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# UAV Tracking Servo Design and Simulation Validation for Guidance Application

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## ABSTRACT

This chapter describes structure and design validation of a robust PID controller for path planning of an Unmanned Aerial Vehicle. This is the outermost loop of mission planning algorithm which has to track the pre described planned path with minimum tracking error. Tracking being kinematic in nature is based on servomechanism principle. Output of this loop is demanded acceleration as vehicle guidance command. This command is tracked by the autopilot as inner loop through aerodynamic or thrust vector control depending on mission phase. Present research is focused on evolving servo controller topology of outer loop for kinematic tracking to generate demanded acceleration based on available sensor measurements. Present system has been designed based on PID concept which has been arrived at based on a) pole placement and b) LQR techniques. Obviously LQR design gives maximum robustness. Ultimately robustness study in presence of actuator is based on classical framework with proper gain margin and phase margin. Whole design has been validated through three dimensional trajectory tracking simulation.

**Keywords:** PID Controller, Pole Placement Design, LQR Design, Position Servo Tracker, Unmanned Aerial Vehicle.


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# 1. INTRODUCTION

Unmanned Air Vehicles (UAVs) are being used for military application, agriculture, surveillance, surveying, photography, cinematography, 3D mapping, natural disaster recovery, search and rescue operation, product delivery, recon- naissance, general use by hobbyist and many more [1]. UAV autopilot design and development technology has seen significant development in last twenty five years. Its development is driven by innovation in sensors, actuators, autopilot and embedded control systems. Beard et al. has given excellent treatment on UAV controller design [2]. Here total plant state variables consist of $(V, \alpha, \beta, p, q, r, \psi, \theta, \phi, x, y, z)$ and control inputs are $(\delta_e, \delta_a, \delta_r, \delta_t)$. The system output consists of micro electromechanical systems (MEMS) based sensors for feedback consist of accelerometers, angular rate gyro, Global Positioning System (GPS), magnetometer, altimeter and Inertial Navigation System (INS). They have discussed Transfer Function (TF) based classical controller design for complete mission activity such full flight take-off, climb, loiter, waypoint navigation, maneuver along pitch and yaw plane, flare and landing. Now let us carry out state of the art brief literature survey on research pertaining to UAV autopilot design since twenty first century beginning.

One well cited earliest research paper is by Sagahyroon et al. [3]. Here they have discussed the design, modeling, implementation, and testing of a PID based an UAV controller for pitch, roll, and heading control. Ren et al. [4] carried out nonlinear trajectory tracking controller of UAV under the constraint of heading rate and velocity input. Sadrey et al. [5] designed a robust nonlinear controller for UAV path planning mission using a combination of Nonlinear Dynamical Inversion (NDI) and $H_\infty$ control. They employed outer loop consisting of $(V, \gamma, \varphi, \psi)$ in slow time scale and inner-loop consisting of $(\alpha, p, q, r)$ in faster time scale. Tennakoon *et al.* [6] reported design of UAV controller for high maneuver tracking based on classical control using Stability Augmentation System (SAS). Low [7] designed a nonlinear trajectory tracking controller along a fixed plane to track predefined $(x, y, \psi)$ as waypoint tracking for a fixed wing UAV to execute a time critical mission reliably. Kada et al. [8] designed a robust PID controller for pitch plane autopilot of UAV for angle tracking only. Dubey et al. developed nonlinear autopilot primarily for fixed wing UAVs using NDI and Linear Quadratic Regulator (LQR) control architecture. Sun et al. [9] designed nonlinear trajectory-tracking controller of UAV based on a generalized design model using Lyapunov based backstepping. Latest research is by Khan et al. [10] who studied automatic landing of a UAV by designing flare control law using LQR technique. So research carried out on

UAV controller design can be summarized as a) The controllers have been designed using both linear as well as nonlinear control techniques but more papers are available on nonlinear controller design than classical counterpart b) Trajectory tracking for waypoint navigation is basically kinematic guidance module as outermost loop of controller. On this important topic papers using classical control are less than nonlinear control. c) The researchers in linear control framework have discussed mainly on (attitude, altitude, velocity, latax) tracking. It is basically the dynamic tracking part which depends on aerodynamics as well as propulsion.

So, in linear control paradigm open literature on waypoint tracking as guidance subsystem are scanty but same are abundant on nonlinear control paradigm. The authors have understood this technical gap and proposes classical control-based trajectory tracker for waypoint navigation in three dimensions. The output of the trackers is demanded acceleration to be tracked by latax autopilot of UAV. The trajectory tracker has been designed using PID controller, initially tuned using pole placement technique heuristically and later fine-tuned using LQR technique which is claimed as novelty of this chapter. It is worth to mention at this juncture that in a practical flight vehicle (FV) such as (UAV, aircraft, space vehicle, missile) only classical controller is used. Its popularity is due to physical feel of robustness in terms of minimum gain margin (GM) and phase margin (PM) of (6 dB, 30 deg.) for flight clearance. Equivalent feel for robustness is not available in nonlinear control theory till date. Based on author's experience [11], nonlinear controller works only better if model is exact. But due to inherent uncertainty in aerodynamic coefficients and thrust of plant, in real world in presence of uncertainty nonlinear control works no way better than classical control. But in industry nonlinear controller results are used to fine tune classical controller design. Present servo controller for tracker design is based on research papers by Tennakoon *et al.* and Menon et al. [6], [12]. First the problem formulation is discussed in Section 2. The validation of designed tracker through simulation has been discussed in Section 3. The chapter concludes with discussion of future work in Section 4.

## 2. PROBLEM FORMULATION

### 2.1. Plant Kinematic Model

A constant speed target has been considered without loss of generality to generate any curvilinear trajectory by preprogrammed control input as acceleration components ($\eta_y$, $\eta_p$) along yaw and pitch plane respectively. The governing equations of motion to compute ($x, y, z, \dot{x}, \dot{y}, \dot{z}$) are (Fig. 1, [13])

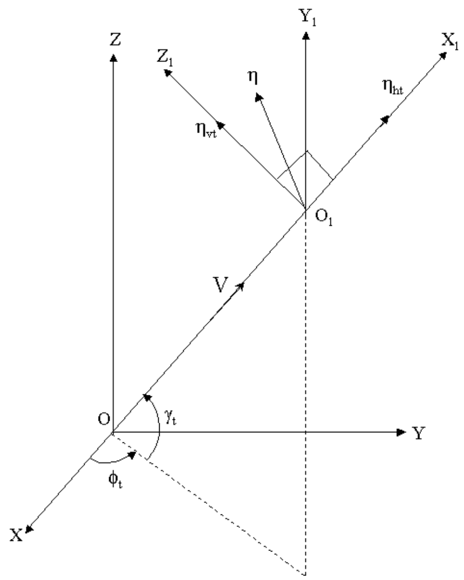



**Fig. 1.** Axes System for UAV Point mass model

$$\frac{dv}{dt} = 0.0 \qquad \frac{d\gamma}{dt} = \eta_v \frac{g}{v}$$

$$\frac{d\varphi}{dt} = \eta_v \frac{g}{v\cos\gamma} \qquad \frac{dy}{dt} = V\cos\gamma\sin\phi \tag{1}$$

$$\frac{dh}{dt} = V\sin\gamma \qquad \frac{dx}{dt} = V\cos\gamma\cos\phi$$

Direction Cosine Matrix (DCM) is obtained through rotation by

1) ($\phi$) about z in (x y z)
2) ($-\gamma$) about y axis to get finally ($x_1y_1z_1$) in final rotation as follow

$$C_c^p = \begin{bmatrix} \cos\gamma\cos\phi & \cos\gamma\sin\phi & \sin\gamma \\ -\sin\gamma & \cos\gamma & 0 \\ -\sin\gamma\cos\phi & -\sin\gamma\sin\phi & \cos\gamma \end{bmatrix} \tag{2}$$

### 2.2. Tracking Servo Controller Design

To design a controller to track (xd, yd, zd) and flight path angles (φd, γd) based on available feedback from INS using transfer function (TF), closed loop transfer function (CLTF) and open loop transfer function (OLTF) are [14]

$$\frac{C(s)}{R(s)} = \frac{G(s)}{1+G(s)H(s)} \text{ and } \frac{B(s)}{E(s)} = G(s)H(s) \tag{3}$$

### 2.2.1 Position Tracking Servo (Simplest Design)

For position tracking the control input is acceleration *a* which is integrated once to obtain velocity *v* and double integrated to obtain position *x*. Position and velocity both being available for feedback [12]

$$v_d = k_p(x_d - x) \text{ and } a = (v_d - v) \tag{4}$$

Position tracker servo design topologies in closed and open loop are in Fig. 2. Corresponding CLTF and OLTF are [14, 15]

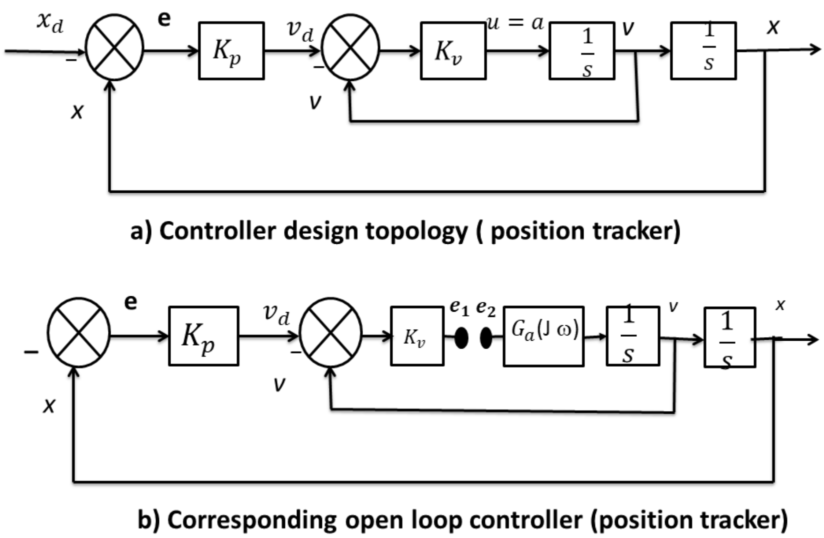



**Fig. 2.** Position Tracker (Closed + Open Loop + Standard)

$$\frac{x}{x_d} = \frac{k_p k_v}{s^2 + k_v s + k_p k_v} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}(CLTF) \text{ and}$$

(5)

$$G(s)H(s) = \frac{(k_i + k_p s)}{s^2} G_a(s)(OLTF)$$

In Eqn. 5 plant CLTF is made equivalent of second order TF is

$$s^2 / s^2 + 2\zeta_n \omega_n s_n + \omega_n^2$$

where, ($\zeta_n$, $\omega_n$) are desired damping coefficients and bandwidth (BW) of the tracker. Here the choice for design value of $\zeta_n$ is 0.7 for optimum step response. Choice of $\omega_n$ is based on tracker output latax as guidance demand to be tracked by autopilot. Based on separation principle latax loop BW should be one third of rate loop BW which is one third of Actuator BW [15]. By equating present CLTF with second order system we get,

$$K_P = \frac{\omega_n^2}{k_v} \text{ and } k_v = 2\zeta_n \omega_n \tag{6}$$

### 2.2.2 Position Tracking Servo (PID Design)

The position tracker as mentioned above (Section II-B.1) is simplest tracker to obtain guidance demanded latax by tracking waypoints. As it consists of both position and velocity feedback it is equivalent to PD controller. As from INS position, velocity and acceleration components (x, v, a) are available definitely PID controller is also realizable which is more preferred because it guarantees zero steady state error. Here the open loop plant is

$$x/a = 1/s^2$$

which has to be stabilized. But the plant being unstable, standard Ziegler-Nichols rule for PID controller tuning cannot be implemented (pp. 571, [14]). So PID controller design has been carried out in state space. Initially heuristic design has been carried out using pole placement and later fine-tuned using LQR which will be discussed now.

Standard CLTF for PID controller (Fig. 3) has three poles as shown below and it has to be placed judiciously.

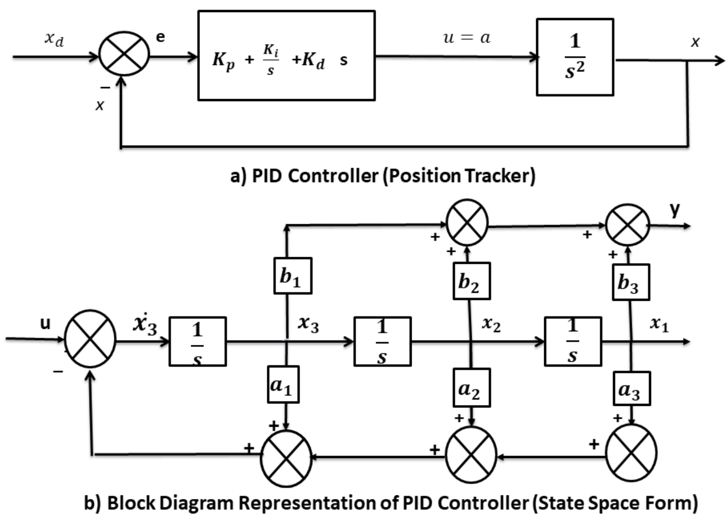



**Fig. 3.** Position Tracker (Closed + PID + Block Diagram)

$$\frac{x}{x_d} = \frac{k_d s^2 + k_p s + k_i}{s^2 + k_d s^2 + k_p s + k_i} = \frac{b_1 s^2 + b_2 s + b_3}{s^2 + a_1 s^2 + a_2 s + a_3}$$

$$\begin{bmatrix} a_1 & a_2 & a_3 \end{bmatrix} = \begin{bmatrix} k_d & k_p & k_i \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} b_1 & b_2 & b_3 \end{bmatrix} = \begin{bmatrix} k_d & k_p & k_i \end{bmatrix}$$

Above TF (Eqn. 7) has to be casted in state space form, for given input/output relation

$$\frac{y}{u} = \frac{y}{x} \times \frac{x}{u}$$

where, (x1, x2, x3) = (x, x˙, x¨)

$$\frac{y}{x} = b_1 s^2 + b_2 s + b_3 \text{ and}$$

$$(8)$$

$$\frac{x}{u} = \frac{1}{s^3 + a_1 s^2 + a_2 s + a_3}$$

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ -a_3 & -a_2 & -a_1 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u \text{ and}$$

$$(9)$$

$$y = \begin{bmatrix} b_3 & b_2 & b_1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_2 \end{bmatrix}$$

Then above Eqn. 8 can be written in state space form as (Fig. 3)

**Pole Placement Design**

**I**n above TF (Eqn. 8) the denominator is $s^3 + a_1 s^2 + a_2 s + +a_3$ and three poles to be placed (pp. 243 [16]). Here generally $u$ = - $K_x$ where K is gain matrix. Tracker being designed for guidance loop BW should not be high. The actuator being used of 10 Hz, BW of latax to be tracked is 1 Hz based on separation theorem. The dominant pole ($\sigma_1$) should be along negative x axis close to origin and other two poles ($\sigma_2 \pm j\ \omega_2$) should dictate the system damping, Details of pole placement technique is available in Frankline et al. (pp. 131-134, pp. 477 [17]). Two methods of pole placement will be discussed now.

**Method # 1**: Closed loop poles or eigenvalues ($\lambda_1$, $\lambda_2$, $\lambda_3$) are placed heuristically (pp. 481 [17]). For given ($\zeta_n$, $\omega_n$)

$$\lambda_1 = -0.5 \text{ and}$$
$$\lambda_{2,3} = \left(-\zeta_n\omega_n \pm \sqrt{1-\zeta_n^2\omega_n}\right) = \sigma_2 \pm j\omega_2 \tag{10}$$

The value of $\lambda_1$ is taken heuristically by tracking (τ, BW, PM, GM) for the given actuator specification. In closed loop the system matrix becomes (**A – BK**). Pole placement can be carried out using Ackerman's Formula (ACKER) or PLACE of MATLAB.

**Method # 2**: Here the pole placement design is carried out using optimal control based LQR design (pp. 337 [16], pp. 793 [14], pp. 525-536 [18]). Corresponding cost function is

$$J = \int_0^\infty \left(x^T Q x + u^T R u\right) dt \text{ and}$$
$$u = -Kx \tag{11}$$

where (**Q**, **R**) are weighting matrices. The optimal control **u** and gain **K** is obtained by solving Algebric Riccati Equation (ARE) using MATLAB command LQR (Eqn. 12).

$$A^T P + PA - PB\, R^{-1} B^T + Q = 0 \text{ and}$$
$$K = R^{-1} BP \text{ where } u = -Kx \tag{12}$$

It is to be noted that in LQR design closed loop poles ($\lambda_1$, $\lambda_2$, $\lambda_3$) are not evolved heuristically unlike in Method # 1. They are obtained by solving ARE (Eqn. 12), where (**Q**, **R**) selection is designer's choice (pp. 485-489 [17], pp. 535-536 [18], pp. 149 [19]).

### 2.2.3 Angle Tracking Servo

The CLTF and corresponding OLTF of proposed present γ tracker are shown in Fig. 4 and the equations are,

$$\frac{\gamma}{\gamma_d} = \frac{k_p s + k_i k_p}{s^2 + k_p s + k_i k_p}(CLTF) \text{ and}$$

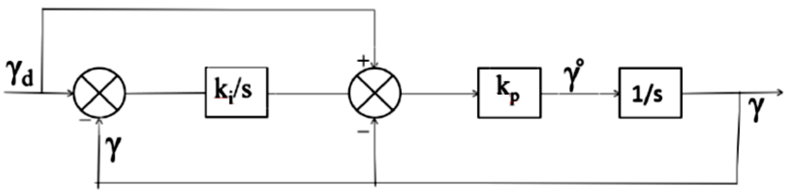
(13)

$$\mathrm{G}(s)H(s) = \frac{k_v(s + k_p)}{s^2} G_a(s)(OLTF)$$

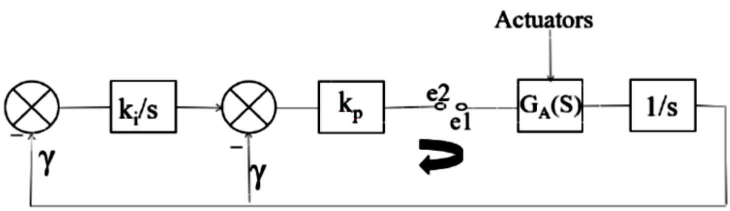
Equating above CLTF (Eqn. 13) with second order TF of $\gamma$ tracker for given $(\zeta_n, \omega_n)$ we get,

$$k_P = 2\zeta_n \omega_n \text{ and } k_v = \frac{\omega_n^2}{k_v}$$

$$G_a(s) = \frac{\omega_a^2}{s^2 + 2\zeta_a \omega_a s + \omega_a^2} \tag{14}$$




a) Controller Design Topology of γ tracker




b)Corresponding Open Loop Controller of γ tracker

**Fig. 4.** γ-Tracker Topology (Closed + Open Loop)

Total guidance demanded latax along pitch is V $\dot{\gamma}$ where $\dot{\gamma}$ is available as output of present γ-tracker. φ tracker can be designed in similar fashion and guidance demanded latax alony yaw plane is V cos(γ)$\dot{\varphi}$ (Eqn. 1, [20]). So based on the specification of ($\zeta_n$, $\omega_n$), the controller integral and proportional gains ($K_i$, $K_p$) are calculated using Eqn. 13. In present context of UAV design, actuator required has been considered of ($\zeta_a$, $\omega_a$) = (0.4, 10 *Hz*). Based on frequency separation theory the rate loop (γ- tracking loop) bandwidth $\omega_n$ is approximately one third of actuator frequency $\omega_a$. This implies that $\omega_n = \omega_a /3$. So ($\zeta_n$, $\omega_n$) = (0.707, 3.33 Hz) have been considered to be the specification for gains calculation using Eqn. 14. $\zeta_n$= 0.707 has been considered in design because that gives optimum steady state performance in the in the second order system. Here actuator TF model $G_a(s) = \omega_a^2 / s^2 + 2\zeta_a \omega_a s + \omega_a^2$ has been considered for robustness study (calculation of GM, PM).

## 3. SIMULATION RESULTS AND DISCUSSION

Now let us discuss performance of position and angle tracker through simulation. Here position tracker performance has been studied along x-direction and $\gamma$-tracker performance has been studied for angle tracking. As the tracker performance is limited to kinematics, same model is valid for (y, z)-tracker and $\varphi$ tracker also. So due to brevity, discussion on their performance study has been skipped.

### 3.1 Generation of Input Data to be Tracked

Based on point mass model (Section II-A) UAV trajectory has been simulated for 15 seconds with initial (V m/s, γ (deg),φ (deg), h (m),y (m),x (m)) as (700, 90, 0, 7000, 1, 5000). The system input is ($\eta_y$, $\eta_p$) ( Fig. 5). These valurs have been passed through shaping filter ω/(s+ω) and output latax $(\tilde{\eta}_y, \tilde{\eta}_p)$ are fed to Eqn. 1 as control input. Here, ω = 10 rad/s or time constant of 0.1 sec considered to mimic realistic maneuver. Our aim is to track (x, γ) as reference trajectory evolved through solving Eqn. 1. Present tracker outputs are ($\ddot{x}$.V $\dot{\gamma}$) guidance demanded latax to be tracked by autopilot.

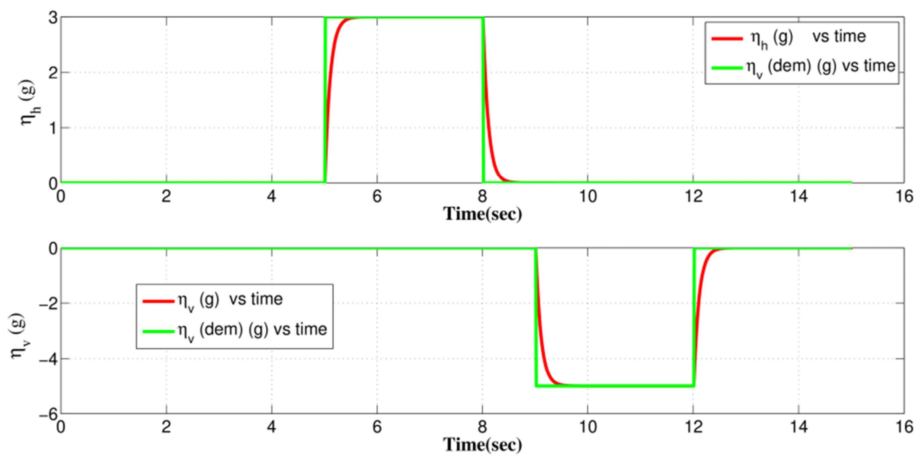



**Fig. 5.** ($\eta_y$ , $\eta_p$) Time History as Control Input

### 3.2 Position Tracking Performance

Pole placement design using Method # 1 has already been discussed in Section II-B.2. Method #2 is based on LQR design. LQR controller performance is obtained by carrying out 1) sensitivity study over R keeping Q as constant unit matrix and 2) sensitivity study over Q by varying $\rho$ keeping R as unity (Table 1). For different variations of $(R, \rho)$ ε $[0.01, 0.10, 1.0, 10, 100]$ the pole locations, state feedback gain, $\tau$, $(k_p\ k_i\ k_d)$, (PM, $\omega_g$) and BW have been evaluated. Our aim is to get the BW of tracker as 1 Hz . From the table we see that for both a) (R= 0.1) with unity Q and b) ($\rho$ = 10) with unity R the BW = 6 rad/sec = 1 Hz has been obtained. Corresponding $\tau$ = 0.1 sec, $(k_p\ k_i\ k_d)$ = (6.30, 3.10, 4.80), PM = $71^0$ at $\omega_g$ = 5 rad/sec. It is to be noted that from both ( R, Q ) sensitivity studies the results are consistent.

Now performance of different position trackers (Section 2.2.1-Section 2.2.2) in frequency domain is shown in Table 2. Their comparison (Standard, PID (Method #1), PID (Method # 2)) for tracking a step command is shown Fig. 6. From this study it is clear that for given actuator specification, LQR based PID controller design is the best because of minimum rise time as well as maximum bandwidth. From the position tracking guidance demanded latax also has been calculated for the cases and here also LQR design has best tracking performance in terms of minimum tracking error (Fig. 7). Corresponding position tracking performance also is shown in Fig. 8. The position tracking error is within 10m after it takes 2 seconds to settle from initial transients. So best performance of LQR based PID controller design (Method #2) has been demonstrated.

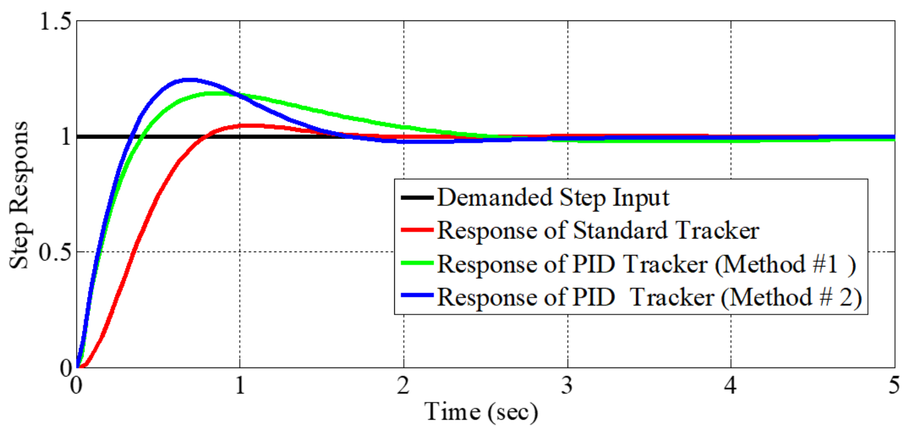



**Fig. 6.** Step Responses (Position Tracker)

**Table 1.** LQR Controller Performce with Sensivity in (Q, R)

| Sensitivity in R with Q constant to I (3 × 3 ) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Sr. No. | **R** | Poles $\lambda_1, \lambda_2, \lambda_3$ | Gain | $\tau$ (sec) | $K_p$, $K_i$, $K_d$ | (PM, $\omega_g$) (deg, rad/s) | BW (rad/s) |
| 1 | 0.010 | −10 −0.86 ± 0.50 i | 10.0, 18.0, 11.0) | 0.08 | 18.2, 10.0, 11.7 | 73, 12.0 | 13.8 |
| 2 | 0.100 | −3.0 −0.87 ± 0.52 i | 3.00, 6.00, 5.00 | 0.18 | 6.30, 3.10, 4.80 | 71, 5.00 | 6.00 |
| 3 | 1.000 | −1.0 −0.71 ± 0.71 i | 1.00, 2.00, 2.00 | 0.33 | 2.40, 1.00, 2.40 | 64, 2.50 | 3.20 |
| 4 | 10.00 | −.65 −0.40 ± 0.50 i | 0.30, 1.00, 1, 50 | 0.52 | 1.02, 0.30, 1.45 | 61, 1.48 | 2.04 |
| 5 | 100.0 | −.45 −0.25 ± 0.40 i | 0.10, 0.44, 0.95 | 0.80 | 0.44, 0.10, 0.95 | 60, 0.96 | 1.34 |
| Sensitivity in Q = I (3 × 3 ρ with R = 1 | | | | | | | |
| Sr. No. | ρ | Poles $\lambda_1, \lambda_2, \lambda_3$ | Gain | $\tau$ (sec) | $K_p$, $K_i$, $K_d$ | (PM, $\omega g$ (deg, rad/s) | BW (rad/s) |
| 1 | 0.010 | −0.45, −0.25 ± 0.40 *i* | 0.10, 0.44, 0.95 | 0.90 | 0.44, 0.10, 0.95 | 61, 1.00 | 1.40 |
| 2 | 0.100 | −0.65, −0.40 ± 0.57 *i* | 0.31, 1.01, 1.45 | 0.56 | 1.01, 0.30, 1.45 | 62, 1.50 | 2.04 |
| 3 | 1.000 | −1.00, −0.70 ± 0.70 *i* | 2.41, 1.00, 2.41 | 0.35 | 2.41, 1.00, 2.41 | 65, 2.50 | 3.28 |
| 4 | 10.00 | −3.00, −0.88 ± 0.55 *i* | 3.10, 6.30, 4.70 | 0.21 | 6.33, 3.16, 4.76 | 70, 4.80 | 6.00 |
| 5 | 100.0 | −9.90, −0.86 ± 0.50 *i* | 10.0, 18.0, 12.0 | 0.09 | 18.2, 10.0, 11.0 | 73, 12.0 | 13.8 |

**Table 2.** Comparision of Different Position Tracker Performance

| | Sensitivity in R with Q constant to I (3 × 3 | | | | | |
|---|---|---|---|---|---|---|
| Sr. No. | Tracker Type | Gain ($K_p$, $K_i$, $K_d$) | (PM, $\omega g$) (deg, rad/s) | ( GM, $\omega p$) (deg, rad/sec) | $\tau$ (sec) | BW (rad/s) |
| 1 | Standard Tracker | 3.00, --, 5.90 | 70.0, 4.00 | 45.0, 21.0 | 0.43 | 5.0 |
| 2 | PID Design (Method #1) | 11.0, 4.50, 4.70 | 60.0, 6.0 | 35.0, 22.0 | 0.20 | 5.7 |
| 3 | PID Design (Method #2) | 6.33, 3.16, 4.76 | 70.0, 5.0 | 32.0, 25.0 | 0.18 | 6.0 |

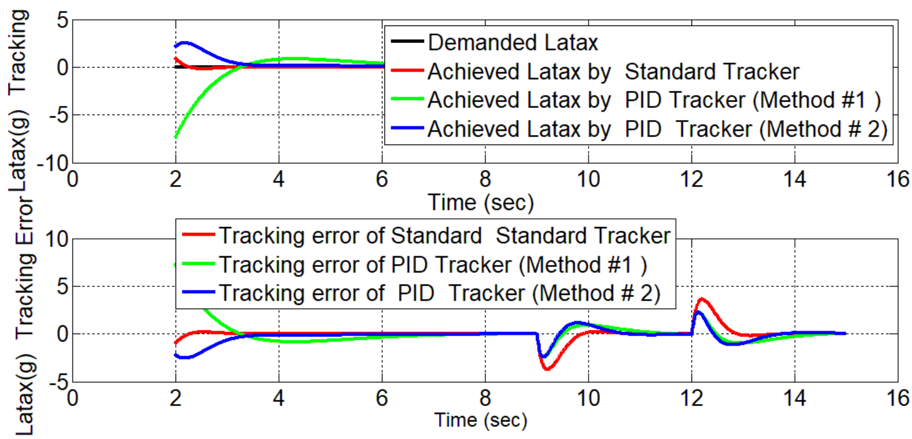



**Fig. 7.** Acceleration from Position Tracker (all cases)

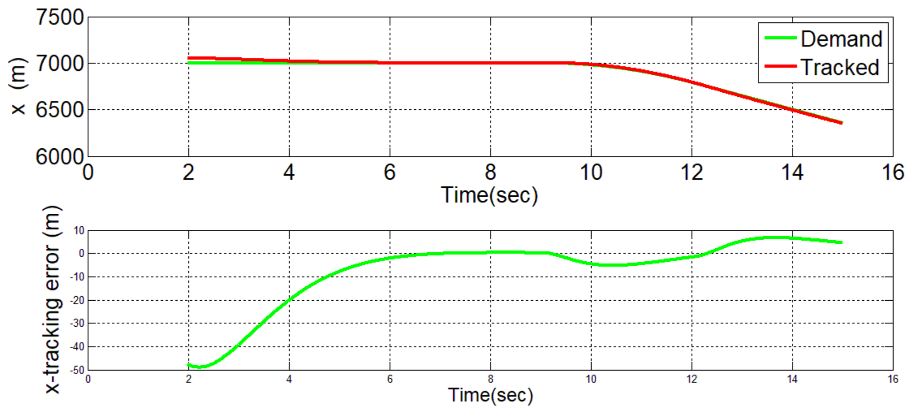



**Fig. 8.** x-tracking + Tracking Error (PID # 2)

### 3.3 Angle Tracking Performance

As discussed before, the input to be tracked by this controller is $\gamma_d$ (Fig. 4). From Fig. 4 it is seen that tracker outputs are ($\gamma$, $\dot{\gamma}$) respectively. Step response of present CLTF (Eqn. 13) is shown in Fig. 9. From the figure it is noticed that rise time of this controller is order of 50 milli second. Initially there is an overshoot which is due to zero in CLTF. Having the zero is the effect of integrator which forces the steady state error to zero. The OLTF in same equation has been used for robustness study including actuator in the loop. In present case study (PM, GM) are (28.9deg, 2.84dB) which is adequate from robustness point of view.

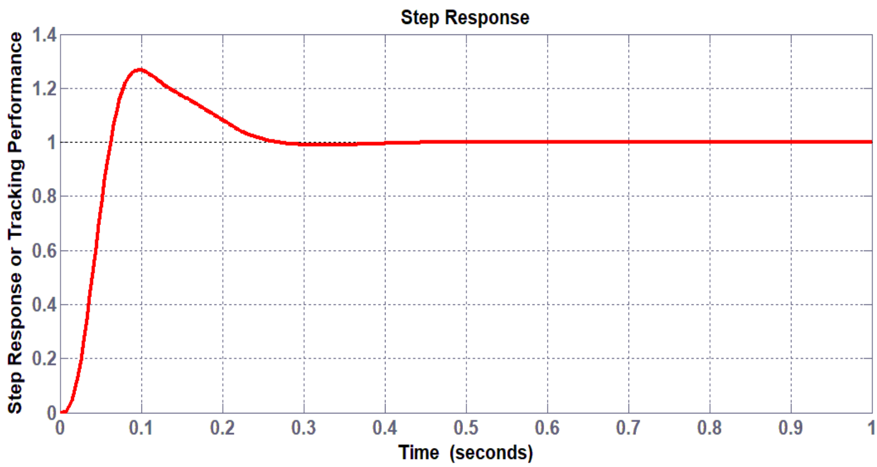



**Fig. 9.** Step Response ($\gamma$-Tracker)

Corresponding (Phase cross over frequency, Gain cross over frequency ) as ($\omega_p$, $\omega_g$) = (40, 56.5) rad/s. The Bode plot is shown in Fig. 10. This is the study in frequency domain. In time domain study, time history of $\gamma$ tracking and ($\gamma_d - \gamma$) tracking error are shown in Fig. 11. Similarly time history of $\dot{\gamma}$ tracking and ($\dot{\gamma}_d - \dot{\gamma}$) tracking error are shown in Fig. 12. Initially $\gamma$ to be tracked is 90 deg. So starting data for $\gamma$ has been taken as 80 deg. So initially there is $\dot{\gamma}$ built up as transient and and it takes 100 millisecond for transient to mitigate and after that both ($\gamma, \dot{\gamma}$) tracking performances are smooth and tracking errors are close to zero. This indicates that in Kinematic level tracking performance is excellent. through simulation also.

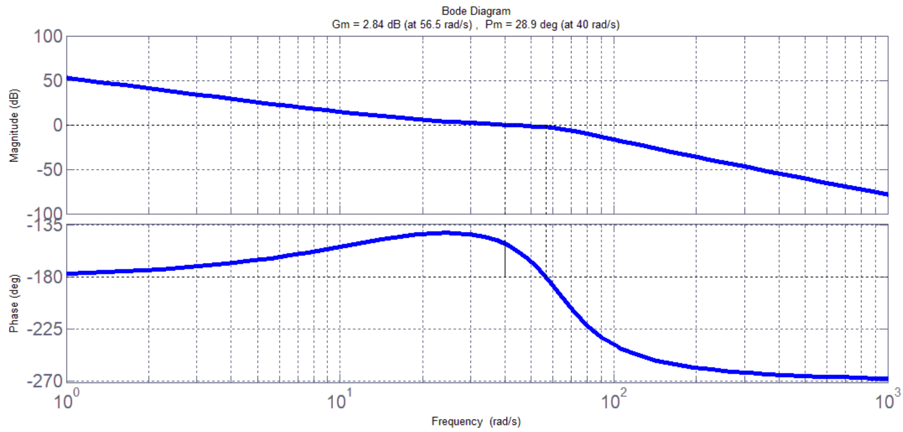



**Fig. 10.** Bode Plot (γ-Tracker OLTF)

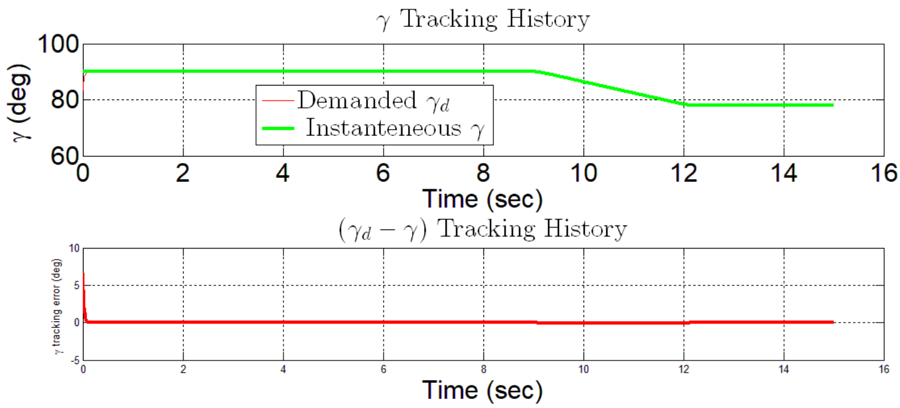



**Fig. 11.** γ-Tracking + Tracking Error

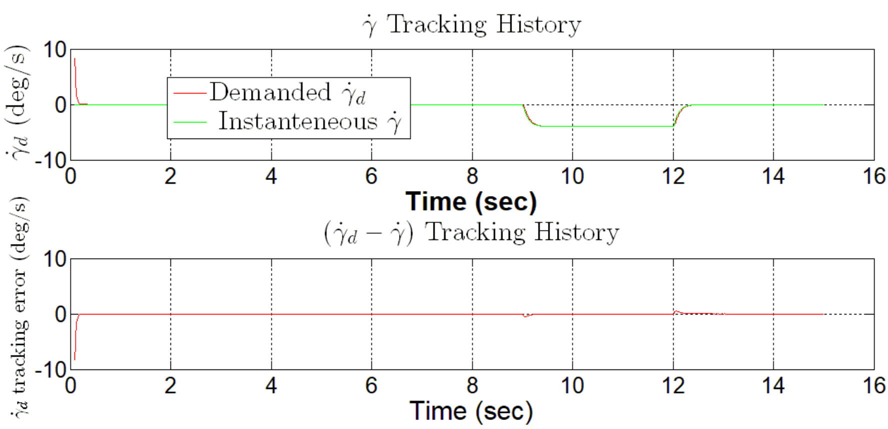



**Fig. 12.** $\dot{\gamma}$ Tracking + Tracking Error

## 4. CONCLUSION

UAV controller design consists of outer kinematic loop where based on position or angle tracking error guidance demanded latax is evolved. In inner loop based on demanded latax demanded body rates are calculated to evolve demanded control surface deflections ($\delta_e$, $\delta_a$, $\delta_r$, $\delta_t$) which is achieved through actuator. Enough open access published literature exist for both in nonlinear control. But for waypoint tracking using kinematic tacking research papers are scanty in classical control framework. The authors propose design of kinematic tracker using pole placement based PID controller in classical framework. Through frequency domain design and realistic time domain simulation it has been shown that LQR based PID design of tracker is best from tracking point of view. One important point to state that (GM,PM) dependes on actuator BW. Higher the actuator BW, PM will be more. Some times the compensator can be used for improving (GM, PM) characteristics. Similarly angle tracking based kinematic tracker also has been proposed. Guidance demanded longitudinal and lateral accelerations are output of these trackers. Immediate future activity is to design latex and rate tracking autopilot to realize the complete controller design of UAV. All these proposed trackers are realizable onboard with specified actuator based on onboard INS measurements.

## NOMENCLATURE

| | | |
|---|---|---|
| $\eta_y$, $\eta_p$ | : | Latax along (yaw, pitch) plane = L/(m g) |
| $G_a$(s) | : | Actuator TF |
| B (s) | : | Feedback signal |
| E (s) | : | Error signal |
| G (s) | : | Forward path TF |
| H (s) | : | Feedback path TF |
| Kp, Kv | : | Position loop and velocity loop gain |
| p, q, r | : | Body rates (roll, pitch, yaw) |
| R (s) | : | Input signal |
| V, α, β | : | Velocity, angle of attack and sideslip angle |
| x, y, z | : | Position along (east, north, up) along a given direction |
| $x_d$, $v_d$ | : | Position demand and velocity demand in servo loop |
| Y (s) | : | Output signal |
| γ, ψ | : | Flight path angle of UAV along ( pitch, yaw) |
| θ, h | : | Attitude and altitude |
| τ | : | Rise Time |
| ψ, θ, φ | : | Euler angle sequence along (yaw, pitch, roll) |
| $\omega_g$, $\omega_p$ | : | Gain crossover and phase crossover frequency |

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