Non-linear Mathematical Model of a Quad-Tiltrotor UAV Spatial Motion

D B Litvin\textsuperscript{1}, I P Shepet\textsuperscript{2}, L N Korolkova\textsuperscript{2}, D L Vinokursky\textsuperscript{3}, L A Lyutikova\textsuperscript{4}

\textsuperscript{1}Stavropol State Agrarian University, Zootekhnichesky Lane, 12, Stavropol, 355017, Russia
\textsuperscript{2}Technological Institute of service (branch of don state technical University), Kulakov Avenue, 41/1, Stavropol, 355000, Russia
\textsuperscript{3}North Caucasus Federal University, Pushkin street, 1, Stavropol, 355017, Russia
\textsuperscript{4}Institute of Applied Mathematics and Automation of Kabardin-Balkar Scientific Centre of RAS (IAMA KBSC RAS), Shortanov street, 89 A, Nalchik, 360000, Russia

E-mail litvin-372@yandex.ru

Abstract: The article presents a design scheme of a quad-tiltrotor unmanned aerial vehicle (UAV), which combines a safe vertical take-off and landing procedures and a relatively large flight range inherent in the aircraft. In order to reduce the cost and weight of the quad-tiltrotor UAV, to increase its reliability, a circuit with minimization of movable executive drives is considered. Namely, in the proposed structural scheme of the quad-tiltrotor UAV there are no deflectable airfoils. In addition, the rotors of all four engines are rotated by the same setting angle in the longitudinal plane using a single actuator. The research results showed that the quad-tiltrotor UAV of the proposed scheme as a whole is statically controlled. All the necessary balancing forces and moments are formed independently of each other only by a coordinated change in engine speed and control of the overall setting angle of their thrust vectors. It is also shown that there is a so-called degenerate flight mode in which static controllability is not provided. Theoretically, this is reflected in the degeneracy of the linear equation system matrix for determining the balance values of engine thrusts. Physically, the specified mode corresponds to the case when the resulting thrust vector of the engines lies on a straight line passing through the centre of gravity of the aircraft, and therefore it cannot create a pitch moment. The paper proposes two ways to overcome this limitation. The constructive method offers a special arrangement of rotor bushings. The algorithmic method carries out a quick transition through a degenerate balancing mode using a control system.

Keywords: Quadcopter, Quad-Tiltrotor, Unmanned Aerial Vehicle (UAV), Model of Motion, Static Controllability.

1. Introduction

For research we chose a model of a quad-tiltrotor UAV. The design of the drone is a flying wing with 4 rotary engines [9]. Such constructive scheme is chosen in order to provide a greater radius of action compared to the quadrocopter [1, 7,8,11,14,17] while maintaining a safe vertical take-off and landing modes [4,14,18]. It is assumed that in the steady cruising mode, the wing will create most of the lift. The use of four engines provides the quad-tiltrotor UAV with a wide range of alignments [2, 12].
An important feature of the proposed design, in comparison with the known ones [5, 9, 12-16], is the absence of airfoils control. The second feature of the quad-tiltrotor UAV is that the rotors of all four engines are rotated by the same installation angle in the longitudinal plane using a single actuator [14, 18]. These features are designed to facilitate, simplify and cheapen the quad-tiltrotor UAV design [13].

At the same time, the formation of both the lifting force and all the necessary control forces and moments should be provided only by coordinated changes in engine revolutions and a joint turn of their thrust vectors [6, 10].

The purpose of the study is to develop a mathematical model of the quad-tiltrotor UAV movement, to show the fundamental possibility of its controllability over all channels and to identify the existing restrictions on the control in transient flight modes [14, 18].

2. The validation of motion quad-tiltrotor UAV model structure and assumptions

The first step in the study of the stability and controllability characteristics of the “aircraft - autopilot” system is to build a model of the aircraft’s movement. To obtain the model, the following assumptions were used:
- the design of the quad-tiltrotor UAV was considered as a solid [3], aeroelastic deformations were not taken into account;
- the design of the aircraft was assumed symmetrical, in which the centre of mass is located in the plane of symmetry and coincides with the origin of the coordinate system associated with the object (according to Russian State Standard 20058-80 Aircraft dynamics in atmosphere. Terms, definitions and symbols);
- the axis of the associated coordinate system is directed along the main axes of aircraft inertness, the centrifugal moments of inertness are zero;
- the atmosphere was supposed to be calm with a known dependence of pressure on altitude.

A non-linear mathematical model of the spatial motion of the quad-tiltrotor UAV includes dynamic and kinematic equations of motion, equations of motion parameters relations in various coordinate systems, as well as supporting (exterior) models [2].

Dynamic equations of spatial motion of the quad-tiltrotor UAV as a solid in a connected coordinate system under the above assumptions:

\[
M \begin{bmatrix} \dot{V}_{Kx} \\ \dot{V}_{Ky} \\ \dot{V}_{Kz} \end{bmatrix} + \begin{bmatrix} 0 & -\omega_{x} & \omega_{y} \\ \omega_{x} & 0 & -\omega_{z} \\ -\omega_{y} & \omega_{z} & 0 \end{bmatrix} \begin{bmatrix} V_{Kx} \\ V_{Ky} \\ V_{Kz} \end{bmatrix} = M_{ca} (\alpha, \beta) \begin{bmatrix} -X_{a} \\ Y_{a} \\ Z_{a} \end{bmatrix} + \begin{bmatrix} P_{x} \\ P_{y} \\ P_{z} \end{bmatrix} + M_{cg} (\psi, \phi, \gamma) \begin{bmatrix} 0 \\ 0 \\ -G \end{bmatrix},
\]

where
\[
I_{x} \dot{\omega}_{x} + \omega_{y} \omega_{z} (I_{z} - I_{y}) = M_{x} + M_{p_{x}};
I_{y} \dot{\omega}_{y} + \omega_{z} \omega_{x} (I_{z} - I_{x}) = M_{y} + M_{p_{y}};
I_{z} \dot{\omega}_{z} + \omega_{x} \omega_{y} (I_{y} - I_{x}) = M_{z} + M_{p_{z}} - 4I_{p_{x}} \cdot \beta
\]

where \( M_{ca} \) is the transfer matrix from the wind-axis system \( O_{Xa}YZa \) to body axis system \( OXYZ \) of the following form:

\[
M_{ca} = M_{a} M_{\beta}; \quad M_{a} = \begin{bmatrix} \cos \alpha & \sin \alpha & 0 \\ -\sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}; \quad M_{\beta} = \begin{bmatrix} \cos \beta & 0 & -\sin \beta \\ 0 & 1 & 0 \\ \sin \beta & 0 & \cos \beta \end{bmatrix},
\]

\( \alpha, \beta \) are incidence and gliding angles;
\( M_{cg} \) is the transfer matrix from the normal axis system \( OXYgZg \) to body axis system \( OXYZ \) of the form:
\[ M_{cg} = M_x M_y M_{\psi}; \quad M_{\psi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \gamma & \sin \gamma \\ 0 & -\sin \gamma & \cos \gamma \end{bmatrix}; \quad M_{\theta} = \begin{bmatrix} \cos \theta & \sin \theta & 0 \\ -\sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}; \quad M_{\psi} = \begin{bmatrix} \cos \psi & 0 & -\sin \psi \\ 0 & 1 & 0 \\ \sin \psi & 0 & \cos \psi \end{bmatrix}. \]

\( \theta, \gamma, \psi \) are pitch, bank and yaw angles;

\[ \overrightarrow{F} = (P_x, P_y, P_z)^T \] is the resultant engine thrust vector;

\[ \overrightarrow{M} = (M_x, M_y, M_z)^T \] и \( \overrightarrow{M}_p = (M_{px}, M_{py}, M_{pz})^T \) are vectors of aerodynamic and engine thrust moments;

\( I_{Dx} \) is the engine inertness rotary moment.

Kinematic equations of translational and rotational movements are:

\[ \begin{bmatrix} \dot{X}_g \\ \dot{Y}_g \\ \dot{Z}_g \end{bmatrix} = \begin{bmatrix} \dot{L} \\ \dot{H} \\ \dot{Z} \end{bmatrix} = \begin{bmatrix} V_{Kx} \\ V_{Ky} \\ V_{Kz} \end{bmatrix}, \]

\[ \begin{bmatrix} V_{Kx} \\ V_{Ky} \\ V_{Kz} \end{bmatrix} = M_{gk}(\psi, \theta) \begin{bmatrix} V_{Kx} \\ V_{Ky} \\ V_{Kz} \end{bmatrix} = \begin{bmatrix} \cos \theta \cos \Psi \\ \sin \Psi \cos \theta \\ -\cos \theta \sin \Psi \end{bmatrix}, \]

Equations of constraints are:

\[ \begin{bmatrix} V_{Kx} \\ V_{Ky} \\ V_{Kz} \end{bmatrix} = M_{k}(\psi, \theta) \begin{bmatrix} V_{Kx} \\ V_{Ky} \\ V_{Kz} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \]

\( \begin{bmatrix} \dot{X}_g \\ \dot{Y}_g \\ \dot{Z}_g \end{bmatrix} = \begin{bmatrix} \dot{X}_g \\ \dot{Y}_g \\ \dot{Z}_g \end{bmatrix} = \begin{bmatrix} \dot{X}_g \\ \dot{Y}_g \\ \dot{Z}_g \end{bmatrix} = \begin{bmatrix} \psi & 0 & \sin \Psi \\ 0 & 1 & 0 \\ -\sin \Psi & 0 & \cos \Psi \end{bmatrix} \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}. \]

\( \theta, \Psi \) are climb and path angles;

\[ \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = M_{k}(\psi, \theta) \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} V_x \cos \alpha \cos \beta \\ -V \sin \alpha \cos \beta \\ V \sin \beta \end{bmatrix}, \]

\[ V = \begin{bmatrix} V_x \\ V_y \\ V_z \end{bmatrix} = \begin{bmatrix} W_{u} \\ W_{v} \\ W_{w} \end{bmatrix}, \]

\[ V = \begin{bmatrix} V_x \\ V_y \end{bmatrix} = \begin{bmatrix} V_x \cos \beta \\ V_y \sin \beta \end{bmatrix} = \begin{bmatrix} V_x \cos \beta \\ V_y \sin \beta \end{bmatrix} \]

Supporting models are:

- aerodynamic:

\[ R_n = \left[ -X_n \quad Y_n \quad Z_n \right]^T = \rho \frac{V^2}{2} S \left[ -c_{xu} \quad c_{yu} \quad c_{zu} \right]^T; \quad c_{xu,yu,zu} = c_{xu,yu,zu}(x,u,w); \]
\[ \vec{M} = \begin{bmatrix} M_x & M_y & M_z \end{bmatrix}^T = \rho \frac{V^2}{2} S \begin{bmatrix} m_1 & m_1 & m_2 b_x \end{bmatrix}^T; \quad m_{x,y,z} = m_{x,y,z} (x,u,w); \quad \text{(10)} \]

- traction electric engines:
\[ P = \begin{bmatrix} P_x & P_y & P_z \end{bmatrix}^T = \sum_{i=1}^{4} P_i (x,u_i,\delta,w); \quad \text{(11)} \]
\[ M_p (x,u_1,\delta,w) = \begin{bmatrix} M_{p_x} & M_{p_y} & M_{p_z} \end{bmatrix}^T = \sum_{i=1}^{4} (\vec{r}_i \times \vec{P}_i + \vec{M}_m); \quad \text{(12)} \]

- atmosphere:
\[ \rho = \rho (H); \]

- aircraft control system:
\[ \delta = \delta (u_\delta); \quad P_i = P_i (u_i), \quad i=1,4; \quad \text{(13)} \]

where \( u_\delta, u_i \) are signals of control.

3. Model of a system for generating control forces and moments of the quad-tiltrotor UAV

In order for the motion model presented above to take on a complete form, it must be supplemented by the equations of forces and moments inherent in the particular quad-tiltrotor UAV.

The vector of the resulting engine thrust in projections on the axis of the associated coordinate system will take the form:
\[ \vec{F} = \begin{bmatrix} P_x \\ P_y \\ P_z \end{bmatrix} = \rho \cdot \vec{P}_z = \begin{bmatrix} \cos \delta \\ \sin \delta \end{bmatrix} P_z; \quad \vec{p} = \begin{bmatrix} \cos \delta \\ \sin \delta \end{bmatrix}, \quad \text{(14)} \]

where \( \vec{F}, \vec{p} \) are full and normalized vectors of total engine thrust;
\( \delta \) is engine installation angle in the body axis system;
\( P_z = P_1 + P_2 + P_3 + P_4 \) is the module of the total engine thrust vector.

The resulting moment of engine thrust force can be represented as:
\[ \vec{M}_p = \sum_{i=1}^{4} \vec{M}_{ri} = \sum_{i=1}^{4} \left( \vec{r}_i \times \vec{P}_i + \vec{M}_{ri} \right), \quad \text{(15)} \]

where \( \vec{r}_i = \begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix} \) is the radius vector of the mass center position of the i-th engine in the body axis system;
\[ \vec{P}_i = \begin{bmatrix} \cos \delta & \sin \delta & 0 \end{bmatrix} \cdot P_i \] is thrust vector;
\[ \vec{M}_{ri} = \begin{bmatrix} \cos \delta & \sin \delta & 0 \end{bmatrix} \cdot \vec{M}_{ri} \] is reactive moment vector of i-th engine in the body axis system.

If the vector product is presented in matrix form, then the moment created by the i-th engine will take the form:
\[ \vec{M}_{pi} = \vec{r}_i \times \vec{P}_i + \vec{M}_{ri} = \begin{bmatrix} 0 & -r_z & r_y \\ r_z & 0 & -r_x \\ -r_y & r_x & 0 \end{bmatrix} \begin{bmatrix} \cos \delta \\ \sin \delta \end{bmatrix} P_i \pm a_m \begin{bmatrix} \cos \delta \\ \sin \delta \end{bmatrix} P_i = \begin{bmatrix} \pm a_m & -r_z & r_y \\ r_z & \pm a_m & -r_x \\ -r_y & r_x & \pm a_m \end{bmatrix} \begin{bmatrix} \cos \delta \\ \sin \delta \end{bmatrix} P_i, \quad \text{(16)} \]

where \( a_m = \frac{\vec{M}_{ri}}{P_i} \) is the coefficient of proportionality between the engine thrust and the reactive moment created by it. The sign of the moment is determined by the direction of rotor rotation.

For the considered quad-tiltrotor UAV scheme, the coordinates of the radius vectors of the position of the engines are as follows:
\[ r = (\vec{r}_1, \vec{r}_2, \vec{r}_3, \vec{r}_4) = (-l_x, l_x, l_y, -l_y, l_z, l_z, -l_z, -l_z, -l_z). \] (17)

Given the accepted direction of motor matrix configuration (16) the defining moments are expressed as follows:

\[
R_i = \begin{cases}
  a_m & -l_z & 0 \\
  -a_m & l_z & 0 \\
  l_y & -l_y & a_m \\
  -l_y & a_m & -l_z
\end{cases} \quad ; \quad R_i = \begin{cases}
  a_m & -l_z & l_x \\
  -a_m & l_z & l_x \\
  l_y & -l_y & a_m \\
  -l_y & a_m & -l_z
\end{cases}
\] (18)

Then expression (15) can be represented as:

\[
\bar{M}_r = \sum_{i=1}^4 R_i \begin{pmatrix}
  \cos \delta \\
  \sin \delta \\
  0
\end{pmatrix} \begin{pmatrix}
  l_x \sin \delta (P_i - P_1 - P_2 + P_3) \\
  l_y \cos \delta (-P_i + P_2 - P_3 - P_4) + a_m \sin \delta (P_1 - P_2 + P_3 - P_4)
\end{pmatrix}
\] (19)

The nonlinear model presented above is closed with respect to its phase coordinates, but due to its complexity, it is unsuitable for practical use. Let to consider a special case of spatial motion in the form of a straight, uniform flight at a constant height in a calm atmosphere, in which part of the lifting force is created by the wing and part by the screws.

We have the following reference values for motion parameters:

\[
\begin{align*}
  \theta &= \Psi = \gamma = \psi = \dot{\vartheta} = \dot{\psi} = 0; \\
  \vartheta &= \alpha = \text{const} \neq 0; \\
  W_{\alpha x} &= W_{\alpha y} = W_{\alpha z} = 0,
\end{align*}
\] (20)

In this case, the reference phase trajectory degenerates to a point in the phase space, and the model of motion becomes stationary. In this mode, the dynamic equations of translational motion (1) are usually represented in projections on the axis of the wind-axes system \( OX_aY_aZ_a \), which for the reference motion become non-differential balance equations:

\[
\begin{bmatrix}
  0 \\
  0 \\
  0
\end{bmatrix} = \begin{pmatrix}
  -X_{a0} \\
  -Y_{a0} \\
  0
\end{pmatrix} + \begin{pmatrix}
  \cos A_0 \\
  \sin A_0 \\
  0
\end{pmatrix} P_{\Sigma 0} - \begin{pmatrix}
  0 \\
  0 \\
  G_0
\end{pmatrix} \tag{21}
\]

where \( P_{\Sigma 0} = (P_{10} + P_{20} + P_{30} + P_{40}) \), \( A_0 = \vartheta_0 - \alpha_0 + \delta_0 = \alpha_0 + \delta_0 \).

From these equations we find the module and direction of the resulting thrust, as well as the angle of the engines:

\[
P_{\Sigma 0} = P_{10} + P_{20} + P_{30} + P_{40} = \sqrt{X_{a0}^2 + (G_0 - Y_{a0})^2}; \quad \tan A_0 = \frac{G_0 - Y_{a0}}{X_{a0}}, \quad \delta_0 = A_0 - \alpha_0. \tag{22}
\]

The balance equations of rotational motion (2), (19), considering that the resultant aerodynamic force is applied to the center of mass of the aircraft, take the form:

\[
\bar{M}_{\alpha 0} = \begin{pmatrix}
  l_x \sin \delta_0 (P_{10} - P_{20} - P_{30} + P_{40}) \\
  l_y \cos \delta_0 (-P_{10} + P_{20} + P_{30} - P_{40}) + a_m \sin \delta_0 (P_{10} - P_{20} + P_{30} - P_{40})
\end{pmatrix} \begin{pmatrix}
  \cos \delta_0 \\
  \sin \delta_0
\end{pmatrix} \begin{pmatrix}
  0 \\
  0
\end{pmatrix} \tag{23}
\]

Three equations (23) and first equation (22) are generated the system of linear equations as regard to \( P_{10}, P_{20}, P_{30}, P_{40} \). Dividing these equations by \( P_{\Sigma 0} \), we get:
\[
\begin{pmatrix}
 l \sin \delta_0 + a_m \cos \delta_0 & -l \sin \delta_0 - a_m \cos \delta_0 & -l \sin \delta_0 + a_m \cos \delta_0 & l \sin \delta_0 - a_m \cos \delta_0 \\
 -l \cos \delta_0 + a_m \sin \delta_0 & l \cos \delta_0 - a_m \sin \delta_0 & l \cos \delta_0 + a_m \sin \delta_0 & -l \cos \delta_0 - a_m \sin \delta_0 \\
 -l \sin \delta_0 + l_y \cos \delta_0 & -l \sin \delta_0 - l_y \cos \delta_0 & l \sin \delta_0 - l_y \cos \delta_0 & l \sin \delta_0 + l_y \cos \delta_0 \\
 1 & 1 & 1 & 1
\end{pmatrix}
\begin{pmatrix}
 p_{10} \\
 p_{20} \\
 p_{30} \\
 p_{40}
\end{pmatrix} =
\begin{pmatrix}
 0 \\
 0 \\
 0 \\
 1
\end{pmatrix}, \quad (24)
\]

where \( p_{i0} = \frac{P_{i0}}{P_{20}} \) is the thrust fraction of the i-th engine in the total thrust of all engines.

It is known that this system has a unique solution if its determinant is not equal to zero. It can be shown that the determinant of the original system of equations is determined by the expression:

\[
\Delta = 16 a_m l_z \left( l_y \sin \delta_0 - l_x \cos \delta_0 \right),
\]

which becomes zero at:

\[
tg \delta_0 = \frac{l_x}{l_z}; \quad \delta_0 = \arctg \frac{l_x}{l_z}. \quad (25)
\]

With this value of the engine setting angle, the system does not have a unique solution. Physically, this means that the resulting thrust vector passes through the aircraft mass centre. Engines do not create a longitudinal moment, and the possible distribution of the components of the total thrust becomes ambiguous.

To exclude the possibility of such a "degenerate" steady-state flight mode is possible by constructive improvements. It is proposed that the front pair of engines be positioned higher, and the rear pair, below the OXZ plane of the body axis system, symmetrically with respect to its origin, as shown in the figure. The motor bushings here are indicated by bold dots.

Then, with a positive incidence angle \( \alpha \), the thrust vector in the steady-state should deviation below OX, i.e. at a negative angle \( \delta \).

![Figure 1. Recommended positioning of engines in the OXY plane of the body axis system](image)

It should be noted that, unlike an airplane, the quad-tiltrotor UAV does not have a strict relationship between the steady-state flight mode (H, V) and the balanced value of the incidence angle. For the quad-tiltrotor UAV, the incidence angle can be set within certain limits in the interests of solving tasks external to the control.

The calculation of the steady-state flight mode is based on task H and V. Then it is determined from the condition of ensuring the maximum aerodynamic quality of the wing, the aerodynamic forces of the fuselage \( Xa \) and \( Ya \), then, according to formulas (22) and (24), the balancing values of the engine thrusts (total thrust) are calculated. Moreover, if the balancing value of the angle of inclination of the engines is close to the critical value (25), then it is necessary to change the incidence angle (pitch) in one direction or another. If the settings angle of the engines \( \delta_0 \) (22) satisfies the controllability condition (25), then the balanced values of the engine thrusts are determined from the system (24).
4. Discussion

The design scheme of the quad-tiltrotor UAV proposed in the work compares with the known ones in that it has only one movable control drive, which provides a change in the overall settings angle of all four engines. Aerodynamic control surfaces are absent. Minimization of the number of movable controls should provide cheaper and easier construction, increase its reliability. The paper studies the static controllability of the quad-tiltrotor UAV. It has been established that the proposed structural scheme of the quad-tiltrotor UAV is controllable since both the lifting force and all the necessary control forces and moments can be formed independently. However, there is a flight mode in which the resulting thrust vector of the engines lies on a straight line passing through the center of gravity of the aircraft, and therefore it cannot create a control moment. It is possible to reduce the risk of such a “degenerate” flight mode by the special placement of the propellers, as suggested above, but it cannot be completely eliminated in this way. The solution seems to be the creation of a control system that, when the flight mode approaches critical, should ensure the fastest possible transition through the critical angle of engine installation to another balancing mode.

5. Conclusions

Thus, the paper shows the fundamental possibility of static controllability of the quad-tiltrotor UAV of the proposed design scheme and defines condition (25) under which longitudinal controllability at the time of pitch is not provided. Methods are proposed for minimizing the influence of the indicated degenerate flight regime. In the future, to analyse the dynamic properties of the proposed aircraft, it is necessary to develop its linear dynamic model of spatial motion in deviations from the reference trajectory.

References

[1] Campo L V, Ledezma A and Corrales J C 2020 Optimization of coverage mission for lightweight unmanned aerial vehicles applied in crop data acquisition Expert Syst. Appl. 149 113227
[2] Azouz N, Benzemrane K, Damm G and Pradel G 2007 Modeling and development of a 4 rotors helicopter UAV IFAC Proceedings Volumes (IFAC-PapersOnline) vol 6 (IFAC Secretariat) pp 215–20
[3] Us K Y, Cevher A, Sever M and Kirli A 2019 On the Effect of Slung Load on Quadrotor Performance Procedia Computer Science vol 158 (Elsevier B.V.) pp 346–54
[4] Anweiler S and Piwowarski D 2017 Multicopter platform prototype for environmental monitoring J. Clean. Prod. 155 204–11
[5] Wandrie L J, Klug P E and Clark M E 2019 Evaluation of two unmanned aircraft systems as tools for protecting crops from blackbird damage Crop Prot. 117 15–9
[6] Ferdaus M M, Pratama M, Anavatti S G and Garratt M A 2019 Online identification of a rotary wing Unmanned Aerial Vehicle from data streams Appl. Soft Comput. J. 76 313–25
[7] Meshcheryakov R V., Trefilov P M, Chekhov A V., Diane S A K, Rusakov K D, Lesiv E A, Kolodochka M A, Shchukin K O, Novoselskiy A K and Goncharova E 2019 An application of swarm of quadcopters for searching operations IFAC-PapersOnLine vol 52 (Elsevier B.V.) pp 14–8
[8] Ribeiro T T, Conceição A G S, Sa I and Corke P 2015 Nonlinear Model Predictive Formation Control for Quadcopters IFAC-PapersOnLine 48 39–44
[9] Bonyan Khamseh H, Janabi-Sharifi F and Abdessameud A 2018 Aerial manipulation—A literature survey Rob. Auton. Syst. 107 221–35
[10] Thien R T Y and Kim Y 2018 Decentralized Formation Flight via PID and Integral Sliding Mode Control IFAC-PapersOnLine 51 13–5
[11] Pitchiah H K and Moshiri A A M 2019 Design and analysis of roto – Cylindrical wing for a drone aircraft Mater. Today Proc. 22 393–9
[12] Sanchez A, Escareño J, Garcia O and Lozano R 2008 Autonomous Hovering of a Noncyclic
Tiltrotor UAV: Modeling, Control and Implementation. *IFAC Proc. Vol. 41* 803–8

[13] De Almeida M M and Raffo G V. 2015 Nonlinear Control of a TiltRotor UAV for Load Transportation. *IFAC-PapersOnLine* 48 232–7

[14] LIU N, CAI Z, ZHAO J and WANG Y 2020 Predictor-based model reference adaptive roll and yaw control of a quad-tiltrotor UAV. *Chinese J. Aeronaut.* 33 282–95

[15] Zhao A, He D and Wen D 2020 Structural design and experimental verification of a novel split aileron wing. *Aerosp. Sci. Technol.* 98 105635

[16] Zhu Z, Guo H and Ma J 2019 Aerodynamic layout optimization design of a barrel-launched UAV wing considering control capability of multiple control surfaces. *Aerosp. Sci. Technol.* 93 105297

[17] Wu Q, Sun P and Boukerche A 2019 Unmanned aerial vehicle-assisted energy-efficient data collection scheme for sustainable wireless sensor networks. *Comput. Networks* 165 106927

[18] Liu Z, He Y, Yang L and Han J 2017 Control techniques of tilt rotor unmanned aerial vehicle systems: A review. *Chinese J. Aeronaut.* 30 135–48