Design of an Experimental Test Bench for a UAV Type Convertiplane

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Abstract

This paper deals with the design of a test bench for an unnamed aerial vehicle UAV type convertiplane with controlled electric drives and tilt rotors (propellers) executed on a quadcopter pattern. This experimental test bench provides an intermediate step between simulation process and real time flight of the UAV, it allows to test and evaluate solutions in safe and controllable environment conditions. Thus, the development of methods of state estimation and control UAV becomes possible, in addition the developed system can be used for teaching about the basis of automatic control in multirotor aerial vehicles. The test bench presented in this paper contains a convertiplane type quadcopter attached on the base through a universal joint which let the UAV be able to rotate around plane axes x and y, while the vertical axis z is fixed, in turn this part of the system is fixed through a bar connected with a linear guideway block that moves over a linear guide which depends of the generated lifting force by the UAV. To determinate the travelled road of the system and the different parameters of the behavior of the convertiplane it has been also implemented a measuring system.

Keywords: test bench platform, convertiplane, mathematical modelling of UAVs, UAV control systems, UAV trajectory planning

1. Introduction

Nowadays small-sized unmanned aerial vehicles (UAVs) represent a suitable alternative for monitoring, ground mapping, agricultural and environmental preservation practices, fire detection, transmission power line infra-red supervision, etc. in large, dangerous or remote areas. UAV systems can be equipped with a wide variety of sensors due to the given task [1–3, 5, 6, 9]. In addition, the use of modern manufacturing capabilities and element base, the availability of new composite materials have led to production of aerial vehicles with lightweight and strong hulls; the development of micro-electronic components, such as microcontrollers, sensors, receivers, drivers, miniature-type cameras, etc. helped to create high-precision navigating and flight stabilization systems for aerial vehicles, as well as digital data transmission over long distances [2, 4, 7, 8, 10]. Control techniques of multirotor aerial vehicles is a particularly discussed topic in several works of Russian and foreign researchers.

Currently the analysis of existing models of autonomous multi-rotor highly manoeuvrable small unmanned aerial vehicles (UAV) weighing up to 5 kg, that can carry payload, is the most promising and needed field of research for both the military and civil spheres. Modern UAV is a flying laboratory, which includes an aerial vehicle and a hardware-software complex that allows operating the device in manual, semi-automatic or automatic mode, as well as receiving, storing and displaying the telemetry data received from the UAV.
After concluding a UAV project, it is indispensable to perform tests and evaluate its controlled response, such as check up its control loops to check if it reached the project requirements.

There are two options for checking the proper functioning of a drone: real-time outdoor test and test using a platform. Especially when we talk about the development of completely autonomous aerial systems, as well as non-traditional configurations of the aircraft, carrying out the outdoor tests generates a high risk on the UAV, which can lose control or bump into an obstacle at any time, etc. Thus, it is advisable to consider the use of safe and reliable experimental platforms, it allows to test it and evaluate solutions in safe and controllable environment conditions.

There are different concepts of test benches which vary from the simplest approaches, where the UAV is fixed to a joint with wires [4] or rotates around single fixed axis [5]. The most sophisticated devices deliver more than 3 DOF [2]. The aim of this paper is to present a useful, versatile and low-cost solution for testing and tuning the flight controller before the phase of flight tests.

This paper is organized as follows: Section 2 presents a full description of the kinematics and dynamics of the developed UAV type convertiplane executed on a quadcopter platform used in this work with; Section 3 shows the designed test bench platform in this work, with all its constructive characteristics; Section 4 presents the simulation results obtained in this work; Section 5 concludes this purpose, such as some notes about future work.

2. Mathematical modelling of a UAV type convertiplane

The scheme of the quadcopter convertiplane is provided in figure 1. Consider the motion of the convertiplane in a fixed cartesian coordinate system OXY. Let us assume that CX1Y1Z1 (i = 1–4) are local coordinate systems, passing through the center of mass of the rotors apparatus and the centers of mass of the i-th electric drive with propellers, hereinafter referred to as the rotor. The orientation of the body in the air is set by the aircraft yaw angles $\psi$, pitch $\theta$ and tilt $\phi$ angles. However, from the stability point of view, it is of interest to study the pitch of the device relative to its transverse axis C1 at an angle $\theta$ when the thrust vectors of rotary drives 1,2 at an angle $\phi$, which is carried out in a plane parallel to the plane CX1Y1. Angle $\beta$ can vary from 0 to 90°.

Now we will denote by the symbols (0) and (1) the vectors defined in the coordinate systems OXYZ and CX1Y1Z1, respectively. The position of the center of mass of the convertiplane is given by the vector $\vec{r}_{cm}^{(0)} = [X, Y, Z]^T$, and its orientation in space by the vector $\vec{a} = [\phi, \psi, \theta]^T$ [4]. Thus, the vector $\vec{f}^{(0)} = [f_{x}, f_{y}, f_{z}]^T$ fully defines the spatial location of the convertiplane.

The forces applied to the convertiplane, which can be divided into forces that are set in absolute system of coordinates OXY: gravity force $\vec{G}_{i}$ applied to the center of mass $C$ and forces, defined in the movable coordinate system CX1Y1: the forces generated by the propellers $\vec{F}_{i}$, applied at the center of mass of the rotors $\vec{A}_{i}$; aerodynamic forces acting on the wing surface $Q_{1,2}$, called the force of drag, directed to the opposite side of the axis CX1 and $Q_{8}$ force acting on the fuselage and lifting forces of the wing $\vec{F}_{1,2}$ and fuselage $\vec{F}_8$ [6, 8].

![Figure 1. Calculation scheme for the study of movements relative to the transverse axis C1: $\vec{Q}_1, \vec{L}_i$ — vector of the quantity of motion and the kinetic moment; $\vec{w}_i$ — vector of the angular velocity of rotation of the i-th rotor; $\omega_e$ — angular velocity of rotation of the convertiplane body.](image)

The moments of traction forces can be presented in the following way:

$$\mathbf{M}_i = \vec{r}_{cm} \cdot \vec{f}_i^{(1)}$$  \hspace{1cm} (1)

and the thrust vector:

$$\vec{f}_i^{(1)} = \vec{b}_i^T \vec{\alpha}_i |\vec{\alpha}_i|$$  \hspace{1cm} (2)

where $\vec{b}_i = (b_x, b_y, b_z)^T$ — aerodynamic coefficient, the module of which is $b_i = \frac{c \rho S R^2}{2}$ [6, 8, 12].

The thrust vectors of the propellers, wing lift force and drag force in the zero-coordinate system can be determined in accordance with the following formulas [7, 8, 10]:

$$\vec{F}_1^{(0)} = T_{10} \cdot \vec{F}_1^{(1)}, \vec{F}_2^{(0)} = T_{10} \cdot \vec{F}_2^{(1)}, \vec{Q}_1^{(0)} = T_{10} \cdot \vec{Q}_1^{(1)}, \vec{Q}_2^{(0)} = T_{10} \cdot \vec{Q}_2^{(1)}$$  \hspace{1cm} (3)

where $T_{10}$ is a transition matrix from (1) to (0) coordinate systems has the following form:

$$T_{10} = \begin{bmatrix} \cos \theta & -\sin \theta & 0 \\ \sin \theta & \cos \theta & 0 \\ 0 & 0 & 1 \end{bmatrix}$$  \hspace{1cm} (4)

The forces acting on the wing surface depend on the design and nature of the load. Thus, the position of the center of the aerodynamic load pressure depends on the flight mode. In accordance with the theorems of mechanics, it is possible to bring an arbitrary system of forces to the center of mass, i.e. $\{\vec{F}_{1,2}, \vec{Q}_{1,2}\} \Rightarrow \{\vec{P}_j, \vec{Q}_j, \mathbf{M}_j\}$, where $j = 1–4$. 

The forces generated by the propellers $\vec{F}_{i}$, applied at the center of mass of the rotors $\vec{A}_{i}$; aerodynamic forces acting on the wing surface $Q_{1,2}$, called the force of drag, directed to the opposite side of the axis CX1 and $Q_{8}$ force acting on the fuselage and lifting forces of the wing $\vec{F}_{1,2}$ and fuselage $\vec{F}_8$. 

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**Figure 1.** Calculation scheme for the study of movements relative to the transverse axis C1: $\vec{Q}_1, \vec{L}_i$ — vector of the quantity of motion and the kinetic moment; $\vec{w}_i$ — vector of the angular velocity of rotation of the i-th rotor; $\omega_e$ — angular velocity of rotation of the convertiplane body.

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**Notes:**
- $\vec{r}_{cm}$: center of mass position vector.
- $\vec{f}_i^{(1)}$: thrust vector.
- $\vec{b}_i$: aerodynamic coefficient vector.
- $T_{10}$: transition matrix.
- $\vec{F}_1^{(0)}$: thrust vector in the zero-coordinate system.
The modules of the wing lift force $P_l^{(1)}$ and drag force $Q_d^{(1)}$ will determine by the following formulas [7, 8]:

$$P_l^{(1)} = \frac{\rho \omega \beta v^2}{2} = \mu \|V\|, \quad Q_d^{(1)} = \frac{\rho \omega \beta v^2}{2} = k \|V\|,$$

where $\rho$ is the air density, $c_l$ is the lift coefficient, $c_D$ is the coefficient of drag, which depends on the geometry of the wing, $S$ — wing surface, $V$ — speed of the incoming airflow.

The system of differential equations describing the change in the generalized coordinates, determining the position of the convertiplane center of mass in space under the action of the propeller thrust forces, lifting force, drag forces and weight forces can be obtained from the general theorems of dynamics [4, 11, 12]:

$$\frac{d\omega}{dt} = \sum P_e,$$

$$\frac{dL}{dt} = \frac{dL}{dt} + (\omega_c \times L) = \sum M_C,$$

Vectors $\dot{Q}$ and $\ddot{L}$ for a mechanical system consisting of a body and 4 propellers will have the form:

$$\ddot{Q} = \sum_{i=1}^{4} m_i \ddot{v}_i, \quad \ddot{L} = J_C + \sum_{i=1}^{4} I_i \ddot{\omega}_i$$

where $I_i$ — inertia tensor.

Then, we present the vector product of equation (7) in matrix form [12]:

$$\begin{pmatrix} \omega_c \times L \end{pmatrix} = \lambda(\dot{\omega}_c) \cdot \ddot{L} = \begin{pmatrix} 0 & -\omega_c & \omega_c \end{pmatrix} \begin{pmatrix} L_x, & L_y, & L_z \end{pmatrix}$$

In our case $\omega_c = \dot{\theta}$, $\omega_c L_x = 0$, $\omega_c L_y = 0$.

Then, taking into account (9), equations (6) and (7) will take the form:

$$\ddot{Q} = \ddot{P}_e,$$

$$\ddot{L} = \ddot{L} + \lambda(\dot{\omega}_c) \ddot{L} = \sum \dddot{M}_C$$

Next, we consider the linear motion of the convertiplane, so the moment of traction forces of the propellers relative to the axis $CZ$ has the form:

$$\sum_{i=1}^{4} M_{iz}^{(i)} = (F_{ix} \cos \beta - F_{iz})b_2 + (F_{iy} \cos \beta - F_{iz})b_3 = b_2 \left(\omega_x^2 + \omega_z^2 \right) \cos \beta + b_3 \left(\omega_x^2 - \omega_z^2 \right) + aP_l^{(0)}(X)^2$$

or, taking into account the propeller drives [11, 12, 16–18], we obtain a system of nonlinear differential equations describing the plane motion of the convertiplane in the longitudinal plane:

$$\begin{cases} \dot{X}(t) = \frac{1}{M}(\sum_i F_{ix}^{(0)} + \sum_i Q_{iz}^{(0)}) \\ \dot{Y}(t) = \frac{1}{M}(\sum_i F_{iy}^{(0)} - Mg + \sum_i P_{iy}^{(0)}) \\ \dot{\theta} = \sum_{i=1}^{4} M_{iz}^{(i)} \\ \dot{\omega}_i = \frac{\omega_c}{L_i(\Delta)}, \quad i = 1 - 4 \end{cases}$$

where $M = \sum M_k$ — mass of the convertiplane, $U_i = U_i(\Delta)$ — control voltages applied to electric motors, depending on the magnitude of the error $\Delta = (AX, AY, AZ)^T$, $\alpha$ — the arm of the wing lifting force.

$$U_i(\Delta) = k_p(\Delta) + k_d \frac{d\omega_c}{dt}$$

where $k_p$, $k_d$ — coefficients respectively proportional and differential controller.

Deviations of the real positions of the center of mass and the pitch angle $\theta$ of the convertiplane lead to errors and require corrective action:

$$X(t) - X^*(t) = \Delta X$$

$$Y(t) - Y^*(t) = \Delta Y$$

$$\theta - \theta^* = \Delta \theta$$

In general conditions the system (12) is nonlinear and its solution is convenient to perform it using numerical methods.

3. Development of a test bench platform for a UAV type convertiplane

In this study, a test platform for rotary wing UAVs with multi-rotors is presented. The proposed test platform draft done by SolidWorks is presented in figures 2a and 2b. As can be seen from this figure, the UAV that is hanged on to the test platform and can move easily at all axes $x$ and $y$. also the convertiplane is able to realize a circular motion trajectory. By using this platform, the pre-flight tests, such as pitch, roll, yaw and elevation will be realized.

In order to present the results obtained from the test bench platform is used a Bluetooth wireless connection, the operator receives the information to the station using a computer where the information is plotted.

The developed test bench platform is presented in figures 2a and 2b and contains a support base 1, on which a linear guide 2 is fixed, in turn on the linear guide 2 a platform 3 is movably mounted. On the platform 3 is fixed a universal joint 4, which is connected to the load 9 through a system of blocks 7 and 8 mounted on the vertical linear guide. At the ends of the linear guide 2 a pair of bearings are installed. A measuring system is installed to determine the kinematic characteristics (not shown).

Figure 2a. Test bench platform for a UAV type convertiplane isometric view on software Solidworks: 1 — support base, 2 — linear guide, 3 — platform, 5 — convertiplane, 9 — load.
Figure 2b. Test bench platform for a UAV type convertiplane frontal view on software Solidworks: 4 — universal joint (2 DOF), 6 — cable, 7, 8 — system of blocks, 9 — load.

The test bench platform works as follows. The convertiplane 5 is fixed motionless on a two-axis universal joint 4, which is mounted on a platform 3. Through a cable 6 the load 9 is suspended such as the convertiplane 5 is in a certain equilibrium position. The system is turned on, the measuring system installed on-board the convertiplane 5 as in the bench platform are tested. The two-axis universal joint 4 allows the convertiplane to rotate in the horizontal plane X, Y. The communication and data transmission is carried out via Bluetooth. According to the given algorithm, the convertiplane 5 performs various manoeuvres in order to determine the created lift force, the behaviour during a circular trajectory checking the stability of the system when the UAV turns in the horizontal plane relative to the axes x and y. Thus, the test bench platform allows determine the kinematic characteristics of the UAV system.

4. Evaluation

In order to prove the concept of the presented test bench platform, few experiments were conducted. The objective of the tests was to confirm the proper operation of the presented system in development of flight controller.

It has been established that the process of modeling is divided in 3 stages: I — take off, II — trajectory, III — landing.

The first step for system modeling is the definition of the initial conditions to be used. For vertical flight we considered the initial conditions of the UAV, which are given by the form:

\[ X = X_0, Y = Y_0, Z = Z(t) \]  \hspace{1cm} (15)

where \( X, Y, Z \) — given coordinates, \( X_0, Y_0 \) — initial coordinates for X and Y, \( Z(t) = at^3 + bt^2 + ct + d \) — function used to describe the lift of the convertiplane.

To determine the value of the constants used in formula 15 is necessary to establish the initial conditions of the system as shown in table 1.

Table 1. Parameters for the lift and circular trajectory of the convertiplane

| Time [s] | Position [m] | Velocity [m/s] |
|----------|--------------|----------------|
| Initial conditions | \( t_0 = 0 \) | \( Z_0 = 0 \) | \( Z'_0 = 0 \) |
| Final conditions | \( t_1 = t_1 \) | \( Z_1 = H \) | \( Z'_1 = 0 \) |

Then, the next step is about the modeling of the circular trajectory of the convertiplane. For circular trajectory we considered the following coordinates, which are given by the form:

\[ X = a \sin(\omega t), Y = b \sin(\omega t), Z = \text{const} \]  \hspace{1cm} (16)

where \( X, Y, Z \) — given coordinates; \( a, b \) — coefficients; \( \omega \) — frequency; \( t \) — time.

To determine the value of the constants used in formula 16 is necessary to establish the initial conditions of the system as shown in table 2.

Table 2. Parameters for the circular trajectory of the convertiplane

| Time [s] | Position [m] | Velocity [m/s] |
|----------|--------------|----------------|
| Initial conditions | \( t_1 = t_1 \) | \( Z_1 = H \) | \( Z'_1 = 0 \) |
| Final conditions | \( t_2 = t_2 \) | \( Z_2 = H \) | \( Z'_2 = 0 \) |

According to the geometrical characteristics of the developed test bench platform for a convertiplane, the maximum possible height value is 1 meter. The results obtained from the modeling of the system are shown in figures 3–6.

Figure 3. Movement of the convertiplane along x-axis: \( X \) — given trajectory, \( X' \) — obtained trajectory, \( \Delta X \) — error between \( X \) and \( X' \).

Figure 4. Movement of the convertiplane along y-axis: \( Y \) — given trajectory, \( Y' \) — obtained trajectory, \( \Delta Y \) — error between \( Y \) and \( Y' \).
5. Conclusions

In this paper a test bench platform for an unnamed aerial vehicle UAV type convertiplane with controlled electric drives and tilt rotors (propellers) executed on a quadcopter pattern has been designed. Also a mathematical model of a UAV type convertiplane has been developed. The obtained results in real time flight of the UAV correspond to the results obtained through simulation process. A control method for the movement of the convertiplane, including the assignment of an arbitrary trajectory in form of functions has been proposed. Thus, the use of the developed test bench platform has made possible to test the designed UAV in a safe and controllable environment conditions. Further, there will be improved the physical model the test bench platform with the aim to positioning it as a research tool, as well as a teaching tool for the development of control systems and design in general of UAVs.

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