Study on UAV Based on Fused Filament Fabrication

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Abstract: Air Unmanned Aerial Vehicles (UAVs) have the characteristics of simple structure and convenient carrying, while quadrotor UAVs have better manoeuvrability, can achieve fixed-point hover, and have vertical takeoff and landing capabilities. Additive Manufacturing (AM) is also often referred to as 3D printing. In the past ten years, AM technology has received extensive attention. Among the seven categories of AM technologies released by the American Society for Testing and Materials, Fused Filament Fabrication (FFF) is one of the most widely used and essential processing technologies in additive manufacturing. It mainly manufactures models by extruding molten wire (such as plastics, resins, composites, etc.). First, consider the additive manufacturing of the quadrotor aerial UAV entirely through fused filament fabrication, and control the UAV's flexibility by adjusting the filling material's parameter during the additive manufacturing process. However, the increased flexibility makes it difficult to control the UAV, and the structural, aerodynamic and aeroelastic effects must be further explored.

Keywords: Additive Manufacturing, Fused Filament Fabrication, Unmanned Aerial Vehicles, Multi-Rotors Dynamics

Introduction

Additive Manufacturing technology has the potential to significantly save costs due to its ability to reduce material waste and produce complex geometry without tools. Therefore, they have received considerable attention in the past decade. The fused filament fabrication process, also known as fusion deposition modelling, is one of the most popular AM methods for polymer or composite parts manufacturing. The process uses a continuous filament of thermoplastic material as raw material (Song et al., 2018). Molten raw materials are extruded from the print head and deposited layer by layer on the construction platform. This leads to the formation of the design and required parts. The FFF process usually starts from the solid model of the planned interest generated in the CAD system. The model is oriented by the required construction direction and is post-processed into stereolithography (STL) in CAD system. Then the STL representation is decomposed into horizontal layers to represent the thin section of the product. The solid models of these structures are then defined and similarly sliced. Then the actual instruction code of the FFF machine is generated, including the path plan of each layer of the slicing model. The only post-processing activity required is dismantling the support structure (Brenken et al., 2018).

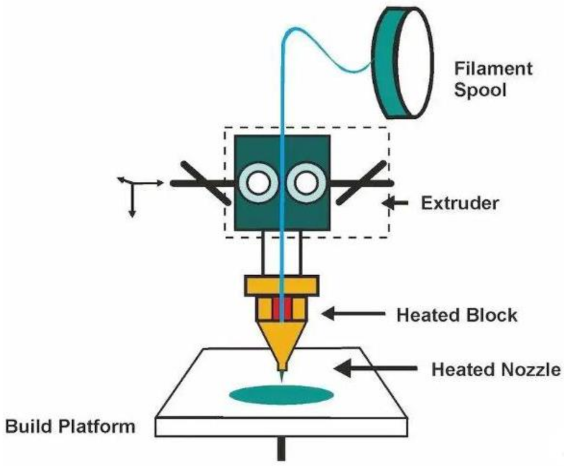

Figure 1 Fused Filament Fabrication

In the development process of aircraft, compared with rotorcraft, fixed-wing aircraft have the advantages of fast speed, long range and hefty load (Peng & Zhang, 2020). In contrast, rotorcraft have the advantages of vertical takeoff and landing without picking up the site, and low altitude, low, speed hover monitoring. Four-rotor UAVs are multi-rotor aircraft that can take off, land freely, and hover. Because of its high flexibility and low cost, it is widely used in various fields. It has practical significance and application value in how to keep the attitude of the four-rotor UAV flying smoothly in the case of external interference or self-failure (Gobbato et al., 2012; Suwoyo et al., 2018; Suwoyo et al., 2020).

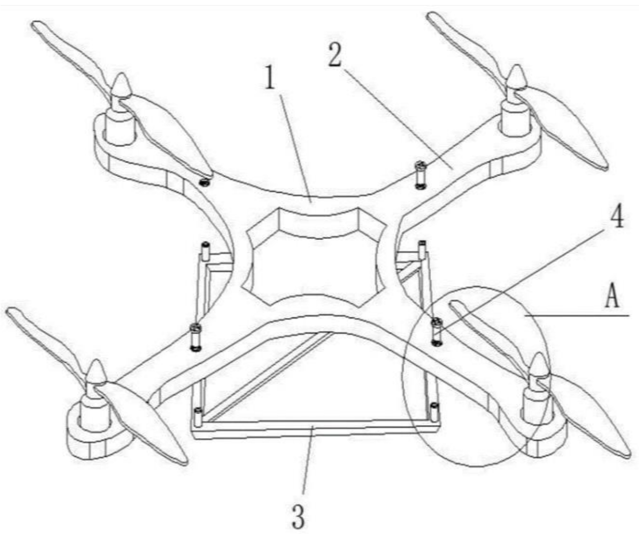

Figure 2 Quadrotor UAV

Research Method

Basic requirements for UAV design

The frame structure is the central load-bearing part of the UAV (Adriansyah et al., 2021). Whether the frame structure is intact is an important indicator to measure the overall structural stability of the UAV when the UAV is subjected to such alternating loads as lift, torque, engine vibration, aircraft weight and lifting impact during flight missions (Kristiawan et al., 2021; Suwoyo et al., 2021). Therefore, the design of the UAV frame will be focused on (Tian et al., 2020). There is no standard design scheme for structural design, which shall be designed flexibly according to work needs, and shall also meet the following basic requirements:

1. The layout is clear and reasonable. The frame structure should first ensure a reasonable connection with other parts of the UAV and, based on this, according to the requirements of the internal space of the UAV, finally ensure that the relative position relationship between the parts of the UAV is not disturbed.
2. Lightweight requirements. Lightweight design requires that under the premise of meeting the strength, stiffness and other load conditions, the overall structure weight should be as light as possible, and the push-weight ratio should be as high as possible according to the characteristics of the light weight of the structure itself to meet the lightweight design requirements.
3. Safety and economy. The frame structure shall be designed to meet the safety requirements without fatigue damage and other dangerous situations within the service life (Hidayat et al., 2020). At the same time, it is necessary to ensure that all parts meet the requirements of economy and technology in combination with the factors such as processability and actual processing difficulty.

Principle of motion of the quadrotor UAV

The four-rotor aircraft has four separate rotors. Although it is a rotor aircraft, its principle is entirely different from that of a single-rotor aircraft (Xia et al., 2022). The helicopter is a typical single-rotor UAV, which counteracts the main rotor torque with the torque generated by the tail rotor. The four-rotor aircraft controls the lift and torque acting on the airframe by relying on the different rotational speeds of the four rotors to control the movement of the four rotors and simultaneously realizes the role of the balancing torque (Jun et al., 2018; Karahan et al., 2021). Given this feature, the four-rotor aircraft is more accessible to achieve the goal of miniaturization and is more lightweight than the helicopter. Generally, the four rotors of a four-rotor aircraft are in the same plane, at the same height, and symmetrically distributed around the airframe.

The rotor is divided into two pairs of forward and reverse propellers of the same size and distance from the center of gravity. Among the four rotors, 1 and 3 rotate counterclockwise, and 2 and 4 rotate clockwise. Therefore, during vertical takeoff and landing and hovering flight, the torque generated by the rotor is offset by each other. The rotor rotation direction is shown in Figure 3 (Horstrand et al., 2019).

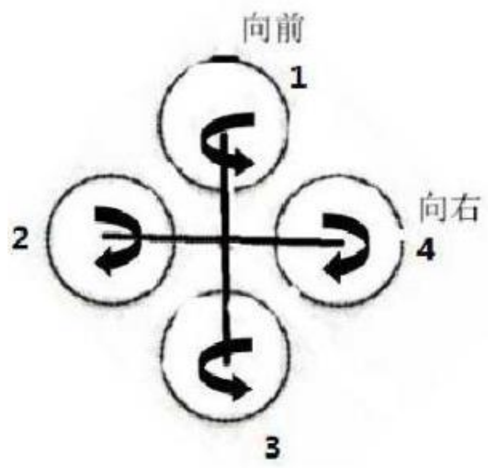

Figure 3 Rotor Rotation Direction of The Quadrotor UAV

In the figure, the rotor on the diagonal has the same rotation direction, and the rotation directions of the two diagonals are different. If rotors 1 and 3 rotate counterclockwise, then rotors 2 and 4 rotate reversely in the forward direction of the axis, and the negative direction is the backward direction. The direction indicated by the arrow indicates the change in motor speed, upward indicates the increase of motor speed, and downward indicates the decrease of motor speed. A four-rotor aircraft's motion states can be roughly divided into six primary states: pitch, roll, yaw, forward and backwards, lateral, hover and vertical takeoff and landing.

1. Hover and vertical take-off and landing: increase the speed of the four motors simultaneously to increase the rotor speed and, thus, the total lift. It can be in hover when it increases to the same weight as the real aircraft. When the total lift continues to increase on this basis, the lift of the four-rotor aircraft is greater than the gravity, which can produce an upward acceleration to achieve the effect of vertical rise; On the contrary, if the rotating speeds of the four motors are reduced at the same time when the lift generated by the rotor is less than its gravity, the four-rotor aircraft will generate downward acceleration, so that the aircraft will make a vertical downward movement until landing.

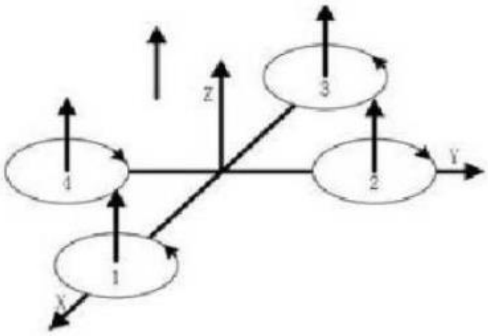

Figure 4 Hover and Vertical Take-Off and Landing of The Quadrotor UAV

2. Pitch motion: Increase the speed of motor one by a specific value and decrease the speed of motor three by the same value, while the speeds of 2 and 4 will not change. The increase in the lift of rotor 1 is the same as the decrease in rotor 3. The imbalance of the rotor's lift causes the aircraft to produce unbalanced torque, which causes the fuselage to rotate around the y-axis. Similarly, reduce the speed of motor one and increase the speed of motor 3. The fuselage will rotate around the y-axis in another direction to achieve the pitching motion of the aircraft.

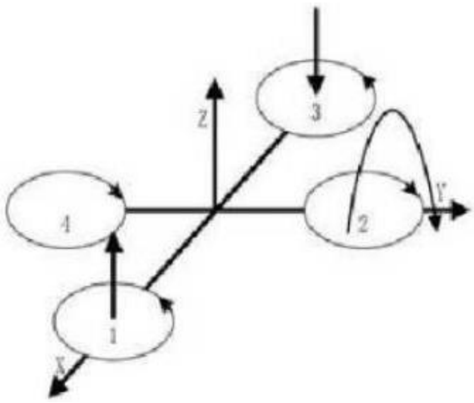

Figure 5 Pitch Motion of The Quadrotor UAV

3. Rolling motion: the principle is the same as pitch motion. Changing the speed of motors 2 and 4 and maintaining the speed of motors 1 and 3 can make the fuselage deflect around the x-axis to achieve the rolling motion of the aircraft.

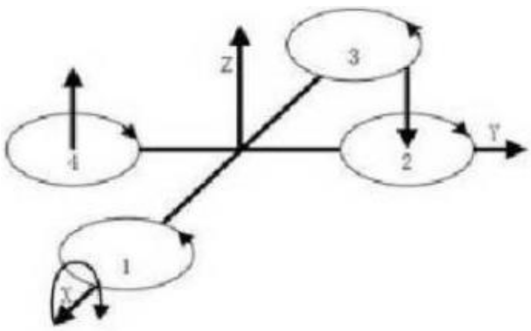

Figure 6 Rolling Motion of The Quadrotor UAV

4. Yaw motion: adjust two of the four rotors in the four-rotor aircraft to clockwise rotation and two to counterclockwise rotation and make the two rotors on the diagonal rotate in the same direction to offset the influence of anti-torque during rotor rotation. That is to say, the same motor speed will make the counter torque generated by the rotor offset each other so that the aircraft will not rotate: otherwise, the aircraft will rotate. When the speed of motors 1 and 3 is higher than 2 and 4, the reverse torque generated by rotors 1 and 3 is more significant than that generated by rotors 2 and 4. Therefore, the fuselage rotates around the z-axis under torque to achieve yaw motion.

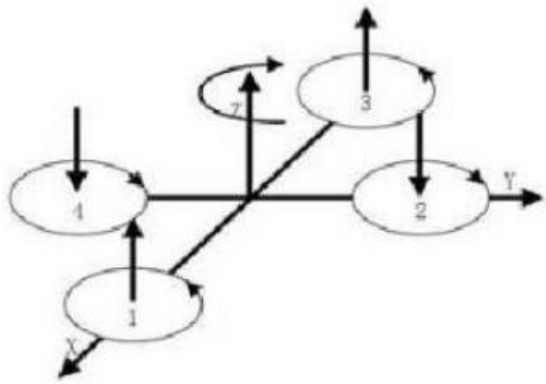

Figure 7 Yaw Motion of The Quadrotor UAV

5. Forward and backward motion: To realize the forward and backward motion of the aircraft, a force shall be generated in the horizontal direction. Increase the speed of rotor three and decrease the speed of rotor 1, while the speed of the other two motors remains unchanged. The aircraft must first produce a certain degree of tilt, which will make the rotor produce a horizontal component to achieve the forward flight movement of the aircraft. The operation method of backward flight is opposite to that of forward flight.

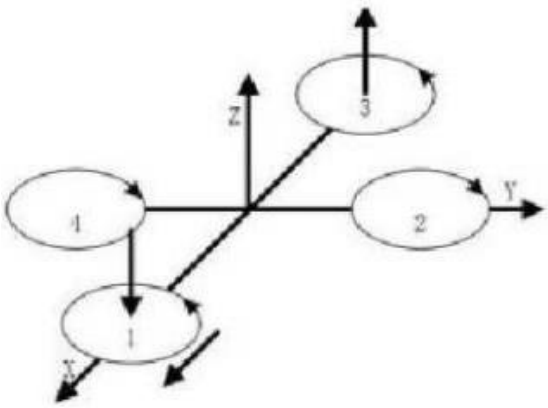

Figure 8 Forward and Backward Motion of The Quadrotor UAV

6. Lateral motion: because of structural symmetry, the working principle of inclined flight is consistent with that of forward and backward motion.

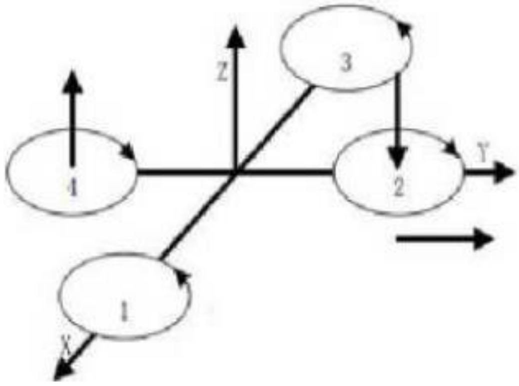

Figure 9 Lateral Motion of The Quadrotor UAV

The key paramount of UAV

Although a UAV design is specific to its mission profile, one common goal is high endurance. Higher endurance translates to longer flight time with longer breaks for refuelling or recharging the battery (Amodu et al., 2022). The basic parameters affecting the endurance of a fuel-powered propeller-driven fixed-wing UAV can be calculated using the classical Breguet method as follows Equation 1:

$$E = K(\frac{\mu p}{BSFC})(\frac{C_L^{\frac{3}{2}}}{C_D})\sqrt{\rho}\frac{1}{(\frac{W_i}{S})^{\frac{1}{2}}}[\frac{1}{1-(\frac{wf}{wi})^{\frac{1}{2}}}-1]$$

$$E = K\left(\frac{\eta p}{BSFC}\right)\left(\frac{C_L^{\frac{3}{2}}}{C_D}\right)\sqrt{\rho}\frac{1}{\left(\frac{wi}{S}\right)^{\frac{1}{2}}}\left[\frac{1}{1-\left(\frac{wf}{wi}\right)^{\frac{1}{2}}}-1\right] \tag{1}$$

where E is the endurance, K is a constant, ηp is the propeller efficiency, $BSFC$ is the brake-specific fuel consumption, C_L is the lift coefficient, C_D is the drag coefficient, ρ is the air density, wi is the initial weight of aircraft, wf is the weight of fuel, and S is the wing area. In order to have longer endurance, one should maximize the aerodynamic parameter $\frac{C_L^{\frac{3}{2}}}{C_D}$ and minimize the structural weight to reduce wing loading $wi\ S$ and increase fuel weight fraction $wf\ wi$. The term $\eta p\ BSFC$ is related to the propeller and engine efficiency and is out of the scope of discussion for this article. Although the above equation only holds for fuel-powered propeller-driven fixed-wing UAVs, it generalizes that good aerodynamics and light aircraft structure are of utmost importance for any flying vehicle.

UAV belongs to aircraft like aircraft, so the area S of the UAV wing, takeoff weight $m0$ of UAV and static thrust $P0$ of the UAV power unit are still the key points in the process of UAV parameter selection. With these three basic parameters, the lifting load P and takeoff thrust ratio P can be calculated according to the following Equation 2 and Equation 3.

$$p = \frac{m0g}{10S} \tag{2}$$

$$\bar{P} = \frac{10P}{m0g} \tag{3}$$

The maximum take-off weight according to the design requirements of quadrotor UAV, Through the reference of other UAV model parameters and the query of relevant documents and design manuals, the takeoff thrust weight ratio and wing load at takeoff can be obtained through analysis and calculation. The maximum level of flight speed when flying at a constant speed at a certain altitude, Equation 4:

$$v\,max = \sqrt{\frac{2T}{C_D\,\rho\,S}} \tag{4}$$

T is the thrust, D_C is the drag coefficient, and ρ is the working gas density. Lift and lift coefficient, Equation 1:

$$L = \frac{1}{2}\rho\,V^2\,S\,C_L \tag{5}$$

Where L is the lift, ρ is the density of working gas, V is the flight speed, C_L is the wing lift coefficient, Resistance and resistance coefficient, Equation 2:

$$D = \frac{1}{2}\rho\,V^2\,S\,C_D \tag{6}$$

Where D is the resistance, $a\ C_D$ is the resistance coefficient, and the ratio of C_L to C_D is the lift drag ratio.

Result and Discussion

The basic process flow of molten filament manufacturing is as follows: establish a 3D model with CAD software, select the surface model in the industrial standard STL (StereoLithography) format as the input for 3D printing, slice the modelling in the software, import the STL model, set the layer thickness, generate the printing sequence, generate the 2D continuous path, generate the 3D continuous path, generate and import the corresponding code, and finally print on the platform.

Algorithm 1

```
function INCREMENTAL-SLICING (n, T[1...n], k, P[1...k], δ, srt)
    // Split the triangle list.
    L[1...k+1] ← BUILD-TRIANGLE-LISTS (n, T, k, P, δ, srt);
    // Perform a plane sweep.
    A ← { };
    for i ∈ {1, ..., k} do
        A ← A ∪ L[i];
        S[i] ← ∅;
        for each t ∈ A do
            if t.z_max < P[i] then
                A ← A \ {t};
            else
                (q1, q2) ← COMPUTE-INTERSECTION (t, P[i]);
                S[i] ← S[i] ∪ {(q1, q2)};
            end if
        end for
    end for
    return S[1...k];
end function
```

Figure 10 One Algorithm of Slice

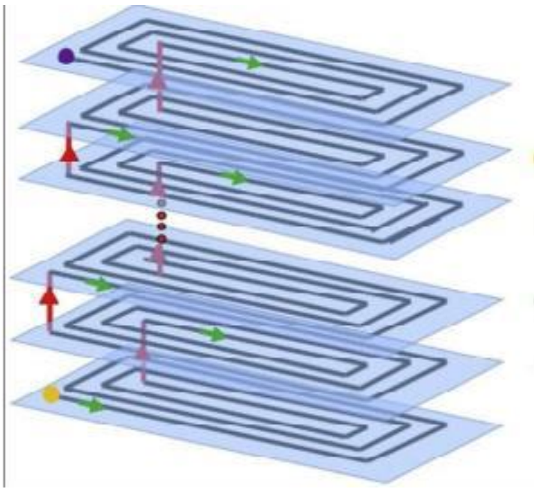

Figure 11 The Filling Process

The advance of the AM

AM allows designers to manufacture complex structures, which are difficult to manufacture with traditional methods. AM technology does not require moulds and tools, thus saving time, cost and effort. The equipment is easy to operate, the daily maintenance is relatively simple, and the equipment and process are more economical and cheaper than other 3D printing methods. The process is relatively environment-friendly and does not require harsh chemicals. The equipment can be placed directly on the desktop or on the rack. The process is in independent operation - no additional equipment is required, and the materials are diversified, with various engineering characteristics; relatively low equipment price means multiple printers can run simultaneously, flexible and scalable manufacturing and shorter delivery time. In FFF process, the printer uses a second nozzle to lay a continuous composite fibre bundle in a conventional FFF thermoplastic component. Parts manufactured by FFF process are solid and hard due to their reinforcing fibres.

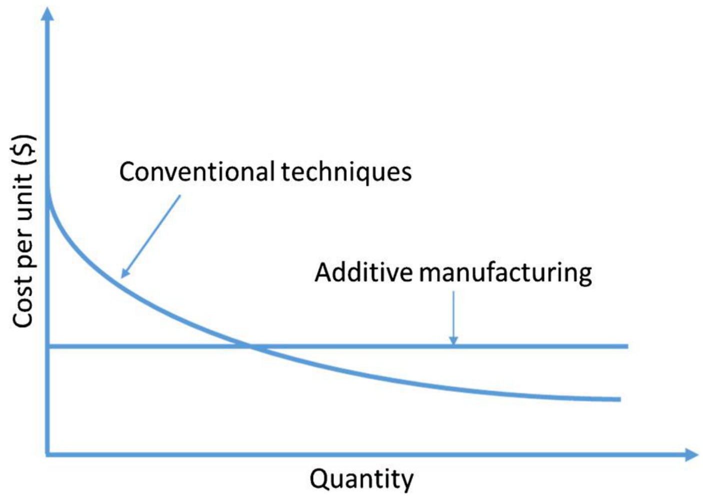

Figure 12 A Graph Depicting the Cost Per Unit Vs Quantity for Conventional and Additive

The choice of materials

New materials such as Filaflex or thermoplastic polyurethane (TPU) are usually used for 3d printing, which is flexible and elastic. Other soft structures are based on highly flexible silicone, such as Ecoflex. In the design of a soft aerial robot system, nature is the primary source of inspiration. Animals are mainly composed of soft parts used to move effectively and safely in different environments.

Conclusions

Additive manufacturing technology provides a further impetus for the survival and development of UAVs. Adjusting a series of influence factors such as materials' type and density can help us manufacture different advanced UAVs. However, the selection of materials and related parameters of materials requires constant exploration and optimization. Although AM has all the advantages, it still has limitations that need to be solved. The lack of high-strength materials, characterization methods, anisotropic properties and small building volume has destroyed AM as a feasible scheme for the large-scale production of UAVs. However, with the critical development of materials, design, structure and printer technology, AM will be used increasingly in the production of UAV components, which is undoubted.

References

Adriansyah, A., Ihsanto, E., Gunardi, Y., Suwoyo, H., Andika, J., & Shamsudin, A. U. (2021, 20-21 Oct. 2021). Design a Simulation Tools for Goal Seeking Behavior of a Mobile Robot. 2021 International Conference on Computer System, Information Technology, and Electrical Engineering (COSITE),

Amodu, O. A., Busari, S. A., & Othman, M. (2022). Physical layer aspects of terahertz-enabled UAV communications: Challenges and opportunities. *Vehicular Communications, 38*. https://doi.org/10.1016/j.vehcom.2022.100540

Brenken, B., Barocio, E., Favaloro, A., Kunc, V., & Pipes, R. B. (2018). Fused filament fabrication of fiber-reinforced polymers: A review. *Additive Manufacturing, 21*, 1-16.

Gobbato, M., Conte, J. P., Kosmatka, J. B., & Farrar, C. R. (2012). A reliability-based framework for fatigue damage prognosis of composite aircraft structures. *Probabilistic Engineering Mechanics, 29*, 176-188.

Hidayat, T., Mahardiko, R., & Alaydrus, M. (2020). Mobile cellular technology forecast for the Indonesian telecommunications industry. *Journal of Telecommunications and the Digital Economy, 8*(1), 37-48.

Horstrand, P., Guerra, R., Rodríguez, A., Díaz, M., López, S., & López, J. F. (2019). A UAV Platform Based on a Hyperspectral Sensor for Image Capturing and On-Board Processing. *IEEE Access, 7*, 66919-66938. https://doi.org/10.1109/ACCESS.2019.2913957

Jun, W., Xiong-Dong, Y., & Yu-Yang, T. (2018, 21-23 Aug. 2018). Fault-Tolerant Control Design of Quadrotor UAV Based on CPSO. 2018 IEEE 4th International Conference on Control Science and Systems Engineering (ICCSSE),

Karahan, M., Akay, A. N., & Kasnakoglu, C. (2021, 21-23 Oct. 2021). Nonlinear Modeling and Robust Control of a Quadrotor UAV under Uncertain Parameters and White Gaussian Noise. 2021 5th International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT),

Kristiawan, R. B., Imaduddin, F., Ariawan, D., & Arifin, Z. (2021). A review on the fused deposition modeling (FDM) 3D printing: Filament processing, materials, and printing parameters. *Open Engineering, 11*(1), 639-649.

Peng, J., & Zhang, P. (2020, 6-8 Dec. 2020). Velocity Prediction Method of Quadrotor UAV Based on BP Neural Network. 2020 International Symposium on Autonomous Systems (ISAS),

Song, Z., Zhang, H., Liu, F., Chen, S., & Zhang, F. (2018, 6-8 July 2018). Unmanned Aerial Vehicle Coverage Path Planning Algorithm Based on Cellular Automata. 2018 International Conference on Information Systems and Computer Aided Education (ICISCAE),

Suwoyo, H., Tian, Y., Deng, C., & Adriansyah, A. (2018). Improving a wall-following robot performance with a PID-genetic algorithm controller. 2018 5th International Conference on Electrical Engineering, Computer Science and Informatics (EECSI),

Suwoyo, H., Tian, Y., & Hajar, M. H. I. (2020). Enhancing the Performance of the Wall-Following Robot Based on FLC-GA.

Suwoyo, H., Tian, Y., Wang, W., Li, L., Adriansyah, A., Xi, F., & Yuan, G. (2021). Maximum likelihood estimation-assisted ASVSF through state covariance-based 2D SLAM algorithm. *TELKOMNIKA (Telecommunication Computing Electronics and Control), 19*(1), 327-338.

Tian, Y., Suwoyo, H., Wang, W., Mbemba, D., & Li, L. (2020). An AEKF-SLAM algorithm with recursive noise statistic based on MLE and EM. *Journal of Intelligent & Robotic Systems, 97*(2), 339-355.

Xia, K., Shin, M., Chung, W., Kim, M., Lee, S., & Son, H. (2022). Landing a quadrotor UAV on a moving platform with sway motion using robust control. *Control Engineering Practice, 128*. https://doi.org/10.1016/j.conengprac.2022.105288