A RESEARCH INTO THE EFFECT OF ATMOSPHERIC TURBULENCE ON THE MOTION OF A QUADROCOPTER WITH PID CONTROL

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Abstract: This report looks at Dryden’s atmospheric turbulence model. Applying the turbulent model to the motion of a quadcopter with PID control. Analysis of the impact of atmospheric disturbances on a quadrocopter flight.

Keywords: DRYDEN, ATMOSPHERIC TURBULENCE, QUADROCOPTER, PID CONTROL

1. Introduction

All types of aircraft are influenced by atmospheric turbulence and air currents. Depending on the size, type and height of the flight, atmospheric disturbances influence them differently. [5, 6]. One and the same disturbance, acting on a unmanned airplane flying high altitude [2], for example UAV Predator, and on the quadrocopter[4] flying several meters above the ground, will have little or no impact on flight parameters in the first case, and from there on the proper performance of the task, while in the case of the quadrocopter it can lead to a collision with the ground or a nearby obstacle (a building, a tree, etc.)[1]. This requires modeling and research of the quadrocopter movement, using different control methods in the presence of atmospheric disturbances.


In modeling the atmosphere, the most widely distributed model is the International Standard Atmosphere [8].

The reason for the occurrence of air currents is the uneven distribution of air pressure in the atmosphere. Depending on the season, the place above the ground, the relief of the area and the presence of vapors in the atmosphere, the air is heated differently by the sun. What is more, significant differences in temperature between the different layers in the horizontal and vertical directions appear resulting in a change in the density and pressure. Therefore, the solar-transmitted thermal energy is transformed into movement of air particles. They move at different speeds in different directions. If the particle speed exceeds a certain limit, the motion becomes turbulent. Such movement is of a random nature and is accompanied by significant vortexes forming [10, 13].

All air currents can be divided into two types: vertical and horizontal.

Vertical currents include ascending and descending streams, cloudy streams and vortices. The influence of these currents on the flight depends on the size of the vertical component of the air velocity, the spatial area occupied by the current, the velocity of the flight, etc.

Horizontal currents include constant by size and direction winds, wind strata, gusts, waves and whirlwinds.

Each air flow is accompanied by vortex generating. In this case, the higher the flow velocity, the higher the speed of the vortex. The formation of vortices is the result of the turbulent air movement. Turbulence is caused by friction of the air with the surface of the ground, heat movement, friction between the air layers, etc.

The whirlwinds accompanying the turbulent motion may have a vertical or horizontal axis of rotation, and more commonly encountered are the ones with a horizontal axis of rotation.

In an urban environment quadrocopter flight, the presence of an air stream or a gust of wind may cause a strong turbulence to occur in unexpected locations. The reason for this is the interaction of air masses with different buildings [11].

3. Modeling of quadrocopter flight with PID control in turbulent environment.

In the modeling of turbulence, the Dryden and Karman models are most commonly used [9].

There, the variable component of wind speed is described by statistical methods. All of the models use, to a certain degree, assumptions about: homogeneity, isotropy and stationarity. Under these assumptions, the statistical characteristics depend only on the distance between the points and the averaging interval.

The wind distribution in space is considered to be frozen and, depending on the time, it is assumed that the airplane pierces this distribution (Taylor hypothesis). For isotropic turbulence estimation, two components of the random wind speed are used: component of the tangent to the trajectory \( V_t \) and the normal component \( V_n \).

The statistical processing of experimental results is reduced to approximation with empirical formulas, where spectral densities are fractionally rational functions of the frequency. [3, 9]. Thus, wind influences are represented as white noise that goes through linear form filters with a classical structure. The spectral density functions are [9]:

\[
\begin{align*}
S_u(\Omega) &= \sigma_u^2 \frac{2\pi}{\Omega} \frac{1}{1 + (\Omega_\text{L})^2}; \\
S_v(\Omega) &= \sigma_v^2 \frac{2\pi}{\Omega} \frac{1}{1 + (\Omega_\text{L})^2}; \\
S_w(\Omega) &= \sigma_w^2 \frac{2\pi}{\Omega} \frac{1}{1 + (\Omega_\text{L})^2},
\end{align*}
\]

where:
- \( \sigma \) - is the dispersion of the turbulent movement;
- \( \Omega \) – spatial frequency;
- \( \Omega_\text{L} \) – scale of turbulence;
- \( S \) - a distance between two points of the turbulence field.

Fig. 1 Turbulence in urban conditions [12].
The equations for the translational motion are obtained as a consequence of the theorem of varying the amount of motion.

\[ m \frac{d\vec{V}}{dt} = \sum \vec{F} \]

After substitution, the full differential equations for the movement of the center of mass of the quadrocopter are obtained:

\[
\begin{align*}
V_x &= \frac{dV_x}{dt} = \frac{F_x}{m} - \omega_y V_z + \omega_z V_y; \\
V_y &= \frac{dV_y}{dt} = \frac{F_y}{m} - \omega_z V_x + \omega_x V_z; \\
V_z &= \frac{dV_z}{dt} = \frac{F_z}{m} - \omega_x V_y + \omega_y V_x.
\end{align*}
\]

The external forces acting on the axis of the coupled coordinate system of the quadrocopter are:

\[
F = \begin{bmatrix}
F_x \\
F_y \\
F_z
\end{bmatrix} = \begin{bmatrix}
-\omega_z^2 - \omega_x^2 + \omega_y^2 k \cos \theta \\
\omega_z \omega_x + \omega_y \cos \theta \\
\omega_x \omega_y + \omega_z \cos \theta
\end{bmatrix},
\]

where \( f_i = k \omega_i \) is the thrust generated by the \( i \)-th engine;

\( G \cos \gamma \cos \theta \) is the force of gravity directed at the local vertical.

\[ \frac{d\vec{V}}{dt} = \sum \vec{M} \]

Complete equations for rotary motion around the center of the mass are:

\[
\begin{align*}
\dot{\omega}_x &= \frac{1}{I_x} [M_x - (I_z - I_y) \omega_y \omega_z]; \\
\dot{\omega}_y &= \frac{1}{I_y} [M_y - (I_z - I_x) \omega_z \omega_x]; \\
\dot{\omega}_z &= \frac{1}{I_z} [M_z - (I_y - I_x) \omega_x \omega_y].
\end{align*}
\]

The quadrocopter has a symmetrical structure with four propellers. Therefore, the cross inertia moments are very small and can be ignored.

The angular velocity of the rotor \( i \), designated \( \omega_i \), creates a force \( f_i \) in the direction of the axis of the rotor. The angular velocity and the acceleration of the rotor also create a reactive moment \( \tau_{Mi} \) around the axis of the rotor [7].

\[
\tau_{Mi} = b \omega_i^2 + I_M \omega_i.
\]

where: \( b \) is a constant, proportional to the reactive moment,

\( I_M \) is the inertia moment of the rotor.

Usually, the effect of the change in angular velocity is considered to be small, and is therefore omitted.

External moments acting on the axis of the body-fixed frame are:

\[
\vec{M} = \begin{bmatrix}
M_x \\
M_y \\
M_z
\end{bmatrix} = \begin{bmatrix}
hk(-\omega_1^2 - \omega_2^2 + \omega_3^2 + \omega_4^2) \\
hk(-\omega_1 \omega_2 + \omega_3 \omega_4 + \omega_1 \omega_4) \\
hk(-\omega_1 \omega_2 - \omega_3 \omega_4 - \omega_1^2 + \omega_2^2 + \omega_3^2 + \omega_4^2)
\end{bmatrix}.
\]

where \( h \) is the distance between the rotor and the corresponding axis of the body-fixed frame.

The angular position of the quadrocopter relative to the ground coordinate system \( O_1x_1y_1z_1 \) is set by three angles: \( \psi - \text{Yaw}, \gamma - \text{Pitch}, \theta - \text{Roll} \). The relationship between these angles and the angular velocities around the axes of the body-fixed frame are given by the following differential equations:

\[
\begin{align*}
\dot{\psi} &= \frac{\omega_2 \cos \gamma + \omega_4 \sin \gamma}{\cos \theta}, \\
\dot{\gamma} &= \omega_z + t g \theta (\omega_x \cos \gamma + \omega_y \sin \gamma), \\
\dot{\theta} &= \omega_x \sin \gamma + \omega_y \cos \gamma.
\end{align*}
\]

The spatial displacement of the quadrocopter is described by means of the guiding matrix of directing cosines and the linear velocities in the body-fixed frame.

\[
\begin{bmatrix}
\dot{X} \\
\dot{Y} \\
\dot{Z}
\end{bmatrix} = C(\phi, \theta, \psi) \begin{bmatrix}
V_x \\
V_y \\
V_z
\end{bmatrix}.
\]

The system of equations \( 5 + 8, 10 + 18 \) is realized in the environment of Simulink. Four PID regulators are added to control flight height and angles \( \psi \), \( \theta \) and \( \gamma \). Atmospheric disturbances are presented with a Dryden model [14] and are added to the closed system (fig. 3).

**Fig.3** Quadrocopter flight model with added atmospheric disturbance.

**4. Results**

Fig.4 shows the working of predetermined angles \( \psi \), \( \theta \) and \( \gamma \) from the quadrocopter without atmospheric disturbance.

**Fig.4** Angles of Yaw \( \psi \), Pitch \( \gamma \) and Roll \( \theta \) without added interference.

Figures 5 and 6 show the turbulent disturbances acting on the axes of the body-fixed frame. They are generated under the following conditions:

- Wind speed at the low-altitude – 8 (m/s);
- Probability of exceedance of high-altitude intensity: 10\(^{-2}\);
- Scale length at medium/high altitudes: 533.4(m).
Changing the setting of PID controllers by increasing the robustness of the system reduces the impact of atmospheric disturbances but reduces the speed of the system. Figure 8 shows the change of the angles of Yaw $\psi$, Pitch $\gamma$ and Roll $\vartheta$ under the same initial conditions, with added disturbances and with the new settings of the PID regulators.

In fig. 7 is shown the influence of the disturbances on a quadcopter flight without change in the setting of PID controller shown in fig.5 and fig.6.

From Figures 7, 8 and 9 the following conclusions can be maid:

- Angles Yaw $\psi$, Pitch $\gamma$ and Roll $\vartheta$, defining the spatial position and behavior of the quadrocopter, are influenced by the intensity of the wind, but with increasing system robustness, this influence weakens;
- The change in wind intensity has a greater effect on flight height than its angular position, and increased robustness can not compensate for atmospheric turbulence.

5. Conclusions

1. A mathematical model of a real quadrocopter is created;

2. The motion of a quadrocopter is modeled in the presence of atmospheric disturbances;

3. From the results obtained, it is possible to determine the upper limit of the atmospheric disturbances in which a quadrocopter can be used;

4. The quadrocopter whose model has been studied can be used in open spaces at winds up to 25 (m / s) and in urban environments at winds up to 10 (m / s).

6. Bibliography


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