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Research paper

Design of Robust & Predictive Controller for Altitude Stabilization and Trajectory Tracking of a Quad-Copter

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Abstract

Controlling the non-linear dynamics of the quad-copter has stimulated many control engineers to investigate & design the variety of controllers in order to control and stabilize the various aspects of quad copter such as the attitude, altitude, heading, xy position and even in trajectory following in the presence of disturbance. This is because of the quad-copter's application and importance in the variety of fields such as military, rescue, agriculture, surveillance, investigation, etc. Altitude control & stabilization problem of the quad-copter is the main focus of this research study. A dynamic and predictive controller is designed for the said problem based on Model predictive controller. In order to deal with the uncertainties & dynamics of the model during the flight operation and to ensure the robustness for the designed system, the sliding mode control technique is presented. Proportional-Integral-Derivative controller is also implemented for the system to make a comparative analysis with the rest of the designed controllers. Apart from controlling & stabilizing the altitude, these controllers are also capable for the trajectory tracking of the quad-copter. The six degree of freedom coupled model of quad-copter is taken into account and the same is then de-coupled for quad-copter hovering. In order to confirm the asymptotically stable state of the system, stability analysis of the proposed controller design is also done. The designed system is simulated in MATLAB/SIMULINK and also the comparison for robust and predictive controller is presented in order to depict the degree of potency of the proposed controller.

Keywords: Quadcopter, robust & predictive controller, altitude, trajectory tracking.

1. Introduction

Over the last few years, there have been a massive growth in the implementation and usage of remote controlled airborne vehicles, also called as quadcopter or quad rotor or drones. Among the various configurations of unmanned aerial vehicles such as fixed & rotary wings and Flapping & blimp wing UAVs, the quadcopter among the rotary wing UAVs has been remained under the investigation by different researchers. Quad rotor has become more useful and expedient for completion of different operations and variety of applications such as agriculture, rescue operations because of its features such as hovering and vertical takeoff and landing due to its nature and the way it can perform the different tasks for both military and civilian scenarios as mentioned in [1,2]. Also apart from these applications quad-rotors in their autopilot modes are also being utilized for research as well as industrial applications.

The hostile dynamics of quadrotor due to the moment of inertia present in the systems enforces the utilization of the efficient, dynamic & vigorous approach control so that quadrotor can be operated in optimum manner for fixed point hovering, VTOL and maneuvering. Since, not only the designing of the controller for the quadcopter is complicated task but the modeling of the nonlinear system itself is also complex task.

Different types of controllers including linear and nonlinear such as Linear Quadratic Regulator, Proportional Integral Derivative, Sliding Mode Controller have been incorporated and being implemented by using a variety of control algorithms to control different characteristics like altitude and attitude of quadcopter's nonlinear dynamical system. The altitude of flying robot was controlled by implementing the adaptive neuro PID controller with genetic algorithm by [3] and also same typed efforts were put by [4] by implementing the PID controller with genetic algorithm to have the nonlinear gain for controlling the altitude of the quadrotor and the mathematical designing and modeling of the dynamic system was also the main focus of this research. Similarly,[5] utilized a modified PID based controller to regulate the attitude factor of the quadrotor by controlling the roll, pitch and yaw angle in the presence of disturbances and also presenting the mathematical model of the nonlinear system. [6] presented the modeling of quadcopter attitude using Euler's angle description and the system is linearized at the hovering point for the designing of the PID controller in cascading mode to make the system stabilized at hovering point but the designed system was failed in achieving the full flight operation of quadcopter. In order to control the heading and attitude of the quadcopter, adaptive pole placement based self-tuned PID controller was implemented by [7] which showed well performance when parameters were tuned online. Beside PID controllers, MPC was also utilized for controlling the quadcopter dynamics as depicted in [8-11]. For tracking the chosen position Model predictive controller was implemented by [8] in order to control the rotational angles whereas [9] implemented the MPC for having the desired attitude of the dynamic system. In conjunction with implementation of MPC, this controller was used with well performance in the application of qaudrotor in dropping the payload carried while [11] used linear MPC for trajectory tracking of the quad copter with consideration of state and control constraints. The altitude of the quadcopter was controlled by implementing the Sliding mode controller by [12] with well performance whereas [13] developed the sliding mode controller and controlled both the altitude and attitude of the quadcopter.

The quadcopter is a nonlinear dynamical in nature and an unstable system. Newton-Euler method is implemented for formulating the system in terms of its mathematical model as it is being applied by many researchers in the literature. Six degree of freedom coupled model of quadcopter is formulated in this study which has been decoupled for the quadcopter hovering in order to fulfil the requirement of this paper. The model taken into account is under actuated system but its part having rotational mechanism is finely actuated when formulated and part having translational mechanism is under actuated. This paper aims to manage the altitude of the quadcopter by implementing the dynamic and predictive controller with the help of Model predictive controller. The same is also implemented by implying the sliding mode control to achieve the desired objective while ensuring the robustness. Apart from controlling & stabilizing the altitude, these controllers are also capable for the trajectory tracking of the quad-copter.

The paper is organized as follows: section 2 provides the formulation of the nonlinear dynamical system of quadcopter whereas section 3 presents the formulation of control technique using MPC, SMC & PID controllers and the stability analysis is given in section 4. Section 5 is presented with the simulation results of the said controllers for the designed system and the final concluding statements are presented in section 6.

2. Modeling of Quadrotor

As mentioned above, the Newton-Euler equations have been utilized in the paper for formulating the non-linear dynamics of the Quadcopter as the same is derived and used by [1, 4 and 11]. Since it is a six degrees of freedom with multi-input and multi-output under actuated system. Two propellers in Quadrotor describes the x & y axis of the body frame while the z-axis pointing towards the ground. Inertial frame is considered as Earth frame of reference while the body frame points the center of quadcopter body. The quadrotor's orientation is described by the rotation R_{bi} i-e, rotation from body to initial fame. The orientation and the absolute position of the quadcopter may be represented by $[\phi \quad \theta \quad \psi]$ (roll angle, pitch angle & yaw angles) and $[x \quad y \quad z]$ notations respectively. The derivation for mass Rotation matrix R_{bi} is dependent on the series of principal rotations and given below in (1) [1,4,11] while considering the rotation of roll angle, pitch angle and yaw angle about the x-axis, y-axis and z-axis respectively in the orientation of the quadcopter may be depicted from Figure 1.

$$R_{bi} = \begin{pmatrix} c(\theta)c(\phi) & s(\phi)s(\theta)c(\psi) & c(\phi)s(\theta)c(\psi)+s(\phi)s(\psi) \\ c(\theta)s(\phi) & s(\phi)s(\theta)s(\psi)+c(\theta)c(\psi) & c(\phi)s(\theta)s(\psi)-s(\theta)c(\psi) \\ -s(\theta) & s(\phi)c(\theta) & c(\phi)c(\theta) \end{pmatrix} \quad (1)$$

In order to have the information regarding quadcopter's angular velocity Euler rates $\dot{\eta}$ and anglular body rates ω are related as:

$$\omega = R\dot{\eta} \quad (2)$$

where $\omega = [p \quad q \quad r]^T$ and $\dot{\eta} = \left[\dot{\phi} \quad \dot{\theta} \quad \dot{\psi}\right]^T$ are measured in body frame and initial frame respectively and R is given as:

$$R = \left(1 \quad 0 \quad -s(\theta); \quad 0 \quad c(\phi) \quad s(\phi)c(\theta); \quad 0 \quad -s(\phi) \quad c(\phi)c(\theta)\right) \quad (3)$$

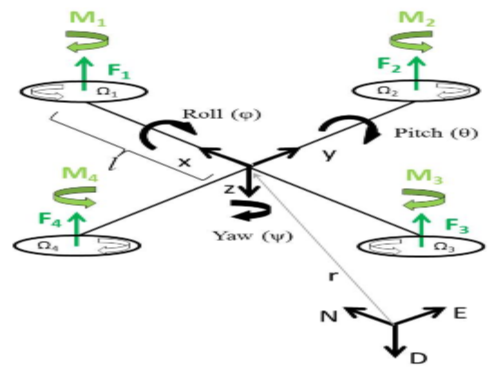


Fig. 1. Rotation of roll angle, pitch angle and yaw angle about the x-axis, y-axis and z-axis respectively

2.1. Dynamic Model

Since the rotational part of the quadcopter is described by the $[\phi \quad \theta \quad \psi]$ angles while the translational part of the same system is described by the x and y position and altitude. Newton Euler's method provides the basis to derive the rotational equations in the body frame as [13, 14]:

$$J_{qi}\dot{\omega} + \omega \times J_{qi}\omega + M_g = M_b \quad (4)$$

$$\omega \times J_{qi}\omega + J_{qi}\dot{\omega} + \omega \times [0 \quad 0 \quad J_r \quad \Omega_r]^T - M_b = 0$$
(5)

$$\Omega_r = -(\Omega_1 - \Omega_2 + \Omega_3 - \Omega_4) \quad (6)$$

Where J_{qi} is diagonal inertial matrix of Quadrotor, ω & $\dot{\omega}$ are angular and rate of change of angular velocity respectively, M_g is the gyroscopic moments caused by the rotors inertia, M_b represents body frame moments while acting on the quadrotor, J_r is the inertia of the rotor, Ω_r is the relative speed of the rotor and Ω_i is the angular velocity of i_{th} rotor. The orientation parameters of the quadcopter are approximated and can be found as [1,4]:

$$\ddot{\phi} = b_{1\_r}U_{2q} - a_{2\_r}x_{4q}\Omega_r + a_{1\_r}x_{4q}x_{6q} \quad (8)$$

$$\ddot{\theta} = b_{2\_r}U_{3q} + a_{4\_r}x_{2q}\Omega_r + a_{3\_r}x_{2q}x_{6q} \tag{9}$$

$$\ddot{\psi} = b_{3\_r}U_{4q} + a_{5\_r}x_{2q}x_{4q} \tag{10}$$

Apart from the rotational system of the quadrotor in the body frame, the translational part is also derived in the Earth frame concentrated on the Newton's 2nd law and translational equations are given as according to [13]:

$$m(\ddot{x};\ddot{y};\ddot{z}) = (0;0;mg) + \left(-(U_{1q}s\phi s\psi + U_{1q}c\phi c\psi s\theta); -(U_{1q}c\phi s\psi s\theta - U_{1q}c\psi s\theta); -U_{1q}c\phi c\theta\right) \tag{11}$$

where m is the mass of quadrotor, g is the acceleration due to gravity. From (11), the acceleration terms ($\ddot{x}$, $\ddot{y}$, $\ddot{z}$) can easily be obtained.

2.2. State-Space model of the system

To reach the problem as simpler, the state space is formulated and here in this case linear & angular velocities as well as quad copter's position in space is defined by the state vector. Four input vector of quadcopter is given as:

$$U_q = \begin{pmatrix} U_{1q} & U_{2q} & U_{3q} & U_{4q} \end{pmatrix} \tag{12}$$

Where U_{1q} is input for the system hovering and altitude, U_{2q} , U_{3q} and U_{4q} are the inputs for orienting the quadrotor and used for the roll, pitch and the yaw angles of the quadcopter respectively. Equation (11) can be decomposed into acceleration terms and may be written in terms of state variables as given in [1, 4]:

$$\ddot{x} = -\frac{U_{1q}}{m}(sx_{1q}sx_{5q} + cx_{1q}cx_{5q}sx_{3q}) \tag{13}$$

$$\ddot{y} = -\frac{U_{1q}}{m}(cx_{1q}sx_{5q}sx_{3q} - cx_{5q}sx_{1q}) \tag{14}$$

$$\ddot{z} = g - \frac{U_{1q}}{m}(cx_{1q}cx_{3q}) \tag{15}$$

Now the state vector for quadcopter system in general form and system state space representation based on (8) to (10) and (13) to (15) is given in (16) and (17) respectively [1, 4, 11]:

$$X_q = \begin{pmatrix} \phi_q & \dot{\phi}_q & \theta_q & \dot{\theta}_q & \psi_q & \dot{\psi}_q & z_q & \dot{z}_q & x_q & \dot{x}_q & y_q & \dot{y}_q \end{pmatrix}^T \tag{16}$$

$$f_q(X_q, U_q) = \begin{pmatrix} x_{2q}; b_{1\_r}U_{2q} - a_{2\_r}x_{4q}\Omega_r + a_{1\_r}x_{4q}x_{6q}; x_{4q}; b_{2\_r}U_{3q} + a_{4\_r}x_{2q}\Omega_r + a_{3\_r}x_{2q}x_{6q}; x_{6q} \\ b_{3\_r}U_{4q} + a_{5\_r}x_{2q}x_{4q}; x_{8q}; g - \frac{U_{1q}}{m}(cx_{1q}cx_{3q}); x_{10q}; -\frac{U_{1q}}{m}(sx_{1q}sx_{5q} + cx_{1q}cx_{5q}sx_{3q}) \\ x_{12q}; -\frac{U_{1q}}{m}(cx_{1q}sx_{5q}sx_{3q} - cx_{5q}sx_{1q}) \end{pmatrix} \tag{17}$$

2.3. De-coupling for hovering

By keeping in view the objective of this paper, the derived mathematical model is de-coupled for quadcopter hovering. In order to have this, few assumptions are made so that quadcopter has stable hovering. As there are no any aero dynamical lifting surfaces therefore aerodynamic moments and forces are assumed to be negligible [1, 4, 11]. Mathematically, these assumptions are given as below and based on these assumptions the system in (11) may be reduced as given in (18).

$$\dot{\phi}_q = \dot{\theta}_q = \dot{\psi}_q = 0,\ \phi = \theta = \psi = 0,\ c\phi = c\theta = c\psi = 1\ \&\ s\phi = s\theta = s\psi = 0$$

$$m(\ddot{x};\ddot{y};\ddot{z}) = (0;0;mg) + (0;0;-U_{1q}c\phi c\theta) \tag{18}$$

This equation makes the designing of controller bit easy as well as robustness of the system may also be analyzed. Since the system derived in (18) is highly unstable having nonlinear dynamics.

3. Control design

Altitude controller is developed to make the system stable in hovering. A generalized block diagram for the altitude controller is depicted in Figure 2.

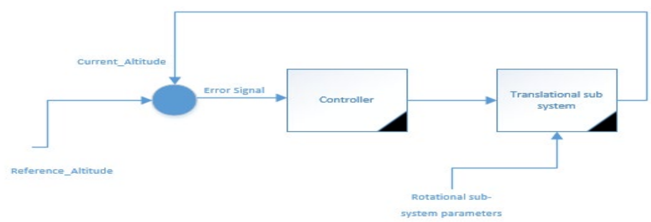


Fig.2. Block diagram of Altitude controller.

In current paper, altitude controller is modelled and designed based on Model predictive controller as well as Sliding mode controller in order to present the degree of potency and effectiveness of the controller as judged from the results. Apart from this, the same controller is also implemented using PID controller to having more analysis and justification of results. Now we discuss the individual controller design for the altitude control system.

3.1. Proportional Derivative Integral Controller

A PID controller is designed and implemented for controlling the altitude of the quad rotor. The output generated by the PID controller is u_{pid} and the desired altitude is represented here as z_{da} so the equation of PID controller which is implemented is given as:

$$u_{pid} = k_p(z_a - z_{da}) + k_d(\dot{z}_a - \dot{z}_{da}) + k_i\int(z_a - z_{da})dt \tag{19}$$

Where k_p , k_d and k_i are the proportional, derivative and integral gains of PID controller respectively, z_a , z_{da} and $\dot{z}_{da}$ are the altitude, desired altitude and the rate of change of the desired altitude respectively.

3.2. Model Predictive Controller

According to [15], an unambiguous process model is utilized by the model predictive controller where the control variable values are computed as future value so as the response of the model can be predicted in the future. Optimization is performed by the MPC inside the moving horizon window where the plant information has been provided in the beginning. A reference model is given to the controller for following it and forcing the system to move in conjunction with the reference model. The responsibility of the controller is to derive the error between the actual and desired values of the attitude to zero value or at least as minimum as possible value. The optimization problem to be solved by the MPC is codifies ad:

$$J_a = \sum_{j=1}^{N_{ph}} \Big(\big(z_{da}(k_j+p\,|\,k_j) - z_a(k_j+p\,|\,k_j)\big)^T \big(z_{da}(k_j+p\,|\,k_j) - z_a(k_j+p\,|\,k_j)\big) \Big) + \eta_{mpc}^T \Lambda_l \eta_{mpc}^T \tag{20}$$

Where z_{da} and z_a are the desired system response and actual system response respectively.

3.3. Sliding Mode Controller

SMC controller algorithm is implemented in such a way that state trajectories are compensated when they have the variations from reaching the sliding surface. Apart from this compensation the time derivative of the sliding surface is ensured to keep it on zero value in order to stay of trajectories on the sliding surface. Since the vertical input U_{1q} is the input that is responsible to control the altitude of the quadcopter in the desired manner. When implemented the SMC controller for the quadcopter altitude, the output generated by the SMC controller is u_{smc} given as [1]:

$$u_{smc} = \frac{m}{\mathrm{c}\phi c\theta}\left(k_b s + k_a \,\mathrm{sgn}(s) + c(\dot{z}_a - \dot{z}_{da}) + g - \ddot{z}_{da}\right) \tag{21}$$

Where s is the sliding surface given as $s = \dot{e} + ce$ and here e is the error term defining the difference between altitude and the desired one.

4. Stability

In this section we present the stability analysis for both the MPC and SMC controller to guarantee the stability of the designed algorithm. Since the stability of the designed algorithm may be confirmed from the analysis of simulation results that output is reaching to steady state value without exhibiting any oscillatory response. Apart from this, lyapunov function is defined for proving the asymptotic stability of the Model predictive controller as given in [16, 17] which is defined as:

$$V(x(k+1),k+1) - V(x(k),k) \le -x(k_j+1)^T S\, x(k_j+1) - \Delta u(k_j)^T \Lambda_l\, \Delta u(k_j) < 0 \tag{22}$$

The condition number for the designed algorithm is 2.04 x10^4 indicating numerically well-conditioned algorithm without using exponentially increasing or decreasing weights but it can be improved by introducing the exponential weights in the cost function according to [17]. As for as designed algorithm of SMC controller is concerned, the sliding surface is defined as:

$$\vartheta = S_S^T X_{state} \ \text{ or } \ \vartheta = \begin{pmatrix} s_1 & s_2 \end{pmatrix}\begin{pmatrix} z - z_d \,;\, \dot{z} - \dot{z}_d \end{pmatrix} \tag{23}$$

Sliding surface is chosen such that $\lim_{to\to\infty} \dot{\vartheta} \to 0$ i.e; $\lim_{to\to\infty} \vartheta \to 0$ and this shall ensure that state error vector tends to zero with respect to time as time tends to infinity. Now the lyapunov function for the SMC stability is considered to be as follows as given in [18]:

$$V(\vartheta) = \frac{1}{2}(\vartheta)^2 \tag{24}$$

The condition number is determined in order to achieve the chosen value of sliding surface, $\dot{V}(\vartheta)$ can be extracted negative definite as:

$$\dot{V}(\vartheta) = \vartheta\dot{\vartheta} \le -\eta_{smc}^2 \left|\vartheta\right|^2 \tag{25}$$

Since the condition in the (25) ensures the convergence of the system trajectories towards the sliding surface within finite time period.

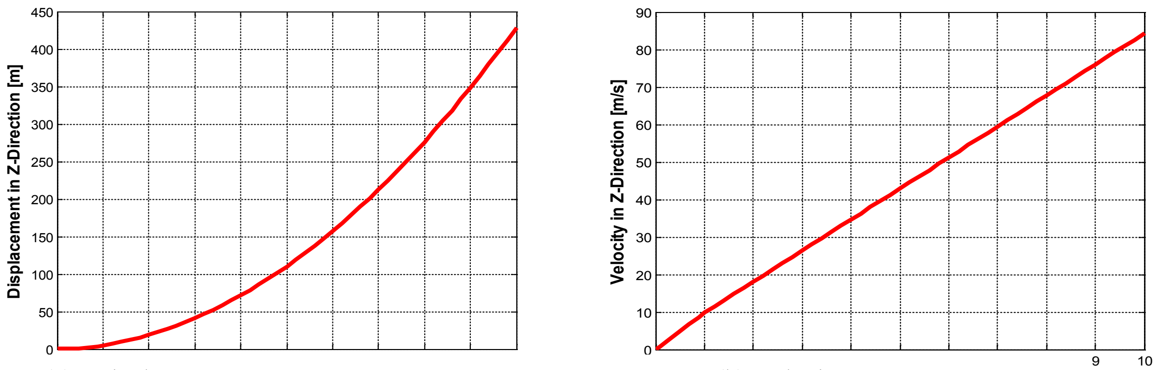
5. Simulations & Results

The formulated system and the designed controller are simulated using MATLAB software. The simulation results are presented by simulating the open loop response of the system first and rest of the simulations presented for the controller design for PID, MPC and SMC. Apart from MPC and SMC, the PID controller is implemented for comparison and analysis purpose. The open loop response of the system derived in (18) is shown in Figure 3 which clearly indicates the highly unstable & nonlinear dynamics as well as the correctness of the derived system model. The task of the altitude controller is to stabilize the height of the quadcopter. Simulation of the derived system is performed for all three controllers PID, MPC and SMC are shown in Figure 4, Figure 5 and Figure 6 respectively. The response of the system indicates that system settles down without any oscillations and smoothly with SMC controller while there is a bit oscillatory response in the initial period with the MPC controller and then settles down quickly as compared to system response implemented with PID controller.

PID controller takes more time to reach steady state value as compared to the other controllers. SMC among all three controllers is more robust as shown by its response given in Figure 6. MPC controller provides the future moves of the controller based on the current and past data and hence depicted the system response shown in Figure 5 which is settling down after some initial overshoot which is very small. The parameters selected for all three controllers for the simulation are given in Table 1. Since the designed controllers are also capable of following the trajectory provided. Figure 7 shows the performance of PID controller for following the reference trajectory as it is oscillatory when the direction of the trajectory is changing. Beside PID controller, MPC has much better performance in following the trajectory with minimum oscillatory response when the reference trajectory is being changed but having a bit delay as shown in Figure 8.

Table 1. Controller parameters

PID Controller		**MPC Controller**		**SMC Controller**	
K_p	8.85	N_{ch}	3	K_a	18
K_i	1.65	N_{ph}	80	K_b	14
K_d	5.06	R	0.3	c	4



(a) Displacement (b) Velocity

Fig. 3. Open loop system response

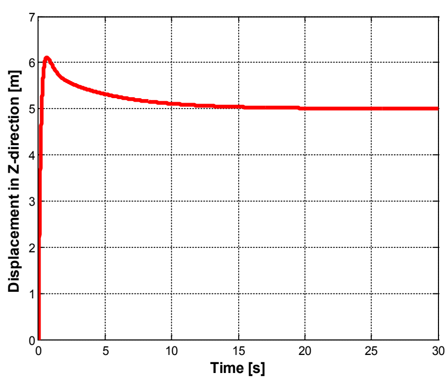


Fig.4. System response with PID

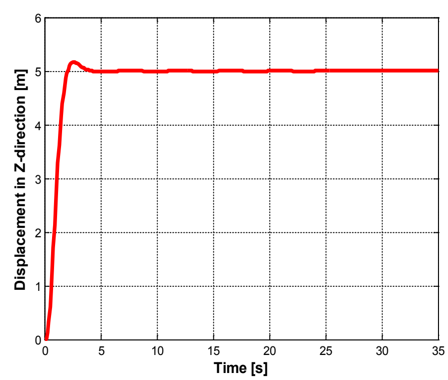


Fig. 5. System response with MPC

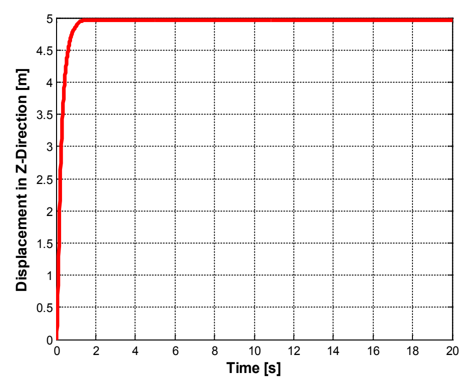


Fig. 6. System response with SMC

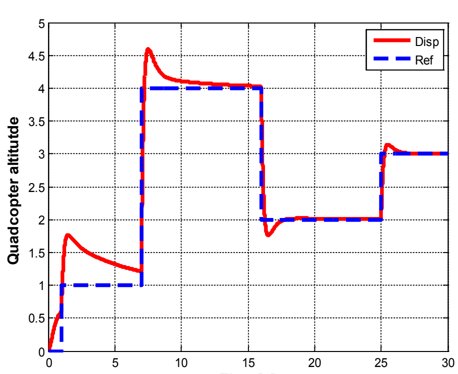


Fig. 7. Reference Trajectory by PID

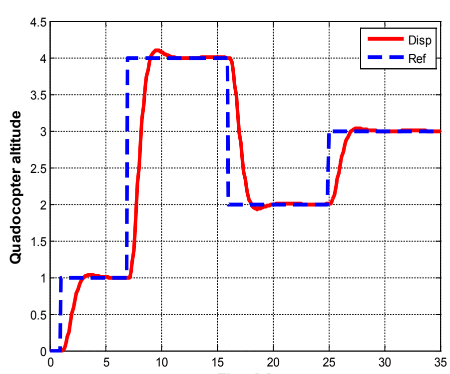


Fig. 8. Reference Trajectory by MPC

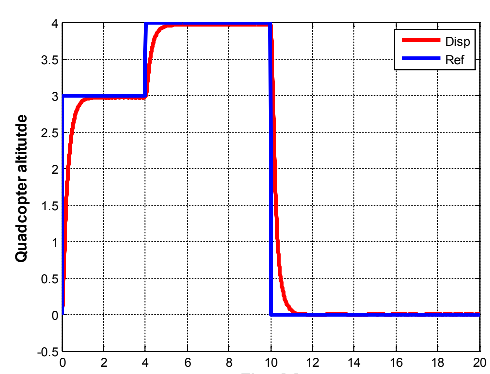


Fig. 9. Reference Trajectory by SMC

As compared to both PID and MPC controller, SMC has proved its robustness and its ability to deal with un-certainties, the way it is following the reference trajectory shown in Figure 9. SMC response having negligible oscillations and having minimum delay as compared to MPC.

6. Conclusion

Six degree of freedom quadcopter model is presented which is then de –coupled for its hovering. To control the non-linear and unstable dynamics of the quadcopter for its altitude, Model predictive controller and sliding mode controller is designed for not only controlling its altitude but also for following the reference trajectory. Open loop system response is presented first to show the nonlinear dynamics of the de-coupled system and then graphs of simulation are presented to show the potency effectiveness, the robustness and the predictive nature of the controllers. Simulation results showed that both MPC and SMC are capable of controlling its altitude also able to follow any reference trajectory being provided for the flight operation but in comparison to both these two SMC results are more robust and efficient with respect to delay, oscillations and overshoots. Apart from these two controllers PID is also implemented for the comparison and analysis purpose and the results showed MPC is better than PID and SMC is much better than both these two. Stability analysis is also made using lyapunov stability function which confirms the asymptotically stability of the designed algorithm as well as convergence of the system trajectories.

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8. References

[1] V.K. Tripathi, L. Behera and N. Verma. Design of Sliding Mode and Backstepping Controllers for a Quadcopter. Proceedings of the 39th National Systems Conference (NSC), **(2015)** December; pp. 1-6, IEEE.

[2] A. Azzam and X. Wang, Quad Rotor Arial Robot Dynamic Modeling and Configuration Stabilization. Proceeding of the 2010 2nd International Asia Conference on Informatics in Control, Automation and Robotics (CAR), **(2010)** March; Vol. 1, pp. 438-444, IEEE.

[3] M. Fatan, B.L. Sefidgari and A.V. Barenji. An Adaptive Neuro PID for Controlling the Altitude of Quadcopter Robot. Proceedings of the 18th International Conference on Methods and Models in Automation and Robotics (MMAR), **(2013)** August; pp. 662-665, IEEE.

[4] K. Khuwaja, N.Z. Lighari, I.C. Tarca and R.C.Tarca. PID Controller Tuning Optimization with Genetic Algorithms for a Quadcopter. Recent Innovations in Mechatronics (RIiM), Vol. 5, No. 1, **(2018).**

[5] E. Paiva, J. Soto, J. Salinas and W. Ipanaqué. Modeling, Simulation and Implementation of a Modified PID Controller for Stabilizing a Quadcopter. Proceedings of the IEEE International Conference on Automatica (ICA-ACCA), **(2016)** October; pp. 1-6, IEEE.

[6] N. Bao, X. Ran, Z. Wu, Y. Xue and K. Wang. Research on Attitude Controller of Quadcopter based on Cascade PID Control Algorithm. Proceedings of the 2017 IEEE 2nd Information Conference on Technology, Networking, Electronic and Automation Control Conference (ITNEC), **(2017)** December; pp. 1493-1497, IEEE.

[7] J. Yang, Z. Cai, Q. Lin and Y. Wang, Self-tuning PID Control Design for Quadrotor UAV based on Adaptive Pole Placement Control. Proceedings of the Chinese Automation Congress (CAC), **(2013)** November; pp. 233-237, IEEE.

[8] G.V. Raffo, M.G. Ortega and F.R. Rubio. An Integral Predictive/Nonlinear H∞ Control Structure for a Quadrotor Helicopter. Automatica, 46(1), pp.29-39, **(2010).**

[9] K. Alexis, G. Nikolakopoulos and A. Tzes. Switching Model Predictive Attitude Control for a Quadrotor Helicopter Subject to Atmospheric Disturbances. Control Engineering Practice, 19(10), pp.1195-1207, **(2011)**

[10] I. Sadeghzadeh, M. Abdolhosseini and Y.M. Zhang. Payload Drop Application of Unmanned Quadrotor Helicopter using Gain-Scheduled PID and Model Predictive Control Techniques. Proceedings of the International Conference on Intelligent Robotics and Applications **(2012)** October; pp. 386-395, Springer, Berlin, Heidelberg.

[11] G. Ganga and M.M. Dharmana. MPC Controller for Trajectory Tracking Control of Quadcopter. Proceedings of the International Conference on Circuit, Power and Computing Technologies (ICCPCT), (**2017)** April; pp. 1-6, IEEE.

[12] S. Bouabdallah and R. Siegwart. Backstepping and sliding-mode techniques applied to an indoor micro quadrotor. In Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on, pages 2247-2252, **(2005)**. doi: 10.1109/ROBOT.2005.1570447.

[13] A. Nagaty, S. Saeedi, C. Thibault, M. Seto and H. Li. Control and Navigation Framework for Quadrotor Helicopters. Journal of Intelligent and Robotic Systems, 70(1-4), pp.1-12, **(2013).**

[14] D. Gautam and C. Ha. Control of a quadrotor using a smart self-tuning fuzzy PID controller. International Journal of Advanced Robotic Systems, 10(11), p.380, **(2013).**

[15] S.J. Qin and T.A. Badgwell. A Survey of Industrial Model Predictive Control Technology. Control Engineering Practice, 11(7), pp.733-764, **(2003)**

[16] L.Wang “Discrete-time MPC with Constraints”, Advances in Industrial Control, pp 43-84, **(2009).**

[17] H. H. Memon, B. S. Chowdhry and M. Aamir. Optimal power dispatch using model predictive control for energy deficit countries. *13th International Bhurban Conference on Applied Sciences and Technology (IBCAST)*, Islamabad, pp. 245-250, **(2016).**

[18] U. Adeely, A. A. Zaidiz and A. Y. Memon, "Path tracking of a heavy weight torpedo in diving plane using an output feedback sliding mode controller," *12th International Bhurban Conference on Applied Sciences and Technology (IBCAST)*, Islamabad, pp. 489-494, **(2015).**