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Simulation-based Assessment of Quadrotor Linear Control Schemes

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Abstract*: This work aims at finding the most suited control scheme for a typical quad-rotor. Selecting the appropriate controller is essential to achieve system stability. The most common control schemes are compared in terms of their performance in hovering mode. The quad-rotor propellers are modeled based on both momentum theory and blade element theory. The model describing the six-degrees of freedom system is used to develop a control strategy using different types of controllers such as PID, Fuzzy, Optimal, LQ), as well as LQR controller. The current work is confined to linear control schemes in hovering flight mode, where the comparison is based on achieving stable attitude in hovering. The simulation results show that the LQR controller is the most efficient control method to minimize the steady-state error.

Keywords: Modeling and simulation, quad-rotor control, fuzzy-PID logic, LQR control

I. INTRODUCTION

The quad-rotor helicopter's structure of is simple, rigid and symmetric. It consists of four rotors allocated at the ends of a symmetric cross [1, 2]. The symmetry is of considerable significance for stability where the center of gravity should be as much close to the middle of the rotorcraft as probable. In addition, rigidity is required to avoid unstable flight. preserving the lightest possible weight is achieved through lightweight alloys or composites. The motors spin the propellers so as to offer lifting thrust to the quad-rotor [3]. Selecting the suitable propellers is essential to produce proper thrust without overheating the target motors. Quad-rotors practically entirely utilize brushless DC motors, in order to provide thrust-to-weight ratios superior to brushed DC motors. Nevertheless, they necessitate more complex speed controllers. Two ratings namely KV ratings and current ratings are normally given to test motors [4]. The motors of quad-rotors have to all spin at accurate speeds to attain precise flight. Therefore, Electronic Speed Control (ESC) is very important [4]. The ESC informs the motors how fast to rotate at any specified time. Each motor in a quad-rotor needs one ESC. The ESCs are then linked straight to the battery via either a wiring harness or power distribution board. These speed controllers receive commands as PWM signals and give a proper motor speed. Many ESCs includes a built-in battery eliminator circuit, which permits operating the flight control board and radio receiver with need for a direct connection to the battery. Lithium Polymer (LIPO) batteries are utilized solely due to their high precise energy [5]. RC transmitter sends radio signals to the radio receiver (Rx) as well as transforms them into control signals for each control channel (throttle, yaw, roll & pitch). The flight controller which is called the "brain" of the quad-rotor executes the required operations to retain the quad-rotor steady and manageable. It receives user control commands from the Rx, associates them with readings received from the attitude sensors, and computes the essential motor output. It comprises of sensors as gyroscopes and accelerometers that conclude how fast each motor of the quad-rotor rotates. The attitude sensor sends the flight controller readings of the quad-rotor orientation in space. This minimally requires a gyroscope, but most quad-rotors also integrate an accelerometer in order to achieve self-stabilizing quad-rotor. A 6-axis inertial measurement unit comprising of a gyroscope and accelerometer on the same board is needed for a quad-rotor application [6].

multivariable and nonlinear systems are among the challenges facing the control of quad-rotor, it has four actuators and six degrees of freedom. This indicates that it is an under-actuated system [7]. Controlling quad-rotor is achieved through changing the speeds of the motors. Due to the fact that the system dynamics require continuous alteration of its motors instantaneously, uncontrolled flight of a quad-rotor seems impossible by one operator.

Quadrotor development has attained popularity amongst researchers [8]. Several researchers have worked towards determining the best control method of quad-rotors by comparing different methods [9-12]. However, the number of the compared methods was limited to a maximum of four. Therefore, many available control schemes were not considered. Zulu and John [19] reviewed the existing control algorithms for quadrotors. However, they have not provided any simulation results, as their comparison was based on qualitative data. In this work, for the purpose of comparing control schemes, a quad-rotor model based on momentum and blade element theories is used, where a vertical wind disturbance is applied to the quad-rotor during a hovering maneuver. The responses of the model to the control schemes are compared in order to find the best suited control method.

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II. QUAD-ROTOR MODEL

The speed of motors determines the flight conduct of quad-rotor. They vary in rotation with or against each other. According to its input, the system's model could be employed to envisage the quad-rotor's position and direction. It can also be utilized to improve a strategy through which controlling the velocity of each engines leads to attaining the preferred motion.

The usage of diverse coordinating frames is indispensable for determining the quad-rotor's position and attitude. For illustration, evaluating the equations of motion requires attaching a coordinate frame to the quad-rotors. Nonetheless, the forces and moments performing on the quad-rotor and the IMU sensor values are assessed regarding the frame of body. Lastly, the location and speediness of the quad-rotor are assessed utilizing GPS measurements in connection with an inertial frame positioned at the main station. The key reference frames are demonstrated in Figure 1. They are the inertial frame (i.e.,F_i=(X_i, Y_i, Z_i)) which is a terrain static synchronizing system with the source positioned on the ground, the body frame (i.e.F_b=(X_b, Y_b, Z_b) which is placed at the CG of the quad-rotor, and the vehicle frame (i.e. F_v=(X_v, Y_v, Z_v)) which is the vehicle frame with the source positioned at the CG of the quad-rotor. Interpretation and spinning matrices are utilized to convert one coordinating reference frame into a new needed reference frame. For instance, the transformation from F_i to F_v affords the displacement trajectory from the source of the inertial frame to the CG of the quad-rotor. In addition, the transformation from F_v to F_b rotation yields the roll, pitch and yaw angels.

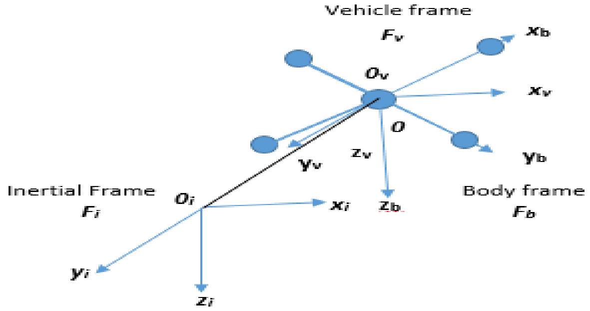

Fig. 1: The key frames of reference: inertial, body and vehicle .

The position and orientation of quad-rotor's referred to them as (P) and (Ω) respectively within a given frame *F* are defined in Equations 1 and 2:

$$P^T_F = [P_x, P_y, P_z] \qquad (1)$$

and

$$\Omega^T_F = [\varphi, \Theta, \psi] \qquad (2)$$

The dynamic model of the quad-rotor was built using Newton-Euler formalism based on certain assumptions: a) The quad-rotor body structure is a rigid, b) the quad-rotor frame is symmetrical and c) the CG accords with the midpoint of the quad-rotor's rigid frame. To calculate the moment of inertia, it is assumed that the quad-rotor as an essential domain of radius *r* and mass *Mo* encircled by main point masses demonstrating the motors. All motors are assumed to have a mass *m* connected to the dominant sphere via an arm of length *l*. [13-15]. The quad-rotor's total mass is represented by *M*.

The forces influencing the quad-rotor comprise the aerodynamic lift produced by all rotors, and the gravitational force performing in opposite to the entire lift produced. The moments are the torques produced so as to move the roll, pitch and yaw. The mounting force (thrust) - which is the overall quad-rotor thrust- is the summation of each propeller's thrust, (i.e., ($T = Tf + Tr + Tb + Tl$). The rolling torque is the torque formed by upsurge the left rotor's thrust whereas reducing that of the right rotor, or vice versa (i.e.,$\tau_\phi = l(Tl - Tr)$). The pitching torque is generated by rising the front rotor's thrust whereas reducing that of the back rotor, or vice versa (i.e. $\tau_\theta = l(Tf - Tb)$. The yawing torque is the outcome of all torques produced because of the rotating rotors. The front and back rotors rotate in the right-handed direction, but the left and right rotors rotate in the anticlockwise direction. An unevenness amongst these pairs leads to a yawing torque which makes the quad-rotor rotate about its z-axis (i.e. $\tau_\psi = \tau_f + \tau_b - \tau_r - \tau_l$). Together with the other forces, the gravity performs through the CG of the quad-rotor. This force is stated as$W_{fv} = \begin{bmatrix} 0 \\ 0 \\ mg \end{bmatrix}$, where *g* is the gravity constant.

III. HOEVRING CONTROLOF QUAD-ROTOR

The problem considered in this work is stabilizing the quad-rotor in the hovering mode. The results are obtained via nonlinear simulation of the quad-rotor model, that encompassed controlling the inner-loop attitude and altitude, outer-loop position, and aerodynamic influences on the basis of free stream velocity. A primary hover scenario was illustrated to see the relative enactment of the numerous suggested controllers. In each instance, the simulation characterizes flight time (30s) with a target position of (0, 0, 2) in ENU synchronizes. All disparities in position were basically the consequence of vehicle dynamics, time delay, wind disturbances, and discretization. The wind disturbances were compared with subsequent estimations of wind velocity data obtained from accelerometer. The comparison demonstrated the probability of extracting wind velocity estimates from accelerometer data. The several parameters employed in the model are displayed in Table 1.

Table 1: Quad-rotor parameters

Symbol	Description	Value	Units
G	Gravity	9.81	M/s^2
M	Mass	0.45	*Kg*
D	Distance	0.225	*M*
I_r	Rotor Inertia	11 x 10^{-3}	$Kg.m^2$
I_{fx}	Roll Inertia	4.86 x 10^{-3}	$Kg.m^2$
I_{fy}	Pitch Inertia	4.86 x 10^{-3}	$Kg.m^2$
I_{fz}	Yaw Inertia	8.8x 10^{-3}	$Kg.m^2$
B	Proportionality Constant	4.95 x 10^{-5}	---
K	Proportionality Constant	1.87 x 10^{-6}	---

To validate the controllers' properties in controlling the attitude for the quad-rotor, the dynamic modeling described in

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Equation (3) and (4) was used along with the parameters in Table 1 to implement the control schemes. Some attitude control architectures are designed using MATLAB Simulink®. These controllers are tested in numerous simulations. The purpose of the controllers is to maintain the quad-rotor within the initial angle such that $(\phi_{init} = \pi/8, \theta_{init} = -\pi/6, \psi_{init} = \pi/12)$ and returns back to the hovering position. Attitude control is also simulated with the bound desired angles. Nine different control schemes are tested, starting with the PID controller.

A.PID Controller

Four independent digital PID controllers are used to control the dynamic quad-rotor motion, including pitch, roll, yaw, and altitude. The input of PID controller for pitch, yaw, and roll angles from the IMU sensor readings is expressed in degrees. The controller set-point for the axes of both the pitch and roll is zero degrees, while the set-point for the yaw axis is the initial value itself. Altitude controller receives ultrasonic distance sensor readings and set-point in the form of the desired height. The controllers send the duty cycles of PWM to control the motor speed. The controller test has three stages; roll pitch control, yaw control, and altitude control. The controller test is conducted in order to obtain the PID parameters when hovering at a height of 15 cm. Pitch and roll controller tests are performed on a pair of opposing motors.
When the controller test was performed in pitch axis, the red and yellow motor speeds were controlled while the green and blue motors were not turned on. The speed difference between the two motors (red and yellow) causes pitch angle deviation. Controller test in roll axis also used the same method to test pitch controller. However, in this test, the speeds of blue and green motors were controlled, while the red and yellow motors were turned off. PID tuning was performed at each angular position. The target was capable of producing a stable pitch and roll at 0^o. When the disruption of the deviation angle was given to the system, the controller was able to make improvements to return to the set-point as shown in the Figure 2. The third kind of PID controller which was used in the test was capable of stabilizing the pitch and roll axes positions, as presented in Figure 3. When the disturbance was given, the third PID controller mode tended to have a faster recovery time.

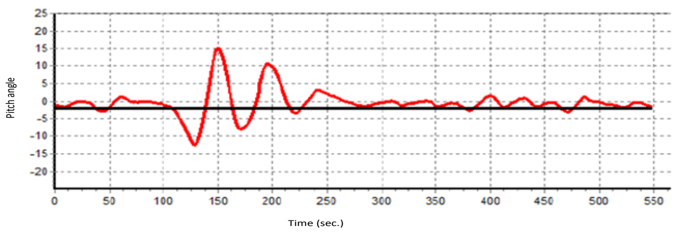

Fig. 2: Pitch angle vs time using PID mode 1 with Kp = 0.12,Kd = 0.03

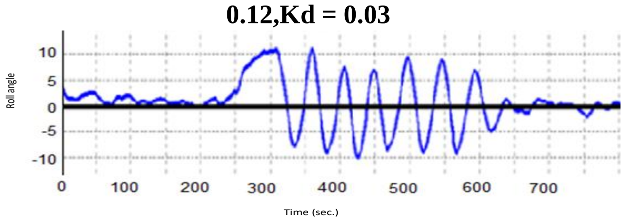

Fig. 3: Roll angle vs time using PID mode 2 with Kp = 0.14, Kd = 0.8, Ki = 0.00

Yaw axis control is conducted using PID mode 1. The controller set-point was the value of the yaw sensor reading in the first time (initial value). Set-point value was 90^o. PID controllers were able to restore the position of heading when a disturbance or deviation angle was given to the quad-rotor as shown in Figure 4. The results in Table 2 shows that simple PID controller (mode 1) was not able to make a stable attitude during the quad-rotor hovering phase. However, an alternative PID controller with filtered derivative action (mode 3) was able to stabilize the quad-rotor, with minor drifting effect. On the other hand, simple PID controller could not stabilize the quad-rotor attitude hovering at a height of 15 cm, where RMS error on roll and pitch axes was more than 5^o. A PID controller with filtered derivative action did stabilize the hovering quad-rotor (pitch and roll RMS errors were less than 5°). However, there was some drifting action. The PD controller parameters are determined as K_P=0.7, K_D=0.1 for roll-pitch, and K_P =0.9, K_D =0.15 for yaw respectively. The controller showed settling responses (less than 1.2 second) with an acceptable overshoot (10%).

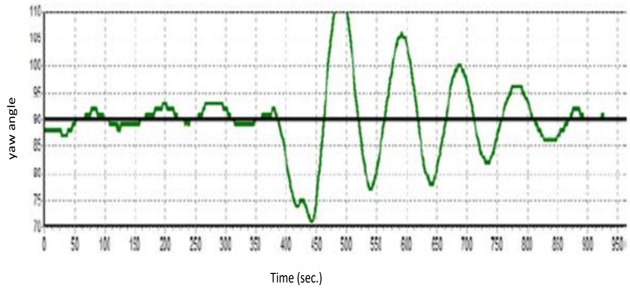

Fig. 4: Yaw PID controller test

Table 2: RMS error attitude and altitude while hovering at 15 cm

PID Controller	pitch RMS error	roll RMS error	yaw RMS error	altitude RMS error	Stability
Mode 1	5.4 °	4.3 °	30 °	5 cm	Unstable
Mode 1	6.2 °	7 °	35 °	5.2 cm	Unstable
Mode 1	5.3 °	6.4 °	45 °	4.5 cm	Unstable
Mode 3	3.4 °	4.3 °	24 °	2.6 cm	Stable
Mode 3	2.5 °	3.6 °	25 °	3 cm	Stable

B.PID-Fuzzy Controller

In the case of direct fuzzy controller, the responses were much smoother than those of PD controller. The results are presented in Figures 5-8. Each independent direct fuzzy controller uses a construction of 25 rules based on the relationship between the error and derivation of the error. This result yields better control performance than the PD controller. In this simulation, the angle responses have smaller overshoot with lower settling time (less than 0.8 second).

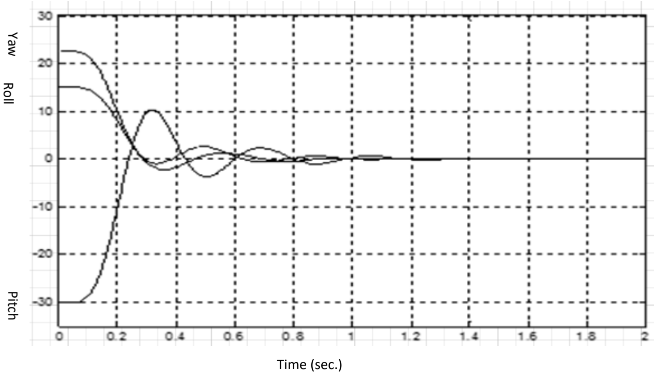

Fig.5: Orientation (ϕ, θ, ψ) for PD control

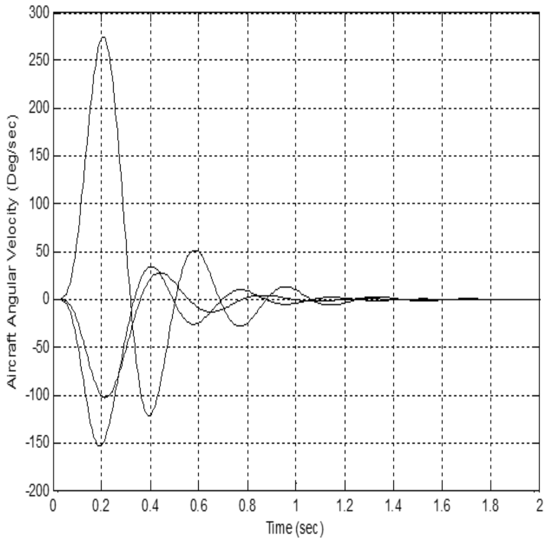

Fig.6: Angular Velocity $(\dot{\phi}, \dot{\theta}, \dot{\psi})$ for PD control

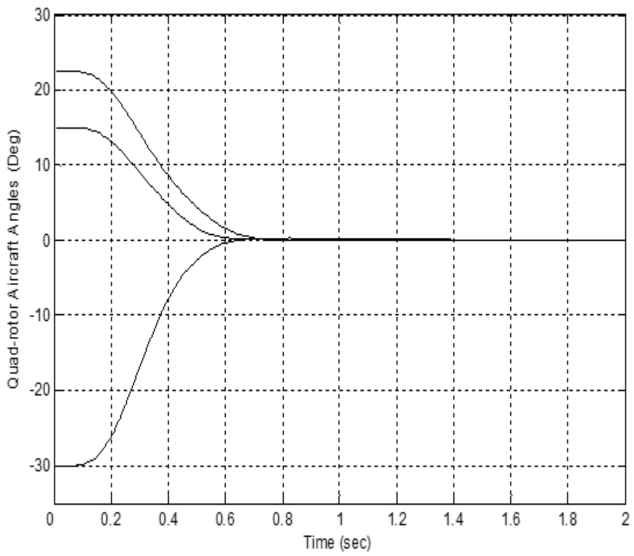

Fig.7: Orientation (ϕ, θ, ψ) for direct Fuzzy control

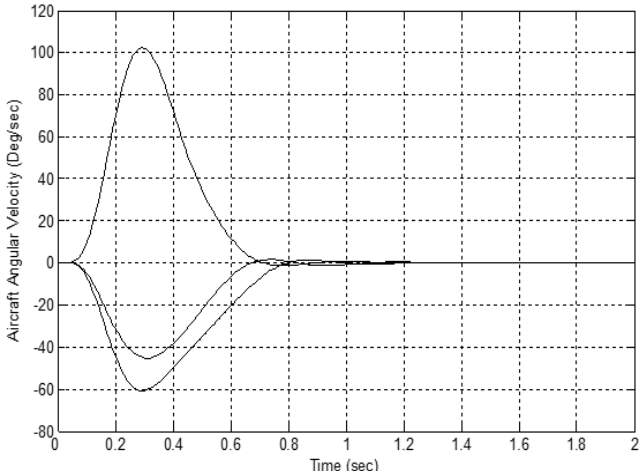

Fig.8: Angular Velocity $(\dot{\phi}, \dot{\theta}, \dot{\psi})$ for direct Fuzzy control

Finally, the performance of self-tuning fuzzy-PID controller is displayed in Figures 9 and 10. The parameters K_P, K_D and β are automatically tuned by the fuzzy controller and the controller quickly and flexibly changed the control torques. This simulation provides a faster response with a settling time less than 0.6 second.

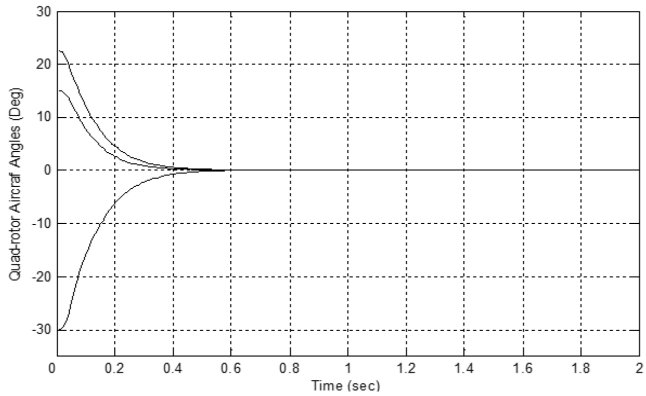

Fig.9: Orientation (ϕ, θ, ψ) for self-tuning Fuzzy-PID control

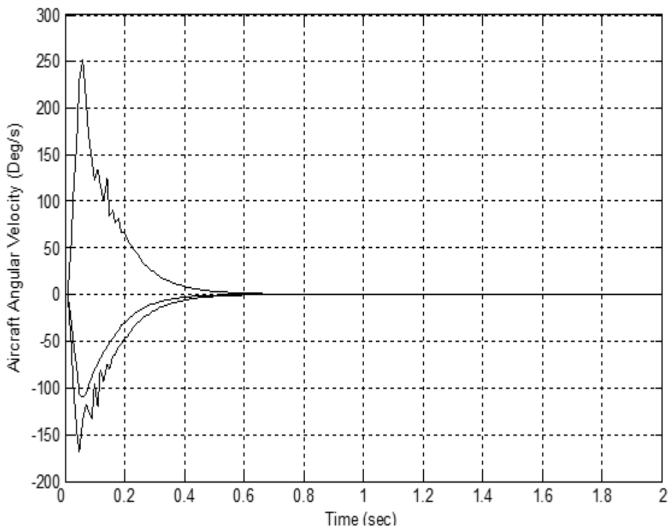

Fig.10: Angular Velocity $(\dot{\phi}, \dot{\theta}, \dot{\psi})$ for self-tuning Fuzzy-PID control

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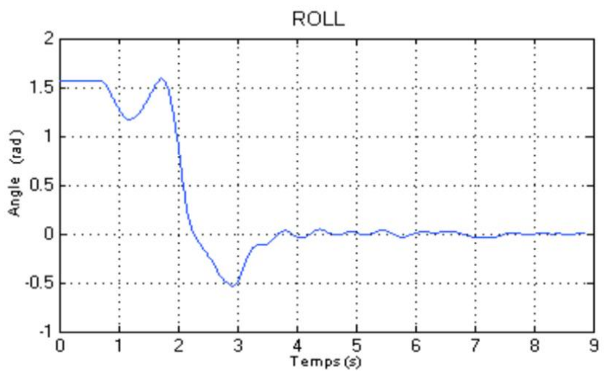
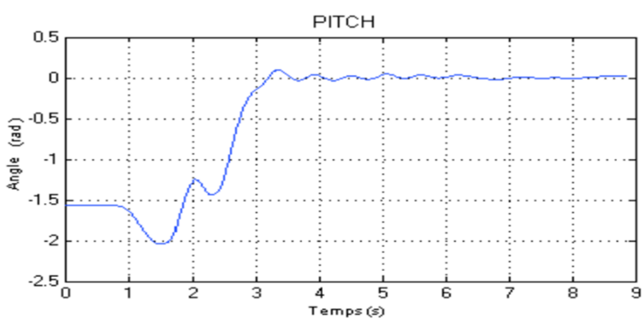
Comparing the outcomes of the above approaches, it is found that the self-tuning fuzzy-PID control is so far the most effective approach for quad-rotor control, because it shows better results than PID and direct fuzzy. It has provided smoother and faster performance, which means it can achieve good attitude control. The self-tuning fuzzy-PID controller can be flexible and effective approach not only for the quad-rotor but also for other control systems. Fuzzy PID controller reduces overshoot very significantly compared to conventional PID controller. Furthermore, fuzzy PID controller is more robust with changes of load and speed. It should be emphasized that this work focuses on zero-wind conditions. Therefore, the double derivative (DD) was utilized to augment damping to the target system in gentle circumstances and develop tracking enactment. The locus in both directions namely East and North is activated by the components of thrust in those directions, triggered by roll and pitch angles. The DD restores the vehicle to zero tilt. In windy environments, nevertheless, the perfect tilt may not be zero. Thus, correcting the wind influences necessitate adding a wind compensator to the external position control loop.

C. Linear Quadrature (LQ) without actuator' dynamics

Considering Pearson method [16], Riccati's equation is solved and the feedback gain matrix is attained. The initial simulation was executed on a model deprived of actuators' dynamics. The outcomes were acceptable despite starting from a crucial position ($\pi/2$) for the orientation angles. The identical simulation containing this actuator's model was implemented and exhibited a robust effect of the actuators' dynamics. The responses of roll, pitch, and yaw are displayed in Figure 11.





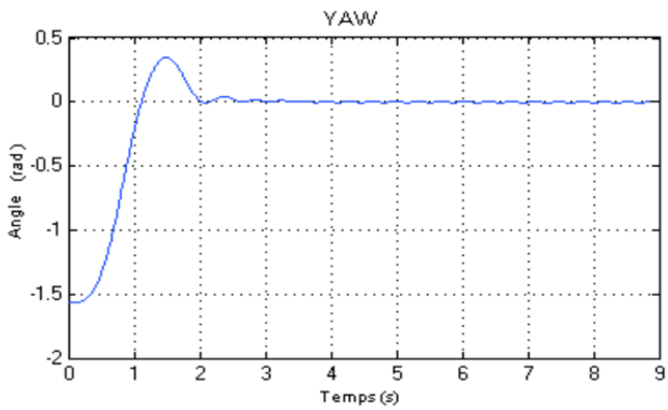


Figure 11: performance of First LQ controller

D. Linear Quadrature (LQ) with actuators' dynamics

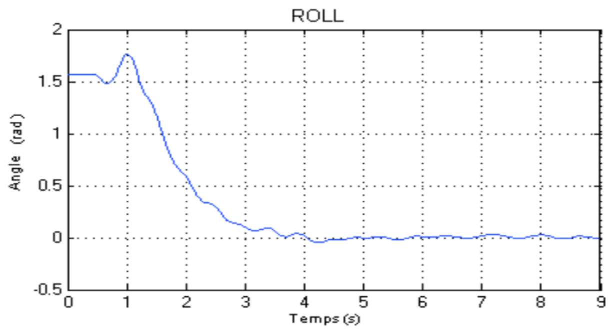
Bearing in mind a perpetual solution to Riccati equation simulated earlier offers sensible outcomes. On the cotrary, Sage-Eisenberg method [16] suggested a variable solution to Riccati equation and a fixed ultimate condition $P(t_f) = 0$. Once discretized, Riccati equation could be restated as:

$$-P_t(hA-I)-(hA^T)P_t+P_t(hBR^{-1}B^T)P_t-(hQ+P_{t+h})=0 \quad (5)$$

Here, t_f is the final time, n is the number of iterations and $h = t_f\, n$ is the iteration period. Equation 5 embodies the system properly in the P_t to P_{t+h} interval. This way was replicated at 100 Hz with actuators' dynamics. Taking $t_f = 0.3$ and $n = 10$, the Q and R gain matrix becomes:

$$K = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 12.83 & 10.02 & 0 & 0 & 0 & 0 \\ 0 & 0 & 12.83 & 10.02 & 0 & 0 \\ 0 & 0 & 0 & 0 & 12.86 & 10.01 \end{pmatrix} \quad (6)$$

In light of the previous controllers, the Sage-Eisenberg approach offered better outcomes, as it enhanced the cost function for every sub-trajectory in the P_t to P_{t+h} interval, as displayed in Figure 12. As in Bellman principle [17], splitting an ideal trajectory produces numerous optimal sub-trajectories.



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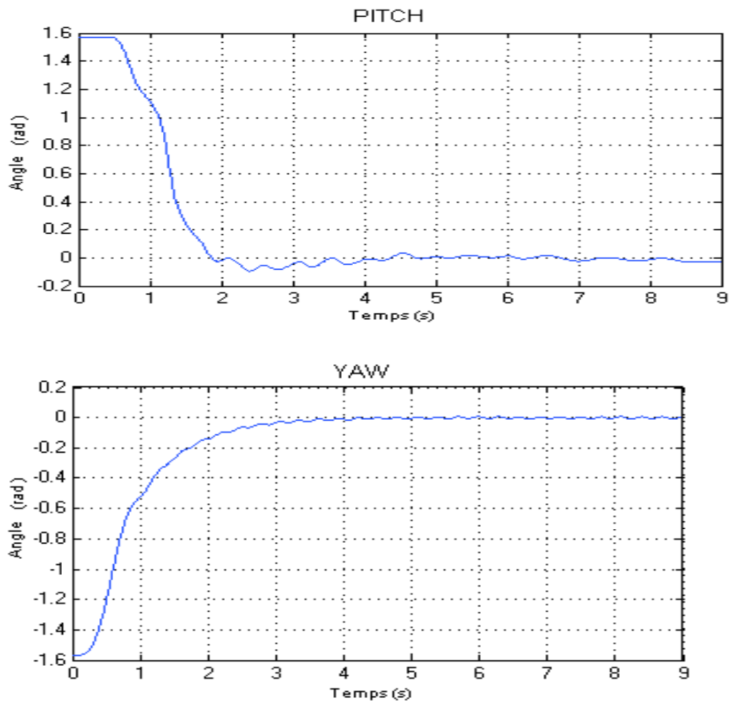


Fig. 12: Second LQ Controller

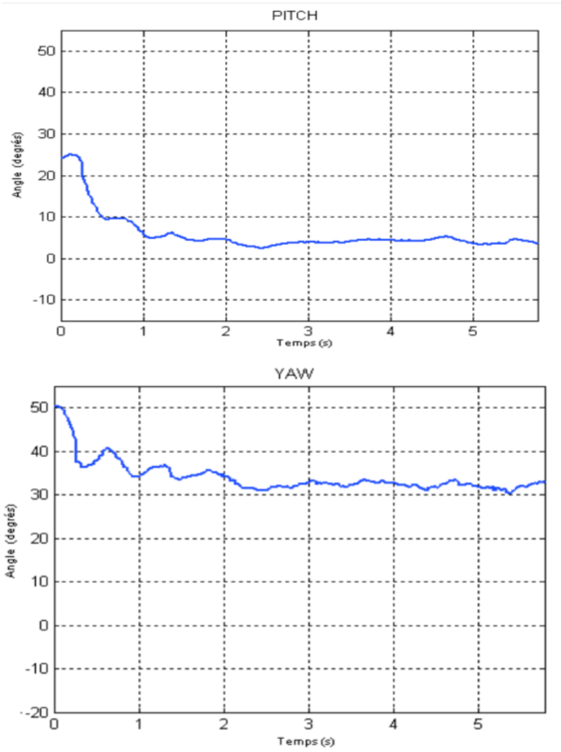


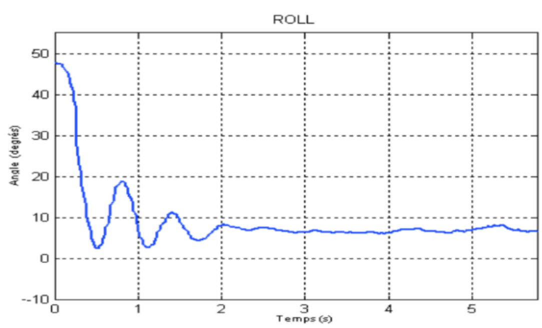
Figure 13: Performance of LQ Controller

E. Linear Quadrature (LQ) with integral term

During the employment of the LQ controller, it was challenging to obtain weight matrices that fulfil the control stability. Furthermore, a minor change in Q or R matrices would introduce a large disparity of the behavior of the controller. Therefore, by taking $t_f = 0.05$, $n = 10$ and suitable matrices: Q and R, the system stabilized as presented in Figure 13. The gain matrix K is

$$K = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 1.059 & 0.391 & -0.001 & 0 & 0 & 0.001 \\ 0.0007 & 0 & 1.059 & 0.391 & 0 & -0.0004 \\ 0.005 & 0.002 & -0.0002 & -0.0001 & 0.015 & 0.028 \end{pmatrix} \quad (7)$$

As presented in Figure 13, a steady-state error on the three orientation angles could be referred to the minor alterations of the propulsion and disturbance produced by the data and power cables.



Conversely, the fact that the LQ controller was improved without bearing in mind actuators' dynamics was also accountable for the average performance. Nevertheless, one could attempt to present a fundamental term in an LQ controller as displayed in [18].

F. Linear Quadratic Regulator (LQR)

The LQR controller is an optimal control algorithm that is concerned with operating a dynamic system at least cost. The LQR control block diagram is presented in Figure 14.The cost of the system is signified by linear differential equations. These equations are defined by a quadratic function. The LQR controller is utilized so as to reduce the small errors. The positive definite matrix Q is utilzed to assess the size of state responses.

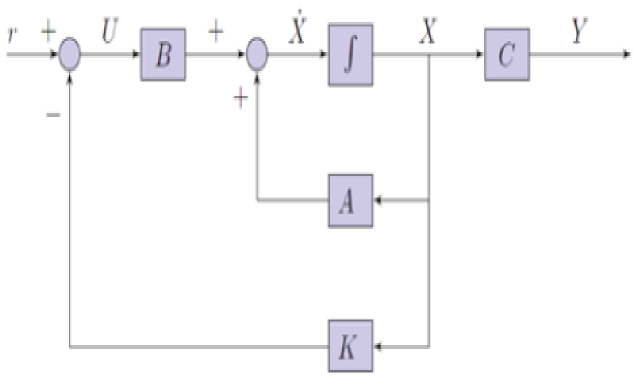


Fig. 14: LQR control block diagram

If the numbers of Q entries were enormous, then a minor deviation of the state from zero would significantly increase the cost.

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Accordingly, the controller would have high gain. The symmetric matrix *R*, that should be positive, is employed to weigh the controller. It can also be diagonal. If the entries of this matrix were great, then the control action would be slight compared to *Q*. If we want to increase the size of the control action, we could decrease the entries of the control weighting matrix. The purpose of this is to adjust the input variables with the intention of making the control aspects easier, so that:

$$\dot{x} = AX + Bu \qquad (8)$$
$$Y = CX + Du \qquad (9)$$

LQR controller reduces the performance index: $u = -kx$. The linear solution that reduces this index is specified by a linear function of states. The initial simulation of LQR controller is to hover at z_d = 2m, which is the preferred quad-rotor height. The favorite quad-rotor directions are $x_d = y_d = 0$, whereas the desired quad-rotor rotations are $\varphi_d = \theta_d = \psi_d = 0$. Figure 15 displays the quad-rotor positions performance, whereas Figure 16 illustrates the attitude angles performance. These outcomes exhibit a stable system with slight steady-state error. The vehicle angles have reached stability and a zero steady-state in less than 3sec and error after 15sec respectively.

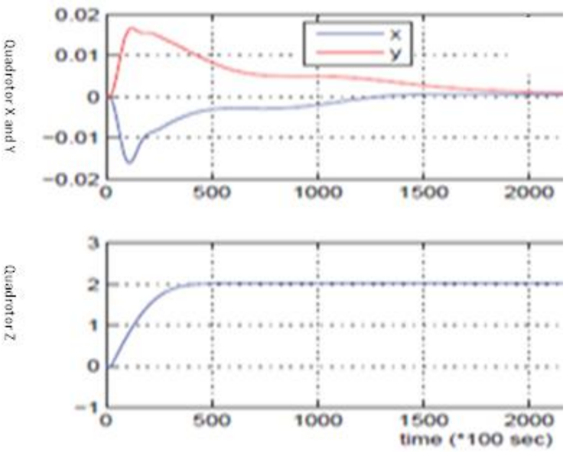

Fig.15: Hovering positions for LQR controller

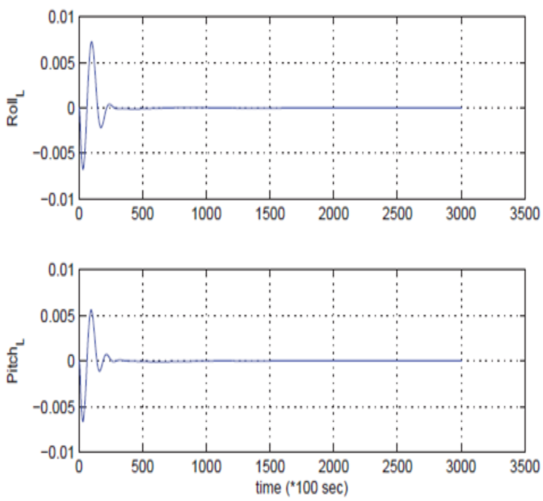

Fig. 16: Hovering angles for LQR controller

IV. SUMMARY OF RESULTS

The performance of different controllers is evaluated by means of time domain variables namely maximum overshoot, settling time, and error index. The control simulations were based on attitude stabilization. Six out of twelve states of quad-rotor manage the attitude of the system, while the other six states comprise the angles (ϕ , θ, ψ) and angular rates (p, q, r) around the three orthogonal body axes. There are two coordinate frames fixed at the ground and at the center of gravity of the quad-rotor. The simulation outcomes of the comparison of the quad-rotor control methods are summarized in Table 3. The results show that LQR is the best controller for hovering control of quad-rotor.

Table 3: Comparison of quad-rotor control methods

Controller	Advantage	Disadvantage	Use
PID	-Simple, stable, -Easy adjustment - high reliability -No processor required.	-Difficult tuning, -poor robustness, -unstable for variable load - high overshoot.	-Suitable for nonlinearity in quad-rotor hovering position.
Fuzzy PID	-Easy tuning -good stability -small overshoot -fast response - more robust with change of load and speed.	-Require finer tuning and simulation before operation.	-Suitable for transfer weight - fast response applications
LQ	-Average stabilization results -Less dynamic.	-Not applied for real time applications.	-Applications which need slower response.
LQR	-Robust - produce very low steady-state error	-Transition delays -slow parameters update	-Suitable for hovering case.

V.CONCLUSION

This research aims to find the suitable control scheme for a typical quad-rotor. It compares different types of controllers in terms of their ability to stabilize a hovering quad-rotor. These controllers include PID, fuzzy PID, LQ, and LQR. The controllers are analyzed based on time domain characteristics namely maximum overshoot, settling time, and steady state error. The control simulations were based on attitude stabilization in hovering mode. The dynamic model of the quad-rotor was obtained bearing in mind the influence of a suspended load to be eight degree of freedom system. The dynamic model was linearized around the hovering point so as to fulfill the suggested control approach requirements.

Though LQ controller displayed average stabilization results, it has slow dynamics. On the other hand, LQR controllers are found suitable for hovering case producing very low steady-state error and being robust. Nonetheless, big transition deferral and utilizing six feedback gains make them inadequate choice when the system requires fast parameters update, and has no direct access to all states of the plant. Although PID controller algorithm is simple, stable, easily adjusted, highly reliable, and does not require a processor, tuning PID control parameters is very difficult, in addition to having poor robustness; when load varies it becomes unstable, giving high overshoot. Considering all the previous factors, the simulation outcomes exhibited that LQR controller efficiently minimizes steady-state error. However, reaching stability conditions is time-consuming.

REFERENCES

1. P. Getsov, S. Zabunov, & G. Mardirossian, "H-Airframe Benefits for Constructing Quad-Rotor Unmanned Helicopters." International Journal of Science and Research 3.8, pp.21-23, (2
2. A. Salih, M. Moghavvemi, H. Mohamed & K. Gaeid, "Modeling and PID Controller Design for a Quad-Rotor Unmanned Air Vehicle," 2010 IEEE International Conference on Automation Quality and Testing Robotics (AQTR), Vol. 1. pp. 1-5,(2010). DOI: 10.1109/AQTR.2010.5520914.
3. M. Ryll, H. Bülthoff, & P. Giordano "Modeling and Control of a Quad-rotor UAV with Tilting Propellers," 2012 IEEE International Conference on Robotics and Automation (ICRA), pp. 4606-4613, (2012). DOI: 10.1109/ICRA.2012.6225129.
4. A. Siddig, A., Alnoor, M. Mustafa, & M. Ahmed, Design of small quad rotor helicopter. Diss. Sudan University of Sciences and Technology. (2015).
5. obverts, J. F., Stirling, T., Zufferey, J. C., & Floreano, D. "Quad-rotor Using Minimal Sensing for Autonomous Indoor Flight," European Micro Air Vehicle Conference and Flight Competition (EMAV2007). No. LIS-CONF-2007, pp. 1-8. (2007
6. G. Hoffmann, H. Huang, S. Waslander & C. Tomlin, "Quad-Rotor Helicopter Flight Dynamics and Control: Theory and Experiment," Proceedings of the AIAA Guidance, Navigation, and Control Conference. Vol. 2. pp. 6461-6480. (2007). DOI: 10.2514/6.2007-6461
7. H. Hou, J. Zhuang, H. Xia, G. Wang, & D. Yu "A Simple Controller of Minisize Quad-Rotor Vehicle." 2010 International Conference on Mechatronics and Automation (ICMA), pp. 1701-1706. (2010). DOI: 10.1109/ICMA.2010.5588802
8. G. Raharja, G. Kim & K. Yoon, Design of an Autonomous Hover Control System for a Small Quadrotor. International Journal Aeronautical and Space Sciences, 11(4), pp. 338-344, (2010). DOI: 10.5139/IJASS.2010.11.4.338
9. L. Argentim, W. Rezende, P. Santos, & R. Aguiar "PID, LQR and LQR-PID on a Quadcopter Platform," In 2013 International Conference on Informatics, Electronics & Vision (ICIEV), pp.1-6. (2013). DOI: 10.1109/ICIEV.2013.6572698
10. S. Bouabdallah, A. Noth, & R. Siegwart, "PID vs LQ Control Techniques Applied to an Indoor Micro Quad-Rotor," Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, (IROS 2004).Vol. 3, pp. 2451-2456). (2004). DOI: 10.1109/IROS.2004.1389776
11. Z. Dydek, A. Annaswamy, and E. Lavretsky "Adaptive Control of Quad-Rotoruavs: A Design Trade Study with Flight Evaluations," IEEE Transactions on Control Systems Technology, Vol. 21, no. 4, pp. 1400–1406 (2013).
12. A. Ghaffar, & T. Richardson, "Model Reference Adaptive Control and LQR Control for Quad-rotor with Parametric Uncertainties." International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering, 9(2), 244-250. (2015).
13. J. Escareno, A. Sanchez, O. Garcia & R. Lozano, "Modeling and Global Control of the Longitudinal Dynamics of A Coaxial Convertible Mini-UAV in Hover Mode." Unmanned Aircraft Systems. Springer Netherlands, 1-3, 261-273. (2008). DOI:10.1007/s10846-008-9265-y
14. S. Bouabdallah, "Design and Control of Quad-Rotors with Application to Autonomous Flying," Ph.D. Dissertation, School of Computer and Communication, Ecole Polytechnique Federale de Lausanne. (2007) DOI: 10.5075/epfl-thesis-3727
15. V. Yurkevich. Design of Nonlinear Control Systems with the Highest Derivative in Feedback. World Scientific Publishing. (2004). DOI: 10.1142/5569
16. R. Longchamp, Commande Sous-optimale Adaptative de Systèmes Nonlineaires. Phd thesis, Switzerland, Federal Institute of Technology (EPFL), (1978).
17. P. Naslin Introduction à la Commande Optima le, Dunod, (1966).
18. G. Franklin, J. Powell, & M. Workman. Digital Control of Dynamic Systems. M9Menlo Park: Addison-wesley, (1990). DOI: 10.1002/oca.4660060111
19. A. Zulu and S. John, "A review of Control Algorithm for Autonomous Quadrotors," Open Journal of Applied Sciences 4, 547-556. (2014),

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