Short Review on PID Control in Drone

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Abstract: As one of the most widely used technologies across various industries, quadcopters have proven to meet the high expectations. This paper focuses on the critical role of the Inertial Measurement Unit (IMU) in quadcopters, aiming to explore the relationship between IMU sensors and their application in commonly used quadcopters. The data collected by the inertial measurement Units is transmitted to control the quadcopter through Pulse Integral Derivative (PID) control system.

Keywords: Drones, Aircraft; PID Control; Control System

1. Introduction

Quadcopter, or quadroter, is unmanned aerial vehicle (UAV)[1] that can takeoff and land vertically. It uses four rotors that provides astrong thrust to propel the vehicle to takeoff, and the rotors are evenly distributed to make sure the quadroter is dynamically balanced while flying.

Compared to helicopters or other aerial vehicle with propeller as their power source, quadcopters are able to take off within a short period of time. The simple and light-weighted structure enabled them to acquire higher acceleration during motion and to pass through narrow terrain with higher flexibility.

Although quadcopters are structurally simple, it is extremely hard to manipulate quadcopters with perfect precision. Experiencing low air resistance while moving, quadcopters' relatively high inertia has made it hard to halt immediately. Unlike cars that lies on the solid ground, the air as a fluid cannot provide a frictional force that is strong enough to support the system to make a instant break, and it is also susceptible to surrounding factors like air density and background convection. Moreover, the errors in each loops will accumulate, untimately resulting in drift errors which will be discussed later in the text. Despite all these, quadcopters still being followed due to their relatively low cost and broad range of applications, indicating significant market potential. Luckily, the PID system was founded, suggesting a really good solution towards the instability of drones. In a word, the control system can adjust to the environment condition minutely by censoring and changing its output parameter realtime.

Typically, as the foundation unmanned technique, quadcopters can be employed in various field after combining with specific sensors. For instance, equipped with multi-spectral cameras and other sensors, they can be utilized in precision agriculture for tasks such as crop health monitoring, soil assessment, and pesticide and fertilizer application. Moreover, with real-time monitoring, quadcopters can provide valuable data for disasters assessment and recovery, especially for places that are inaccessible to humans.

PID control remains the most widely used algorithm in unmanned aerial vehicle (UAV)[n] systems, but few of the articles put attention on the relation solely between drones and PID.

2. PID Control System

PID control systems can be categorized based on various aspects to meet different requirements.

Starting with the categorization of the control loop, single-loop PID control[2] refers to the control system regulating only a single variable with only a sensor, a regulator, and an actuator, often applied in simple systems like thermostats in heating systems, washing machines, and oven temperature control in baking. On the other hand, multi-loop PID control[3] is capable of managing multiple variables simultaneously since each loop within multi-loop PID is equipped with an independent regulator. The system is best suited for situations with complex and multi-variable systems like air conditioning systems with temperature and humidity control or robotic arms in manufacturing.

For the aspect of tuning, classical PID control involves manual adjustment of the P, I, and D parameters.

Commonly seen examples are manual voltage stabilizers and irrigation water pump control. While being effective in stable environments, classical PID systems cannot adapt to an environment with undulating parameters. Thus, adaptive PID control[4] is designed to automatically adjust these parameters in response to environmental changes, making it suitable for electric vehicle battery management or autonomous underwater vehicles which both works under dynamic systems.

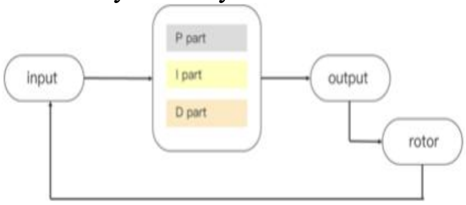

Figure 1. PID Flow Chart

For compensation characteristics, PID control with feed forward[5] is able to anticipate disturbances by providing an experience value, also known as feed forward value signal, to the actuator and adjust the output to furthermore eliminate the error by using a close-loop PID system. It is used in the wind turbine blade pitch control and power plant turbine speed control to make a predicted compensation for extra-demanded output. To compensate for the excess output resulting from the neterror in the circuit, PID control with anti-integral saturation prevents excessive output signal due to accumulation in the integration part, which is described in the former paragraph, causing dramatic fluctuation of actual output in a short period.

Specifically, anti-integral saturation PID control system[6] employs means like adding an upper and downer limit to the integration accumulation or increasing the weight of differentiation part to mitigate the effect.Conveyor belt speed control in manufacturing is a really good case here to visualize the control system' semployment.

Lastly, intelligent PID control and neural networks are also employed by today's industries like autonomous vehicle navigation, which allow for real-time adaptive tuning in complex, evolving environments.

3. PID Control System Working Principal Overview

This figure displays the fundamental framework of a proportional-integration-derivation system. The PID control system initiates as the algorithm receives a command value from the input.

P part

$$P(t) = Kp \times e(t) \quad (1)$$

P part proportional part in the control system is a model that controls the proportional part value output, P(t), in every second. the difference between the ideal value and its current value, e(t) = ωideal − ωinstaneous. It is important to know that ωinstantaneous will turn into steady-state rotational speed when time approaches infinity. kp in the formula can be interpreted as a manageable constant of the equation 3.

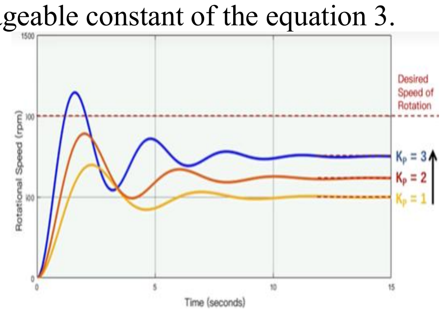

Figure 2. RPM-Time Graph

As shown in the figure, the value of the output will finally reach a relatively stable state, which means the difference between the desired speed of rotation, eideal , and the steady-state rotational speed,e current, will eventually become relatively stable instead of a range for fluctuations.

However, it is self-evident that although the difference between desired and actual rotational speed is reduced along with the increase in the value of kp , ecurrent could never equal to eideal , and that is the formation of steady-state error. That's because when two values coincide, value e(t) will become zero, resulting in zero value for P(t).

I part

$$I(t) = K_i \times \int_0^t e(t)dt = K_i \times \sum_i^t e_i \Delta t \quad (2)$$

Due to the limitation in proportional part's model, Integration part was subsequently put forward to eliminate the steady-state error. Namely, I part is responsible for integrating the area encompassed by the curve of rotational speed and the level of desired speed of rotation. As the area is accumulated, the change in result will be embodied on the net output value, leading to an additional round for increasing or decreasing the rotational speed. The final value, as time passes by, will again reach an new steady-state rotational speed, which is makes up for the difference between the desired speed of rotation and the current speed of rotation.

D part

$$D(t) = K_d \times \frac{de(t)}{dt} \quad (3)$$

D in PID stands for differential, its role in the control system is similar to damper. When the derivative of e(t) is greater than zero, which means the trend of the rotational speed is increasing, the result of D(t) will become negative value to partially counteract the increasing value resulted from proportional part P(t); when $\frac{de(t)}{dt}$ becomes a negative value, viceversa. By doing this, the fluctuation of the system will be greatly reduced compared to the final output only resulted from P part.

(PID control simulations) (4)

4. Drones

4.1 PID Application in Different Kinds of Drones

4.1.1 Fixed-Wing Drones (with VTOL Capabilities)

Fixed-wing drones with vertical take-off and landing (VTOL) capabilities have a similar look to traditional airplanes. However, fixed-wing drones can takeoff vertically by changing the elevation angle of the propeller. The drones can achieve a relatively high speed, and they are used for long-range surveying, mapping, and military uses in most cases.

During the VTOL phase (take-off, hover, and landing), PID control is critical for managing rotor balance and transitions between hovering and forward flight modes. D part of the system can play an important role in stabilizing the drones' body through means of proving a resist control.

Still, while switch between vertical take-off and transitional flight, precise PID tuning is required to manage the stability of the drone in both modes. During transitions, the control system must adjust quickly as the its aerodynamics change, which can be challenging because the P, I, and D parameters tuned for hovering may not be suitable under a high-speed forward flight condition.

4.1.2 FPV Drones

First-Person View (FPV) drones designed for high-speed racing, often piloted using goggles that provide alive camera feed. Although, manipulating an FPV drone seems to have nothing to do with the control system but the user itself, it is impossible to maneuver FPV drones without a PID control system.

Typically, PID has significantly reduced the requirement for users to minutely regulate the motion of the drones; made the predictions of FPV drones' behavior easier; promoted response flexibility to the surrounding situations; and enabled the drones to adapt to complex environments. In reality, working as a damper to the system, the D part's role in the control system will be undermined compared to the I part, because users need an acute reaction for drones in FPV racing, and weighing too much on D part will cause the quadcopter's movement sluggish.

However, there will be a trade off between precision and stability. The I component is essential for keeping position and monitoring during races, but it needs to be finely adjusted. If the integral gain is excessively high, it may cause overshoot, while an insufficient gain could fail to ensure adequate stability, especially during abrupt movements.

4.1.3 Nano and Micro Drones

Nano and Micro drones have very little difference with classical quadcopters, the only difference is their tiny size.

These drones are usually used for military reconnaissance, user entertainment, etc. The smaller size of these drones makes them more sensitive to disturbances, and PID control ensures their stability in tight or confined spaces. Except for P part which is responsible for a swift respond to actions and surroundings, D part is expecially essential in damping oscillations and preventing overshoot due to their relatively small size.

Drones are frequently employed in restricted or confined areas, where precise control over every minor movement is crucial. In such constrained environments, tuning the integral component to facilitate gradual adjustments while avoiding issues such as integral windup or excessive accumulation presents a notable challenge.

4.2 Common Sensors Employed in Drones

4.2.1 Inertial Measurement Unit (IMU)

The Inertial Measurement Unit[7] is composed of an accelerometer and gyroscope, and it can detect several parameters simultaneously instead of a single measurement. As shown in the graph, when the spring inside the sensor is stretched or compressed, the sensor can calculate the angle of inclination if the system is

in the inertial
reference frame. It can measure the acceleration, angular velocity, and orientation of the drone, and it is crucial for maintaining real-time stability and controlling roll, pitch, and yaw.5
Motion Measurement (Rotation, Acceleration, Tilt angle, etc.) Compared to simple models like the mass-string
system (Figure n), and the mass-spring system (Figure n+1), MEMS inertial sensors in IMU actually have a similar working principle. When the whole system experiences a net external force, the mass within the system (Figure
n+2) will also change its position relative to the system due to inertia, and the sensor can transform the result of change into electrical signals to achieve controlling purposes.
Magnetic Field Strength Measurement The sensor is also equipped with a Hall Effect Electronic Magnetometer to embody the effect brought by the variation of magnetic field that the system experiences. In other words, the sensor detects the influence of the magnetic field on the system by utilizing the characteristics of charged particles moving in the magnetic field.
4.2.2 Global Positioning System (GPS)
GPS[8] is critical in giving real-time positioning data, allowing drones to precisely calculate their latitude, longitude, altitude, and speed relative to the ground. This accurate geolocation enables drones to undertake complicated navigation tasks such as waypoint missions and geofencing, which create boundaries using GPS coordinates. The GPS also supports critical safety features like return-to-home (RTH), which allows the drone to return to its launch site autonomously in the event of a signal loss or low battery.
4.2.3 Thermal Sensors
Thermal sensors are sensors that detect thermal radiation from every object in the surrounding environment and feedback with images to users. Specifically, the external detector receives thermal radiation distribution from the objects' surface, converting the optical signal into an electrical signal, which is then processed into a thermal image. Processed under the same working principle as a thermal imager, the image is composed of different color patterns that vary due to their differences in surface temperature. This sensor is commonly used in search and rescue
missions, and it saved thousands of lives by exploiting its ability to identify the thermal radiation from human skin accurately even when buried underground.

5. Limitations

Although quadcopters and drones have already become thoughts that can surmount real life applications, bolstered by relatively complete theoretical systems, drones still have defects that may affect their performance seriously during motion.
First, while drones' structural strength is always being valued by designers to endure strong physical influences from surroundings, their weight is designed to be relatively light to maintain their physical activity. Since materials with both traits of high endurance with strength and trait of light mass are rare to be found, material selection in designing quadcopters is hypercritical, leading to a relatively high production and maintenance cost despite its fragile structure.
Nevertheless, the implementation of PID control significantly enhances the capability of drones to make precise, controlled adjustments in their motion. This not only reduces the necessity for high structural integrity but also contributes to prolonging the lifespan of lighter materials.
Furthermore, a well-tuned PID control system facilitates smoother and more stable flight, thereby minimizing structural stress during maneuvers. As a result, this approach helps safeguard delicate components, even when utilizing lighter materials. In addition, the sensors and executors on drones are vulnerable to fluctuations in their working environment, such as airflow and extreme temperatures, which makes it hard to acquire accurate performance parameters.
Second, quadcopter UAVs are under-actuated systems with six basic motion states, vertical motion, pitch motion, roll motion, yaw motion, forward and backward motion, and lateral motion, but only four control inputs. Its characteristics of multivariable, nonlinear, strong coupling, and interference sensitivity make the designing process of the flight control system very difficult.
Still, with the help of proportional (P) and derivative (D) part , the drone can effectively respond to minor
6 disturbances such as wind gusts or thermal fluctuations, thereby ensuring the drone's stability in varying conditions.
Third, cumulative error in drones can cause their estimated position to deviate from actual

position or result in the wobble and tilt of drones, which seriously affect the maneuverability and reliability of the aircraft. This situation is caused by the gradual accumulation of minor inaccuracies in data reported by sensors, control input, or the controlling algorithms overtime.

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