Tracking Control for the Electro Optical Tracking System Based on the Self – Tuning Fuzzy PID Control

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Abstract: **The paper presents the self – tuning Fuzzy PID control algorithm for the Electro – Optical tracking system. The proposed controller has been designed and compared with the PID controller that was designed before. The simulation results show the efficiency and the application ability of the proposed controller.**

Index Terms: **Electro Optical Tracking System, Tracking, The Self Tuning Fuzzy PID Control, Fuzzy Control, Inertial Stabilization Platform.**

Symbols:

Symbols	Unit	Definition
${}^{A}J,\ {}^{B}J$		*The inertia matrices of the pitch and yaw gimbal*
T_p, T_y	N.m	*The total external torque about the pitch and yaw axis*
T_{Dp}, T_{Dy}	N.m	*The torque disturbance of the pitch and yaw gimbal*
$t_e\ t_e^{'}$	kg/m2	*Moment of motor (up, down)*
$\overline{H}$	$Kg.m^2/s$	*The angular momentum*

I. SYSTEM OVERVIEW

The Electro-Optical Tracking System attempts to align its detector axis combined of the pitch and yaw gimbal with a LOS joining the tracker and the target. The tracker contains two loops: outer track loop, and inner stabilization loop as shown in Figure 1.

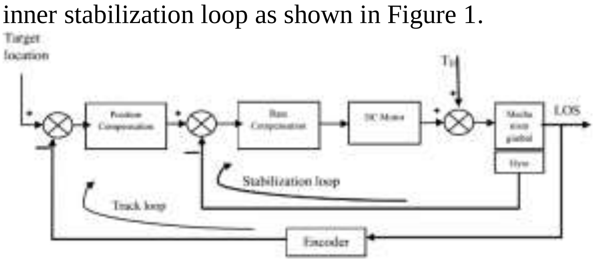


Figure 1: The functional block diagram of stabilization/tracking system for one axis gimbal

The important requirement of the EOTSs is that the optical sensor axis must be accurately pointed to a fixed or moving target. Therefore, the sensor's line of sight (LOS) must be strictly controlled. To maintaining sensor orientation toward a target is a serious challenge. An Inertial Stabilization Platform (ISP) is an appropriate way that can solve this challenge [1]. Besides the mathematic model of the system obtained and cross coupling also gave in this section. The term "cross coupling" which describes the impact of the pitch gimbal to the yaw gimbal and inversely, is based on the relations of the torques affected on them. The cross coupling expresses the properties of the system dynamics. As a result, that is also defined as the effect on one axis by the rotation of another [2, 3]. A two-axis rate gyro is usually placed on the pitch gimbal, measuring the rotational rates in the two directions of interest. These gyro signals are utilized as feedback to torque motors acting on the gimbal.

To maintaining, the sensor's LOS is very challenging because of the system design's quality, the environment's noise, the impact between the yaw axis and the pitch axis when rotating and so on. Some of the recent papers that research on this academic background can be found. The papers [4, 5] used the conventional PID controller, the modified PID controller, and cascade PI controller for solving the above challenge. The papers [3, 6] designed two different structures of the Fuzzy PID controller to implement to system. Moreover, the papers [8, 9] shows the design steps and simulation results for the back-stepping/sliding mode control when use it for the tracking system. The last, the paper [9] used the LQG/LTR controller and H_{∞} controller for maintaining the sensor's LOS. The general target of all the above research has just solved the stability of the stabilization loop or the control input is the angular velocity. Besides, the track loop or the input is the angular is not mentioned.

The paper proposes to use the adaptive PID controller based on fuzzy logic inference Zhao, Tomizuka and Isaka [12] that can guarantee stabilization and the performance of tracking loop. Besides, the self – tuning Fuzzy PID controller adapts with the change in motor's parameters, the weight of Gimbal and the reduction of fuzzy rule that not only speed up calculation and reducing the usage of microcontroller's memory in embedded algorithm but also guarantee the tracking performance of the system.

This paper based on the following assumptions [3]:

- *The gimbals are rigid bodies.*
- *The gimbals have no static mass unbalance, which means that the gimbal mass centre is supposed to be in the common centre of rotation*
- *The gimbals have dynamic mass unbalance, which mean that the gimbal mass distribution is not symmetrical with respect to the gimbal frame axes.*

The paper is composed of six sections; after this introduction, in the second section, the equation of the gimbal motion is presented. The third section presents the construction of the stabilization loop. The fourth presents the steps to design the proposed controller. The simulation results present in the fifth section and the last section contains the concluding remarks.

II. THE EQUATIONS OF THE GIMBAL MOTION

Two axes and three reference frames of the two-axis gimbal system are assigned in Figure 2. Frame P fixed to the body with axes (i, j, k), frame B fixed to the yaw channel with axes (n, e, k), and frame A fixed to the pitch channel with axes (d, r, e). The r-axis coincides with the original optical sensor axis. The center of rotation is at the frame origin.

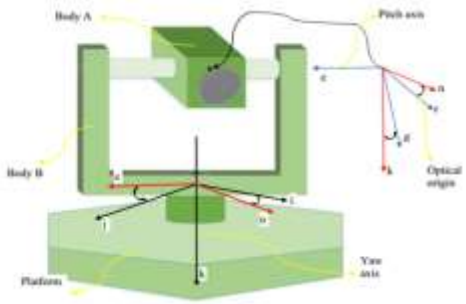


Figure 2: Assign reference frames to the gimbal system

The rotation matrix or the transformation matrix from the frame P to frame B and the transformation matrix from the frame B to frame A

$$ {}^B_P T = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad {}^A_B T = \begin{bmatrix} \cos\theta & 0 & -\sin\theta \\ 0 & 1 & 0 \\ \sin\theta & 0 & \cos\theta \end{bmatrix} \quad (1) $$

Hence, ${}^B_P T$ is the transformation from frame P to frame B, and ${}^A_B T$ is the transformation from frame B to frame A

The inertial angular velocity vectors of frames P, B, and A respectively are

$$ {}^P\overline{\omega_{P/I}} = \begin{bmatrix} \omega_{Pi} \\ \omega_{Pj} \\ \omega_{Pk} \end{bmatrix} \quad {}^B\overline{\omega_{B/I}} = \begin{bmatrix} \omega_{Bn} \\ \omega_{Be} \\ \omega_{Bk} \end{bmatrix} \quad {}^A\overline{\omega_{A/I}} = \begin{bmatrix} \omega_{Ar} \\ \omega_{Ae} \\ \omega_{Ad} \end{bmatrix} \quad (2) $$

Where are the body angular velocities of frame P in relation to inertial space about *i, j,* and *k* axes respectively; are the angular velocities in relation to inertial space about *n, e,* and *k* axes respectively; are the angular velocities in relation to inertial space about *r, e,* and *d* axes respectively.

For the pitch gimbal and the yaw gimbal respectively, the inertia sensor are

$$ {}^A J = \begin{bmatrix} A_r & A_{re} & A_{rd} \\ A_{re} & A_e & A_{de} \\ A_{rd} & A_{de} & A_d \end{bmatrix} \quad {}^B J = \begin{bmatrix} B_n & B_{ne} & B_{nk} \\ B_{ne} & B_e & B_{ke} \\ B_{nk} & B_{ke} & B_k \end{bmatrix} \quad (3) $$

Where A_r, A_e, A_d are moments of inertia about *r, e,* and *d* axes; A_{re}, A_{rd}, A_{de} are moments products of inertia. B_n, B_e, B_k are moments of inertia about *n, e,* and *k* axes; B_{ne}, B_{nk}, B_{ke} are moments products of inertia. Furthermore, in Figure 2, T_p is total external torque about the pitch *e-axis,* and T_y is total external torque about the pitch *k-axis.*

The orientation of two reference frames relative each other can be given by Euler angles, by three consecutive rotations α, θ, ϕ about the *z, y, x* axes respectively. The order is essential: a rotation α about the *z-axis* is followed by a rotation θ about the *y axis* and finally by a rotation ϕ about the *x axis*. For two frames F and G, the inertial angular velocity relation can be derived as [11]

$$ \overline{\omega}^G - \overline{\omega}^F = \begin{bmatrix} \dot{\phi} - \dot{\alpha}\sin\theta \\ \dot{\theta}\cos\phi + \dot{\alpha}\cos\theta\sin\phi \\ \dot{\alpha}\cos\theta\cos\phi - \dot{\theta}\sin\phi \end{bmatrix}_G \quad (4) $$

Where, $\overline{\omega}^F$, $\overline{\omega}^G$ are the inertial angular velocity vectors of frame F and frame G, respectively, and frame F is carried into frame G by the Euler angles α, θ, ϕ. The difference between by the right-hand side, where the components are expresses in frame G.

Between our body-fixed frame P and yaw gimbal frame B we have only a rotation α about the z-axis. With F as P, and G as B, then $\theta = \phi = 0$ and $\alpha = \alpha$ in (Equation 4). Using the angular velocities (Equation 2) we get

$$ \begin{bmatrix} \omega_{Bn} \\ \omega_{Be} \\ \omega_{Bk} \end{bmatrix} - {}^B_P T \begin{bmatrix} \omega_{Pi} \\ \omega_{Pj} \\ \omega_{Pk} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ \dot{\alpha} \end{bmatrix} \quad (5) $$

The vectors are expressed in system B. Inserting the transformation matrix (1) gives

$$ \begin{aligned} \omega_{Bn} &= \omega_{Pi}\cos\alpha + \omega_{Pj}\sin\alpha \\ \omega_{Be} &= -\omega_{Pi}\sin\alpha + \omega_{Pj}\cos\alpha \\ \omega_{Bk} &= \omega_{Pk} + \dot{\alpha} \end{aligned} \quad (6) $$

Similarly, we have

$$ \begin{aligned} \omega_{Ar} &= \omega_{Bn}\cos\theta - \omega_{Bk}\sin\theta \\ \omega_{Ad} &= \omega_{Bn}\sin\theta + \omega_{Bk}\cos\theta \\ \omega_{Ae} &= \omega_{Be} + \dot{\theta} \end{aligned} \quad (7) $$

The kinetic energy of a rotating body is given by the scalar product [11, 4]:

$$T = \bar{\omega}.\frac{\bar{H}}{2};\bar{H} = J.\bar{\omega} \qquad (8)$$

Where $\bar{H}$ is the angular momentum, $\bar{\omega}$ is the inertial angular velocity of the body, and J is the inertia matrix of the body. Thus the total kinetic energy of the system is given by the sum of kinetic energy of yaw and pitch

$$\begin{aligned} T &= T_p + T_y \\ &= \frac{1}{2}\left(A_r\omega_{Ar}^2 + A_e\omega_{Ae}^2 + A_d\omega_{Ad}^2\right) \\ &+ \frac{1}{2}(B_n\omega_{Bn}^2 + B_e\omega_{Be}^2 + B_k\omega_{Bk}^2) \\ &+ B_{ne}\omega_{Bn}\omega_{Be} + B_{nk}\omega_{Bn}\omega_{Bk} + B_{ke}\omega_{Be}\omega_{Bk} \\ &+ A_{re}\omega_{Ar}\omega_{Ae} + A_{rd}\omega_{Ar}\omega_{Ad} + A_{de}\omega_{Ae}\omega_{Ad} \end{aligned} \qquad (9)$$

- Analyze the pitch channel

Use the Lagrange equation to obtain the equation of motion for the pitch gimbal. So, the Lagrange equation for θ [10]:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\theta}}\right) - \frac{\partial T}{\partial \theta} = T_p \qquad (10)$$

The kinetic energy for the pitch gimbal

$$T_p = {}^{A}\overline{\omega_{A/I}} \times \frac{{}^{A}\bar{H}}{2} \qquad (11)$$

So, we obtained the pitch gimbal motion as a differential equation for ω_{Ae} as:

$$\begin{aligned} A_e\dot{\omega}_{Ae} &= T_p + (A_d - A_r)\dot{\omega}_{Ar}\omega_{Ad} + A_{rd}(\omega_{Ar}^2 - \omega_{Ad}^2) \\ &- A_{de}(\dot{\omega}_{Ad} - \omega_{Ae}\omega_{Ar}) - A_{re}(\dot{\omega}_{Ar} + \omega_{Ae}\omega_{Ad}) \end{aligned} \qquad (12)$$

T_p represents the sum of the motor torque and external imperfection disturbance torques. From the control point of view, it is suitable to let T_p represent only the motor torque. External disturbance torques can be included in T_{Dp} [4, 5]

$$\begin{aligned} T_{Dp} &= (A_d - A_r)\dot{\omega}_{Ar}\omega_{Ad} + A_{rd}(\omega_{Ar}^2 - \omega_{Ad}^2) \\ &- A_{de}(\dot{\omega}_{Ad} - \omega_{Ae}\omega_{Ar}) - A_{re}(\dot{\omega}_{Ar} + \omega_{Ae}\omega_{Ad}) \end{aligned} \qquad (13)$$

When the base is nonrotating $\omega_{Pi} = \omega_{Pj} = \omega_{Pk} = 0$, the pitch cross coupling term is

$$\begin{aligned} T_{Dp} &= A_{re}\sin\theta - A_{de}\cos\theta)\dot{\omega}_{Bk} \\ &- \frac{1}{2}\left[(A_d - A_r)\sin(2\theta) + 2\,A_{rd}\cos(2\theta)\right]\dot{\omega}_{Bk} \end{aligned} \qquad (14)$$

- Analyze the yaw channel [12]

The equation of motion for the yaw channel can be obtained by using the moment equation for the motion

$$\bar{T} = \frac{d\,{}^{B}\bar{H}}{dt} + {}^{B}\overline{\omega_{B/I}} \times {}^{B}H \qquad (15)$$

It is the *z – component* of the above equation. So, we obtained the pitch gimbal motion as a differential equation for ω_{Bk} as

$$J_{eq}\dot{\omega}_{Bk} = T_y + T_{d1} + T_{d2} + T_{d3} \qquad (16)$$

Where, $T_d = T_{d1} + T_{d2} + T_{d3}$ represents different yaw inertia disturbances, J_{eq} is the instantaneous moment of inertia about the *k-axis*

With,

$$J_{eq} = B_k + A_r\sin^2\theta + A_d\cos^2\theta - A_{rd}\sin(2\theta) \qquad (17)$$

$$T_{d1} = \omega_{Bn}\omega_{Be}\begin{bmatrix} B_n + A_r\cos^2\theta + A_d\sin^2\theta \\ + A_{rd}\sin(2\theta) - (B_e + A_e) \end{bmatrix} \qquad (18)$$

$$\begin{aligned} T_{d2} &= \left(\omega_{Be}\omega_{Bk} - \dot{\omega}_{Bn}\right)\begin{bmatrix} B_{nk} + A_{rd}\cos(2\theta) \\ + (A_d - A_r)\sin\theta\cos\theta \end{bmatrix} \\ &- \left(B_{ke} + A_{de}\cos\theta - A_{re}\sin\theta\right)\left(\dot{\omega}_{Be} + \omega_{Bn}\omega_{Bk}\right) \\ &- \left(B_{ne} + A_{re}\cos\theta + A_{de}\sin\theta\right)\left(\omega_{Bn}^2 - \omega_{Be}^2\right) \end{aligned} \qquad (19)$$

$$\begin{aligned} T_{d3} &= \ddot{\theta}(A_{re}\sin\theta - A_{de}\cos\theta) \\ &+ \dot{\theta}\left[(A_r - A_d)\left(\omega_{Bn}\cos(2\theta) - \omega_{Bk}\sin(2\theta)\right)\right] \\ &+ \dot{\theta}\left[2A_{re}\left(\omega_{Bn}\sin(2\theta) + \omega_{Bk}\cos(2\theta)\right)\right] \\ &+ \dot{\theta}\left[(A_{de}\sin\theta + A_{re}\cos\theta)(\omega_{Ae} + \omega_{Be}) - A_e\omega_{Bn}\right] \end{aligned} \qquad (20)$$

The disturbances affected on yaw are denoted by

$$T_{Dy} = (T_{d1} + T_{d2} + T_{d3})\cos\theta + T_d' \qquad (21)$$

When the base is nonrotating $\omega_{Pi} = \omega_{Pj} = \omega_{Pk} = 0$, the yaw cross coupling term is

$$\begin{aligned} T_{Dy} &= (A_{re}\sin\theta - A_{de}\cos\theta)\dot{\omega}_{Ae} \\ &+ (A_{re}\cos\theta - A_{de}\sin\theta)\omega_{Ae}^2 \\ &+ \left[(A_d - A_r)\sin(2\theta) + 2A_{rd}\cos(2\theta)\right]\omega_{Ae}\omega_{Bk} \end{aligned} \qquad (22)$$

III. THE STABILIZATION LOOP CONSTRUCTION

The stabilization loop contained the servo motor which is a brushless DC torque motor. Because, it has many advantages, such as high efficiencies, high torque to inertia ratio, greater speed capabilities, low audible capacities and lower EMI characteristic. The dynamic model for servo motor is shown below

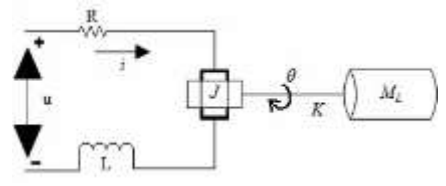


Figure 3: Schematic diagram for the servo motor

The voltage equation below are referred to general reference frame [11]

$$\begin{cases} R_m i + L_m \dfrac{di}{dt} + K_e \dfrac{dq}{dt} = u_m \\ J_m \dfrac{d^2 q}{dt^2} + D_m \dfrac{dq}{dt} + Kq = T_m - T_D \\ T_m = K_T i \end{cases} \quad (23)$$

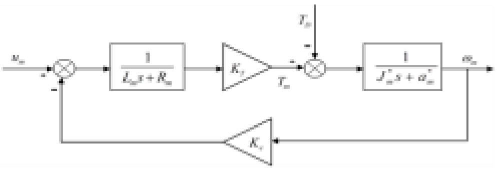


Figure 4: Block diagram of the modified DC servo motor

From Figure 4, $J_m^* = J_m + J_L$ represents the total moment of inertia seen from the motor side, $a_m^* = a_m + a_L$ is the total viscous friction constant seen from the motor side. We obtain the transfer function of the modified DC servo motor

$$G_m(s) = \frac{K_T}{(Ls + R)(J_m^* s + a_m^*) + K_e K_T} \quad (24)$$

Body A's moment of inertia, where it's mass is m_A = 1 kg, the length b_A = 0.2 m and the height a_A = 0.1 m

$$J_L = \frac{m_A(a_A^2 + b_A^2)}{12} = 0.0041(Kg.m^2) \quad (25)$$

The modified DC's transfer function can be obtained as:

$$G_m(s) = \frac{48850.5}{s^2 + 1500s + 41523} \quad (26)$$

The gyroscope's transfer function [12]

$$G_{gyro} = \frac{2500}{s^2 + 70s + 2500} \quad (27)$$

IV. DESIGN OF THE PROPOSED CONTROLLER

This type of controller called as self-tuning PID controller which means that three parameters K_p, K_i, K_d of PID controller are tuned by using fuzzy tuner [12]. Figure 5 shown the structure of the self-tuning fuzzy PID controller.

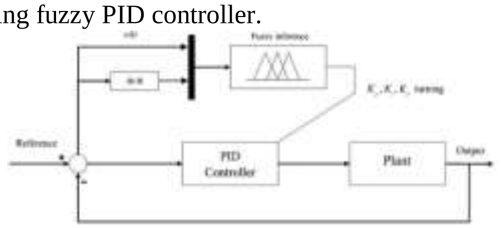


Figure 5: Structure of self-tuning Fuzzy PID controller

The inputs to the controller are the error *e(t)* which is the error between desired position set point and the output; and the rate of change of error *de/dt* which is the derivation of error while the outputs are controller gain K_p, K_i, and K_d. The structure of the self-tuning Fuzzy PID controller is a two input- three output structure as shown in Figure 6.

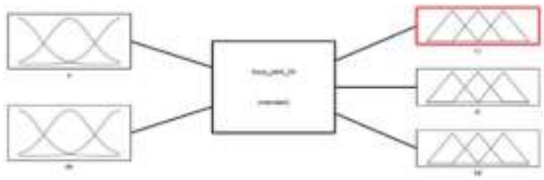


Figure 6: Fuzzy inference block

A. Design the self – tuning Fuzzy PID controller

There are two inputs to fuzzy inference: error *e(t)* and derivative of error *de/dt*, and three outputs for each PID controller parameters respectively $K_p^{'}, K_i^{'}$ and $K_d^{'}$. The task of fuzzy logic control is to obtain the best value for K_p, K_i, K_d by applying some modification.

Base on the obtained parameters of PID controller before and supposing the variable ranges of the parameters K_p, K_i, and K_d of PID controller are respectively $[K_{p\min}, K_{p\max}]$, $[K_{i\min}, K_{i\max}]$, and $[K_{d\min}, K_{d\max}]$. Then, the range of each parameter was determined to obtain a feasible rule bases with high inference efficiency. Therefore, they can be calibrated as follows [12]:

$$K_p^{'} = \frac{K_p - K_{p\min}}{K_{p\max} - K_{p\min}}; \quad K_i^{'} = \frac{K_i - K_{i\min}}{K_{i\max} - K_{i\min}}$$

$$K_d^{'} = \frac{K_d - K_{d\min}}{K_{d\max} - K_{d\min}} \quad (28)$$

For the Pitch channel:

$[K_{p\min}, K_{p\max}]$ = [50, 80]; $[K_{i\min}, K_{i\max}]$ = [3, 6]; $[K_{d\min}, K_{d\max}]$ = [3.5, 6.5]

So,

$$K_p = 30K_p^{'} + 50; K_i = 3K_i^{'} + 3; K_d = 3K_d^{'} + 3.5 \quad (29)$$

For the Yaw channel:

$[K_{p\min}, K_{p\max}]$ = [15, 45]; $[K_{i\min}, K_{i\max}]$ = [5, 7]; $[K_{d\min}, K_{d\max}]$ = [5.5, 7.5]

So,

$$K_p = 30K_p^{'} + 15; K_i = 2K_i^{'} + 5; K_d = 2K_d^{'} + 5.5 \quad (30)$$

Linguistic variables and membership functions

Linguistic variables for *e(t)*, *de(t)*, K_p, K_i, and K_d are NB, NM, NS, ZE, PS, PM, PB denoted Negative Big, Negative Medium, Negative Small, Zero, Positive Small, Positive Medium and Positive Big respectively.

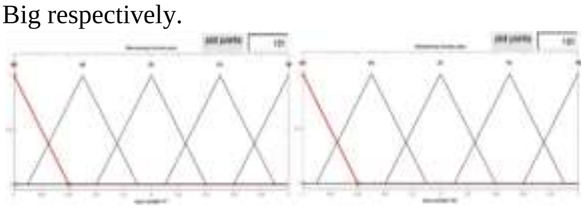


Figure 7: The e(t) – de(t) membership function for both channels on Matlab

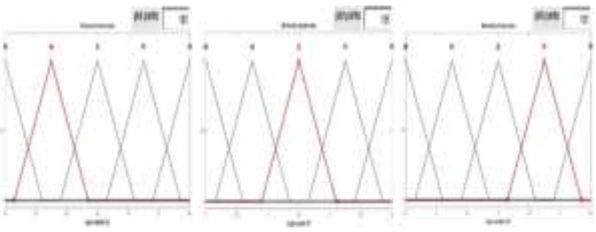


Figure 8: The K_p - K_i - K_d membership function

Fuzzy rules

If-Then rule statements in Table 1 [12].

K_p, K_i, K_d		de(t) NB	NS	ZE	PS	PB
e(t)	NB	PB / NB / NB	PB / NB / NB	PS / NS / NS	PS / NS / NS	ZE / ZE / ZE
	NS	PB / NB / NB	PS / NS / NS	PS / NS / NS	ZE / ZE / ZE	NS / PS / PS
	ZE	PS / NS / NS	PS / NS / NS	ZE / ZE / ZE	NS / PS / PS	NS / PS / PS
	PS	PS / NS / NS	ZE / ZE / ZE	NS / PS / PS	NS / PS / PS	NB / PB / PB
	PB	ZE / ZE / ZE	NS / PS / PS	NS / PS / PS	NB / PB / PB	NB / PB / PB

Table 1: The Fuzzy rules

B. The proposed control architecture

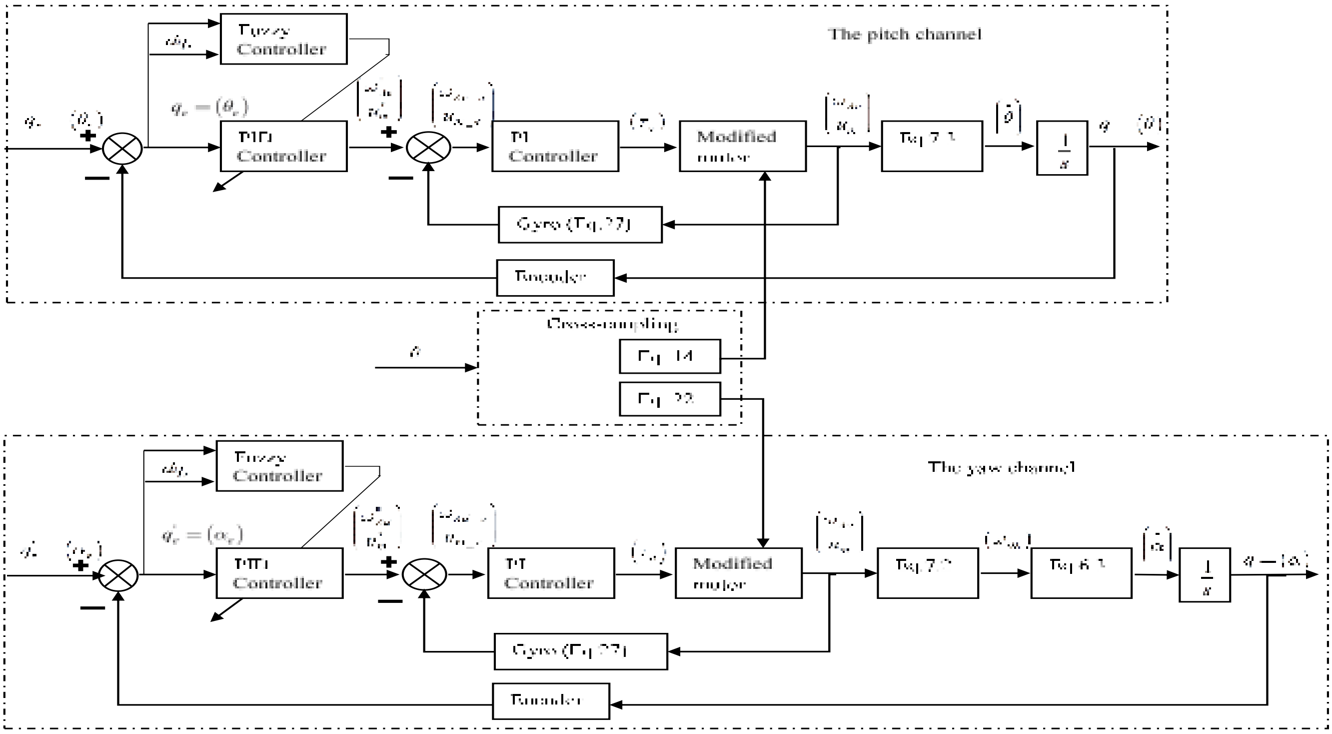
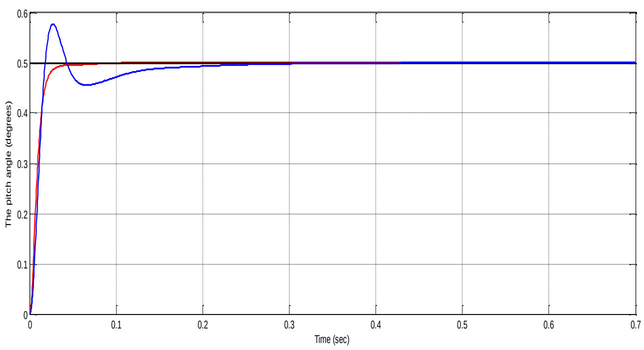


Figure 9: The proposed control architecture

V. SIMULATION RESULTS

The simulation will test for several below cases:

(Note: Red line: FPID, blue line: PID)



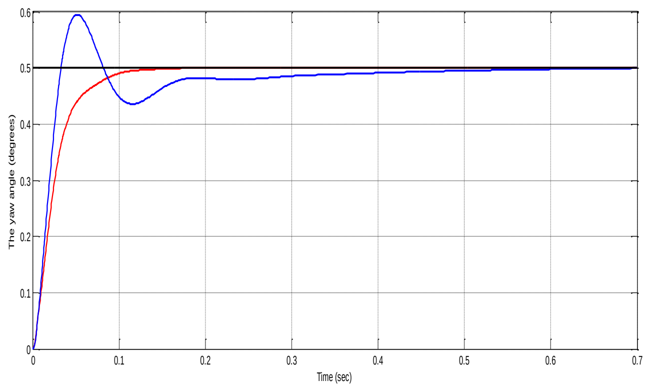


Figure 12: The response of the pitch channel, and the yaw channel in case of $q_r = 0.5$ degrees and $a_r = 0.5$ degrees

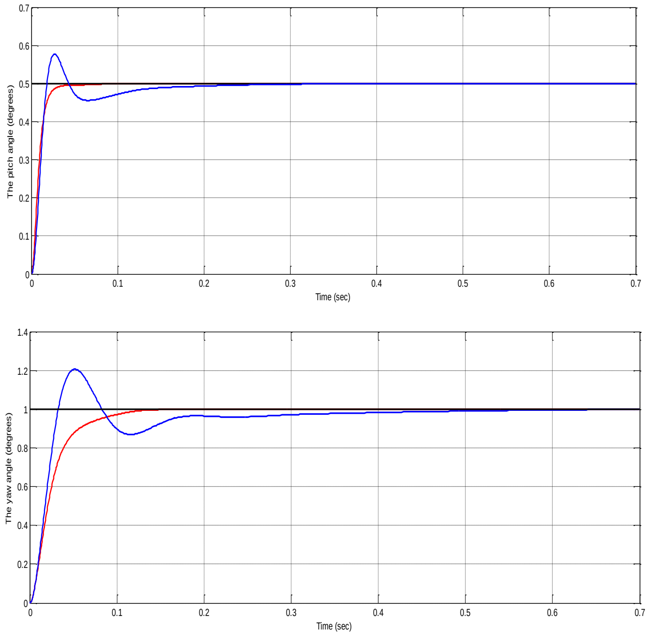


Figure 13: The response of the pitch channel and the yaw channel in case of $q_r = 0.5$ degrees and $a_r = 1$ degrees

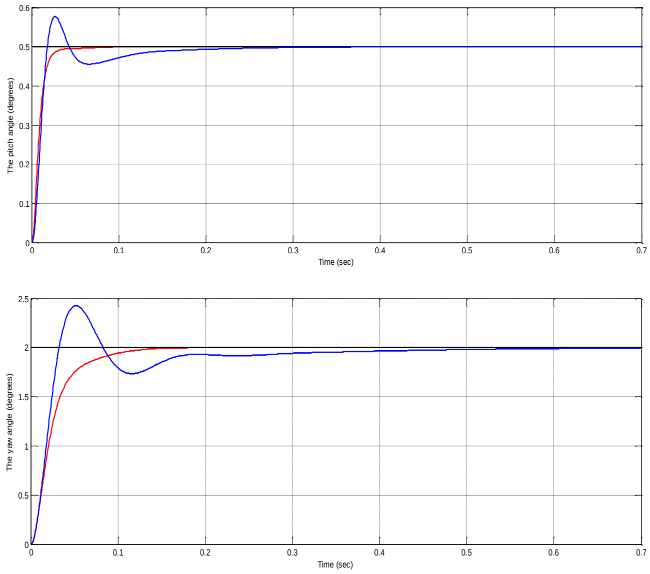


Figure 14: The response of the pitch channel and the yaw channel in case of $q_r = 0.5$ degrees and $a_r = 2$ degrees

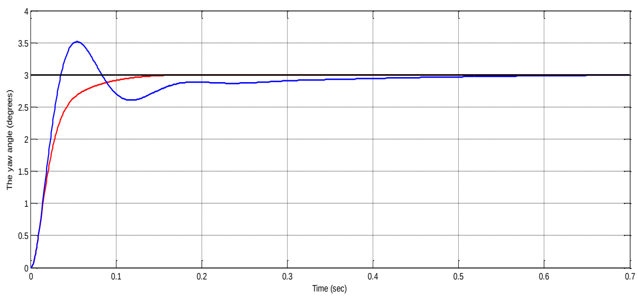


Figure 15: The response of the yaw channel in case of $q_r = 0$ degrees and $a_r = 3$ degrees

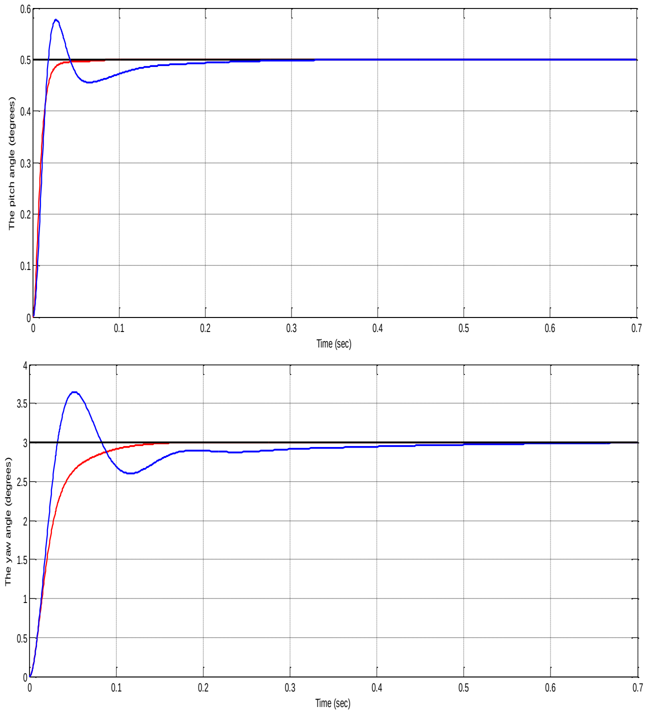


Figure 16: The response of the pitch channel and the yaw channel (b) in case of $q_r = 1$ degrees and $a_r = 3$ degrees

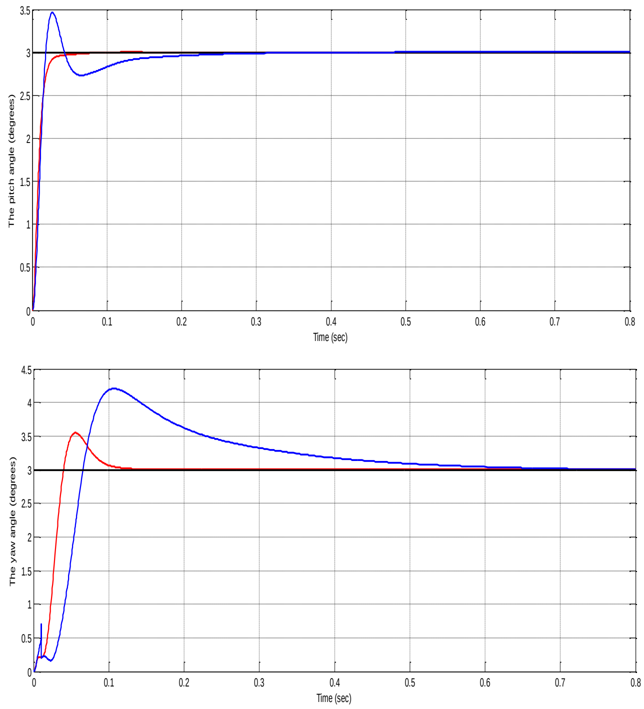


Figure 17: The response of the pitch channel and the yaw channel in case of $q_r = 3$ degrees and $a_r = 3$ degrees

To evaluate the performance the self – tuning Fuzzy PID controller, we have designed a PID controller for this system to compare its performance with the self – tuning Fuzzy PID controller. We divide all above cases to 2 test cases.

Test 1: *The pitch channel was controlled at q_r = 0, 0.5, 1, and 3 degrees, the yaw channel was controlled constantly at a_r = 3 degrees*

		Rise time (sec)		Overshoot (%)		Settling time (sec)		Steady-state error (%)	
Angle (*deg*)	Channel	PID	Fuzzy - PID	PID	Fuzzy- PID	PID	Fuzzy - PID	PID	Fuzzy - PID
$q_r = 0$	Pitch	0	0	0	0	0	0	0	0
$a_r = 3$	Yaw	0.020	0.065	16.75	0	0.30	0.120	0	0
$q_r = 0.5$	Pitch	0.017	0.014	14	0	0.19	0.050	0	0
$a_r = 3$	Yaw	0.018	0.060	18	0	0.29	0.125	1	0
$q_r = 1$	Pitch	0.016	0.015	15	0	0.15	0.045	0	0
$a_r = 3$	Yaw	0.015	0.068	60	0	0.27	0.125	1	0
$q_r = 3$	Pitch	0.015	0.020	15	0	0.18	0.065	0	0
$a_r = 3$	Yaw	0.050	0.030	36.5	18	0.49	0.115	1	0

Table 2: The simulation results of test 1

Test 2: *The pitch channel was controlled constantly at q_r = 0.5 degrees, the yaw channel was controlled at a_r = 0.5, 1, 2, 3 degrees*

		Rise time (sec)		Overshoot (%)		Settling time (sec)		Steady-state error (%)	
Angle (*deg*)	Channel	PID	Fuzzy - PID	PID	Fuzzy - PID	PID	Fuzzy - PID	PID	Fuzzy - PID
$q_r = 0.5$	Pitch	0.017	0.017	14	0	0.190	0.050	0	0
$a_r = 0.5$	Yaw	0.350	0.080	20	0	0.185	0.110	0	0
$q_r = 0.5$	Pitch	0.017	0.017	14	0	0.190	0.050	0	0
$a_r = 1$	Yaw	0.280	0.065	22	0	0.183	0.112	0	0
$q_r = 0.5$	Pitch	0.017	0.017	14	0	0.190	0.050	0	0
$a_r = 2$	Yaw	0.200	0.068	20	0	0.290	0.110	1	0
$q_r = 0.5$	Pitch	0.017	0.017	14	0	0.190	0.050	0	0
$a_r = 3$	Yaw	0.180	0.060	18	0	0.290	0.125	1	0

Table 3: The simulation results of test 2

The simulation results of test 1 show that the rise time is increased as the angle command of the pitch and yaw channel's increasing. Furthermore, that result also occurs on settling time for both controllers. The steady – state error and overshoot are equal 0 (except for fourth case) for the self – tuning Fuzzy PID controller; while, the PID controller has large overshoot in range of 14% - 60%, and has existed the steady – state error at about 1%.

From table 3, when the pitch channel was controlled constantly at a fixed angle command and the yaw channel was controlled variably, the rise time and settling time in the pitch channel is not change for both controllers. In addition, the rise time in yaw channel decreases and the settling time increases as the angle of the yaw increase. The overshoot and steady – state error equal 0 for the self – tuning Fuzzy PID controller. By contrast, the PID controller has overshoot in range of 14% - 22%, and the steady – state error is at 1%.

It clearly concludes that the performance of the self – tuning Fuzzy PID controller is better than the performance of the PID controller in term of rise time, overshoot, settling time, and steady – state error.

VI. RUN TEST

The architecture of the tracking system contains two main parts [13, 14]:

PC: Firstly, the image is received from the camera sensor. Secondly, it will be processed and transformed from the image coordinate to the real world coordinate by image processing algorithm. All feedback signals contained angle and angular velocity are also received. Finally, PC will determine the set value base on the result of the first step and the feedback signals. The set value is sent to the main control board.

Microcontroller: This part is the main control board using Atmega, PIC, ARM microcontroller that contains the controller's algorithm, controls DC servo motor, receives the sensors' signal, and sends data to PC. The input of this part is the reference angle that is received from PC, the sensors' signal, and the output signal is to control the DC servo motor to keep the tracking objects in the camera sensor's field of view.

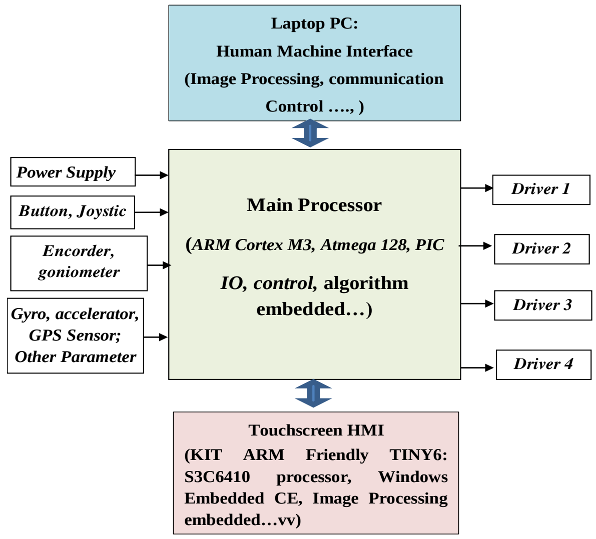


Figure 18: Architecture of Electro Optical Tracking System

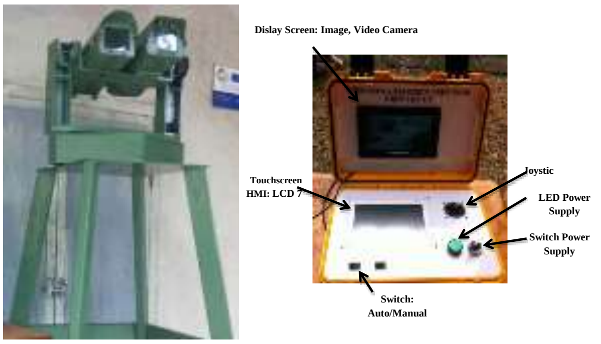


Figure 19: Hardware of Electro Optical Tracking System

The hardware of the electro-optical tracking system was designed and tested include:

1/ The gimbal includes:

- *02 DC servo motors are paired with gearbox for the yaw and pitch angle. The motor's parameter: DC servo, 24V, Encoder 1000ppr.*
- *The joints of gimbal can eliminate noise and cancel error.*

2/ Camera and sensor include:

- *01 colour camera Bosch 1/3'', daytime view*
- *01 thermal camera SR-50, FLIR System, nighttime view*
- *01 laser sensor*

3/ control vali includes:

- *01 main control module used ARM, Atmega microcontroller (containing the Fuzzy PID algorithm).*
- *01 control button module, 01 joystick in manual mode.*
- *01 driver module for controlling DC servo motor and other actuates.*
- *01 supplied power module.*
- *01 tough screen 7'' to use FriendlyARM Tiny6410*
- *01 PC contains HMI software.*

Testing results:

The system was tested using the self – tuning Fuzzy PID algorithm. It can track the moving objects (about 1.8 meters x 0.8 meters) in the range of under 100 meters in the daytime. The image processing speed in the auto tracking mode is about 15 fps. The angular velocity, the accuracy, the pitch and yaw angle parameter, the position of object are updated, displayed and saved exactly. With the above test results, it proved that using the self – tuning Fuzzy PID controller is a good choice for the Electro – Optical Tracking System.

VII. CONCLUSION

The article has suggested an algorithm of tracking control for the Electro – Optical-tracking system that not only guaranteed the tracking of moving objects quickly, exactly but also the gimbal's movement was smooth. The main characteristic of the proposed controller gives acceptable performance for systems with the nonlinear plant with unpredictable parameter variation, uncertain dynamics, time delays and non-linearity. The analysis and simulation results show that the performance of the proposed controller is better than the conventional PID controller.

Simulations have shown exactness of theory's analysis and efficiency of the method.

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Figure 20: The images capture process test run