Quad-copter Control

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Introduction

In recent years, quadcopters have attracted more attention due to the development of cheap controllers which enable them to possess high manoeuvrability, low maintenance costs, and low noise. UAVs have become useful for numerous purposes: aerial photo and video shooting, farm irrigation and crop monitoring, border patrol and rescue missions, electric power line and gas pipeline monitoring.

Quadcopters make use of four propellers in achieving vertical take-off and landing. It employs a variety of sensors to detect various quantities and achieve stability and control. An ultrasound sensor accurately detects the height up to ~15 feet. For greater heights, a pressure sensor is employed (as pressure decreases with altitude). Speed and horizontal motion are measured using image processing techniques through a camera. The Inertial Measurement Unit (IMU) is made up of a 3-axis accelerometer, and a 3-axis gyroscope measures the quadcopter's attitude.

A quadcopter can operate in two configurations: + and x; the opposing rotors in both the configurations spin in the same direction. This direction is opposite to the other pair of rotors, thereby nullifying the torque around the yaw axis (or the z-axis). Along similar lines, we can speed up one pair and slow the other pair to make the quadcopter spin in a particular direction. This doesn't change the altitude since the overall thrust remains the same. The various speeds of different rotors allow for the independent command of thrust, roll, pitch, and yaw.

For stable control, the throttle, roll, pitch, and yaw are needed to successfully controlled so that the vehicle navigates its terrain, while maintaining steady, stable flight, and controlled movement.

Paper: LQR controller design for quad-rotor helicopters

Link to the paper: [LQR controller design for quad-rotor helicopters - IET Journals & Magazine]()

The aim of the paper is to present a step-by-step design of the LQR controller for intelligent control of Quadrotor helicopter. The emphasis will be on the linearised state modelling of the quadrotor helicopter, system's performance index state and control weighting (Q and R), the feedback gain matrix (K), and the tuning.

The control technique of state-space is used for designing a capable LQR controller. Linear and angular Using the laws of aerodynamics and considering only the linear and angular accelerations, the equations for the quadcopter's state-space are derived, resulting in second-order differential equations. But effective LQR designs are based on linear state-space models. Consequently, the equations need to be linearised.

In linearising, one has to work around the stable operating regions of the system. The quadcopter's hovering position, i.e. fixed altitude and no translational or rotational motion, was chosen. Approximation using Taylor series is used for linearization. The state matrix (or vector) after linearisation contains the attitude, the position and velocity, and the altitude of the quadcopter which amounts to a total of 12 members. To simplify calculations, this was reduced into altitude, attitude and position control vectors.

The system's performance index is characterised by a cost function (J) which the controller seeks to minimise. The cost function is an integral containing the state weighting matrix (Q) and the control weighting matrix (R). These weighting matrices help determine the relative importance of the existing error as well as the energy expenditure of the system. These matrices are calculated using a combination of Bryson's method and then trial-and-error for fine-tuning. After attaining the Q and R matrices, the feedback gain matrix(K) is calculated through the Riccati equation. This can be solved easily using MATLAB.

With the feedback gain matrix and state-space equations obtained, the closed-loop system of the quadcopter can be developed. This obeys the optimal control law. Finally, the tuning of the LQR controller is done, which requires the right K values. From simulations, it was observed that the LQR controller could control the dynamic response with no overshoot. The Q and R matrices have opposite effects on the values of K and guidelines were followed to obtain the right value of K. It was observed that at lower values of K, the state variables slowly change to zero, but the controller's response is faster. The opposite happened at higher values of K.

Paper: Modeling, Simulation and Implementation of a modified PID Controller for stabilising a Quadcopter

Link to the paper: [Modeling, simulation and implementation of a modified PID controller for stabilizing a quadcopter - IEEE Conference Publication]

PID controller design requires prior modelling of the system to know it's behaviour. Quadrotors have their four propellers placed on the ends of a cross-like structure. To maintain the balance of overall torque, one pair of rotors rotates in the clockwise direction while the other pair rotates in the counterclockwise direction. The speed of every rotor is controlled independently to generate the thrust and torque to move the aircraft. According to the orientation of motion, there is an "x" mode and a "+" mode. In the cross configuration, the two pairs of propellers (1,3) and (2,4) rotate in opposite directions, which eliminates the use of tail motors. By varying the rotor speed, the thrust force can be changed, and movement can be controlled. The force of each of the rotors that produce (φ angle), pitch (θ angle), and yaw (ψ angle) movements.

The UAV orientation was represented by the orthonormal rotational matrix, which transforms the orientation changes on an inertial coordinate system of its mass centre to a coordinate system fixed to the ground. The kinematics of a rigid body of 6 degrees of freedom was taken into account. Linear, orientation and angular orientation was calculated in terms of φ, θ, and ψ.
The main force applied to the quadcopter and responsible for thrust is given by the vector sum of the thrust of each rotor. The speed of the rotor was calculated in terms of the distance between the quadcopter motor and its centre of gravity(l) and drag coefficient (d).

The velocity test determines that there is a linear relationship between angular velocity squared and PWM. The study of the dynamics of driver-engine nonlinear systems for different ranges of duty cycle was performed. In Simulink, 10 first-order transfer functions for the various ranges were built. The tuning of the controllers was done using a transfer function in the motor's operating point. Considering a PID with the derivative part in the output, the control algorithm receives, as inputs, the sensor data and the reference. The algorithm output determines the PWM signal for the four motors.

For PID tuning, several iterations were performed to minimise the cost function.
The validation process includes checking the degree of approximation between the model and reality. The coefficient of measure of R square was used (value between 0 and 1) in addition to the root mean square error. A non-linear model of excellent performance was developed, which shows disturbance in starting but rapidly gains stability.

Paper: Comparison of PD, PID and Sliding-Mode Position Controllers for V–Tail Quadcopter Stability

Link to the paper: [Comparison of PD, PID and Sliding-Mode Position Controllers for V–Tail Quadcopter Stability]()

This paper presents a comparison of PD, PID, and SMC position controllers for a V-tail quadcopter. The customised design of the V-tail quadcopter is prepared first to know the parameters of this structure. The Designed UAV has a simple mechanical structure, but the control theory is complex, due to its non–linear dynamics. It has a total of 6 DOF (degrees of freedom) and only four actuators, which makes it a complex system to study and control. In the designed UAV, the tail links are at the elevation of an angle beta and the length of the tail links are relatively smaller than the front links, this is how it is different from the commonly used × structure quadcopter.

The Newton–Euler formulation offers equations that describe the translational and rotational dynamics of a rigid body. So, the dynamic analysis of the V-tail quadcopter is done using the Newton–Euler formulation and a reference equation are generated which combines the dynamics of the body in the earth–fixed reference frame and in the mobile reference frame. Then, the dynamic reference equation is made to adapt the v-tail quadcopter taking into account the Coriolis and centripetal effects, Air Drag and the effect of gravity on the vehicle. Now due to the non–linearity of the final generated system and the number of unknown parameters and terms, it becomes necessary to simplify the dynamic model equations when designing the controllers. So taking the assumption that the V–tail quadcopter operates in a quasi-stationary region, the product of the Coriolis and centripetal effects matrix and the velocity vector is neglected because the magnitude of their resultant vector is much smaller than the other terms of the dynamic model equation. The same thing applies to the gyroscopic effects, they are also neglected.

All three controllers, the PD, PID, and SMP controllers are designed separately one by one and the stability analysis for each controller is done using Lyapunov stability analysis treating the V-tail quadcopter as a robot manipulator. The LaSalle theorem is to be applied in order to prove the asymptotic stability of origin. Also, a non-conventional variable is introduced to study the stability analysis of unmanned aerial vehicles when controlled by a PID controller. The system is also simulated for each controller to get separate results, which can be used for comparing the performance and stability of the controllers among each other.

The simulation results validate the proposed controllers and algorithms used for the V-tail quadcopter when the three controllers reach the desired positions on instructed actions. From simulation results, it can be established that the PD and PID controllers make the vehicle behave in the same manner (depending on their gains), but it does not occur the same with the sliding–mode controller. It is found that the PD and PID controllers have an exponential behaviour while the sliding–mode controller has a linear response. Time stabilisation is another remarkable characteristic of the controllers that can be modified by the gains of each but, from simulated results, it could be inferred that the sliding–mode controller stabilizes the vehicle faster than the other two controllers. The similarity in behaviour between the PD and PID controllers was found. Still, the difference is regarding time stabilisation, It was clearly observed that the PD controller responds faster than the PID controller. The PD controller presents an error in the stable state that will not disappear as time goes on, but there is no error in the stable state in the other two controllers. For the yaw movement, the SM controller takes the quadcopter to the specified angle in less time than the PD, and the PID controllers do. The roll and pitch angles are considerably higher for SMC than the other two, making it possible to reach the desired roll and pitch positions in less time as compared with the other two.

References

- Series of videos on state-space by the MATLAB channel on youtube. (https://www.youtube.com/watch?v=hpeKrMG-WP0)
- Series of videos on the control of a quadcopter by the MATLAB channel on youtube. https://www.youtube.com/watch?v=hGcGPUqB67Q
- Quadcopter stabilization by using PID controllers