Modelling and simulation of two axes gimbal fuzzy PI stabilization system in the presence of feedback sensors noise

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Modelling and simulation of two axes gimbal fuzzy PI stabilization system in the presence of feedback sensors noise

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Abstract. The missile guidance in terminal phase is an optimization problem as the miss distance should be minimized. The optimization of missile miss distance is highly affected by the missile seeker performance. Design of gimbal control system suffers always from feedback sensors noise which leads to system instability. In this paper, a promising design of the fuzzy PID controller for a missile seeker gimbal is proposed considering the feedback sensor noise with practical gyro transfer function calculated based on real experimental measurements utilizing MATLB system identification toolbox. Also, the mathematical model of two stabilized axes gimbal. Stabilization is achieved considering the missile motion parameters such as rates, torques and coupling between yaw and roll channels. A Matlab simulation is carried out for evaluating the proposed system modelling and to test the robustness of the fuzzy PID controller in the presence of feedback sensor noise. A comparative analysis with PI based controller is conducted to evaluate the performance of the proposed controller which presents sufficient enhancement to the missile gimbal stability parameters.

1. Introduction

Latest years, stabilized platform-based seekers are widely used in ballistic missiles [1]. Usually, the seeker assembly is attached to the missile nose, the seeker coordinate axis is always aligned with a missile body axis. The seeker's field of view (FOV) is easily defined to be aligned with missile body axis. Furthermore, the hypersonic missile aerodynamic configuration with sharp nose. This configuration has narrow space for nose[2], which is not suitable with large-sized seekers to be fixed easily. However, when the seeker axis is not aligned to the missile body axis, FOV of these seeker lies in the direction of the body. The FOV of seekers are out of a missile axis, which always leads to target miss-tracking. The seeker detector's FOV is always constrained by minimum and maximum angles in missile's horizontal and vertical planes which presented in [3]. Derived from guidance laws, the maximum angle of look will not overdo the constraint angle's border by changing of guidance parameters [4], and a system identification for both electrical servo and gyro using PI controller, and fuzzy PID controller impact angle optimized in guidance law, which considers FOV angle constraint is presented in this paper. A sliding mode control guidance law considering constraints of FOV angle is represented [5]. By utilize a sliding mode theory, the guidance law and FOV angle-controller realizes impact as well designed. Control systems designed for gimbal stabilized platform to enhancement seeker stability in two planes, disturbance end results are produced undesirable influencing of system. Unbalance off mass, cable restraint and coupling between lateral and longitudinal planes are considered a main sources of the disturbance on system position, angular velocity [6]. Operational conditions and angular velocity are main parameters must be monitored. Before actually designing and producing system dynamics of the system are considered. Accordingly, two electrical light or more axes gimbal are required. LOS controller system systems with useful stability is very difficult, due to the coupling between azimuth and elevation planes [7]. Target tracking accuracy and system stabilization is highly affected by the missile dynamics, it's clear that system performance depends on system modelling accuracy [8]. System is rotated into two azimuth and elevation planes, IMU installed on inner gimbal to measure angular acceleration from two channels. Actually, these IMU is applied to develop accuracy of feedback angular velocities, and prevent disturbances due to seeker gimbals. Notably, the deviation produced is calculated utilizing installed target recognition camera or laser quadratic detector installed on inner gimbal axis [9]. PI controller is used to guarantee the system stabilization and improve its performance [10]. Fuzzy controller is presented in [11] for the design of two axes gimbal stabilization.

On the basis of the above, the most important aim of this article is structured as follow: through section 2, the modelling of two-DOF gimbal dynamic system is introduced. Section 3, the design of PI and direct fuzzy PID controllers is presented. Section 4, the simulation results is demonstrated.

2. Two DOF gimbal dynamic system modelling

The guidance system accuracy is critical for the performance of the overall system autonomy and accuracy. It's responsible for minimizing the deviation of missile actual trajectory from the pre-calculated reference trajectory, provide the proper actuation commands to execute the required maneuverer considering the missile time and frequency stability constraints [12].

Recently, proportional navigation guidance law is the most common used guidance law. The missile-target relative velocity measurement and LOS angular rates are essential to more accurate guidance law. The missile seeker is always devoted to angles measurement as described in Figure 1. The angles definitions related to missile-target during flight are θ velocity vector angle relative to inertial space, ϑ missile body x-axis angle with respect to inertial space, relative LOS angle to the inertial frame, ε error in angles of missile-target line and q_d angle of detector with respect to inertial frame.

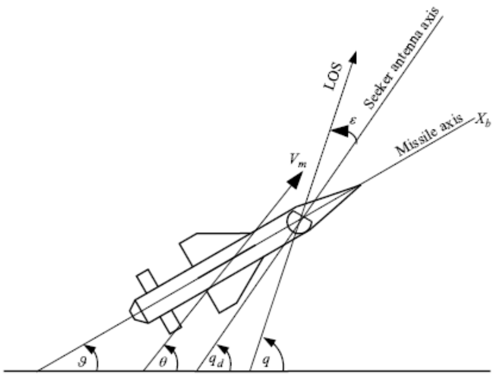


Figure 1. Definitions of angles

Essentially, current missiles which using seekers techniques in terminal phase commonly, categorized as dynamic gyro-based stabilization seekers technique, stabilized platform-seekers, semi-strap down seekers, strap down seekers and roll-pitch-seekers. This paper motivation is enhancement of stabilisation platform-based seeker controller using PI and fuzzy $-PID$ controllers further, a comparative investigation is carried-out for evaluating the two performances for time stability parameters such as, rising time $t_r(sec)$, settling time $t_s(sec)$ and overshoot $OV(\%)$.

Two-degree stabilized platform gimbal-based Laser Seeker, which gimbal is composed of two control loops.

The disturbance of the angular motion is captured and rejected using high-gain IMU sensor through the inner loop, the angular velocity stabilization provides the missile body motion stability and also, acquire the missile LOS angular velocity output. The outer loop is dedicated for missile positional stabilization to ensure the target tracking as shown in Figure 2. Although, MEMS IMU based stabilized seeker provider slower response, lower load, and smaller gimbal angles when compared to stabilized platform-based seeker.

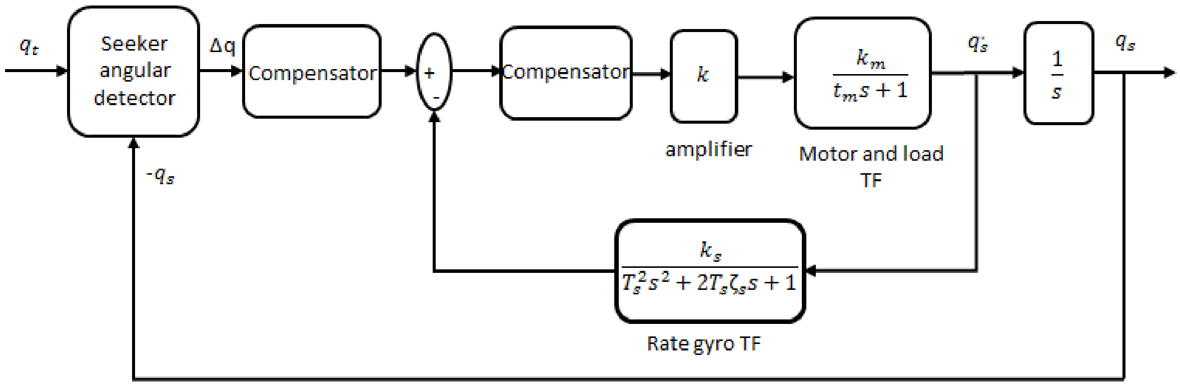


Figure 2. Block diagram of seeker stabilized platform controller

The practical gimbal servo and gyro transfer functions are essential for the modelling and implementation the two DOF gimbal system and applying different technique of controllers and compare such techniques with each other. The transfer function for MEMS gyro VN100 which investigated utilizing system identification tool box with fit estimation data 84.45% in MATLAB by tacking real 15000 measurements for different inputs and save it as experimental work. The rate gyro transfer function in equation 1 is derived from system identification experimental work can be described with second order transfer function as shown.

$$G_{Gyro}(s) = \frac{2.056e06}{s^2 + 2372s + 9.862e05} \quad (1)$$

Servo DC motor transfer function, which parameters are rated current consumed with load $I_e = 3.95$ Ampere, rated voltage $U = 27$ Volt, inductance in motor $L = 0.5433 * 10^{-3}$H, motor internal resistance is $R = 0.9\ Ohm$, estimated friction coefficient for the motor $F_m = 0.8 * 10^{-4} N.M/rad/s$ and Voltage drop on Motor E

$$U(t) = RI(T) + L\frac{dI}{dt} + E \quad (2)$$

$$E = K_e w(t) \quad (3)$$

$$T = K_T\, I(t) \quad (4)$$

$$T = J\frac{d(w_t)}{dt} + F_m w(t) \quad (5)$$

Where E is inverse electrical potential in Motor, T is Torque, J Rotational Inertia, $J\frac{d(w_t)}{dt}$ Moment of Inertia and F_m Friction coefficient. By taking Laplace transformation of equations (2), (3), (4) and (5)

$$U(S) - E = (R + LS)I(S) \tag{6}$$

$$E(S) = K_e w(S) \tag{7}$$

Figure 3 present block diagram of servo system after Laplace transformation, which is fully proportional, to digital servo torque. The utilized HSR-2645CRH servo is a digital based servo, where the speed control is accomplished utilizing PWM technique. It's sufficiently used in wide range of applications such as missile terminal guidance, pedestal platform, camera and seeker stabilization devices and on robots.

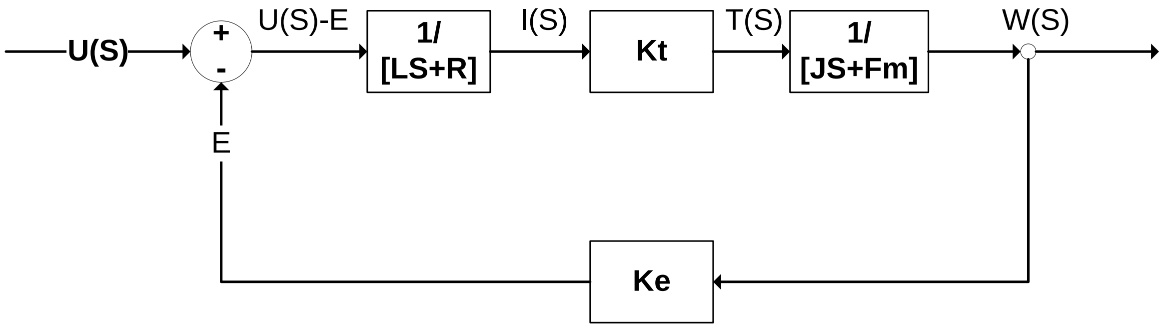


Figure 3. Servo model content transfer functions

From equation (4), (5)

$$T(s) = JSW(S) + F_m W(S) \tag{8}$$

$$T(s) = (JS + F_m)W(S) \tag{9}$$

$$G_d(S) = \frac{W(S)}{U(S)} = \frac{\frac{1}{LS+R}\ K_t \frac{1}{JS+F_m}}{1 + \frac{1}{LS+R}\ K_t \frac{1}{JS+F_m} K_e} \tag{10}$$

$$G_d(S) = \frac{K_t}{(LS+R)(JS+F_m) + K_t K_e} \tag{11}$$

$$G_d(S) = \frac{K_t}{LJS^2 + (R.J + L.F_m)S + (R.F_m + K_t K_e)} \tag{12}$$

$$G_d(S) = \frac{W(S)}{U(S)} = \frac{0.06402}{3.78e-09 * S^2 + 5.762e-06 * S + 0.013744} \tag{13}$$

As demonstrated in the previous section the effect of missile angular motion on seeker performance can be reduced by increasing the open-loop gain. Considering the seeker load, its limited driving bandwidth and due to the motion interference for missile dropped down in low range frequency, the low frequency gain is increased by adding a PI compensator to reduce the coupling effect of missile seeker system.

Following system parameters illustrates, how to implement this approach. The rate gyro transfer function includes the damping- coefficient and time-constant. Missile angular motion interference frequency is in range between 9.8*105 and 1.1*103. So, the PI compensator parameters (k_p andk_i) optimization under these design constraints is required, gain-margin range is 4 dB, a phase-margin is greater than 40, the stabilization loop optimization is to reject the angular motion disturbances located on missile body. The compensator $k_p$and k_i gains should be investigated for maximize loop gain at interference frequency two hertz. Problem of gimbal design is carried out as shown in Figure 4, the servo motor and gyro transfer functions presented into two equation number 1, 13.

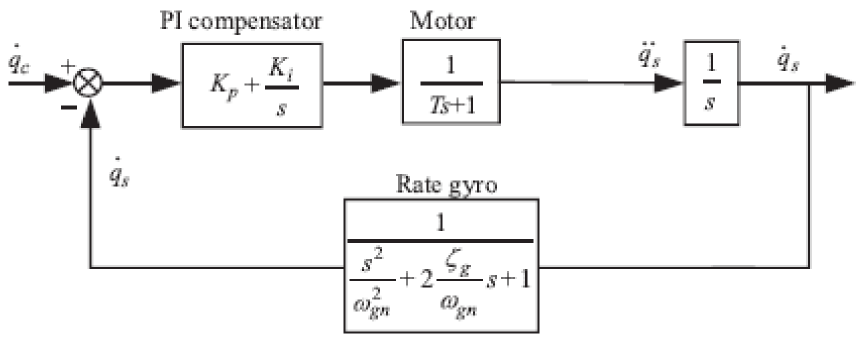


Figure 4. Block diagram of the stabilization loop with PI compensation

Two degree of freedom gimbal with a laser source system is assembled of two systems inner and outer gimbals. To navigate and control laser source systems in lateral and longitudinal axes, to controlling two different loops rate controller is developed. Complete scheme of gimbal system is shown in Figure 5.

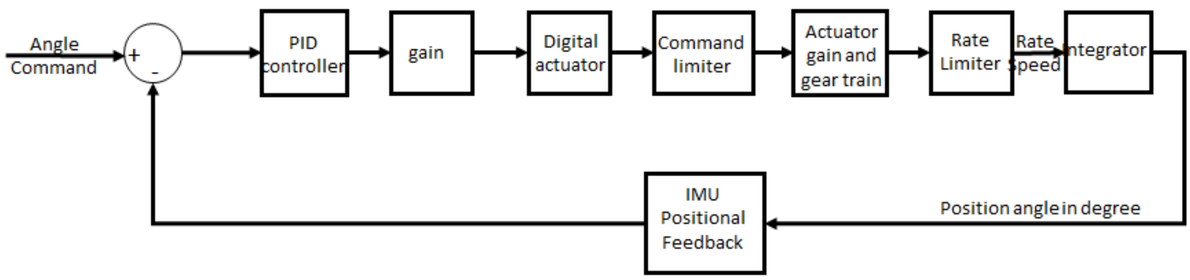


Figure 5. Two-DOF gimbal Block diagram.

3. Design of the PI controller and direct fuzzy PID controllers

The PI controller always shares a poor performance with two DOF plant due to system environmental varying conditions. Consequently, controller parameters have to be re-tuned to maintain good performance with inertia seeker stabilization platform systems proposed. Adaptive fuzzy logic approach is proposed to develop the seeker gimbal control system. Fuzzy controller contains four main stages as shown in figure 6 fuzzification, inference mechanism, rule base, de-fuzzification.

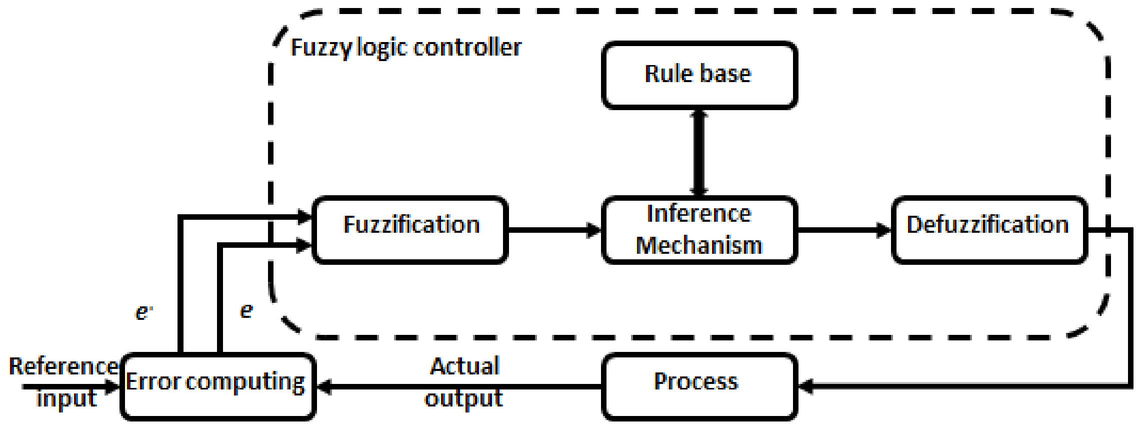


Figure 6. Fuzzy controller block diagram

The membership Fuzzy controller functions used, *PL, PS, ZR, NS, NL* denotes positive large, positive small, zero, negative small, and negative large. The PI controller gains highly affect the dynamic performance and stability. Centre of gravity method outputs had determined according to conditions in table 1.

Table1. Control response

Control Response	Rise Time	Over Shoot	Settling Time	S-S error
Kp	Decrease	Increase	Small change	Decrease
Ki	Decrease	Increase	Increase	Eliminate
Kd	Small change	Decrease	Decrease	Small change

When control parameter K_p gets so large, steady state is damaged and overshoot is too great, if K_i becomes too large, that affect the steady-state error by causing ripples on torque. The overshoot is reduced as K_d gain gets small, the response always suffers from overshoot and slower response (longer settling time). Then the above procedure is designed as an if-then rule statements indicated in Table 2.

The fuzzy-PID-controllers design parameters are classified into two groups, structural and tuning parameters which are calculated offline and online design respectively, the tuning parameters is the main difficult where it includes the membership function and scaling parameters. The difficulty for calculating the tuning parameters requires an experience where, it always calculated using trial and error to accommodate adaptive capability of system process considering the environmental disturbance and system uncertainties. When the compensator is being work and any of tuneable parameter is changed the adaptive is regarded, otherwise the fuzzy controller is working normally. The scaling factors always shares a global and critical effect on the control system performance as the missile angular rates w_{el} *and* w_{az} are considered the most dominant effecting system parameters.

Table 2. Rule bases

Δ_{K_P} Δ_{K_i} Δ_{K_d}	$\dot{e}$					
		NL	NS	ZR	PS	PL
e	NL	PL NL NL	PS NS NS	PS NS NS	PS NS NS	ZR ZR ZR
	NS	PL NL NL	PS NS NS	PS NS NS	ZR ZR ZR	NS PS PS
	ZR	PS NS NS	PS NS NS	ZR ZR ZR	NS PS PS	NS PS PS
	PS	PS NS NS	ZR ZR ZR	NS PS PS	NS PS PS	NL PL PL
	PL	ZR ZR ZR	NS PS PS	NS PS PS	NS PS PS	NL PL PL

4. Simulation results

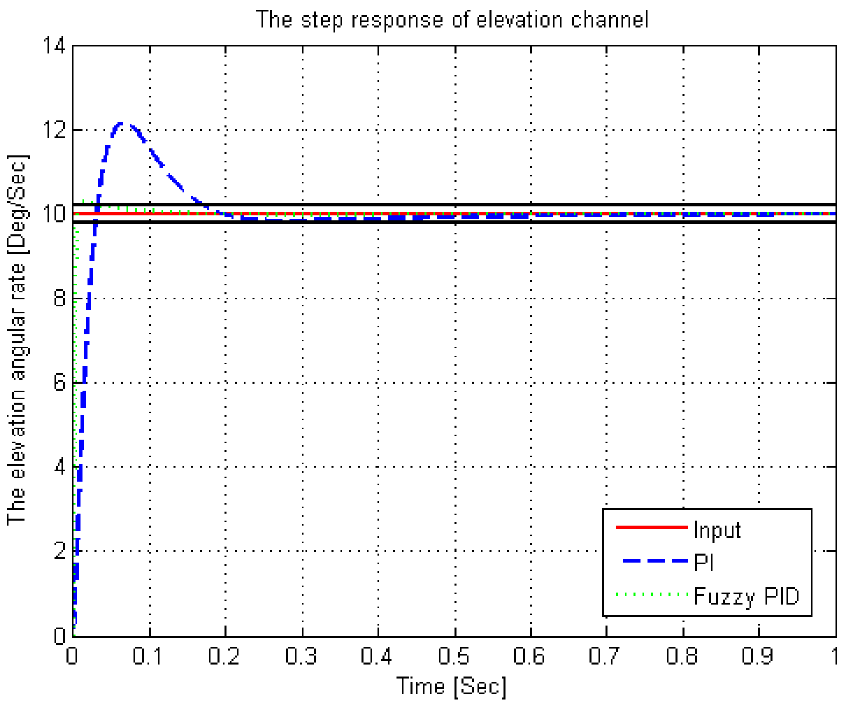
The comparative analysis of conventional PI and Fuzzy PID for digital DC servo controller system is accomplished utilizing various input angular rate commands into two planes azimuth and elevation$w_{el} = w_{az} = 10\ deg/sec.$ w_{az}, w_{el} are changed through interval [0 -12 deg/sec]. Figure 7 one case study the system response is analysed which clearly reflects the efficiency criteria of a fuzzy-PID compensator compared to PI controller. The results as summarized as shown in, tables 3,4 present comparison testes results utilizing overshoot (OV), rising time (t_r), settling time (t_s). While PI is utilized, angular rate creates an increase in settling time, large percentage in overshoot. While fuzzy-PID compensator met the variant in body rates of missile and improves steady state performance and by achieving lower overshoot with fast response as a compared to PI controller. Furthermore, the MATLAB system identification toolbox output for the rate gyro real data is presented in Figure 8 as the calculation of a practical transfer function for the rate gyro is highly affect the controller design, which leads to enhance the overall system performance.

Table 3. Comparison result for the elevation channel

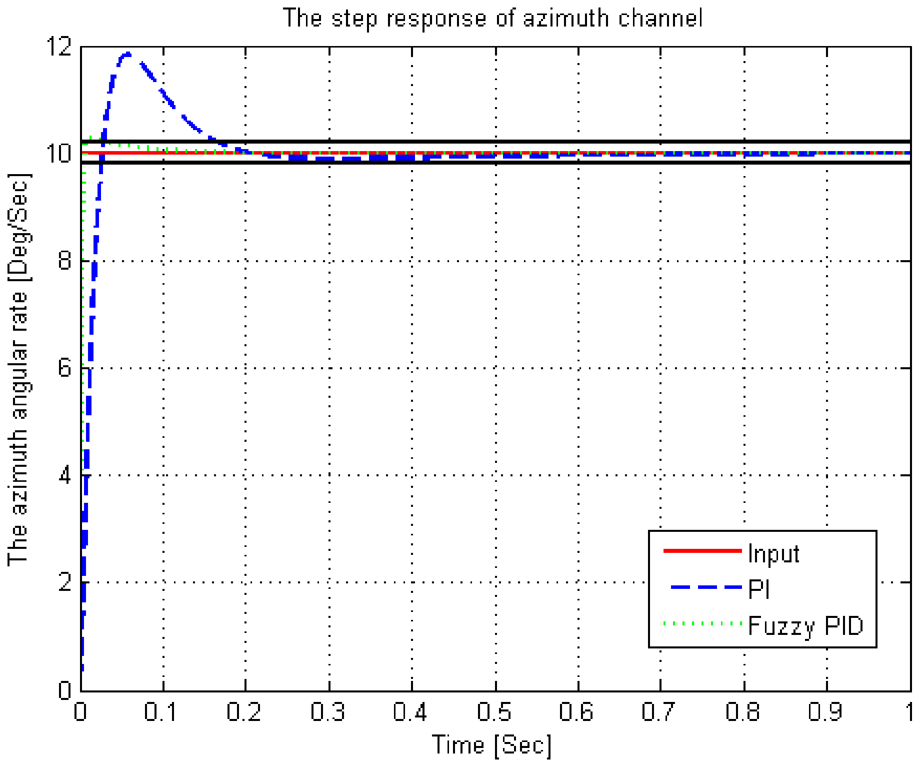
w_{pj} (deg/sec)	PI controller			Fuzzy PID controller		
	$OV(\%)$	$t_s(sec)$	$t_r(sec)$	$OV(\%)$	$t_s(sec)$	$t_r(sec)$
2	10.8	0.195	0.08	3	0.078	0.099
4	19.2	0.184	0.063	5	0.085	0.092
6	28.3	0.175	0.053	7.3	0.099	0.073
8	35	0.265	0.033	6.2	0.156	0.053
10	49	0.276	0.02219	12.3	0.137	0.039

Table 4. Comparison result of horizontal channel

w_{pj} (deg/sec)	PID controller			Fuzzy PID controller		
	$OV(\%)$	$t_s(sec)$	$t_r(sec)$	$OV(\%)$	$t_s(sec)$	$t_r(sec)$
2	7.8	0.166	0.064	7	0.158	0.130
4	17.5	0.178	0.048	2.4	0.137	0.123
6	37	0.198	0.04	3.4	0.138	0.084
8	42	0.21	0.036	4	0.098	0.084
10	53	0.29	0.04	4,9	0.232	0.07



(a) Elevation plane



(b) Azimuth plane

Figure 7. Gimbal system response for $w_{EL} = w_{AZ} = 10\, deg/sec$

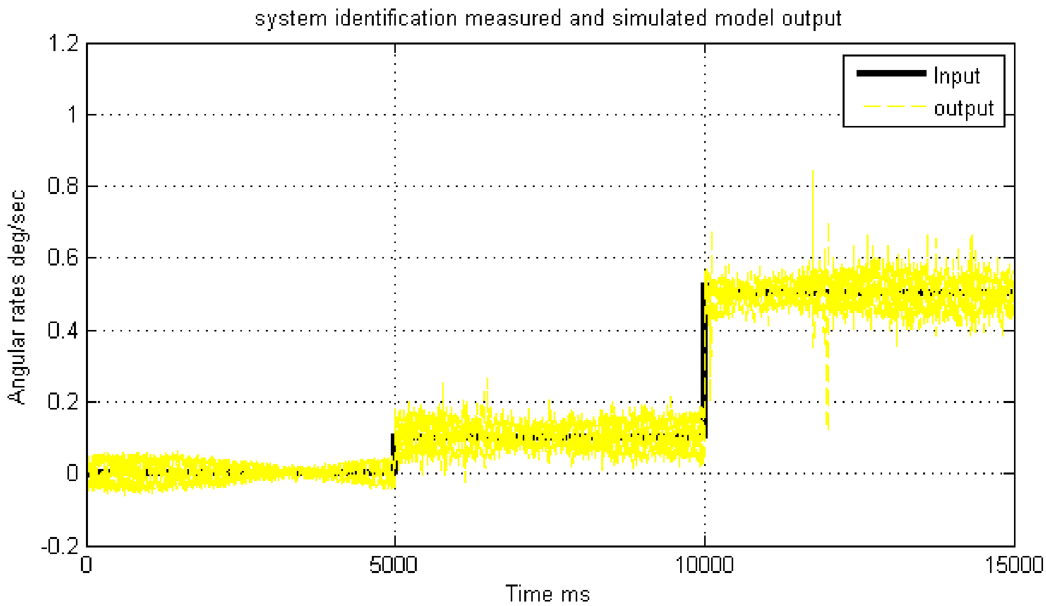


Figure 8. System identification

5. Conclusion

Two axis gimbal system stabilization is very essential for several applications in air borne and missile guidance. Accuracy in performance of these applications plays an essential task to design high performance gimbal control system. Then, computation of the control signal is applied to the two DOF gimbal system. Stabilization of a two-axis laser source gimbal system, a fuzzy PID controller is proposed and improving its performance by responses of gimbal system. Proposed controller parameters tuning method used to tune different accuracy variations performance, tuned fuzzy PID controller gives stable in convergence and accuracy. In a stabilization mode, imposed disturbance on gimbal system has to be removed by proposed controller to reserve the stability of gimbal system. Control signals in azimuth and elevation planes are within the drive power range and smooth. The feasibility of validity of a proposed controller was verified by experimental work by accomplishment an experimental work for capturing the response of gimbal control signal with different position and different angular positions.

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