Camera gimbal stabilization using conventional PID controller and evolutionary algorithms

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CAMERA GIMBAL STABILIZATION USING CONVENTIONAL PID CONTROLLER AND EVOLUTIONARY ALGORITHMS

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Abstract: **In this paper, control system is designed to stabilize the camera gimbal system used in different air borne systems for applications such as target tracking, surveillance, aerial photography, autonomous navigation and so on. This camera gimbal system replaces many traditional tracking systems such as radar which are heavy and large to mount on air vehicles. So, the stabilization of camera gimbal is very important to eliminate shakes and vibrations in photography, provides accuracy in tracking moving target and so on. The control system for this gimbal is developed using various control methods and algorithms to provide better and efficient performance with flexibility, accuracy and feasibility. PID controller is designed to control camera gimbal due to its effectiveness, simplicity and feasibility. The tuning parameters of PID controller are tuned using traditional and evolutionary algorithms such as PSO and GA to provide better performance and accuracy in system response. PSO and GA are used due to its dynamic and static performance, computational efficiency and so on. In this paper, performance of system with conventional PID and PSO, GA tuned PID controllers are compared and optimized algorithm is implemented.**

Keywords— Gimbal, PID controller, Particle Swarm Optimization(PSO), Genetic Algorithm (GA), Ziegler Nichols, Cohen Coon, Kinematics

I. INTRODUCTION

The main aim of this paper is to develop stabilized camera control system which is used in number of applications such as aerial photography, surveillance, missile tracking, and autonomous navigation and so on. The camera control system is supported using a mechanical system known as gimbal system. This camera gimbal is used in moving carrier such as UAV's, MAV's, helicopter [1] and so on for target tracking, rescue operations, to capture motion pictures. Disturbances caused for the system due to motor friction, unbalanced aerodynamics, spring torque forces are compensated using this electro-mechanical system. If the camera positioning is not compensated or stabilized, it produces shakes in the video capturing, blurred images, and failure in object tracking and so on during aerial photography, autonomous target tacking etc. So stabilization of camera is necessary for various applications.

Autonomous operations and tracking of moving target without knowing its future position is a challenging task. The applications such as tracking a moving target, surveillance etc is very important in military applications, civilian purposes etc. So, the stabilization of camera is very much necessary for all these applications. For the development of camera gimbal control system, control algorithm designing is necessary. There are many algorithms such as adaptive control, PID controller, fuzzy logic controller, fractional order controller and so on. The controller used for this system is PID controller. PID controller is the most commonly used controller in the industries for its effectiveness, simplicity and feasibility.

The gimbal mechanism used for control of camera position is a mechanical device which is designed using the rings mounted on axes at right angles to each other. The objects present in unstable environments are arranged in stable position using this mechanical device [2]. Camera used in aerial vehicles is mounted as payload for this gimbal device. PID controller controls the movement of this device which indirectly controls on board camera. Gimbal has variety of applications in aircraft environment, to maintain level of measuring instruments with respect to ground and so on. In this paper, the controller maintains the camera position horizontal to ground axis or world axis. Control of camera can be feasible by manual control, but it is complex and tedious since it requires separate operator to control it [3]. So, autonomous control is preferable than manual control. The advantage of using gimbal control with a particular control algorithm is shown in figure 1.

The gimbal used to control is 3-axis gimbal which consists of servomotor, IMU sensor [4]. It is mounted at the front end of the aerial vehicle below the vehicle as shown in figure 1. The PID controller controls gimbal actuators which control the movement of the camera.

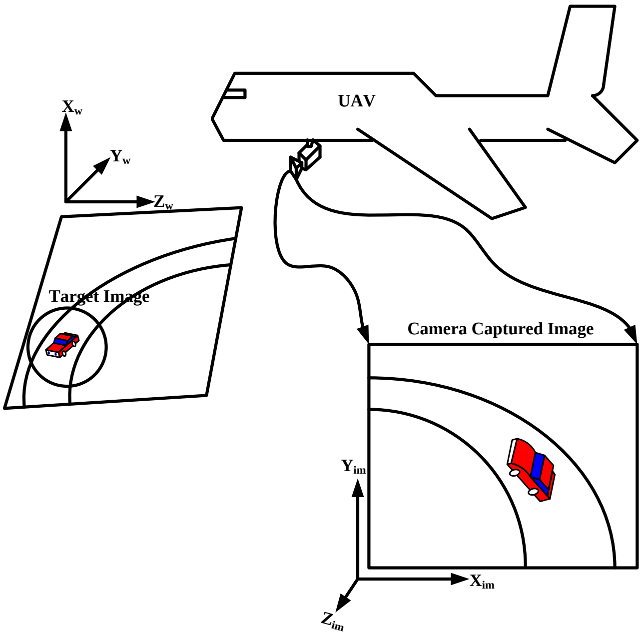

Fig 1: Schematic diagram of Camera Gimbal on UAV

In this application yaw-roll-pitch-axis movement gimbal mechanism is used. The defect in the design of gimbal device may lead to the development of complex control algorithms and performance criteria may not be achieved [5].

II. MATHEMATICAL MODELLING

The designing of control algorithm requires the mathematical model of gimbal device and its actuator [6].

A. *Gimbal Modelling*

The 3-axis gimbal consists of three revolute joints and it has yaw-roll-pitch axis representation. Here θ_1, θ_2, θ_3 represent yaw-roll-pitch angles. The schematic diagram of gimbal kinematics with 3 revolute joints is shown in figure 2.

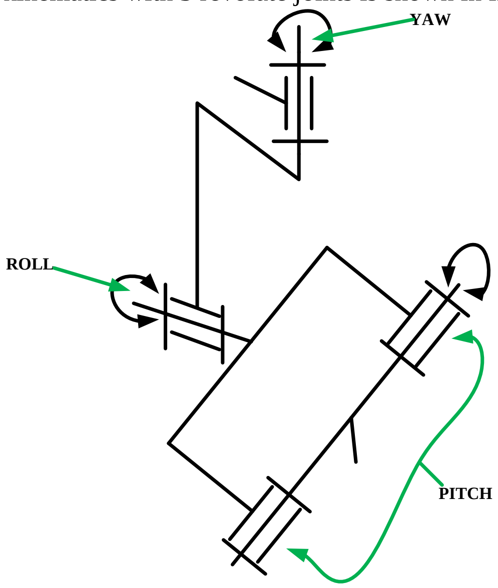

Fig 2: Gimbal Kinematics with 3 revolute joints

Gimbal forward kinematics is derived by using DENAVIT-HARTENBERG convention. The transformation from body (0) to body (3) is shown below

The rotation matrix of yaw axis from the frame of body (0) to the frame of body (1) is

$$ {}^{0}R_{1} = \begin{pmatrix} \cos\theta_1 & -\sin\theta_1 & 0 \\ \sin\theta_1 & \cos\theta_1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (1) $$

The rotation matrix of roll axis from the frame of body (1) and the frame of body (2) is

$$ {}^{1}R_{2} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_2 & -\sin\theta_2 \\ 0 & \sin\theta_2 & \cos\theta_2 \end{pmatrix} \quad (2) $$

The rotation matrix of pitch axis from the frame of body (2) and the frame of body (3) is

$$ {}^{2}R_{3} = \begin{pmatrix} \cos\theta_3 & 0 & \sin\theta_3 \\ 0 & 1 & 0 \\ -\sin\theta_3 & 0 & \cos\theta_3 \end{pmatrix} \quad (3) $$

The total rotation matrix between the base frame (0) and frame of body (3) is

$$ {}^{0}R_{3} = {}^{0}R_{1}\,{}^{1}R_{2}\,{}^{2}R_{3} \quad (4) $$

$$ {}^{0}R_{3} = \begin{pmatrix} C_1C_3 - S_1S_2S_3 & -C_2S_1 & C_1S_3 + C_3S_1S_2 \\ C_3S_1 + C_1S_2S_3 & C_1C_2 & S_1S_3 - C_1C_3S_2 \\ -C_2S_3 & S_2 & C_2C_3 \end{pmatrix} \quad (5) $$

Here $C_i = \mathrm{Cos}\,(\theta_i)$ and $S_i = \mathrm{Sin}\,(\theta_i)$.

The IMU sensor is mounted on the camera frame i.e. body (3) and position encoders mounted to servo motors. The angular position of camera frame is derived from the gyros and accelerometers on IMU mounted on it. α_1, α_2 and α_2 are the angles of yaw, roll and pitch axes of camera frame. $\alpha_{1desired}$, $\alpha_{2desired}$ and $\alpha_{3desired}$ represent the desired position of camera frame with respect to ground frame. ε_1, ε_2 and ε_3 represent the errors of yaw, roll and pitch axes of camera's reference frame.

$$ \varepsilon_1 = \alpha_{1desired} - \alpha_1 \quad (6) $$

$$ \varepsilon_2 = \alpha_{2desired} - \alpha_2 \quad (7) $$

$$ \varepsilon_3 = \alpha_{1desired} - \alpha_3 \quad (8) $$

The rotation matrix of camera's error reference frame is

$$ {}^{3}R_{\varepsilon} = \begin{pmatrix} C\varepsilon_1C\varepsilon_3 - S\varepsilon_1S\varepsilon_2S\varepsilon_3 & -C\varepsilon_2S\varepsilon_1 & C\varepsilon_1S\varepsilon_3 + C\varepsilon_3S\varepsilon_1S\varepsilon_2 \\ C\varepsilon_3S\varepsilon_1 + C\varepsilon_1S\varepsilon_2S\varepsilon_3 & C\varepsilon_1C\varepsilon_2 & S\varepsilon_1S\varepsilon_3 - C\varepsilon_1C\varepsilon_3S\varepsilon_2 \\ -C\varepsilon_2S\varepsilon_3 & S\varepsilon_2 & C\varepsilon_2C\varepsilon_3 \end{pmatrix} \quad (9) $$

Here $C\varepsilon_i = \mathrm{Cos}\,(\varepsilon_i)$ and $S\varepsilon_i = \mathrm{Sin}\,(\varepsilon_i)$.

From the inverse kinematics of gimbal, new joint angles are derived. The total rotation matrix from frame of body (0) to the error frame ε in camera's reference frame is

$$^{0}R_{\varepsilon}(\theta,\varepsilon)={}^{0}R_{3}(\theta)\,{}^{3}R_{\varepsilon}(\varepsilon) \quad (10)$$

θ_1, θ_2 and θ_3 are the current joint angles. The new joint angles of gimbal are calculated as shown in (11).

$$^{0}R_{3}(\theta_{new})={}^{0}R_{\varepsilon}(\theta,\varepsilon) \quad (11)$$

The equation (11) indicates that frame of body (3) is same as error frame (ε) of camera frame. From equation (10) and (11), equation (12) is obtained.

$$^{0}R_{3}(\theta_{new})={}^{0}R_{3}(\theta)\,{}^{3}R_{\varepsilon}(\varepsilon) \quad (12)$$

The right hand side of equation (12) is represented as

$$^{0}R_{3}(\theta)\,{}^{3}R_{\varepsilon}(\varepsilon)=\begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix} \quad (13)$$

r_{ij} represents the components of matrix $^{0}R_{3}(\theta)\,{}^{3}R_{\varepsilon}(\varepsilon)$. The equations derived using inverse kinematics give the desired joint angles as shown below.

$$\theta_{1new}=\tan^{-1}\left(\frac{-r_{12}}{r_{22}}\right) \quad (14)$$

$$\theta_{2new}=\sin^{-1}(r_{32}) \quad (15)$$

$$\theta_{3new}=\tan^{-1}\left(\frac{-r_{31}}{r_{33}}\right) \quad (16)$$

Θ_{1new}, Θ_{2new} and Θ_{3new} are the new desired joint angles.

B. *Motor Modelling*

The transfer function equation of gimbal actuator to obtain desired position using controller is equation (17).

$$\frac{\theta(s)}{V(s)}=\frac{K}{s[(Ls+R)(Js+B)+K^2]} \quad (17)$$

Where,

K represents emf in (Nm/A)
L is inductance in (henry)
R is resistance in (ohm)
J is the moment of inertia of rotor in ($kg.m^2/s^2$)
B is the damping ratio in (N-m/rad)
Θ(s) is the angular position

C. *PID Controller*

PID controller is the most commonly used controller used in industries. Its parameters Kp, Ki and Kd provide accurate closed loop performance and are known as proportional, integral and derivative gains respectively. The PID controller transfer function is

$$G_{PID}=K_P+\frac{K_I}{s}+K_D s \quad (18)$$

III. CONTROL BLOCK DIAGRAM

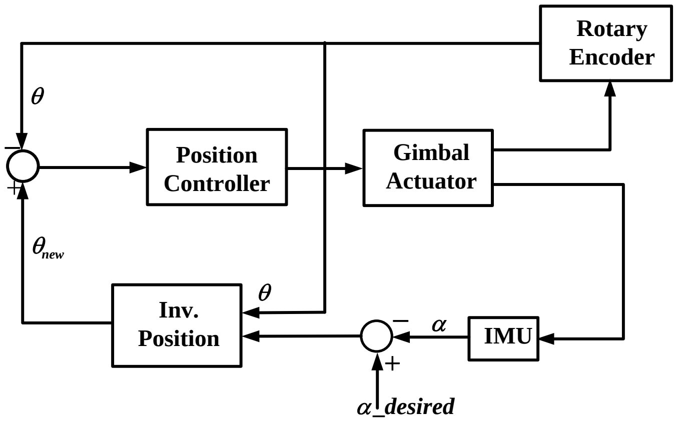

Fig 3: Control block diagram of gimbal

Figure 3 shows the control block diagram used for designing the camera gimbal control system. PID controller performance depends on its parameters which are tuned using different tuning algorithms such as Ziegler Nichols, Cohen Coon, PSO tuning, Genetic algorithm, ACO and so on. In this paper PSO tuned PID controller performance is compared with GA tuned PID controller along with traditional tuning methods.

IV. PSO TUNING METHOD

PSO is a robust stochastic optimization technique and is developed by the inspiration of bird flocking. It solves problems based the movement and intelligence of swarms and provides optima for problems with non linearity, non-differenciality and so on. It is a searching algorithm which gives optimum and shortest position. Birds are known as particles and fly in the problem space of n dimensions (n is the no. of tuning parameters) by considering current optimum particles [7]. It consists of parameters such as swarm size, position, and maximum no. of iterations with random initialization of its position and velocity. In this method, each particle is updated with two best values for every iteration with one best value being the best solution achieved by individual particle so far known as P_{best} and the other best value is the optimum best solution obtained by a particle in the entire population of particles called G_{best}. The particles velocity and position is updated by the following equations.

$$v_{i,m}^{t+1}=w.v_{i,m}^{t}+c_1*rand()*(P_{best(i,m)}-x_{i,m}^{t})+c_2*rand()*(G_{best(m)}-x_{i,m}^{t}) \quad (19)$$

$$x_{i,m}^{t+1}=x_{i,m}^{t}+v_{i,m}^{t+1} \quad (20)$$

Where,

i	- 1, 2, 3…….n
m	- 1, 2, 3.....d
n	- Number of particle population in a group
d	- Dimension of space (no. of tuning parameters)
t	- Current iteration value

$v_{i,m}$ - velocity of a particle I at iteration t
w - Inertia weight factor
c_1, c_2 - learning factors
rand ( ) - random no. between 0 and 1
$X_{i,d}$ - current position of particle i at t iteration
$P_{best\,(i)}$ - best particle position of i_{th} particle
G_{best} - best particle position among all the particles in the population

The flow chart of PSO algorithm implementation is as shown in figure 4.

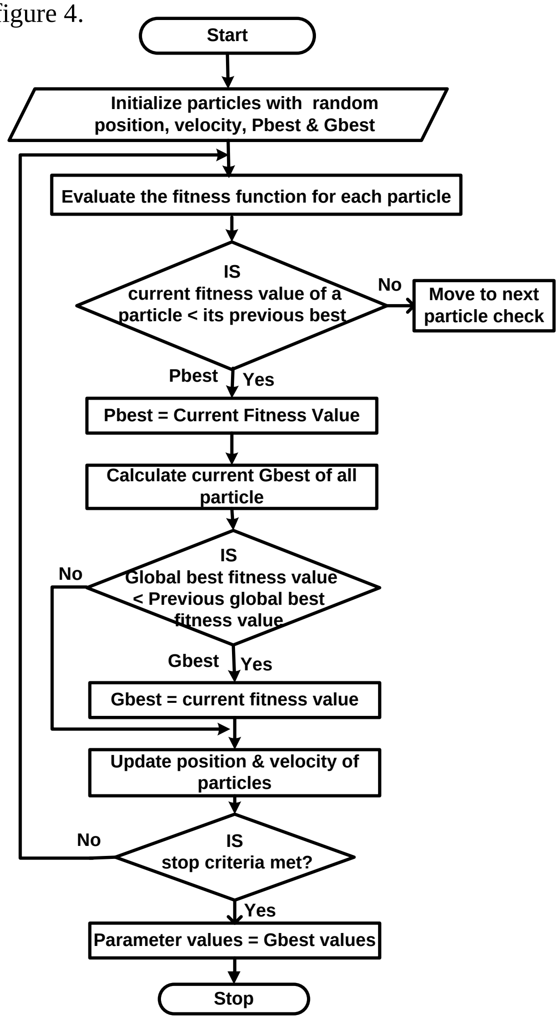

Fig 4: Flow chart of PSO algorithm

V. GENETIC ALGORITHM TUNING METHOD

Genetic Algorithm (GA) is a stochastic global search optimization technique which uses natural process of evolution for finding optimal solution. It is similar to PSO algorithm and here particles are considered as chromosomes. This algorithm starts with zero knowledge of correct solution and depends on system responses to arrive at optimal solution. GA consists of three steps and they are selection of parent chromosomes [8], crossover of these parent chromosomes and the mutation to create new individual better than parents. The procedure is shown in flowchart in figure 5.

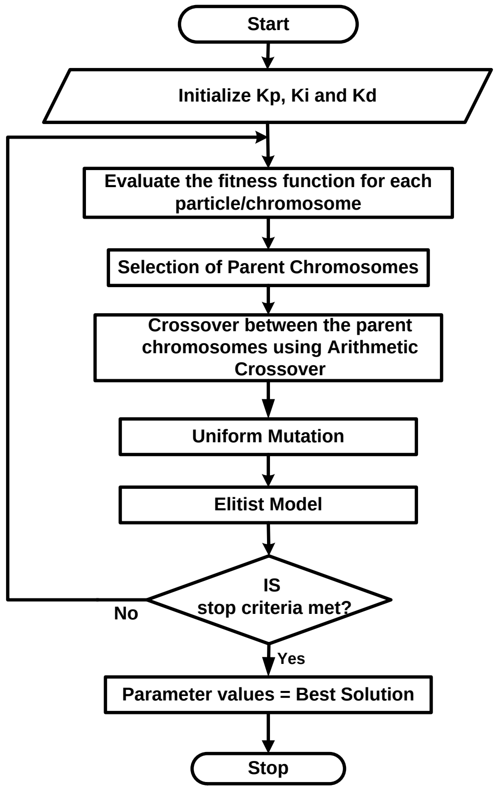

Fig 5: Flow chart of GA algorithm

The Simulink model of 3-axis Camera Gimbal control is shown in figure 6. Here the IMU reading is taken as step input generated using stair generator block in simulink.

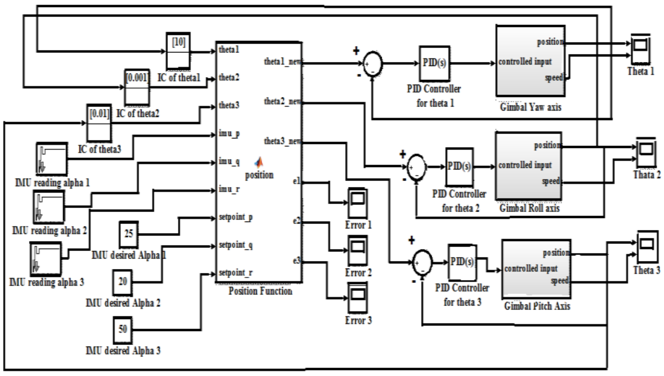

Fig 6: The simulink model of 3-Axis camera gimbal system

The IMU desired angles are the set point angles to be achieved which makes camera stable and points to desired object. The error to PID controller is the difference between the joint angle calculated by inverse kinematics of gimbal and the joint angle obtained by position encoder.

A. *Implementation of PID controller using Conventional Tuning methods*

The responses of the 3-axis gimbal system obtained using traditional tuning methods for tuning parameters of PID controller are shown in figure 7, figure 8 and figure 9.

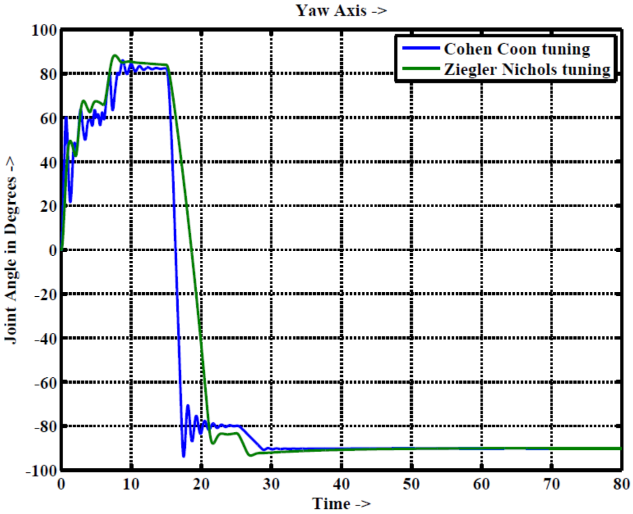

Fig 7: Yaw axis response using conventional tuning method

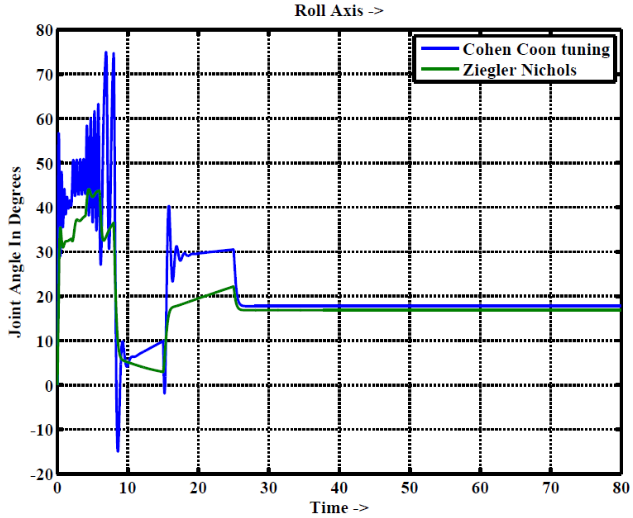

Fig 8: Roll Axis response of 3-axis gimbal system

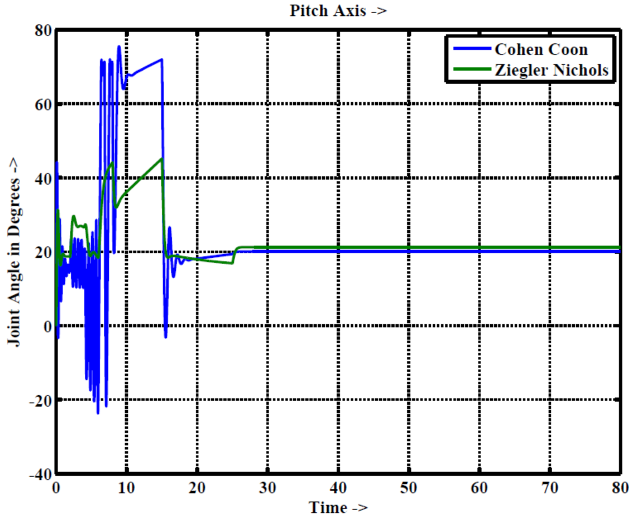

Fig 9: Pitch axis response of 3- axis gimbal system

B. *Implementation of PID controller using EvolutionaryTuning methods*

PSO and GA evolutionary tuning algorithms are used in this paper. The PSO and GA parameters used for tuning PID controllers are shown in table 1 and table 2.

Table 1: The PSO algorithm parameters

Parameter Name	Variable	Value
Cognitive component	c_1	1.5
Social component	c_2	1.5
No. of particles (Population)	n	100
No. of iterations	N	1000
Minimum inertia weight	W_{min}	0.4
Maximum Inertia weight	W_{max}	0.9
Dimension (No. of parameters)	dim	3

The fitness function or objective function used in PSO algorithm and Genetic algorithm is as shown below. Selection of fitness function is crucial for obtaining best solution of PID tuning values. Here β value is taken as 1.5.

$$F=(1-\exp(-\beta))*(Mp+Ess)+\exp(-\beta)*(Ts-Tr) \quad (21)$$

Where, F is fitness value, β is weighing factor, Ess is steady state error, Mp is overshoot, Ts is settling Time and Tr – Rise time.

Table 2: Genetic algorithm parameters

Parameters	Values
Population size	50
Maximum No of generations (iterations)	500
No. of tuning parameters	3
Mutation rate (Uniform)	0.3
Crossover Probability (Arithmetic)	0.8
Selection rate	0.5

The system responses obtained using evolutionary tuning algorithms is shown in figures 10, 11 and 12.

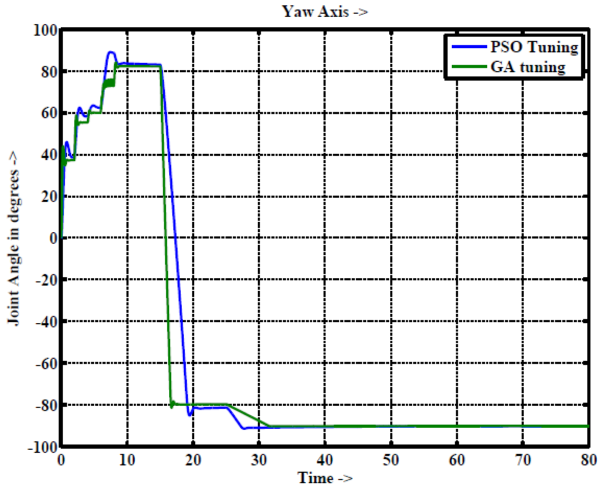

Fig 10: Yaw axis response using Evolutionary techniques

The responses of PSO and GA tuned PID controller for Camera Gimbal control show the final joint angle reading obtained from position encoder.

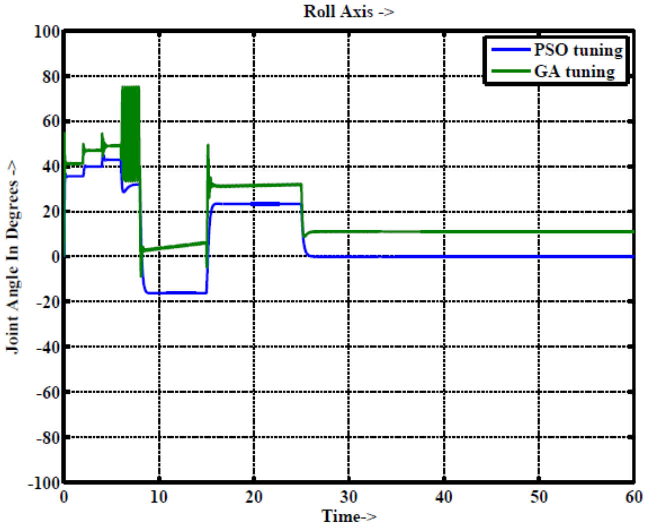

Fig 11: Roll Axis response of system using evolutionary technique

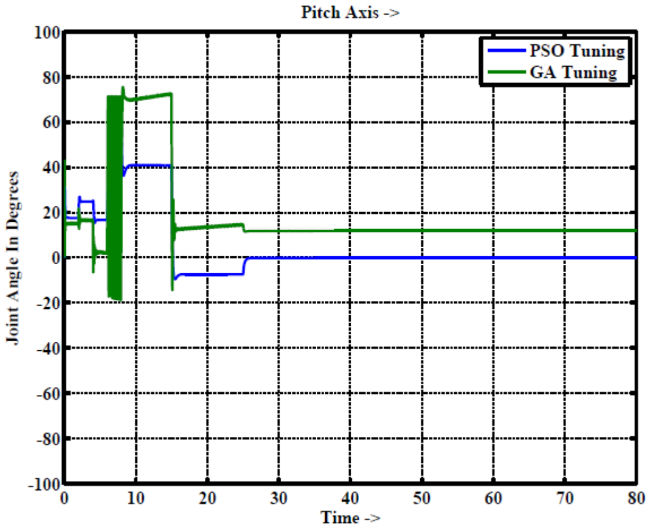

Fig 12: Pitch axis representation of gimbal using evolutionary technique

The responses clearly indicate the performance variation of the system for different tuning algorithms. PSO tuned PID controller gives the better performance of the system compared to other tuning methods. The system performance depends on controller and its tuning parameter values. The step response of gimbal system using different tuning algorithms is shown in figure 13.

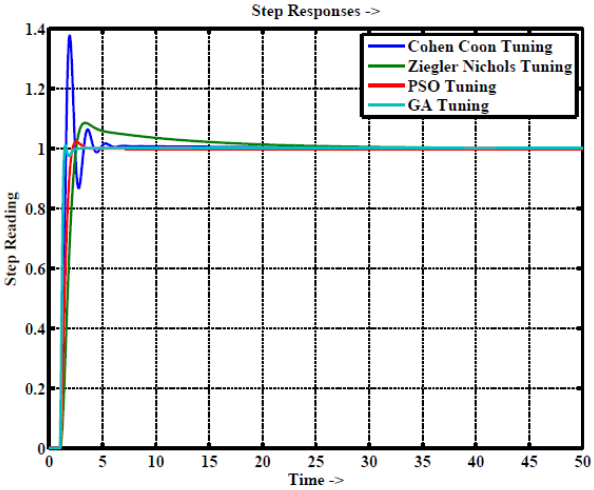

Fig13: Step responses of system for different tuning algorithms

VI. CONCLUSION

The Stabilization of Camera Gimbal is very important for various applications in air borne systems and other systems as discussed. The control system of gimbal plays crucial role in these applications to get accuracy in performance. The PID controller designed stabilizes the camera gimbal and improves its performance as shown by the responses. Tuning methods used to tune PID parameters show different variations in performance in the system and PSO tuned PID controller gives accurate and stable convergence. So, PSO tuned PID controller is preferred to stabilize camera gimbal system.

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