of how to control the process.
iii. Inference mechanism: It is mechanism that uses the fuzzified inputs together with the rule-base to form the fuzzy control action.
iv. Defuzzification interface: it converts the fuzzy conclusion into a crisp value suitable to be used as an input to the process.

### 4.3 LOS Fuzzy Control

A full matrix fuzzy controller is designed to control the two state variables ($\theta_1, \theta_2$) of the LOS system considering the strong coupling effect the system possesses. Two fuzzy controllers are used as direct controllers (forward path between $\theta_1$-$\tau_1$ and $\theta_2$-$\tau_2$) while the other two controllers are used to decouple the cross relationship between $\theta_1$-$\tau_1$ and $\theta_2$-$\tau_2$. Figure (4) shows the controller structure. The four controllers are MISO fuzzy controllers with two inputs representing the error and the change rate of the error. The inputs are given by the following equations.

$$e_{\theta_1}(KT) = \overset{*}{\theta}_1(KT) - \theta_1(KT), \quad c_{\theta_1}(KT) = \frac{e_{\theta_1}(KT) - e_{\theta_1}((K-1)T)}{T} \tag{27}$$

$$e_{\theta 2}(KT) = \overset{*}{\theta}_2(KT) - \theta_2(KT), \quad c_{\theta 2}(KT) = \frac{e_{\theta 2_1}(KT) - e_{\theta 2}((K-1)T)}{T} \tag{28}$$

Where $e$ , $c$ represent the error and the change rate of error respectively and $\overset{*}{\theta}$ , $\theta$ represent the desired and measured angles respectively. Five membership functions are used for each input and output of the four fuzzy controllers. Larger number of membership functions would not enhance the controller performance dramatically; however it will increase the complication of the design process. On the other hand, fewer number of the membership functions will significantly affect the controller performance negatively. Skewed triangular membership functions are used for inputs of the four fuzzy controllers.

For the outputs, singletone membership functions are used. The singletone membership function simplifies the defuzzification when used for crisp outputs. Finally, the rules at rule-base of the fuzzy controller were formed by examining the linearized model of the LOS system in addition to the open loop analysis; the rule base was formed according to the following facts:
The coupling effect dominates the characteristics of the system; hence, to move one gimbal, the controller is required to generate a sufficiently high torque about the gimbal perpendicular axis rather than its axis[13]. Appling a positive torque to the yaw channel will vary both angles positively. Meanwhile, a positive torque in the pitch channel implies a negative variation in the yaw angle and positive one in the pitch angle. The rule base was constructed so that it represents a human expert in the loop. For instance, one rule that a human may use to control the system is "if the pitch angle is less than the set point ($e_{\theta 2}$ is positive) then $\tau_1$ should be positive" an other rule that would represent more detailed information is "if that angle is less than the set point and approaching that point very fast a negative torque may be applied to make shore that we don't over shoot the set point. The rule base are indicated in table (1).

## 5. SIMULATION RESULTS

A prototype for the passive LOS stabilization system has the parameters as follows[7,14]: A ($Kgm^2$) = 0.0392, B ($Kgm^2$) = 0.0211, C ($Kgm^2$) = 0.0153, D ($Kgm^2$) = 0.0049, E ($Kgm^2$) = 0.0019, F ($Kgm^2$) = 0.0018, G ($Kgm^2$) = 0.0036, H ($Kgm^2$) = 0.0057, J ($Kgm^2$) = 0.0089, $\omega_s$ (rad/s) = 800.
Series of rectangular inputs for both $\theta_1$(yaw) and $\theta_2$ (pitch) are applied to the system so that $\theta_1$and $\theta_2$ have different frequencies. The pulses frequencies are set to different values for each channel to examine the coupling effect at different operating conditions. The LQG/LTR controller was applied to the nonlinear model. It can be noted that the system developed undesirable oscillation. The phase plane is shown in Figure (5). It shows that the system has a high coupling effect (see subplots c, d, e, and f) where a variation in one channel developed oscillation in the opposite channel.
Figure (6a,b) represents the phase plan of the yaw and pitch channels respectively when step changes applied to both channels simultaneously. Figure (6 c,d) shows the coupling effect on yaw channel when step change is applied to pitch channel and vise versa in Figure (6 e,f). It can be noted that the control algorithm provides an asymptotically stable system that approaches the equilibrium point in all cases. The coupling effect is minimal even when applying simultaneous changes in both channels. For performance comparison purposes and system qualification. They are: (1) Integral absolute error ($IAE_i$) is used to evaluate the system tracking performance (2) Integral square error ($ISE_i$) is similar to (IAE) however it discriminates between systems that have close (IAE). (3) Integral time multiple Absolute error ($ITAE_i$) is used to evaluate system performance with the time. (4) Integral absolute control action ($IACA_i$) is used to evaluate the efficiency of the system. Table (2) shows that better results were achieved using the fuzzy controller especially after sufficient learning period. Also by reviewing the IAE and ISE of the fuzzy controller, they show that fuzzy controller gives much better performances

## 6. CONCLUSION

In this paper the analysis of the passive LOS stabilization system with the development of its nonlinear mathematical model is derived. LQG/LTR control algorithm is discussed and its design procedure is presented. The controller is implemented and the simulation results are introduced. The results show that the controllers provided an acceptable performance; however, a high overshoot is experienced. Multi-input Multi-output fuzzy controller was implemented to control the (LOS) system and minimize the coupling effect between system states. The structure of controller was introduced. Simulations were performed to examine the system transient and tracking performances. The controller was able to form the control surface that decouples the relation between the control states $\theta_1$, $\theta_2$ and the corresponding control actions $\tau_1$, $\tau_2$ and compensate for the system's nonlinearity. Some of the controller parameters were not optimally selected; even through the system was asymptotically stable with high tracking and transient performances. The study shows that the fuzzy controller provides a more stable system with less sensitivity to the coupling effect. It also shows that the fuzzy controller is more efficient and has a high performance than other algorithms.

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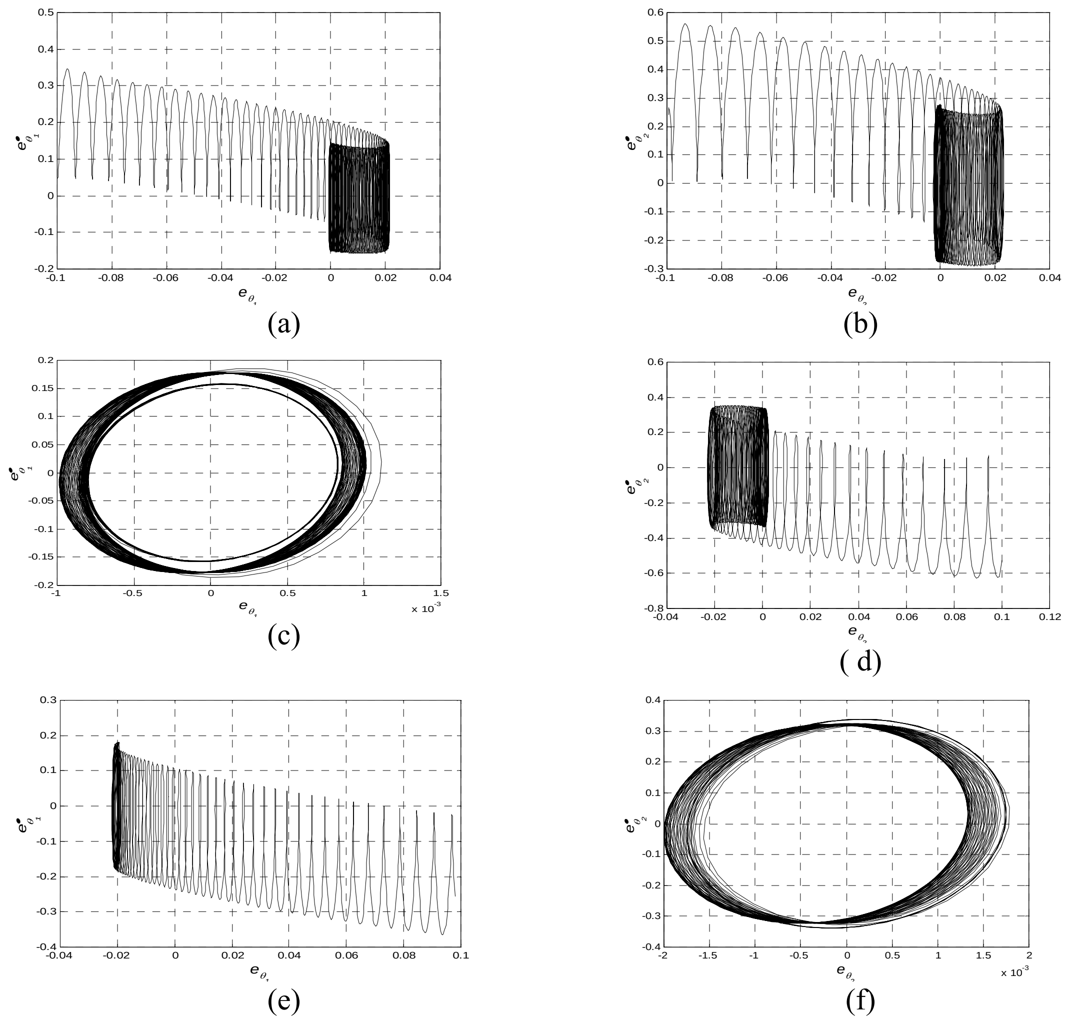


Figure (5) Phase plot of LOS system using LQG/LTR (a) and (b) for channel one and two respectively when applying step inputs to the two channels simultaneously, (c) coupling effect of channel two on channel one (d) no coupling effect on channel two (e) no coupling effect on channel one (f) coupling effect of channel one on channel two.

| *c* \ *e* | NB | NS | ZE | PS | PB |
|---|---|---|---|---|---|
| NB | PS | PB | NB | ZE | PS |
| NS | NS | NB | NB | PB | PS |
| ZE | PS | PO | ZE | PB | NS |
| PS | NS | ZE | PS | PB | NB |
| PB | PB | ZE | PB | PS | NB |

Rule base for the yaw angle direct controller C11

| *c* \ *e* | NB | NS | ZE | PS | PB |
|---|---|---|---|---|---|
| NB | NS | PB | PB | PS | NS |
| NS | PS | PB | PS | NB | NS |
| ZE | NB | PS | ZE | NS | PS |
| PS | PB | PB | NS | ZE | PB |
| PB | NB | PB | NS | NS | PB |

Rule base for the yaw angle direct controller C22

| *c* \ *e* | NB | NS | ZE | PS | PB |
|---|---|---|---|---|---|
| NB | PS | PS | NB | NS | PS |
| NS | NS | ZE | NS | ZE | PS |
| ZE | PB | PS | ZE | NS | NS |
| PS | NB | PB | PS | PB | NB |
| PB | PB | PB | PS | NS | NB |

Rule base for the yaw angle direct controller C21

| *c* \ *e* | NB | NS | ZE | PS | PB |
|---|---|---|---|---|---|
| NB | NS | NS | PS | PS | NS |
| NS | PS | PB | ZE | PS | NS |
| ZE | NB | NB | ZE | PS | PS |
| PS | PB | ZE | NS | PS | PB |
| PB | NB | NB | NS | PS | PB |

Rule base for the yaw angle direct controller C12

Table 1: Rule-bases of the full matrix fuzzy controller for the LOS stabilization system
(NB: Negative big, NS: Negative, ZE: Zero, PS: Positive, PB: Positive big)

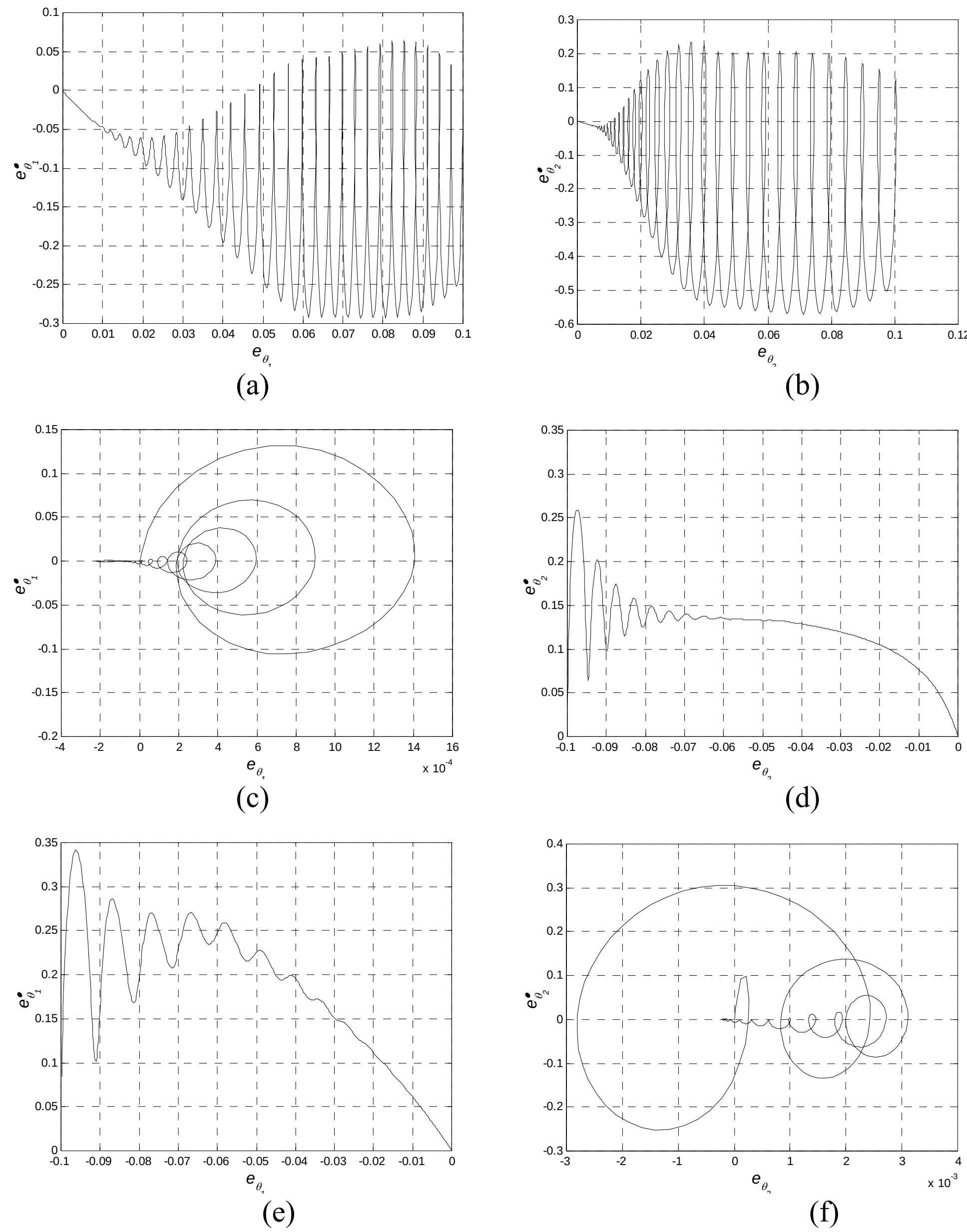


Figure ( 6) Phase plane of LOS system using full matrix fuzzy controller (a) and (b) for channel one and two respectively when applying step inputs to the two channels simultaneously, (c) coupling effect of channel two on channel one (d) no coupling effect on channel two (e) no coupling effect on channel one (f) coupling effect of channel one on channel two

| Controller | IAE | | ITAE | | ISE | | IACA | |
|---|---|---|---|---|---|---|---|---|
| | Yaw | pitch | yaw | pitch | yaw | pitch | τ1 | τ2 |
| FC full matrix | 195.3 | 338 | 2746.5 | 3636.8 | 12.2 | 20.6 | 6646.9 | 3681.1 |
| LQGR nonlinear model | 365.8 | 396 | 12254 | 13626 | 12.8 | 18.2 | 8869.6 | 5484.3 |

Table 2: Comparison Results For Pulsed Reference Signal