Development and application analysis of the quadrotor UAV’s attitude control

Shuaiwen Diao

College of Electrical and Mechanical Engineering, Shenyang Aerospace University, Shenyang City, Liaoning Province, 110136, China.

diaoshuaiwen@stu.sau.edu.cn

Abstract. Due to the economy's tremendous growth and the technology's impressive advancement, the practicality of UAVs has become a hot topic of concern for all sectors of society at present. According to the classification of flight platform configuration, drones may be split into many different types. Quadrotor drones are a common type of aerial robot, which is widely used in civilian and military fields at this stage. The safety and stability of the UAV in use are particularly important, so its flight attitude must be humanly tuned and controlled. This paper mainly analyzes the attitude control technology of quadrotor UAVs. Firstly, the key components and technical difficulties of attitude control are analyzed. Then some common control methods and application scenarios of current mainstream control methods are introduced and analyzed in detail. Finally, future research directions are analyzed and summarized based on the existing methods.

Keywords: quadrotor drones, attitude control, application scenarios, future research directions.

1. Introduction

Due to the economy's tremendous growth and the technology's impressive advancement, the practicality of UAVs has become a hot topic of concern for all sectors of society at present [1]. Today, drones are making a splash in fields such as geological exploration, livelihood support, power inspection, and even military operations. In this context, the safety and stability of the UAV in use are particularly important, so its flight attitude must be humanly tuned and controlled. According to the classification of flight platform configuration, drones may be split into many different types, including fixed-wing drones, rotary-wing drones, unmanned airships, parachute drones, and flutter drones, among others. The quadrotor UAV has been widely studied and used in recent years due to its high maneuverability and ability to perform tasks automatically. However, due to the multi-input, multi-output, and strong coupling characteristics of the quadrotor, makes attitude control a more difficult problem, especially in the face of environmental factors such as strong wind.

In conclusion, the quadrotor UAV's angle control is a crucial technical component for ensuring the UAV's safe and steady operation. This paper analyzes this problem. Firstly, the dynamics model and principle of the quadrotor UAV’s attitude control are introduced in detail. Secondly, the existing attitude control algorithms are further summarized and analyzed. Then, taking the application of the backstepping sliding mode control method in plant protection UAVs as an example, a UAV attitude control system is introduced and analyzed. Finally, the future development of technology is prospected from three perspectives and the full text is summarized.

2. Basic information about quadrotor UAV

2.1. Dynamics model of quadrotor UAV

When building the model of the dynamics of a UAV, it is important to first consider its linear model. Suppose the quadrotor is flying with roll, pitch, and yaw angles, so acceleration equations are:

$$\begin{cases} ma_x = F_t(cos\varphi cos\psi sin\theta + sin\varphi sin\psi) \\ ma_y = F_t(cos\varphi sin\theta sin\psi - cos\psi sin\varphi) \\ ma_z = -mg + F_t cos\varphi cos\theta \\ F_t = F_1 + F_2 + F_3 + F_4 \end{cases} \tag{1}$$

where φ is the roll angle, θ is the pith angle, ψ is the yaw angle, F_t is the total thrust. So, the six equations for the linear motion are:

$$\begin{cases} \dot{x} = v_x \\ \dot{y} = v_y \\ \dot{z} = v_z \\ m\dot{v}_x = F_t(cos\varphi cos\psi sin\theta + sin\varphi sin\psi) \\ m\dot{v}_y = F_t(cos\varphi sin\theta sin\psi - cos\psi sin\varphi) \\ m\dot{v}_z = -mg + F_t cos\varphi cos\theta \end{cases} \tag{2}$$

Next are the equations of angular motion. Based on the Euler equation, we can obtain the following equations:

$$\begin{cases} \dot{\varphi} = p + (rcos\varphi + qsin\varphi)tan\theta \\ \dot{\theta} = qcos\varphi - rsin\varphi \\ \dot{\psi} = \frac{1}{cos\theta}(rcos\varphi + qsin\varphi) \\ I_x\dot{p} = \left(I_y - I_z\right)qr + \tau_p \\ I_y\dot{q} = (I_z - I_x)pr + \tau_q \\ I_z\dot{r} = \left(I_x - I_y\right)pq + \tau_r \end{cases} \tag{3}$$

where τ is the moment, I is the moment of inertia, p is the roll rate, q is the pitch rate, r is the yaw rate.

2.2. Principle of UAV's attitude control

Methods of UAV attitude control have something in common with altitude control, but the difference lies in the object of control [2]. Attitude controllers are usually found in flight controls. The major duties of the attitude controller are angle control and making sure that the small and medium-sized UAVs have enough thrust to fly.

In the case of angle control, for example, an expectation about the angle is first fed to the drone via the remote control. The drone then makes the appropriate action according to the command. After this, the completion of the drone regarding the movement needs to be verified. It is worth noting that the angle data of the drone comes from gyroscopic integration and Kalman filtering rather than directly from the sensor. Finally, the control of the UAV angle is completed by the angle controller in the attitude controller. The complete attitude control process is shown in figure 1.

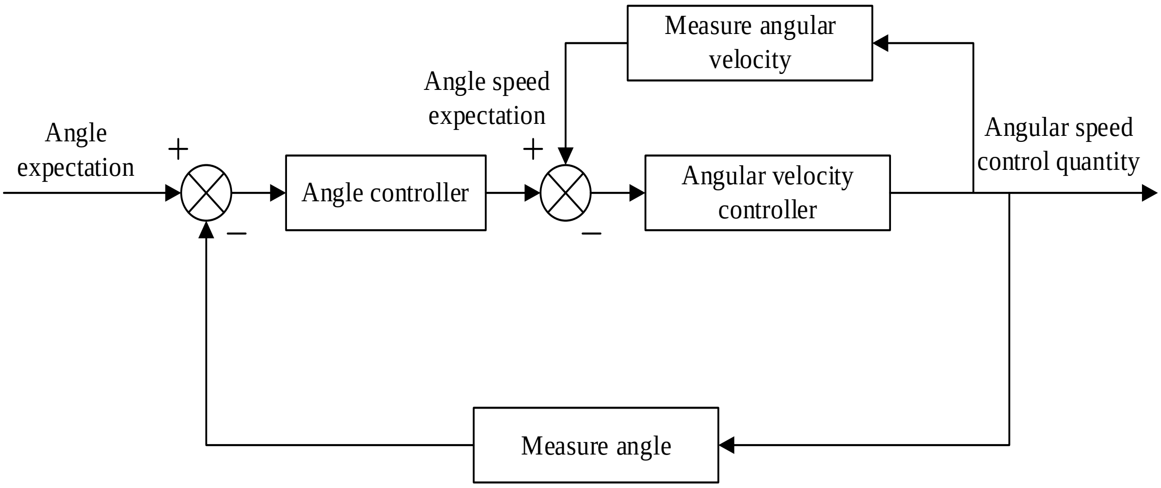

Figure 1. Attitude control process.

3. Specific description of methods

After the modeling of the kinematics of the quadrotor UAV and the analysis of the basic principles of attitude control, some specifics of the attitude control methods will be analyzed in this paragraph.

3.1. Active disturbance rejection control (ADRC)

Active Disturbance Rejection Control is a nonlinear control method which uses PID as basis to extend the system model by additional virtual state variables, as shown in figure 2. A key feature is that it is unnecessary to be familiar with the exact model of the system [3]. In this approach, all uncertainties acting on the controlled object are defined as "unknown disturbances", thus separating the system model from external disturbances. Under the control of a linearly expanding state observer (LESO), the internal uncertainties and external perturbations in the UAV attitude loop are monitored and adjusted in real time [4]. After compensation, the system's dynamic and steady-state characteristics are optimized, with good tracking performance, and thus attitude stability control can be achieved.

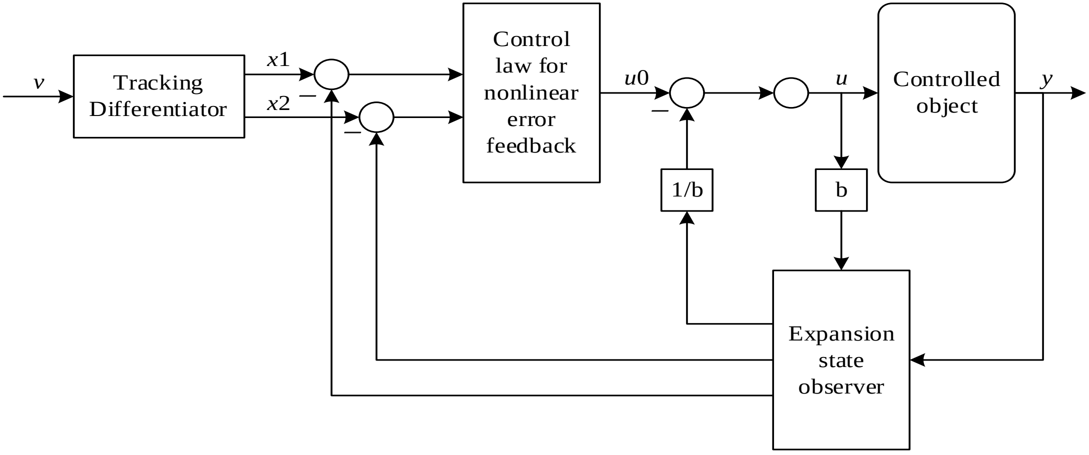

Figure 2. Flow chart of ADRC.

3.2. Backstepping control

This advanced control technique allows for detailed simulation and observation of system disturbances [5]. A unique series of nonlinear dynamical systems is intended to be designed using the backstepping control approach. These systems have a recursive structure, and the design process can be extended to new controllers from a known stable system. Then, in accordance with Lyapunov's stability theorem, each subsystem is created with an intermediate virtual control quantity, gradually stabilizing each external subsystem. The non-dependence of the backstepping control method on the differentiator allows it to be applied to strict feedback systems. In addition, the backstepping control method can also provide good control conditions to ensure that the quadcopter does not crash when it breaks a leg or something like that.

3.3. Adaptive control (APC)

APC is a control method with online parameter identification, which mainly includes model reference adaptive control, self-correcting control, and parametric adaptive control, as shown in figure 3.

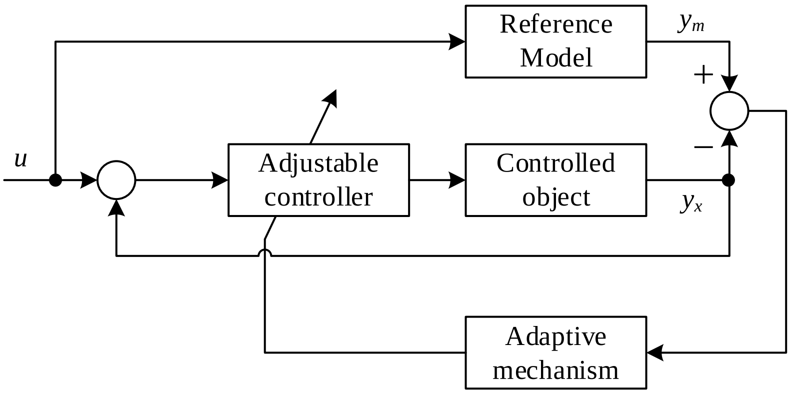

Figure 3. Flow chart of APC.

MRAC is one of APC's most widely studied and commonly used controllers. So this paragraph mainly uses it as the main body to explain the adaptive control method. The concern of MRAC is how to make the dynamic response of the system gradually approach the dynamic response of the reference system in the presence of uncertainty in the system [6]. Usually, variable or initial unknown parameters are present within the control system to which the controller is adapted. Stability control makes sure that the control law does not need to change, whereas adaptive control is concerned with the change of the control law itself when the change is within a certain range. The key to designing control laws is using the gradient approach and stability theory analytical method.

3.4. Sliding mode control

A nonlinear control technique called sliding mode control modifies the kinematics of a nonlinear system by sending a discontinuous control signal that makes the system slide along a normal action cross section. Its purpose is to force the moving trajectory to reach the sliding manifold in a certain time and to be able to stay on that manifold for a period of time, with the matching uncertainty not affecting its movement on the manifold. The trajectory moves to adjacent regions with different control structures under the action of multiple controls, therefore, there will not be a control structure to fully stow the trajectory. Conversely, it will slide along the boundary of the control structure. The existing results also show that by combining the sliding mode control method with neural networks, the controller tracking performance and immunity to interference can be improved [7]. This is a point that could be studied in more depth in the future.

3.5. Comparative analysis

To sum up, in combination with existing articles, the advantages and disadvantages of the above four methods are compared and analyzed horizontally, as shown in Table 1. It can be seen that each algorithm has its corresponding advantages and disadvantages. The author believes that combining the actual needs of the application scenario and selecting the appropriate algorithm after comprehensively considering the applicability of different algorithms can effectively improve the stability of the system.

Table 1. Comparison of four methods.

Control method	Advantage	Disadvantage
Active Disturbance Rejection Control (ADRC)	Can separate the system model from external disturbances	Controller parameters are difficult to determine
Backstepping Control	Fast convergence and better handling of external disturbances	Poor robustness
Adaptive Control (APC)	No advance information about system uncertainty is needed	More complex and costly system
Sliding Mode Control	Simple structure and fast response time	May produce jitter and affect the control effect

4. Application analysis

Today, UAVs have deep applications and play an important role in many areas, as shown in figure 4. They excel in power inspections based on their advanced LIDAR detection and radio communication technologies. They also excel in fire fighting and rescue with their high-temperature tolerance and long endurance and high mobility. The wonderful performance of UAVs in various fields cannot be achieved without the support of advanced control methods. The employment of the backstepping sliding mode control method in plant protection UAVs will be given as an example in this paragraph to show why advanced control methods are required.

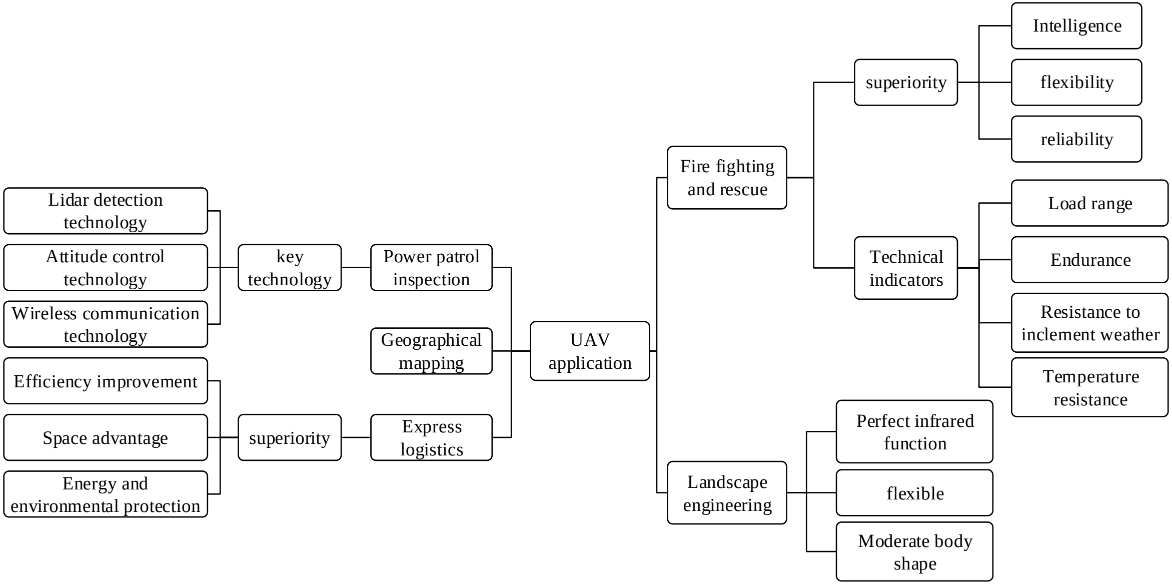

Figure 4. Applications and advantages of UAV.

Since plant protection drones need to operate in different terrains with high loads and high work intensity, the motors and propellers need to rotate at high speed to ensure their normal flight and complete the corresponding commands. This leads to a much higher risk of failure. Hence, it has become a hot topic to figure out how to guarantee the relative stability of the attitude of the plant protection drone even in the event of failure.

Before proceeding with the controller design, a fault model is first created. This model is built based on the following three assumptions: the UAV mass is assumed to be uniformly distributed and the flight is rigid body structure during flight. It is assumed that the UAV's center of mass and gravity are the same. It is assumed that the UAV is not affected by ground effects during travel.

Once the fault model is created, the next step is the design of the controller. First, a simplified model of the state observer is created. The second step is to design a linear quadratic regulator for the linear dynamic link, solve the nonlinear static link, assign it to the control input channel in the real system, and then obtain the optimal control law according to the Hamilton figuration. Finally, the design of the backstepping controller is completed according to the Lyapunov function. Since the backstepping controller has the deficiencies of poor robustness and needs accurate model of the controlled object, the sliding mode controller alignment is added for perfection. Thus, the system operation becomes sliding popular, expanding the range of controller applicability and improving the more general robustness.

In the specific application, according to the existing research results, the result is that the backstepping sliding mode controller can globally optimize the system parameters and adaptively adjust the weighting matrix, as shown in figure 5 [8]. The attitude of the motor is more stable under the condition of adding external disturbances and still can converge to a steady state quickly. The trajectory tracking of UAV flight attitude is good and the response is timely. It can better handle the interference of harsh environmental factors such as strong wind and has good robustness. The backstepping sliding mode controller can ensure the work quality and efficiency of the plant protection drone.

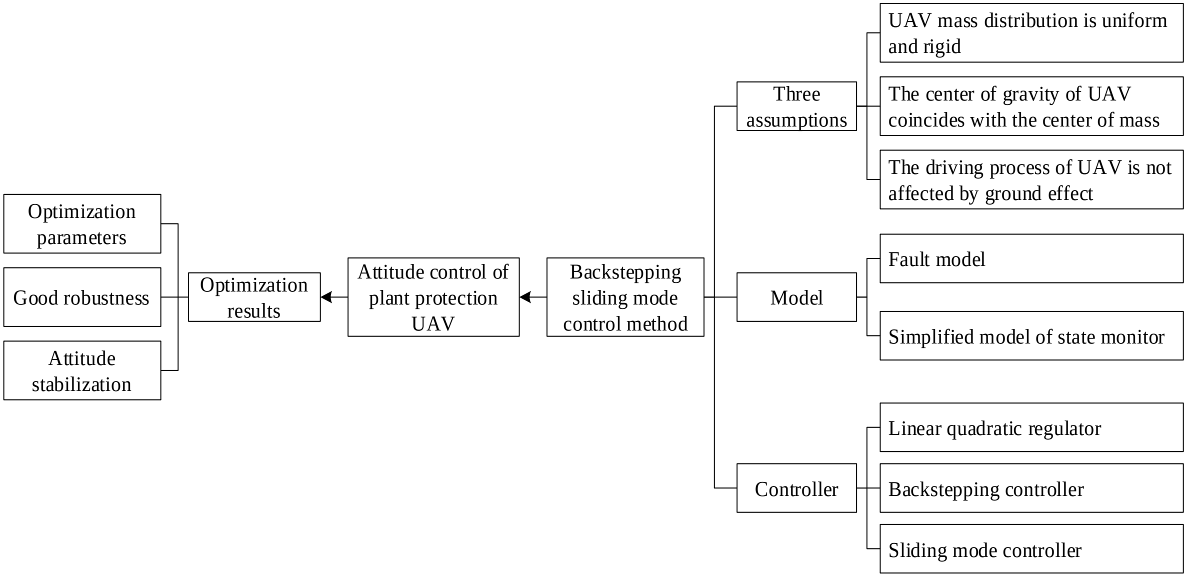

Figure 5. Process of application.

5. Future development

At present, the nonlinear attitude control method of UAV has been relatively perfect, and the feasible research direction for the future will be analyzed from the following three points.

5.1. Addition of neural networks

Neural network is an advanced technology. It operates and works in the way biological nerves do. It is a learning method that is adaptable. Machine vision and speech recognition are two examples of the many challenges that neural networks have been utilized to solve.

Nowadays, some studies show that combining nonlinear control methods with neural networks can achieve better control results. For example, combining adaptive control methods with neural networks can lead to more refined inverse controllers and better-performing PD controllers [9]. Traditional PID controllers can't compete with it. In addition, combining sliding mode controllers with neural networks can increase the advantages of both at the same time. The controller obtained by this method has good instantaneous and steady-state performance with strong anti-interference capability and suppressed sensitivity to parameter variations [10]. To a certain extent, the negative effects of possible jitter are eliminated.

With the above research as a basis, and along with the further development of artificial intelligence in neural networks, there is a considerable possibility of combining one or more control methods with neural networks in the future. This combination may allow for greater maneuverability and automated mission execution capabilities for UAVs. And it could significantly reduce the probability of UAV malfunctions and crashes due to environmental factors. In the future, specific combinations and controller designs remain to be explored.

5.2. Fault tolerance control

Fault-tolerant control of drones is also an area to be explored. Some control methods only enable all motors to work properly or complete movements of too-small magnitude. Therefore, the study of fault tolerance in terms of operational initiative and angular completion could be more in-depth.

5.3. Computer vision technology of UAV

Robotic operating systems interfacing with UAVs are compelling [11]. This connection allows researchers to develop easy control and vision algorithms. In the field of UAV vision, target tracking is still to be developed. In addition to the difficulties at the algorithm level, the selection and improvement of sensors are also worthy of deep consideration. The localization of UAVs indoors and the perception of distance measurement of indoor objects is also an open challenge that can be explored in conjunction with studies such as path planning.

6. Conclusions

This paper summarizes and compares the existing mainstream UAV attitude control methods such as Active Disturbance Rejection Control (ADRC), Backstepping Control, Adaptive Control (APC), and Sliding Mode Control, and illustrates the characteristics, advantages and disadvantages of different methods. The specific applications of the backstepping sliding mode control method in plant protection UAVs are also listed to illustrate the positive impact of advanced control methods on real production life. Finally, the feasible future development directions of UAV attitude control are sorted out and discussed, and several areas mentioned are worth being expected.

References

[1] B. Tian, L. Liu, H. Lu, Z. Zuo, Q. Zong and Y. Zhang, "Multivariable Finite Time Attitude Control for Quadrotor UAV: Theory and Experimentation," in IEEE Transactions on Industrial Electronics, vol. 65, no. 3, pp. 2567-2577, March 2018, doi: 10.1109/TIE.2017.2739700.

[2] K. U. Lee, Y. H. Yun, W. Chang, J. B. Park and Y. H. Choi, "Modeling and altitude control of quad-rotor UAV," 2011 11th International Conference on Control, Automation and Systems, Gyeonggi-do, Korea (South), 2011, pp. 1897-1902.

[3] Z. Ma and S. M. Jiao, "Research on the attitude control of quad-rotor UAV based on active disturbance rejection control," 2017 3rd IEEE International Conference on Control Science and Systems Engineering (ICCSSE), Beijing, China, 2017, pp. 45-49, doi: 10.1109/CCSSE.2017.8087892.

[4] Qiang Gao, Xinpeng Liu, Chunping Liu, Yuehui Ji, Junjie Liu, Quadrotor UAV tandem-level self-anti-disturbance attitude control and trajectory tracking [J/OL]. Electro-Optics and Control.

[5] W. Qingtong, W. Honglin, W. Qingxian and C. Mou, "Backstepping-based attitude control for a quadrotor UAV using nonlinear disturbance observer," 2015 34th Chinese Control Conference (CCC), Hangzhou, China, 2015, pp. 771-776, doi: 10.1109/ChiCC.2015.7259733.

[6] Sadeghzadeh,I., Mehta, A. ., Zhang, . Y., & Rabbath, C.-A. . (2011). Fault-Tolerant Trajectory Tracking Control of a Quadrotor Helicopter Using Gain-Scheduled PID and Model Reference Adaptive Control. Annual Conference of the PHM Society, 3(1).

[7] N. P. Nguyen, N. X. Mung, H. L. N. N. Thanh, T. T. Huynh, N. T. Lam and S. K. Hong, "Adaptive Sliding Mode Control for Attitude and Altitude System of a Quadcopter UAV via Neural Network," in IEEE Access, vol.9,pp.40076-40085,2021, doi:10.1109/ACCESS.2021.3064883.

[8] Jiang Feng, Hui Zhang, Xihai Zhang, Research on attitude control of plant protection UAV based

on backstepping sliding mode algorithm[J]. Journal of Northeast Agricultural University, 2022, 53(1): 55-65. DOI: 10.19720/j.cnki.issn.1005-9369.2022.01.007.

[9] B. -Y. Lee, H. -I. Lee and M. -J. Tahk, "Analysis of adaptive control using on-line neural networks for a quadrotor UAV," 2013 13th International Conference on Control, Automation and Systems (ICCAS 2013), Gwangju, Korea (South), 2013, pp. 1840-1844, doi: 10.1109/ICCAS.2013.6704240.

[10] Razmi, H., & Afshinfar, S. (2019). Neural network-based adaptive sliding mode control design for position and attitude control of a quadrotor UAV. Aerospace Science and technology, 91, 12-27.

[11] Cheema, P., Luo, S., & Gibbens, P. (2016). Development of a Control and Vision Interface for an AR. Drone. In MATEC Web of Conferences (Vol. 56, p. 07002). EDP Sciences.