PID Control Optimization Design of Liquid Oscillation for Quadcopter Drone: Qualitatively Explore the Effects of Liquid Shaking and Improve it

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ABSTRACT

UAVs carrying liquids are subjected to imbalance caused by liquid shaking during flight, which leads to shaking of the UAV itself, especially when braking sharply. While most of the existing studies at home and abroad focus on the structural optimisation of the tank itself, such as adding damping, and most of the research into wobble generation is wind force very few optimise the shaking caused by the liquid by means of a controller. In this paper, we study to reduce the shaking of UAV based on PID control, which can reduce the structural complexity of the water tank and lower the cost. In this paper, we first establish the mathematical equations of UAV dynamics and the equations of liquid-carrying UAV dynamics, and build their Simulink models to regulate their motion by PID. The study shows that the effect caused by liquid shaking is not negligible, and the model in this paper can well optimise this shaking and pave the way for future research on UAVs carrying more dynamic objects.

KEYWORDS

Unmanned aerial vehicle(UAV); Attitude control; MATLAB/Simulink; PID control; Liquid disturbance; Modelling

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1 Introduction

In recent years, the development of drones in various fields has been rapid, and they have been used in many good applications in various fields, such as plant protection drones, which have basically achieved reliable mechanised operations in the processes of ploughing, sowing, harvesting, etc. However, from the point of view of the mechanised plant protection operations, affected by the state of the plants in the mid- and late stages of the growth of the crops, the manual operations and semi-automated operations in the plant protection operations at the present stage still account for the larger proportion.

The study of existing dissertation research papers has a deep significance for the research of this paper. In their paper "Principles and Analysis of Agricultural UAV Technology in Plant Protection Applications," Liang Zhang et al.[1]analyzed agricultural UAVs, identifying significant room for improvement in both technology and dissemination. They categorized UAV types, providing valuable references for the selection of UAVs in this study. They also introduced six flight maneuvers, including vertical ascent/descent, forward/backward movement, left/right movement, pitch, roll, and yaw, laying the foundation for aircraft control principles. Zhi Chai [2], in the research paper "Attitude Control of Quadcopter Drones," defined three coordinate systems and attitude angles, establishing rotation matrices to facilitate the study of drone attitudes and dynamics in this research. They compared the response time, stability, and anti-interference ability of cascade fuzzy PID controllers. Wentao Jiang et al.[3], in their paper "Flight Attitude Control of Quadcopter Drones based on Fuzzy PID," elaborated on the transfer functions of various channels of the quadcopter drone and the fundamental principles of fuzzy PID controllers, including fuzzyfication of input variables, rule formulation, fuzzy reasoning, and defuzzification of output variables. They also compared the performance of fuzzy PID control with traditional PID control, demonstrating the superior performance of fuzzy PID control. Yuchun Li et al.[4], in their paper "Discussion on Several Problems in Liquid Oscillation Dynamics," discussed several issues related to liquid oscillation, including equivalent mechanical models, liquid oscillation damping, and liquid parameter oscillation, aiding the establishment of PID controller models in this study. Wenjun Wu et al.[5], in their paper "Parameterized Mathematical Model Identification of Liquid Oscillation in Heavy Tanker," established an equivalent pendulum model for the liquid inside the storage tank, without considering damping. They derived the expressions of forces and moments acting on the tank body with parameterized values based on this model, providing a reference for establishing the mathematical model of dynamics in this study. They also used CFD software to solve for the tank body's moment and oscillation moment, providing data support for the oscillation moment in this research Bengang Han et al.[6]discussed the application of matlab in UAVs, as well as Mingxing Yang et al.[7] discussed the application of sliding mode control in UAVs to provide process know-how and know-how of control methods for the research of this paper

During the flight of plant protection drones and other drones carrying liquids, they often experience imbalances caused by the liquid shaking, especially during sharp braking maneuvers. While existing studies mainly focus on structural optimization of the tank, such as adding damping[8] [9], and most of the research into wobble generation is wind force[10], very few have explored the use of a controller to optimize the liquid-induced shaking. In this paper, we investigate the reduction of UAV shaking through PID control, which can simplify the water tank structure and reduce costs.

The technology developed in this research can be applied to various liquid-carrying UAVs, offering valuable insights and guidance. The significance of this research lies in advancing intelligent development and the potential to enable UAVs to transport dynamic objects, such as live animals, opening up diverse applications.

2 Methodology

By utilizing PID control, we observe factors such as response time and overshoot of Euler angles to effectively reduce the oscillations caused by the liquid carried by the drone, minimizing the shift in the center of gravity and reducing the extent of drone oscillations. This approach leads to enhanced flight stability by decreasing the braking distance and making the drone's flight more stable.

(1) Principles and modeling of quadcopter drones

The quadcopter drone possesses a visually clear mechanical structure, and its state transition during operation is straightforward and easy to understand. The overall body of the quadcopter can be regarded as a rigid vertical cross structure with perfect symmetry. Additionally, the opposite rotation directions of adjacent rotors eliminate the reactive torque, thereby eliminating the need for additional counter-torque rotors and greatly simplifying the structure of the transmission devices.

To achieve attitude control during the flight of the UAV, it is necessary to modulate the lift generated by the four propellers, which is determined by the different rotor speeds. The quadcopter drone is equipped with four sets of motor-propeller combinations to provide power, yet it possesses six degrees of freedom, enabling it to achieve hovering, vertical, pitch, roll, and yaw motions.

Coordinate System (as shown in Figure 1):The origin O represents the center of mass of the UAV. The X-axis and Y-axis lie in the same plane as the UAV, with the X-axis pointing forward and the Y-axis pointing to the left of the UAV. The Z-axis is vertical to the XOY plane, pointing upwards.

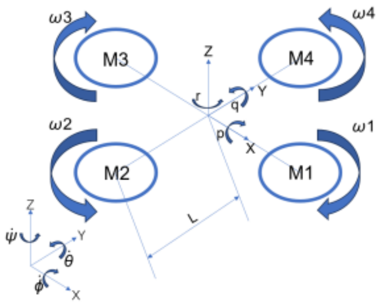

Figure 1. UAV Coordinate System

(2) UAV kinematics and dynamics equations

The quadcopter UAV exhibits two modes of motion: horizontal motion and rotational motion. Here, we utilize the Newton-Euler equations to establish models for each of these motion modes and formulate the following system of equations(as Figure 2 shown):

UAV Displacement, Velocity, and Acceleration Equations:

$$\ddot{x} = \dot{v}_x = a_x$$
$$\ddot{y} = \dot{v}_y = a_y$$
$$\ddot{z} = \dot{v}_z = a_z$$

UAV Force Equation:

$$Ft = F1 + F2 + F3 + F4$$
$$ma_x = Ft(\cos\phi\cos\psi\sin\theta + \sin\theta\sin\psi)$$
$$ma_y = Ft(\cos\phi\sin\theta\sin\psi - \cos\psi\sin\phi)$$
$$ma_z = -mg + Ft\cos\phi\cos\theta$$

UAV Torque Equation:

$$\tau_p = -F2*l + F4*l$$
$$\tau_q = -F1*l + F3*l$$
$$\tau_r = -F1*d + F2*d - F3*d + F4*d$$

UAV Angular Velocity Equation:

$$\dot{\phi} = p + (r\cos\phi + q\sin\phi)\tan\theta$$
$$\dot{\theta} = q\cos\phi - r\sin\phi$$
$$\dot{\psi} = (1/\cos\theta)(r\cos\phi + q\sin\phi)$$

UAV Angular Acceleration Equation:

$$I_x\dot{p} = (I_y - I_z)qr + \tau_p$$
$$I_y\dot{q} = (I_z - I_x)pr + \tau_q$$
$$I_z\dot{r} = (I_x - I_y)pq + \tau_r$$

Figure 2. Equation

(3) Kinematics and dynamics equations of Liquid-Carrying UAV

During the motion of the UAV, especially during abrupt stops and similar situations, the UAV may experience shaking. Due to the inertia, the liquid carried by the UAV maintains its original motion state, which affects the UAV and causes a shift in its center of mass. This change in center of mass can be equivalently transformed into an external torque. Therefore, the torque equation for the UAV is expressed as follows:

$$\tau_p = -F2*l + F4*l + T1$$
$$\tau_q = -F1*l + F3*l + T2$$
$$\tau_r = -F1*d + F2*d - F3*d + F4*d + T3$$
$$(T1, T2, T3 \text{ are equivalent external torques})$$

(4) Building the Simulink PID control model

In today's society, artificial intelligence technology is growing at an astonishing rate, and along with it, automatic control technology is becoming increasingly intelligent. However, in the field of engineering, PID control remains one of the most widely used control methods in practical applications. Currently, the commonly seen flight control systems for quadcopter UAVs on the market employ the PID control algorithm.

The traditional PID controller consists of three components: Proportional (P), Integral (I), and Derivative (D). The proportional component provides the basic control action, the integral component acts as a correction to improve system stability, and the derivative component increases the bandwidth and enhances the transient response speed of the system, improving the quality of the system's transition process. The PID control principle and the logic of the constructed model is depicted in Figure 3:

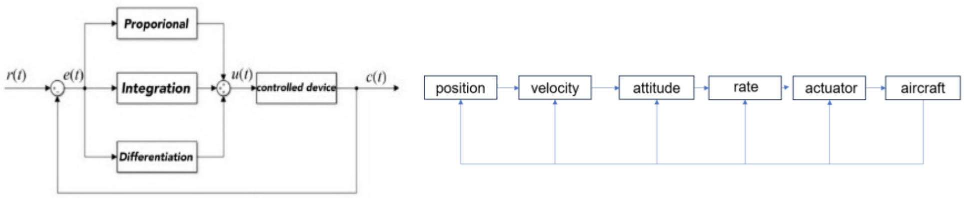

Figure 3. PID Control Principle Block Diagram and Control Logic Diagram)

Based on the above model, a Simulink simulation model is constructed (as shown in Figure 4). The selected UAV is based on the parameters of the DJI T40 agricultural UAV, with slight adjustments. The mass of the UAV is set as m=40kg, and the rotational inertias are adjusted to Ix = 4.2825 Nm, Iy = 6.627 Nm, and Iz = 6.09375 Nm. The wing structure parameters are defined as L=0.9m for the wing length and d=1.3m for the wing diameter.

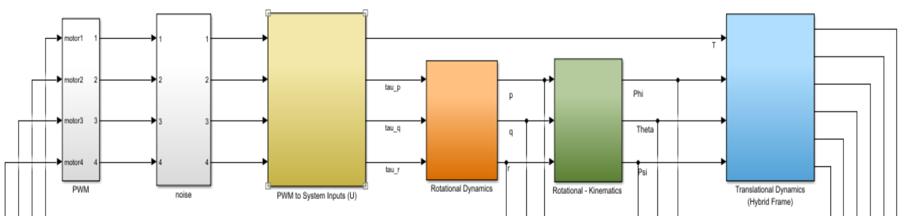

Figure 4. Simulink-Based UAV Controller Model

Building the PID Controller Model (as shown in Figure 5):

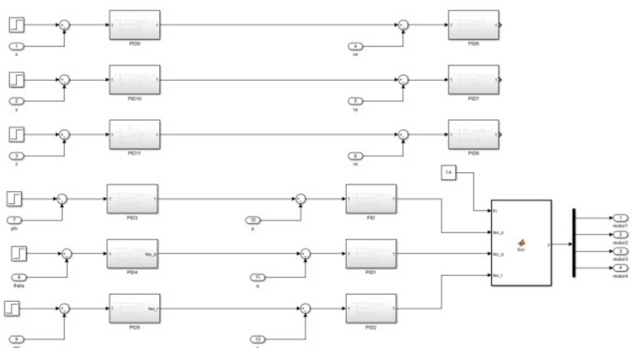

Figure 5. PID Controller Model Built in Simulink

Due to only applying a step signal at the theta angle input, PID4 and PID1 are taken as examples. In the PID4 module, the values of kp, ki, and kd are set as follows: 2, 0.1, and 0.1, respectively (as shown in left side of Figure 6). For the PID1 module, the values of kp, ki, and kd are set as follows: 20, 0.1, and 0.1, respectively (as shown in right side of Figure 6).

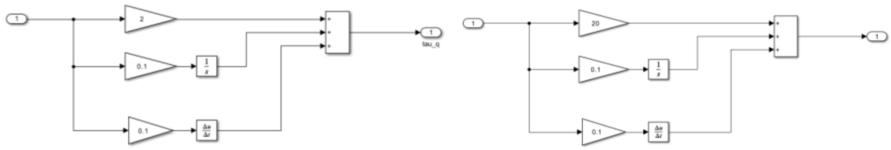

Figure 6. PID4 and PID1

By only applying a step signal with a final value of 0.1 at the theta angle input, the flight maintains a constant speed in the positive x and z directions. From the figure 7, it can be observed that the maximum overshoot of the theta angle is 0.1093, and the response time is approximately 4.28 seconds. There are slight fluctuations in the phi and psi angles, but they quickly return to 0. Overall, the flight of the drone controlled under this system is relatively stable and meets the expected behavior.

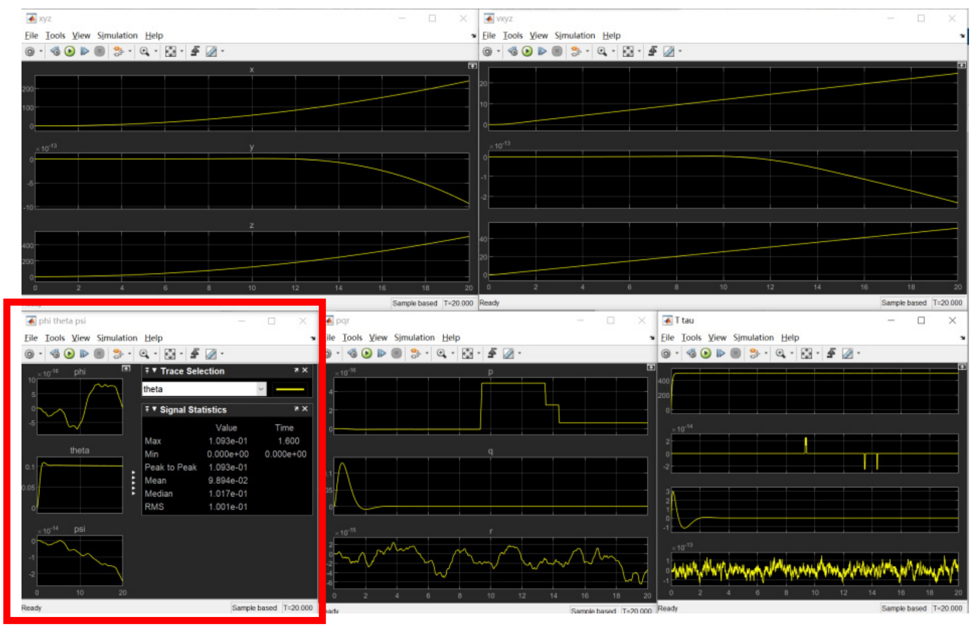

Figure 7. Curves of Drone Velocity, Displacement, Euler Angles, Angular Velocity, and Torque

(5) Building Simulink PID control model for Liquid-Carrying Drone

As analyzed earlier, it is necessary to incorporate an appropriate torque into the drone's torque equation to simulate liquid sloshing. Taking emergency braking as an example, based on the previously established equations for the liquid-carrying motion, an -5 Nm torque is introduced at 10 seconds during the emergency braking (duration of 1 second). This torque is implemented using an external pulse function (as shown in left side of Figure 8). The emergency braking is achieved using an external step function in the opposite direction (as shown in right side Figure 8). The controller is constructed as shown in the figure.

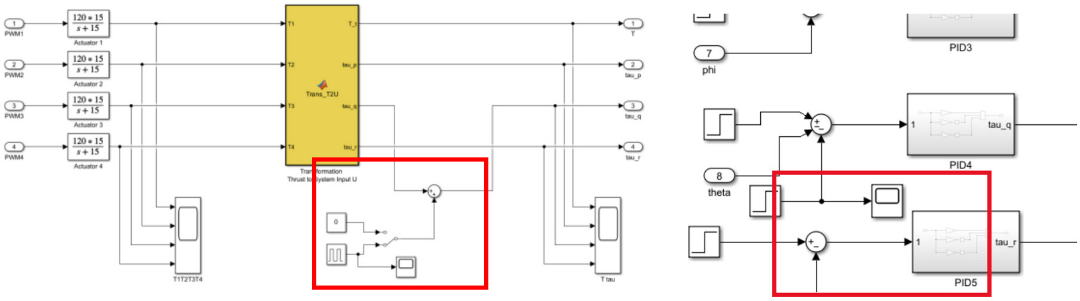

Figure 8. Simulink Model for Torque Control and PID Control of Liquid-Carrying Drone

At this point, if we do not consider the disturbance caused by the liquid during emergency braking, that is, by deactivating the pulse function channel, the Euler angle variation is shown in left side of Figure 9. It can be observed that during emergency braking, the maximum change in the theta angle is -0.007755 radians.

Figure 9. Euler Angle Variation without Considering Liquid Disturbance and Considering Liquid Disturbance

When considering the Euler angle variation with the liquid disturbance, and enabling the pulse function channel, the Euler angle variation is shown in right side of Figure 9. It can be observed that theta angle exhibits significant oscillation at around 10.93 seconds, reaching approximately -0.05 radians. This value is more than six times larger than the theta angle variation observed when not considering the liquid disturbance. This highlights the need to optimize the PID control for addressing the liquid disturbance issue, emphasizing the significance of this study.

After modifying the PID parameters, the Euler angle variation is shown in Figure 10. The theta angle is approximately -0.009796 radians, with the most significant oscillation occurring at around 10.810 seconds. The final optimized model demonstrates a disturbance amplitude only one-fifth of the previous model before the improvement.

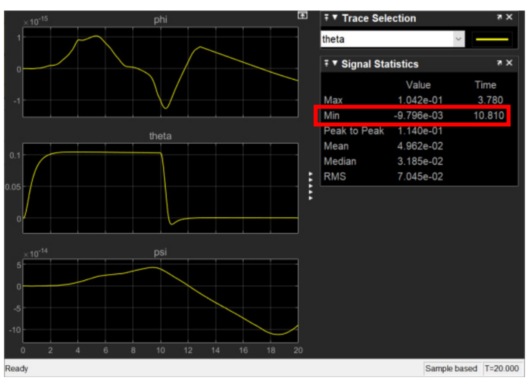

Figure 10. Euler Angle Variation Considering Liquid Sloshing After Improvement

The final system parameters for PID4 and PID1 on the theta channel are shown in Figure 11. Similar adjustments can be made for other channels.

Parameter	Kp	Ki	Kd
PID4	1.5	0.1	0.1
PID1	35	0.01	0.01

Figure 11. PID4 and PID1 Parameter Settings

(6) Effects of liquid sloshing under different conditions

When the velocity is increased, i.e., by simultaneously setting a larger step response termination value and a higher magnitude pulse function, the resulting Euler angle variations are shown in of Figure 12. For a step response termination value of 0.2 and a pulse function magnitude of -10, the system's oscillation amplitude during emergency braking is -0.01969 radians. For a step response termination value of 0.3 and a pulse function magnitude of -15, the system's oscillation amplitude during emergency braking is -0.02939 radians. It can be observed that with an increase in the system's initial velocity, the impact of sloshing becomes more pronounced.

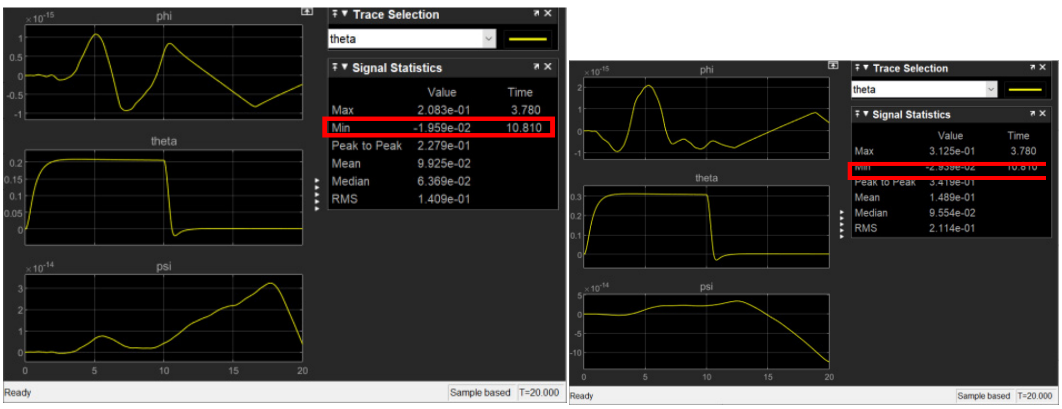

Figure 12 shows the Euler angle variations for different conditions: a step response termination value of 0.2 and a pulse function magnitude of -10, and a step response termination value of 0.3 and a pulse function magnitude of -15.

3 Conclusion

Firstly, the impact of liquid oscillation cannot be ignored. In this model, considering the oscillation resulted in Euler angles being six times larger compared to when the oscillation is not considered. Secondly, by using PID control, the variation in Euler angles can be reduced, leading to a more stable system. After optimizing the PID control, the variation in Euler angles has been reduced by one-fifth. Finally, as the initial velocity of the drone increases, the oscillation caused by the sudden stop of the liquid becomes more significant.

About the Author

Jiaqi Du is undergraduate of College of Mechanical Engineering of Southwest Jiaotong University, and her research field is qualitative exploration of the effects of liquid shaking and its improvement.

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