Design, modeling and tuning of modified PID controller for autopilot in MAVs

Abrar Ul Haq, Sreerama Reddy G. M., Cyril Prasanna Raj P.

Abstract : The dangers of poor pilot performance as well as time and place conditions, low altitude and climate, damage critical aircraft control system. The use of Unmanned Aircraft Vehicle or (UAV) in sensitive and important Operation is required and there is a need for autopilot that can tune the MAV in different environment conditions. Furthermore, designing the controller system is one of the main discussed Dynamic issues in Flying Objects. In this paper an attempted is made to determine the optimal coefficients of PID controller that can reject disturbances and still operate the MAV in stable positions. Basic PID controller is designed and is adopted to control the MAV, a modified techniques incorporating ISA-PID is designed to reject disturbances. The PID parameters are determined to be reduce the rise time less than 3 seconds, settling time to be less than 8 seconds and overshoot to be less than 5%. The developed model is suitable for PID controller in autopilot.

Keywords Unmanned Aircraft Vehicle, MAV, PID controller, ISA-PID, autopilot

---

1. Introduction

Unmanned aircraft (UA) have been used for military purposes such as reconnaissance, weapons delivery, battlefield communications, and hazardous environment [1]. Examples of UAs are reconnaissance and weapons delivery, disaster management, toxic chemical detection and border security. Micro air vehicles (MAV) are becoming popular on the battlefield, as they are easily transported and deployed by soldiers in the field. MAVs have become cheaper, smaller and easy to transport, non-military applications are gaining interest such as pizza delivery, postal services and home security. As non-military uses become more popular, creating user-friendly MAVs is the need for commercial viability. MAVs are finding their way into law enforcement, crop surveillance, fire fighting, communication relays, search and rescue, etc. Auto piloting of Mavs is required as they need to be managed without human intervention. Most commercial autopilots used in MVAs must be hand-tuned when installed in an aircraft. This involves an experienced remote control (RC) pilot flying the MAV to tune proportional-integral-derivative control (PID) gains and trim the airplane. Such a process can be expensive and time intensive. Due to manufacturing processes, temperature sensitivities, crashes, and changing atmospheric conditions, the tuned values vary from aircraft to aircraft and sometimes on each airplane throughout the day. For many applications, tuning the autopilot can range from annoying to unacceptable. Thus, an autopilot should be self tuning and fault tolerant. Adaptive control schemes show promise for fulfilling these requirements. PID values are different for each MAV, even if they have the same physical geometry. Adaptive control is an approach at allowing one autopilot to control every MAV while requiring minimal tuning. Because of the physical size of the MAVs, a small autopilot is used that has limited code space, memory, and computational resources [2-5]. PID control can control a large set of plants, and its intent is to drive the error between a desired reference signal and the output of the plant to zero. It does this by operating on that error and passing the result to the plant's input. As the plant's parameters change, the PID controller may need to be re-tuned. Parameter variation can be caused by changes in environmental conditions, state changes (i.e. airplane dynamics changing as a result of airspeed, angle of attack, and sideslip angle), time progression, etc. For MAVs, this means that a PID controller that is tuned in one flight regime may not work as well or become unstable under another flight regime, thus requiring re-tuning. Adaptive control typically does not suffer from this problem. The goal of adaptive control is to adjust to unknown or changing plant parameters. This is accomplished by either changing parameters in the controller to minimize error, or using plant parameter estimates to change the control signal.

Fiuzy The main problem in the design of Autopilot is in Aerodynamic Parameters with low precision, the designed controller should not be sensitive to change of values. The Equations of Motion and UAV behavior is non-linear and Varies with time causing nonidealities. Three factors causing to complexity in the designing are: 1 - uncertain of the Aerodynamic Coefficients (uncertainly parametric), 2 -

ISSN 2229-5518

Nonlinear Dynamics and not eliminate Coupling effects (not modeled Dynamics) and final: 3 - non-minimum height dynamics phase [6]. Several adaptive techniques have been introduced to solving the problem of uncertainly that they solve by parametric linear method [7, 8]. In [8], an adaptive controller is used to improve the strength High Classic Controller's parameter (Resistance compared with the Aerodynamic coefficients) of an UAV. Feedback linearization [9], is another popular technique that has many applications in designing of flight control system [9-12]. In [16] only Aerodynamic Coefficients are considered for autopilot and have demonstrated to improve the resistance parameter. In [18] a fuzzy PID Controller for linear non-minimum phase systems has been designed. In this paper, attempt to design an optimal PID controller with tuning of PID parameters are studied using mathematical models and simulation results. The disturbances and its impact on PID controller are analyzed for vehicle stability. Based on the optimal coefficients by obtained by the tuning algorithms that has been designed PID control parameters are identified so that improve control of the height, in the introduced pilot. Section II discusses Mathematical Model (Dynamic) UAV, section III discusses Classic Pilot and section IV discusses PID controllers, section V discusses design of PID controllers and conclusion in section VI.

2. Mathematical models of Unmanned Aircraft Vehicle (UAV)

The mathematical model for MAV has been arrived at with reasonable assumptions for mass and moment of inertia are constant. Motion Nonlinear Equations of UAV are as follows [1]:

$$\dot{U} = -9.8\sin\theta - QW + RV - 0.0125U - 16.36\alpha + 16.6\delta_E + 4.5$$

$$\dot{V} = 9.8\sin\phi\cos\theta + PW - RU - 263.7\beta - 0.0053P + 1.64R - 0.0032\delta_A - 58.2\delta_R$$

$$\dot{W} = 9.8\sin\phi\cos\theta + QU - PV - 0.069U - 259\alpha - 1.3Q + 57.5\delta_E + 21$$

$$\dot{P} = -1.51QR + 0.04PQ + 76.7\beta - 1.9P - 0.68R + 149\delta_A + 105\delta_R$$

$$\dot{Q} = 1.03PR - 0.017(P^2 - R^2) - 988\alpha - 8.9Q + 1362\delta_E - 0.284$$

$$\dot{R} = -0.038QR - 0.85PQ + 306\beta - 0.044P - 2.82R + 2.27\delta_A + 434\delta_R$$

$$\dot{\alpha} = \frac{\dot{W}\cos\alpha - \dot{U}\sin\alpha}{V_t\cos\beta}$$

$$\dot{\beta} = \frac{1}{V_t}[-\dot{U}\cos\alpha\sin\beta + \dot{V}\cos\beta - \dot{W}\sin\alpha\sin\beta]$$

$$\dot{\phi} = P + Q\sin\phi\tan\theta + R\cos\phi\tan\theta$$

$$\dot{\theta} = Q\cos\phi - R\sin\phi$$

$$\dot{\psi} = (Q\sin\phi + R\cos\phi)\sec\theta$$

$$\dot{h} = V_t\sin\gamma$$

$$V_t = \sqrt{U^2 + V^2 + W^2}$$

$$\gamma = \theta - \alpha$$

$$\delta_E = \delta_{E\min} + \delta_e$$

----------- (1)

This parameter such defined δ_E is Elevator angle, δ_{Emin} is Elevator angle in trim condition, δ_e is Elevator angle Compared to amount of trim, δ_R is Rudder angel, δ_A is Aileron angle, **h** is height, Φ is Roll angle, is Pitch angle, Ψ is Side angle, P is Rate of Roll angle, Q is Rate of pitch angle, R is Rate of yaw angle, U Longitudinal velocity, **W** is Vertical velocity, **V** is Lateral velocity, **Vt** is the total Rate, α is Attack angle and β is lateral movement angle. Some variables of UAV are defined in the Figure 1. The purpose is design the Autopilot for height, which is capable to control the height of Aircraft by using the elevator height. Equation 1, shows the nonlinear behavior UAV. By linearization the nonlinear Equations around trim flight Cruise condition, nominal linear model for height be made in the Transfer Function or Equation 2.

$$\frac{h(s)}{\delta_e(s)} = \frac{-57.3(s-24.6)(s+21)(s+0.008)}{s(s^2+0.011s+0.022)(s^2+2.12s+98.4)}$$

----------- (2)

ISSN 2229-5518

It is assumed that the nominal linear model is a mathematical model, so that it developed based on Autopilot. The relationship between height output variable and input Elevator variable has unstable zero. Moreover flight characteristics in short period and Phugoid mode are undesirable.

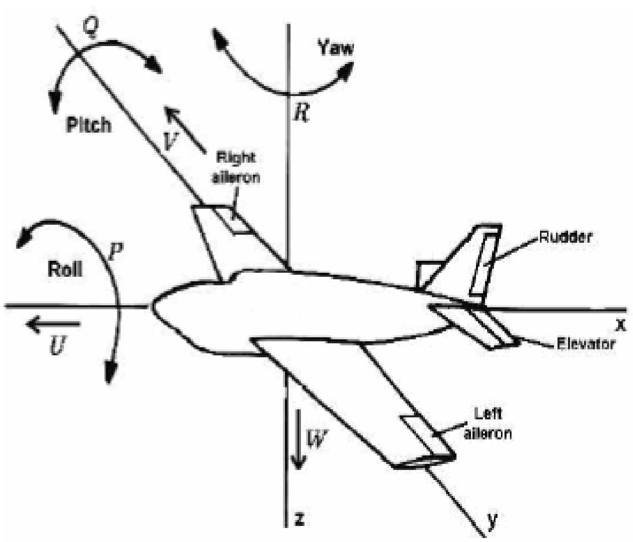


Figure 1: Flight Parameters of Unmanned Aircraft along the three coordinate

To investigate the strength parameter of autopilot, we used the linear non-nominal model. In linear non-nominal model we assume an important stability derivative such as C Du, C ma, C mq and CLu , shows as Table 1. With applying the change, the nominal non-linear Transfer Function model obtained as follows; by Equation 3.

$$\frac{h(s)}{\delta_e(s)} = \frac{-57.3(s-25.5)(s+21.6)(s+0.0017)}{s(s^2+0.0055s+0.021)(s^2+1.82s+64)}$$ ----------- (3)

3. Design of Classic Autopilot

In common, designed Autopilot for Height based on special structures that have three-ring. In this structure, the Rate of pitch angle, Pitch Angle and Height measured, such that Autopilot (Controller) for Pitch Angle is the inner loop for Height Autopilot, and the Rate controller of Pitch Angle is inner loop for pitch Autopilot. This makes the structure to be Robust against the complex parametric uncertainty. So should be designed **3** controllers and measured **3** variables. In this paper, the Pitch Angle and rate of Pitch – Angle becomes removed and we used a single-loop structure. In this simple structure, height measured just by the altimeter. In this section, the Angle and Height classic Autopilot, will designed for the nominal linear model. By using a nominal linear model and root locus method, the Compensator Transfer Function will design, it's Equation 4.

$$G_{C_b} = \frac{0.012(s+0.05)(s^2+2.12s+98.4))}{(s+20)(s^2+6s+15.25)}$$ ----------- (4)

In Compensator designing, a lot of efforts reduce the effects of an unstable zero. Phugoid and short period modes improved. In [3] and [12] also used this method to design compensator, by given ζ=0.6, ω_n = 2.31 in Figure 2.

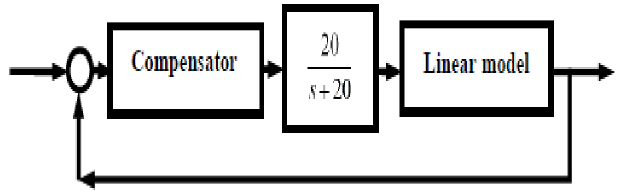


Figure 2: Control modes for design the height compensation

To evaluate the Autopilot, it is necessary to set the height and side angle to nominal linear model. The height is set to 10 meters, and the side angle is between 0 to10.

4. Design of PID Controller

Industrial PID controllers are usually available as a packaged, and it's performing well with the industrial process problems. The PID controller requires optimal tuning. Figure 3 shows the diagram of a simple closed-loop control system. In this structure, the controller (Gc(s)) has to provide closed-loop stability, smooth reference tracking, shape of the dynamic and the static qualities of the disturbance response, reduction of the effect of supply disturbance and attenuation of the measurement noise effect [26].

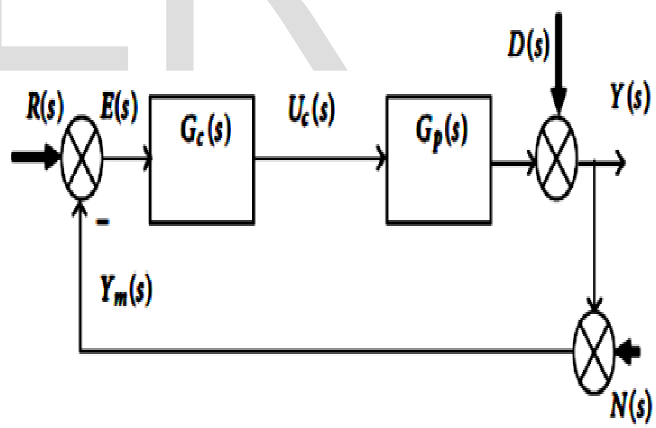


Figure 4: Closed-loop control system

In this study reference tracking, load disturbance rejection, and measurement noise attenuation are considered. Closed-loop response of the system with set point R(s), load disturbance D(s), and noise N(s) can be expressed as Equations 5.

$$Y(s)=\left[\frac{Gp(s)Gc(s)}{1+Gp(s)Gc(s)}\right]R(s)+\left[\frac{1}{1+Gp(s)Gc(s)}\right]D(s)-\left[\frac{Gp(s)Gc(s)}{1+Gp(s)Gc(s)}\right]N(s)$$

$$Y(s)=[T(s)*[R(s)-N(s)]+(S(s)*D(s)]$$ ---- (5)

Where the complementary sensitivity function and sensitivity function of the above loop are represented in Equation 6, respectively.

$$T(s)=\frac{Y(s)}{R(s)}=\left[\frac{Gp(s)Gc(s)}{1+Gp(s)Gc(s)}\right]$$

$$S(s)=\left[\frac{1}{1+Gp(s)Gc(s)}\right] \quad \text{----------- (6)}$$

The final steady state response of the system for the set point tracking and the load disturbance rejection is given in Equation 7, respectively:

$$y_R(\infty)=\lim sY_R(s)=\lim_{t\to\infty} sx\left[\frac{Gp(s)Gc(s)}{1+Gp(s)Gc(s)}\right]\left(\frac{A}{s}\right)=A$$

$$y_D(\infty)=\lim_{t\to\infty} sx\left[\frac{1}{1+Gp(s)Gc(s)}\right]\left(\frac{L}{s}\right)=0 \quad \text{----------- (7)}$$

Where *A* is amplitude of the reference signal and *L* is disturbance amplitude. To achieve a satisfactory *yR*(∞) and *yD*(∞), it is necessary to have an optimally tuned **PID** parameters. From the literature it is observed that to get a guaranteed robust performance, the integral Controller gain "*Ki*" should have an Optimized value. In this study, a no interacting form of PID (*GPID*) Controller Structure is considered. For real control applications, the Feedback Signal is the sum of the measured output and Measurement noise Component. A low pass filter is used with the derivative term to reduce the effect of measurement noise. The PID structures are defined as the following or Equation (8):

$$G_{PID}(s)=K_p e(t)+K_d\frac{de(t)}{dt}+K_i\int_0^t e(\tau)d(\tau)+K_p\left[1+\frac{1}{T_i s}+\frac{T_d s}{\frac{T_d s}{N}+1}\right] \quad \text{----------- (8)}$$

Kp/Ti = Ki, , *Kp * Td = Kd*, and *N* = filter constant

Cost Function In Optimization Algorithms as Equation 9,

$$O=w^1T_r+w^2M_p+w^3T_s \quad \text{----------- (9)}$$

In Cost Function, w1, w2, w3 respectively are the weight or important coefficient of system performance. Tr, Mp, Ts are the Rise Time, Maximum Over Shot and Settling Time. Suggested Cost Function makes all Coefficients and parameters be same, and caused more impact of characteristics [20].

4.1 Types PID Controller

In control theory the ideal PID controller in parallel structure is represented in the continuous time domain as in Equation (10)

$$u(t)=K_p e(t)+K_i\int_0^t e(\tau)d\tau+K_d\frac{de(t)}{dt} \quad \text{----------- (10)}$$

where: *Kp* - proportional gain, *Ki*- integral gain, *Kd*- derivative gain. A block diagram that illustrates given controller structure is shown in the Fig. 5.

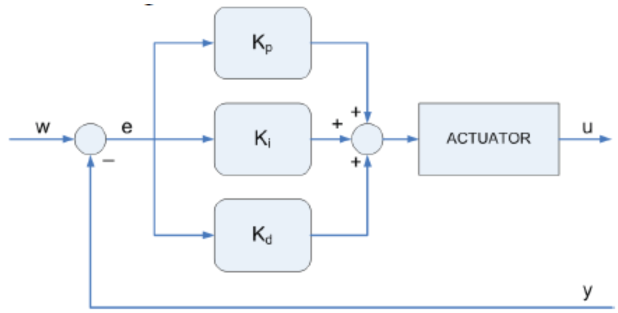


Figure 5: Type A PID controller

The problem with conventional PID controllers is their reaction to a step change in the input signal which produces an impulse function in the controller action. There are two sources of the violent controller reaction, the proportional term and derivative term. Therefore, there are two PID controller structures that can avoid this issue. In literature exists different names [21], [22]: type B and type C; derivative- of-output controller and set-point-on-I-only controller; PI-D and I-PD controllers. The main idea of the modified structures is to move either the derivative part or both derivative and proportional part from the main path to the feedback path. Therefore, they are not directly subjected by jump of set value, while their influence on the control reaction is preserved, since the change in set point will be still transferred by the remaining terms.

PID Controller – type B

It is more suitable in practical implementation to use "derivative of output controller form". The equation of type B controller is as in Equation (11),

$$u(t)=K_p e(t)+K_i\int_0^t e(\tau)d\tau-K_d\frac{dy(t)}{dt} \quad \text{----------- (11)}$$

A block diagram that illustrates given controller structure is shown in Fig. 6.

ISSN 2229-5518

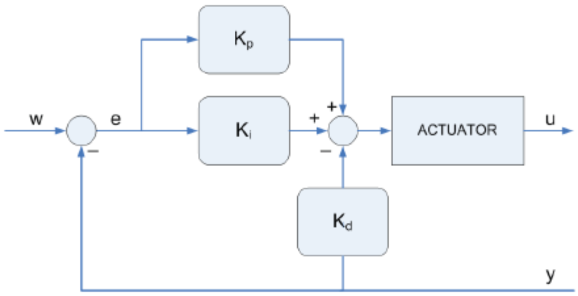


Figure 6: Type B PID controller

PID Controller – type C

This structure is not so often as PI-D structure, but it has certain advantages. Control law for this structure is given in Equation (12),

$$u(t) = -K_p y(t) + K_i \int_0^t e(\tau) d\tau - K_d \frac{dy(t)}{dt} \quad \text{----------- (12)}$$

Block diagram for type C controller is shown in Fig. 7.

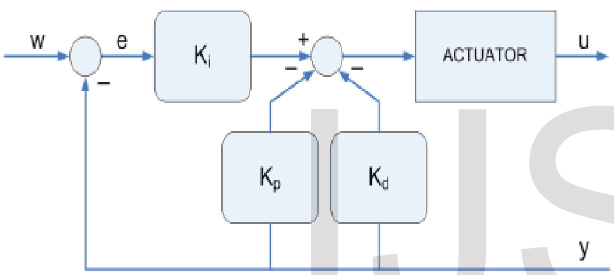


Figure 7: Type C PID controller

With this structure transfer of reference value discontinuities to control signal is completely avoided. Control signal has less sharp changes than with other structures.

5. Designing PID for Disturbance Rejection

The UAV model discussed in Equation 3 is reproduced as in Equation (13) with single stage unit.

$$G(s) = \frac{6(s+5)}{(s+1)(s+2)(s+3)(s+4)} e^{-s} \quad \text{----------- (13)}$$

The transfer function consists of single zero and four poles that are modeled in Matlab with output delay of 1 unit and gain of 6 units. With initial values set for PID controller the transient response is as shown Figure 8.

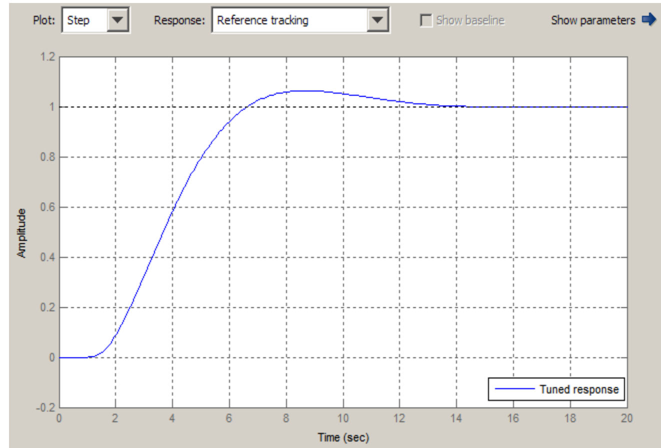


Figure 8: Plant response

Figure 9 shows the controller parameters for Kp and Kd, with rise time and settling time of 3.61 and 11.9 seconds. The overshoot is 6.28% and system is said to be stable.

Controller parameters

	Tuned
Kp	0.22729
Ki	0.22657
Kd	
Tf	

Performance and robustness

	Tuned
Rise time (sec)	3.61
Settling time (sec)	11.9
Overshoot (%)	6.28
Peak	1.06
Gain margin (db @ rad/sec)	10.7 @ 0.852
Phase margin (deg @ rad/sec)	60 @ 0.279
Closed-loop stability	Stable

Figure 9: Controller properties and parameters

The UAV which is stable is now disturber by an external signal, assuming that a step disturbance occurs at the plant input and the plant needs to reject disturbance during its stable flight. It is expected that the reference tracking performance is degraded as disturbance rejection performance improves. Because the attenuation of low frequency disturbance is inversely proportional to integral gain Ki, maximizing the integral gain is a useful heuristic to obtain a PI controller with good disturbance rejection [23]. The input disturbance is assumed to be a step function, the transient response is as shown in Figure 10, the peak deviation is about 1 and it settles to less than 0.1 in about 9 seconds [23].

ISSN 2229-5518

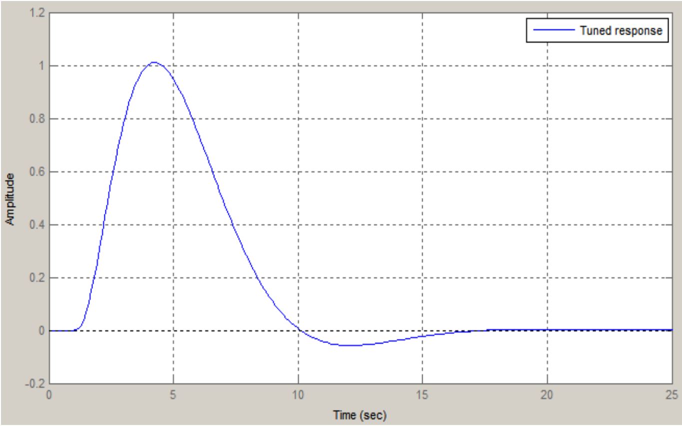
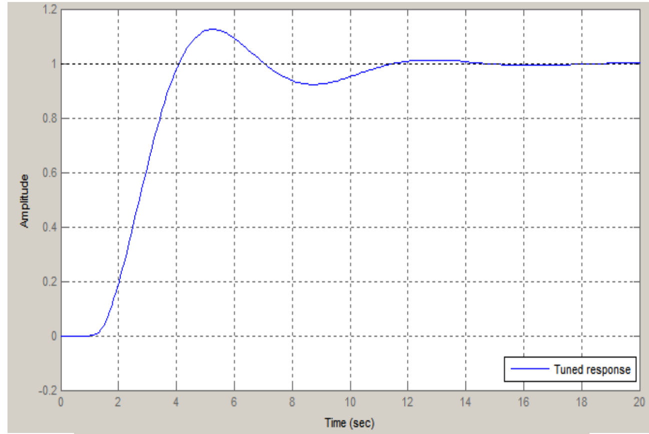


Figure 10: Input disturbance to be rejected by the system

The response speed (open loop bandwidth) need to be determined for rejection, Ki gain first increases and then decreases, with the maximum value occurring at 0.3. When Ki is 0.3, the peak deviation is reduced to 0.9 (about 10% improvements) and it settles to less than 0.1 in about 6.7 seconds (about 25% improvement). With increase in the bandwidth, the step reference tracking response becomes more oscillated. Additionally the overshoot exceeds 15 percent, which is usually unacceptable as shown in Figure 11. This type of performance trade-off between reference tracking and disturbance rejection often exists because a single PID controller is not able to satisfy both design goals at the same time [23].



Controller parameters

	Tuned
Kp	0.556
Ki	0.29798
Kd	
Tf	

Performance and robustness

	Tuned
Rise time (sec)	1.99
Settling time (sec)	10.8
Overshoot (%)	12.5
Peak	1.13
Gain margin (db @ rad/sec)	6.75 @ 1.02
Phase margin (deg @ rad/sec)	60 @ 0.422
Closed-loop stability	Stable

Figure 11 (a) Modified reference tracking response (b) Control parameters

Continuous-time PI controller in parallel form, from input "e" to output "u" with Kp = 0.64362 and Ki = 0.30314 is redesigned to reject step disturbances. A simple solution to make a PI controller perform well for both reference tracking and disturbance rejection is to upgrade it to an ISA-PID controller. It improves reference tracking response by providing an additional tuning parameters *b* that allows independent control of the impact of the reference signal on the proportional action. In the ISA-PID structure, there is a feedback controller C and a feed-forward filter F as shown in Figure 12.

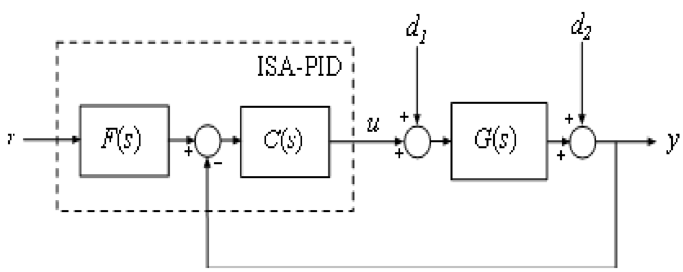


Figure 12 Modified PID controller with ISA-PID algorithm [23]

In this work, C is a regular PI controller in parallel form that can be represented by a PID object as in Equation (14),

ISSN 2229-5518

$$C(s) = pid(Kp, Ki) = Kp + \frac{Ki}{s}$$ ----------- (14)

F is a pre-filter that involves Kp and Ki gains from C plus the set-point weight **b** as in Equation (15),

$$F(s) = \frac{b * Kp * s + Ki}{Kp * s + Ki}$$ ----------- (15)

Therefore the ISA-PID controller has two inputs (r and y) and one output (u). Weight **b** is a real number and is set between 0 and 1. When b decreases, the overshoot in the reference tracking response is reduced. The modified transfer function is as in Equation (16),

Transfer function from input "r" to output "u":
0.4505 s^2 + 0.5153 s + 0.1428
----
s^2 + 0.471 s

Transfer function from input "y" to output "u": -----(16)
-0.6436 s - 0.3031
----
s

The reference tracking response with ISA-PID [23] controller has much less overshoot because set-point weight **b** reduces overshoot. Figure 13 shows the transient response of the modified PID controller.

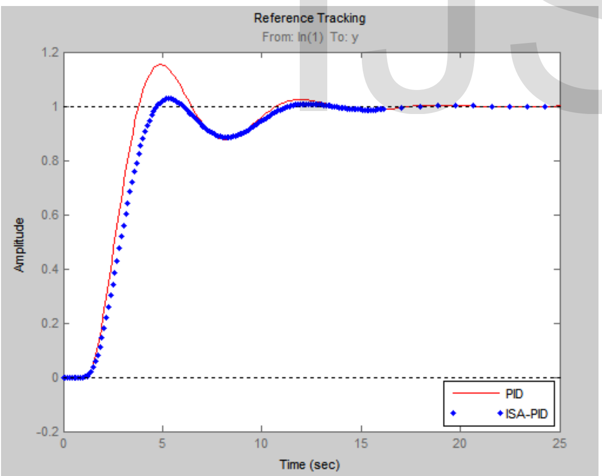


Figure 13: Transient response of ISA-PID controller

Figure 14 shows the disturbance rejection of PID and ISA-PID controller.

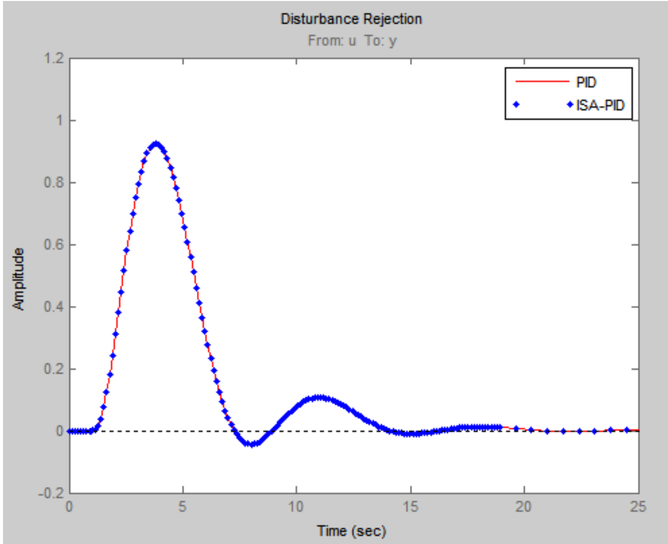


Figure 14: Disturbance rejection of PID controllers

The test results are extended to different set of MAV configurations, Figure 14 shows the bode plot of PID controller [23].

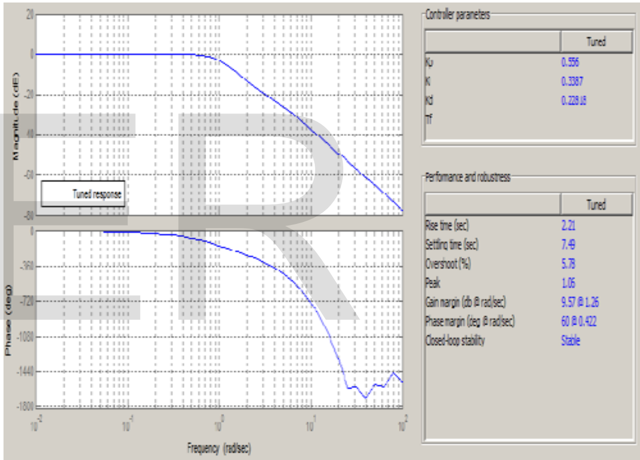


Figure 15 PID controllers with case 2 MAV configuration

6. Conclusion

Tuning the controller requires knowledge of the relationship between the input and output variables of the system to be controlled. Since the UAV is a complex nonlinear system, this relationship between the input signal and the output signal is not so simple. However around some operating point, the relationship between the signals can be described by a linear model. The results were obtained through simulations in Matlab and experiments on the model. The simulations possessed a key role, contributing to the tuning of the PID controller in a controlled environment. Both the simulations and the experiments, used the same reference signal or set-point signal, which is equivalent to performing a shift of the UAV in X and Y directions, returning to the initial position afterwards. Although PID controllers work well on Miniature Air Vehicles (MAVs), they require tuning for each MAV. Also, they quickly lose performance in the presence of actuator failures or changes in the MAV dynamics. Adaptive control algorithms that self tune to each

MAV and compensate for changes in the MAV during flight need to be explored.

Acknowledgements: The authors would like to acknowledge Mathworks for providing the design examples in preparing paper work. We also acknowledge R&D Centre, MSEC, Bangalore for the support and facility provided.

References

1. *Unmanned Aircraft Systems Roadmap 2005-2030*, Office of the Secretary of Defense, Aug. 2005.
2. S. E. A. P. Costa, "Controle e Simulação de um Quadrirotor Convencional", M.S. thesis, Tech. Univ. of Lisbon. Lisbon. 2008.
3. T. Bresciani, "Modelling, Identification and Control of a quad-rotor Helicopter", Lund Univ. Lund. 2008.
4. J. Domingues, "quad-rotor Prototype", M.S. thesis. Tech Univ of Lisbon, Lisbon. 2009.
5. Tayebi and S. McGilvray, "Attitude Stabilization of a VTOL Quadrotor Aircraft", IEEE Transaction on Control Systems Technology, Vol. 14, No. 3, pp. 562 – 571. 2006.
6. Alireza and M. Mortazavi. Designning Fuzzy Autopilot for U. A.V. Aerospace Mechanic Journal of I.R.of Iran, Vol 6, No3, pp 1-10, **(2011).**
7. K. poulos, I. Kokotovic, P. Morse and A.S. Systematic Design of Adaptive Controllers for Feedback Linearizable Systems.IEEE Transaction on Automatic Control Journal, Vol 36, No 11, pp 1241-1253, **(1991).**
8. Barkana. Classical and Simple Adaptive Control for Non-minimum Phase Autopilot Design AIAA. Journal of Guidance, Control and Dynamics Vol 28, No 4, pp 631-638, **(2005).**
9. J .Slotine, J.E and W.Li. Applied Non-linear Control. Printice-Hall Publisher, Englewood Cliffs, New Jersey, **(1991).**
10. P.K.A. Menon, M.E. Badget, R.A.Walker, and E.L Duke. Non-linear Flight Test Trajectory Controllers for Aircraft. AIAA Journal of Guidance Control and Dynamics. Vol 10, No 1, pp 67-72, **(1987).**
11. M. Tahk, M. Briggs, and P.K.A Menon. Application of Plant Inversion via State Feedback to Missile Autopilot Design. Proceeding IEEE Conf, Decision Control, Austin, Texas. pp 730-735, **(1986).**
12. M. Azam, and S.N. Singh. Inevitability and Trajectory Control for Non-linear Maneuvers of Aircraft. AIAA Journal of Guidance Control and Dynamics. Vol 17, No 1, pp 192-200, **(1994).**
13. D.J. Bugajski, and D.F. Enns. Non-linear Control Law with Application to High Angle-of-Attack Flight. AIAA Journal of Guidance Control and Dynamics, Vol 15, No 3, pp 761-769, **(1992).**
14. L.X. Wang. A Course in Fuzzy Systems and Control. Upper Saddle River, Prentice-Hall, New Jersey, **(1997).**
15. S.F. Wu, C.J.H. Engelen, R. Babuska, Q.P. Chu and J.A. Mulder. Fuzzy Logic Based Full- Envelope Autonomous Flight Control for an Atmospheric Re-Entry Spacecraft, Journal of Control Eng. Vol 11, No 1, pp 11-25, **(2003).**
16. B. Kadmiry, and D. Driankov. A Fuzzy Flight Controller Combining Linguistic and Model- Based Fuzzy Control. Journal of Fuzzy Sets and System. Vol 146, No 3, pp 313-347, **(2004).**
17. Cohen, and D.E. Bossert. Fuzzy Logic Non- minimum Phase Autopilot Design. AIAA Journal of Guidance, Navigation, and Control Conf and Exhibit. 11-14 August, Austin, Texas, (**2003).**
18. D.E. Bossert, and K. Cohen. PID and Fuzzy Logic Pitch Attitude Hold Systems for a Fighter Jet. AIAA Journal of Guidance, Navigation, and Control Conf and Exhibit, 5-8 August, Monterey, California, **(2002).**
19. T.H.S. Li, and M.Y. Shieh. Design of a GA- based PID Controller for Non minimum Phase Systems. Journal of Fuzzy Sets and Systems, Vol 111, No 2, pp. 183-197, **(2000).**
20. V. Rajinikanth and K. Latha. Tuning and Retuning of PID Controller for Unstable Systems Using Evolutionary Algorithm. International Scholarly Research Network ISRN Chemical Engineering Vol 5, No 3, pp 10 -21, **(2012)**
21. A. Visioli, "Practical PID Control", Springer-Verlag, London 2006
22. H. L. Wade, "Basic and Advanced Regulatory Control: System Design and application", ISA, United States of America, 2004.
23. http://www.mathworks.in/help/control/examples/designing-pid-for-disturbance-rejection-with-pid-tuner.html