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UAV flight mechanics

Described the basics of UAV motion control system. The problems in stabilization of PID controller. Provided comparisons of transfer characteristics for PI and PID controllers.

The flight of multicopter is due to the rotation of the pairs of rotors in opposite directions, in the case quadcopters - two couples. Unlike traditional helicopters, all four rotors work together to create a vertical thrust and weight lifting apparatus in the air. The movement of the quadcopter is controlled by varying the relative thrust of each rotor. This design creates a more stable platform than helicopters with one rotor.

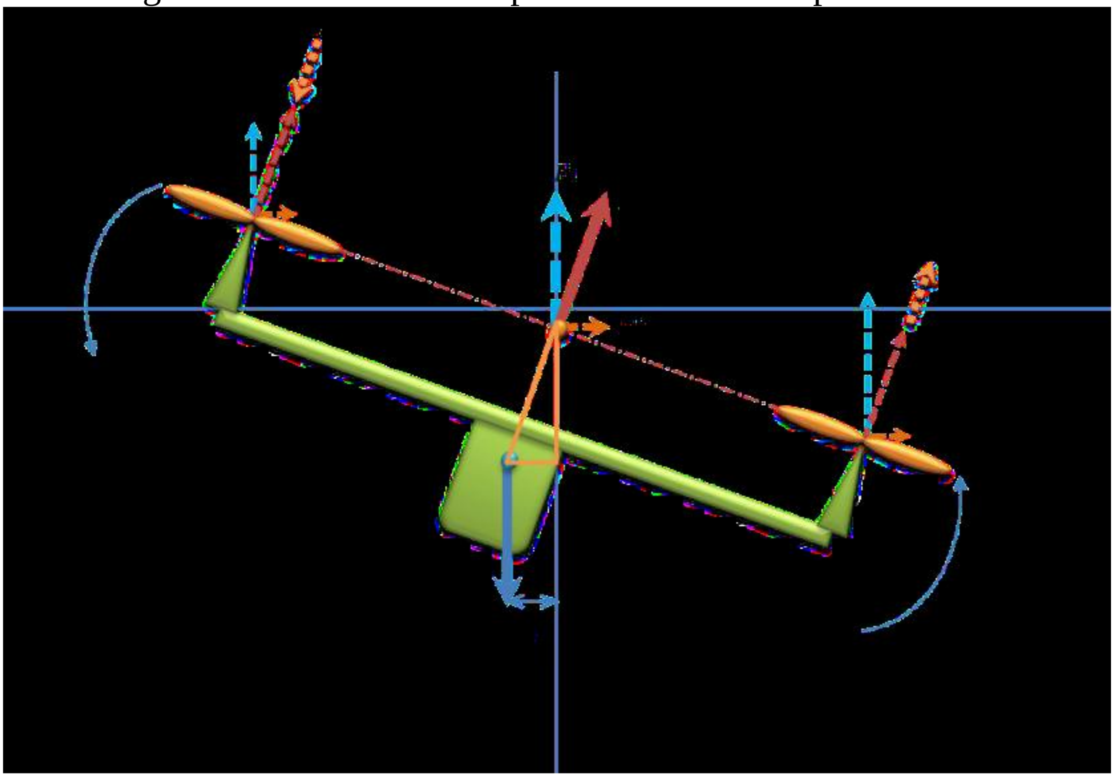

Fig. 1 – Turning the quadcopter by changing thrust of one rotor

Helicopters uses two rotors, one main rotor, which provides lift and shift pitch and roll, and one stabilizer – the tail rotor [1]. Tail rotor used to stabilize the aircraft on the twisting torque of the main rotor. Quadcopters and other multicopters based on four or more rotors which act together to tilt the entire apparatus and perform changes in pitch and roll. Motors controlled by onboard flight controller - through the analysis of the current state of orientation using one or more sensors and auxiliary control. The steeper the angle of the device causes the faster going in this direction, but too steep an angle can cause accidents.

From a technical point of view, this raises an interesting and difficult task of balancing (maintaining a stable position and vertical orientation) by continuously

adjusting the speed of rotation on each rotor. Since the realization of these adjustments
in real time is an extremely difficult task for a human, its work translates into created complex system of regulation – the «PID controller».
As the multicopter, because of its design has resistance to external influences, the flight stabilization system occurs in three corners of his center: roll, pitch and yaw (Fig. 2). However, human reaction speed is not sufficient for effectively stabilization, so in practice used automatic stabilization system based on sensors installed on the quadcopter, such as accelerometers and gyroscopes.

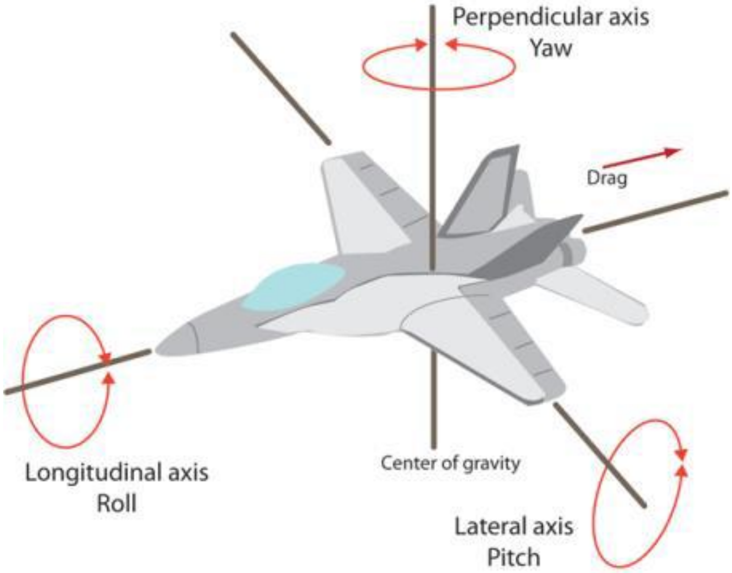

Fig. 2 – Angles of the aircraft compared to the center

Since the yaw angle is not critical for the maintenance of aircraft in the air, the main task is to stabilize the device in roll and pitch.
First of all, it should be noted that the accelerometer is not able to track uniform rotation in the plane perpendicular vector of .
If we assume that the actual acceleration of the device small in comparison with the acceleration of free fall , it is possible to determine the angles of pitch and roll, only by according to indications of the accelerometer. However, practical studies have shown that the natural noisiness of the accelerometer, in conjunction with vibration from the rotation of the propellers and self acceleration of multicopter, which does not allow to determine the angles required for stabilization accuracy. If use a filter with sufficient strength to smooth the signal, the sensor output delay occurs, and prevents timely response for change the position of the aircraft. Moreover, with a strong smoothing, information is lost at a relatively small changes of angle.
Thus, to solve the problem of stabilization uses a combination of accelerometer and gyroscope [2].
To represent rotations convenient to use quaternions – four component vectors. We denote $Q_g(t)$ for representing rotation, calculated at time accordingly to indications at gyroscope, and $Q_a(t)$ – rotation calculated in the same moment according to indications at accelerometer.
To correct the error indications of gyroscope integration, needs to take a

weighted sum of the quaternion:

$$Q(t) = \alpha Q_a(t) + (1-\alpha) Q_g(t) \qquad (1)$$

Where α – correction factor (usually takes values from 0.005 to 0.1).
Getting the angles of orientation of the device (yaw, roll and pitch) using quaternion orientations:

$$\varphi = arctg\left(\frac{1-2Q_y^2-2Q_z^2}{2Q_y\,Q_w-2Q_x\,Q_z}\right) \ (2)$$

$$\gamma = arctg\left(2Q_x\,Q_y - 2Q_y\,Q_w\right) \ (3)$$

$$\theta = arctg\left(\frac{1-2Q_x^2-2Q_z^2}{2Q_x\,Q_w-2Q_y\,Q_z}\right) \ (4)$$

Where Q_w, Q_x, Q_y, Q_z – four components of quaternion; the obtained values – rotation angles of machine: roll, pitch and yaw, respectively.
After the controling program obtain the angles of roll and pitch, it is necessary to apply the correction to the power of each engine to eliminate possible deviations. For this purpose, typically uses PID or PD controllers.
In total there are not so many types of regulators that are used to control the technical process, especially – the aircraft flight. A total of three, namely, P, PI, PID, there are other types but their usage is the exception, rather than rule. All the controllers are different in their characteristics and complexity of implementation. Shortly about the advantages and disadvantages in the usage of each of them:
– Proportional controller (P-controller). Principle of action – producing a control effect on the control object, proportionally to the value of error. Advantages: ease of implementation and configuration. Disadvantages: can not provide stable maintenance parameter – or rather can not provide achievement of a given parameter.
Used in devices where simplicity is required, but there is no need for great precision. In industry is rarely used due to the fact that in more or less complex devices to implement other, more precise controller is easy. Actually used in simple devices with limited functionality with no software control (microcontrollers, microprocessors, etc.).
– Proportional-integral controller (PI-controller). It is one of the most versatile regulators. In fact, PI controller – is a P controller with an additional integral component. I-component, which complements the algorithm, first of all needs to eliminate static error, which is characteristic of a proportional controller. In fact, an integral part is cumulative and thus allows that the PI controller takes into time previous history of changes in the input variable. Advantages: ease of implementation. Disadvantages: output to a target value is prolonged (over time).
It is used in many industrial applications where is necessary accurately hold the parameter which does not change its value instantly, even with the instantaneous change in external environment. For example the temperature can not change instantly because there are the heat capacity, moreover, also the sensor itself can not instantaneously change its temperature. Pressure fluids also can not change instantaneously, so using the PI regulators, for example, for the maintenance of pressure is justified.

– Proportional-integral-derivative controller (PID controller). The most optimal of this three types of regulators, so it widely used. In fact, this is evolution of the PI controller. The proportional component generates a signal which counteracts the deviation of the controlled variable at a given time (the ideology of pure P controller). Integral component accumulates the resultant value, leveling thus lack the P controller – the presence of static errors. D-component, which, as it predicts a deviation from the objectives and monitors speed deviations, so it the fastest in this algorithm. In fact, it is an advantage and a disadvantage at the same time. It is necessary to consider when choosing the law of regulation.
Advantages: best transfer characteristic, excellent speed and accuracy of regulation in comparison with P- and PI- regulators.
Disadvantages: difficult to implement and configure. Modern PID controllers implemented using computer processors. The yield on a given parameter is prolonged (at time).
PID controller, considering in terms of stabilizing the UAV – is algorithm, based on the deviation from the value, which should stabilize, and gives an amendment to the relevant rotors. Assuming the deviation from the required value at time *t* equal to *e (t)* , then the following formula expresses the necessary correction, where K_I, K_I, K_D – proportional, integral and differential coefficients respectively:

$$u(t) = P + I + D = K_P \cdot e(t) + K_I \int_0^t e(\tau)d\tau + K_D \frac{d}{dt} e(t) \quad (5)$$

In the case of PD (proportional-differential) regulator, component *I* is reset, and the previous formula becomes:

$$u(t) = P + D = K_P \cdot e(t) + K_I + K_D \frac{d}{dt} e(t) \quad (6)$$

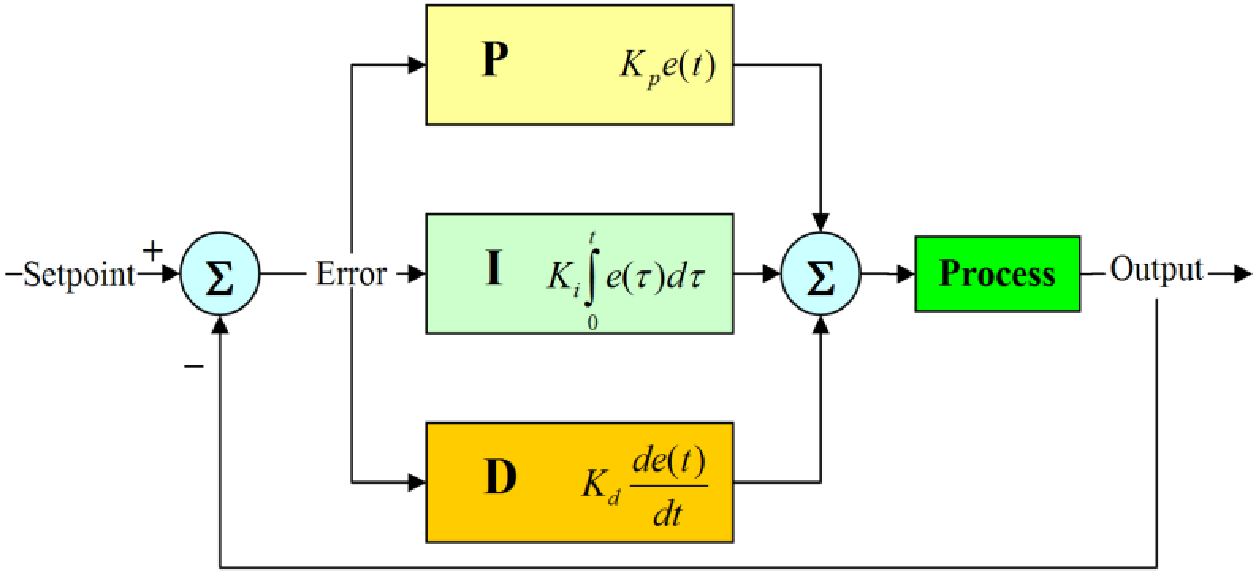

Figure 3 – Functional diagram of the PID regulator
Accelerometer and gyroscope are located on the machine such that their axes are the same direction as multicopter own axes. Thus, the reconstructed deviation angles represent the position stability. Since the task is stabilization of roll and pitch, it can be considered to be independent tasks. It is convenient to represent the angles in the form of two-dimensional (or three-dimensional, with 3 angles) vector, and all

operations on the calculation of corrections carried out in the form of a vector.
In order to quadcopter did not lose height, the amount of thrust of the rotors screws should be kept at an arbitrary inclination. Consider the case of one axis. If denote the time *t* at the total power for the motors at axis $M(t)$, and $P_1(t)$ with $P_2(t)$ – the powers that must be issued for two rotors at each axis respectively, the acquired form designs next formulas:

$$P_1(t) = \sqrt{\frac{M^2(t)+u(t)}{2}} \quad (7)$$

$$P_1(t) = \sqrt{\frac{M^2(t)-u(t)}{2}} \quad (8)$$

Square root arises from the physical law according to which the lift screw is proportional to the square of the angular velocity. We can check, that with this choice of lifting, power force saved:

$$P_1^2(t) + P_2^2(t) = \frac{M^2(t)+u(t)}{2} + \frac{M^2(t)-u(t)}{2} = M^2\,(t) \quad (9)$$

Despite the development of modern theory of automatic control methods, and based on them results like P, PI and PID controllers, which are often used in robotics, in terms of control the behavior of the aircraft and stabilization, disadvantages of these controllers are well known:

– Control systems that are based on PI, PD, PID for solving the problem of flight stabilization quadcopters do not provide the required quality due to the fact that the calculation of their parameters requires an accurate mathematical model of the control object and disturbance, which is very difficult to obtain.

– Aligning the device takes some time to stabilize due to the slowness of the process of calculating the D-component.

– Also, disadvantage of this method is poor quality of regulation and the limited region of stability with some drift of the object parameters and delayed action on the disturbances of the system input (noised data from the sensors).

As a result of disturbances and significant increasing in deviation of the controlled variable (the orientation of the device) with an increasing in the gain or delay, gain of the system should change (it is constant and given in experimental way). At the same time the formation of proportional, integral and differential impacts of the regulator remains the same as in steady and in transient conditions, leading to a deterioration in the quality of regulation, the appearance of oscillations and unstable work.

References

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