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CONCEPT OF TILTROTOR UAV CONTROL SYSTEM

Marcin Ciopcia, Cezary Szczepański

Wroclaw University of Science and Technology
Wybrzeże Wyspiańskiego Street 27, 50-370 Wroclaw, Poland
e-mail: marcin.ciopcia@pwr.edu.pl, cezary.szczepanski@pwr.edu.pl

Abstract

Nowadays, civil UAV industry market grows rapidly. This expansion is followed by the new requirements and expectations against UAVs, which force their constructors to look for less typical solutions.

Expected long time endurance and range are the typical examples of such expectations. Clients are often looking for UAV with VTOL ability and time of flight much greater than 30 minutes and long range. They want to inspect large areas, i.e. between major cities without need of paying for building and maintaining developed aircraft infrastructure. Example of UAV with low infrastructure requirements are multirotors. Major disadvantage of them is short flight time. Elongating time of flight is hard to achieve by classical multirotor with standard Li-Pol batteries available on the market. They have too low energy density in currently used technology. Alternative power solutions, like fuel cells, have low financially rewarding factor, which cause whole projects to be unprofitable. Foregoing circumstances force engineers to find less usual ways for improvement energy efficiency, which will cause extending the time and range of flight. One of them is a tiltrotor.

Tiltrotors are hybrid solutions – they combine airplane and multirotor capabilities to achieve features, which exclude each other in classical constructions. Aircraft-like wing make it able to use its lift-to-drag ratio to achieve energy savings, higher top speed and extended range in comparison with multirotors. UAV is also equipped with multiple multirotor-style engines with additional capability to rotate itself in pitch. In horizontal engine position, vehicle behaves like classical multirotor – allowing pilot to hover and perform VTOL manoeuvres. When engines are tilted to vertical position, whole UAV get performance similar to airplane – high speed and flight endurance.

In the other hand, practical implementation of tiltrotor solution can be problematic: simulation, steering and controlling such aircraft in transition state are complex tasks. Moreover, designed aircraft should follow major rule connected with multirotors: Should have as simple, robust mechanical design as it can.

Proposed article will concentrate on concept and preliminary design of fly-by-wire steering system with unique properties for tiltrotor. One of such properties will be unification of steering method – which eliminates need for switch and setting initial conditions for control subsystems, when flight procedure requires changing flight mode. Second important improvement will be possibility to use transitional states as intermediate state between propeller driven fly and gliding – which allow achieving wide spectrum of flight speeds.

Moreover, huge number degrees of freedom (at least 9) create new opportunities for steering optimization. Extensive thrust vectoring abilities of such UAV could not only implicate substantial efficiency improvement of multirotors, but also improve its manoeuvrability.

The article will focus on basic concepts of kinematics, steering of such UAV and show proposition of energy-usage oriented optimization for its control trajectories. To let mechanical design be simple, all control and steering methods will be implemented in software, which will implicate complex structure of steering system. Overcoming complexity of software should be profitable in relation to expected improvements of UAV capabilities.

Keywords: *UAV, tiltrotor, control system*

1. Introduction

Airplanes revolutionized transportation industry. Thousands of them are flying all over the world each day. They gave us fast, affordable and long-range way for travelling and transport goods all over the world. Unfortunately, huge disadvantage for using airplane as every day transport is requirement to start and landing on aerodrome. In terms of exploitation, building dedicated infrastructure and maintaining it in good condition can be problematic. It needs a lot of space, is expensive to build and sometimes operator have to hold restricted regimes, like cleaning path from small rocks.

Possible solution for such problems can be aircraft with VTOL capabilities, like helicopter. You can build helipad even on roof of the building – which makes it more convenient for everyday use. On the other hand, helicopters are much slower than airplanes. They also have smaller range and bigger fuel consumption. Moreover, constructing helicopter, as small, unmanned aircraft can be difficult – main control mechanisms consists of many small and fragile parts.

Low aerodrome requirements are beneficial not only for civil transport. Aircraft with short landing path are also desired for aircraft carriers and military aerodromes. It not only reduces required budget for new constructions but also makes it able to operate on partially damaged runways.

To meet mentioned demands idea of VTOL airplane was developed. Currently aviation market occupies two basic concepts of such aircrafts: high-pressure nozzle system and tiltrotors. First of them is implemented in such airplanes like Hawker Siddeley AV-8B Harrier I/II or Lockheed Martin F-35B. They use theirs trust vectoring capability, high-pressure nozzles or external fans to lift–off and vertically land on carriers. This kind of solutions is mostly used in military-fighter types of aircrafts, where fuel consumption is not main issue.

Second idea was developed by Boeing-Bell into V-22 Osprey system. Concept is based on two massive propellers driven by turboshaft engines, which have capability of tilt itself to vertical position. This solution gives overall performance between helicopter and turboshaft airplane.

Unfortunately, large-scale tiltrotors struggle from mechanical problems: tilting mechanism must be robust and resistant to significant forces from propellers. Mentioned requirements implicate considerable increase in aircraft weight.

Presented difficulties can be easily overcame in smaller scale. In addition, low mass of engines used in mini-UAV system allows faster adjustment of tilting angle. This feature can be used as primary steering of tiltrotor, allowing simple wing and stabilizer design, without moveable control surfaces.

2. Tilting mechanism

From constructor point of view, tilting mechanism in tiltrotor are crucial parts, which not only rotates, but also transfer thrust and torque from drive system. Because of that, mentioned part must be robust, which also implicates huge mass. In the other hand, let consider mini-class UAV. Modern, composite materials allow achieving significantly more advantageous strength-to-mass ratio relative to full size tiltrotors. Moreover, small mass of drive mechanism and smaller forces from propellers allows significantly faster change of tilt angle. On the other hand, small, mechanical parts of mechanisms are fragile and require precise manufacturing and assembly to avoid unnecessary clearances. In this case is highly recommended to avoid complex mechanisms, like helicopter-style rotor control or tilting gearbox. Fortunately, modern electronics can compensate following disadvantages.

Nowadays modern UAVs often use 3-phase engines for driving propellers. Similar engines are commonly used in gimballed camera holders for photography and movies. In modern automation systems, following types of engines are very common and precise control drivers are already available on the market.

Gimbal engines, with huge number of poles, can maintain and precise change angular position using Field-Oriented-Control (FOC) driver and algorithm. Using computational power, precision of ADC and external encoder, modern microcontroller can calculate and precisely apply torque to control angular position of engine chassis relatively to its mount. Presented system does not require any additional gearboxes – whole mechanism is connected to body only by electromagnetic force. This solution has several advantages: adjusting process can be very fast and torsional stress transmitted by magnetic coupling created by engine can be limited. This factor has significant advantage – it can limit torsional stress on body and prevent drive damage during crash or emergency landing.

FOC-driven tilt mechanism has one major disadvantage: driver drains current from battery to maintain its tilt angle. On the other hand, power consumed by tilt mechanism should be much smaller than main engines requirements – which will cause insignificant impact on time-of-flight.

Similar drivers can be also used to control main engines, which will cause more precise control of theirs thrust and torque [2].

3. Propellers and torque compensation

Propeller size and configuration have significant impact to overall multirotors performance. Typical constructions use fixed-pitch propellers. Steering procedure is performed by changing applied torque on each propeller, which causes change of rotation speed and thrust. In comparison to helicopters, this solution cause significant reduction of mechanical parts in drives mechanism and allows achieving high robustness.

One of the major rules for constructing rigged-frame multirotor is to keep even number of propellers – half of them rotating clockwise, other half counter clockwise. When torque applied to each propeller is the same, i.e. during hover, body of UAV should hold its orientation. In tricopter to maintain, yaw balance rear propeller should have capability to tilt himself in roll – allowing compensating unbalanced reaction for its torque.

In tiltrotor, rotation along yaw axis can be performed by tilting 2 drives into opposite directions. Changing balance between clockwise and counter clockwise spinning propellers can cause unattended phenomena. To better understand this phenomenon, let us consider situation presented on Fig. 1. Let ω_1 and ω_2 be vectors of angular speed corresponding to first and second engine, created using right-hand rule. Reaction torque caused by them is described as M_{R1} and M_{R2}. Regardless for the same values of torque and speed applied to each propeller, sum of net torques M_Σ is unbalanced and cause unattended spin of UAV in yaw (according to right-hand rule).

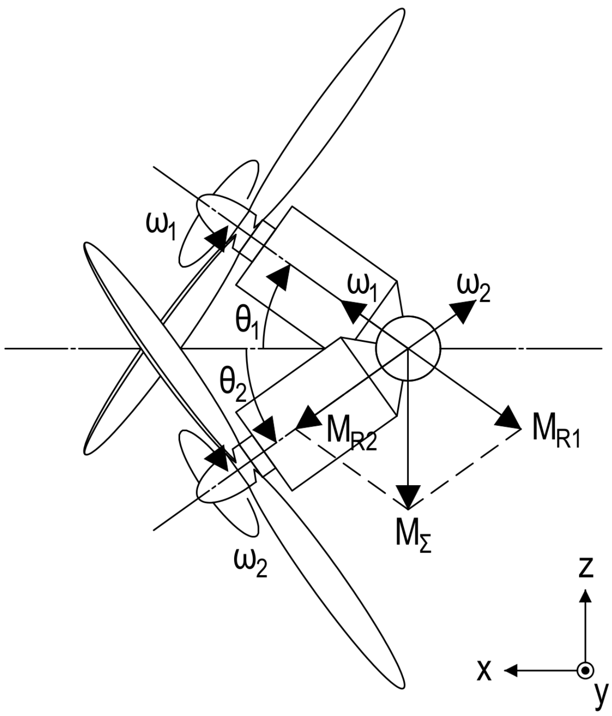

Fig. 1. Reaction torque net corresponding to single propeller drive

Presented phenomenon does not appear, when two counter-rotating propellers are spinning along same axis. If torque applied for each propeller will be the same, reaction forces will have same value but in opposite direction. According to description of Kamov configuration in [1], compensation of torques in drive system will occur and there will be no need for complicated decupling algorithms in steering system. Unfortunately, such arrangement is not beneficial to drive efficiency – because of mutual interference of propellers. On the other hand, possible noise susceptibility in decupling system can cause impossibility to implementation in real life conditions.

4. Kinematics and steering of tiltrotor

Minimal number of fixed-pitch propellers need to perform stable flight is 4. Merging then into 2 drive systems requires additional, mechanically complicated pitch control system for propeller to allow maintain stability. For mini-class UAV in terms of simplicity and robustness fixed-pith propeller and torque control will be preferred to achieve high robustness.

According to requirement of using odd number of propellers and previous limitations minimal required number of propellers is 6, divided into 3 drive systems. Example of such system is presented on Fig. 2.

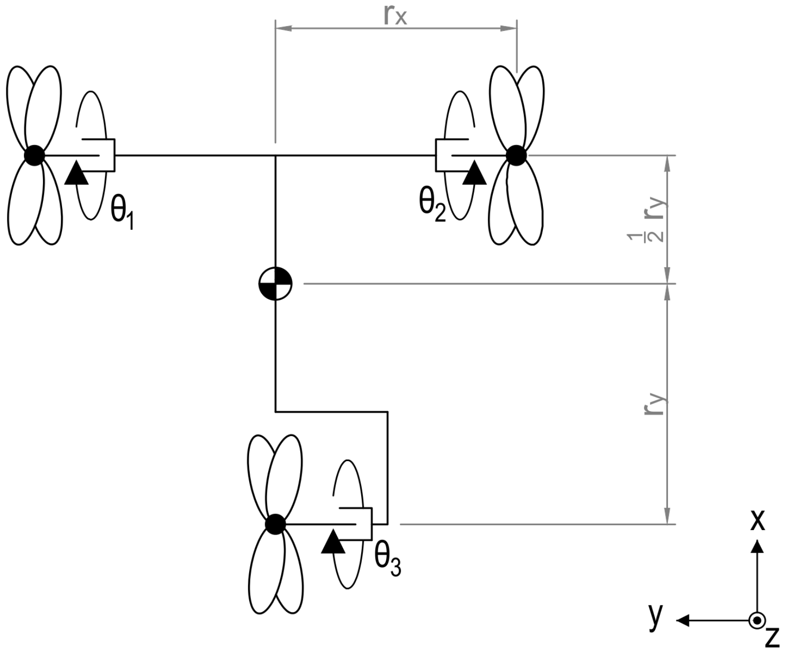

Fig. 2. Kinematic scheme for proposed solution

Let assume entanglement between each pair of rotors and engine driver. Drive model [2], based on Momentum Theory [1] can also provide compensation of nonlinearities and airstream impact on propeller efficiency. Using mentioned models, angular speed and momentum could be calculated, which let design steering system with required thrust, as a reference value for each pair of engine controllers. Steering vector will be then described as follows:

$$u = \begin{pmatrix} u_1 \\ u_2 \\ u_3 \\ \theta_1 \\ \theta_2 \\ \theta_3 \end{pmatrix}. \tag{1}$$

For presented kinematics steering can be converted to more convenient form: as angular and linear accelerations, which is typical for multirotors [4-6]. Net forces and torques are converted to aircraft's centre of gravity (COG) movement rates, by diffeomorphism:

$$u_s = \Phi(u)$$

$$\begin{pmatrix} \ddot{\varphi}_{r_u} \\ \ddot{\varphi}_{p_u} \\ \ddot{\varphi}_{y_u} \\ \ddot{x}_u \\ \ddot{y}_u \\ \ddot{z}_u \end{pmatrix} = \begin{pmatrix} r_x {I_{xx}}^{-1}(u_1 \sin\theta_1 - u_2 \sin\theta_2) \\ r_y {I_{yy}}^{-1}\left(-\frac{1}{2}u_1 \sin\theta_1 - \frac{1}{2}u_2 \sin\theta_2 + u_3 \sin\theta_3\right) \\ \sqrt{{r_x}^2 + \frac{1}{2}{r_y}^2}\, {I_{zz}}^{-1}(u_1 \cos\theta_1 - u_2 \cos\theta_2) \\ m^{-1}(u_1 \cos\theta_1 + u_2 \cos\theta_2 + u_3 \cos\theta_3) \\ 0 \\ m^{-1}(u_1 \sin\theta_1 + u_2 \sin\theta_2 + u_3 \sin\theta_3) \end{pmatrix}. \tag{2}$$

Following equations can be also inverted to calculate inverse diffeomorphism. Inverse transform allows designing control system for material point and converting it by inverted kinematics to actuator forces. To simplify following calculations coefficients defined as may be useful:

$$s_1 = u_1 \sin\theta_1 = \frac{I_{xx}}{2\,r_x}\ddot{\varphi}_{r_u} - \frac{I_{yy}}{2\,r_y}\ddot{\varphi}_{p_u} + \frac{m}{3}\ddot{z}_u,$$

$$s_2 = u_2 \sin\theta_2 = -\frac{I_{xx}}{2\,r_x}\ddot{\varphi}_{r_u} - \frac{I_{yy}}{2\,r_y}\ddot{\varphi}_{p_u} + \frac{m}{3}\ddot{z}_u,$$

$$s_3 = u_3 \sin\theta_3 = \frac{I_{yy}}{2\,r_y}\ddot{\varphi}_{p_u} + \frac{m}{3}\ddot{z}_u,$$

$$c_1 = u_1 \cos\theta_1 = \frac{I_{zz}}{2\sqrt{{r_x}^2 + \frac{1}{2}{r_y}^2}}\ddot{\varphi}_{y_u} + \frac{m}{3}\ddot{x}_u,$$

$$c_2 = u_2 \cos\theta_2 = -\frac{I_{zz}}{2\sqrt{{r_x}^2 + \frac{1}{2}{r_y}^2}}\ddot{\varphi}_{y_u} + \frac{m}{3}\ddot{x}_u,$$

$$c_3 = u_3 \cos\theta_3 = \frac{m}{3}\ddot{x}_u. \tag{3}$$

Then inverted diffeomorphism (inverted kinematics) can be defined then as:

$$u = \Phi^{-1}(u_s)$$

$$\begin{pmatrix} u_1 \\ u_2 \\ u_3 \\ \theta_1 \\ \theta_2 \\ \theta_3 \end{pmatrix} = \begin{pmatrix} \sqrt{{s_1}^2 + {c_1}^2} \\ \sqrt{{s_2}^2 + {c_2}^2} \\ \sqrt{{s_3}^2 + {c_3}^2} \\ atan2\left(\frac{s_1}{u_1}, \frac{c_1}{u_1}\right) \\ atan2\left(\frac{s_2}{u_2}, \frac{c_2}{u_2}\right) \\ atan2\left(\frac{s_3}{u_3}, \frac{c_3}{u_3}\right) \end{pmatrix}. \tag{4}$$

Eq. 1 shows that UAV body has 5 degrees of freedom (DOF) and movement in plane spanned on X and Z-axis can be independent from orientation – movement of aircraft can be invariant to its pitch angle.

5. Energy usage oriented optimization

Key feature of aircraft is ability to create lift from aerodynamics. Efficiency of this process can be rated using lift-to-drag ratio coefficient – defined as ratio between lift force and drag, which must be overcame by engines thrust. For modern airplanes, it can vary from about 6 up to 45 – for most efficient sailplanes. In comparison to multirotor, which generates all its lift from thrust – it can be significant improvement in overall performance.

Figure 3 presents distribution of forces during airplane flight. Let assume vector v as projection of relative airflow vector to XZ plane (stability axis). Angle α between chord line (dashed) and stability axis [3] is called angle of attack (AoA).

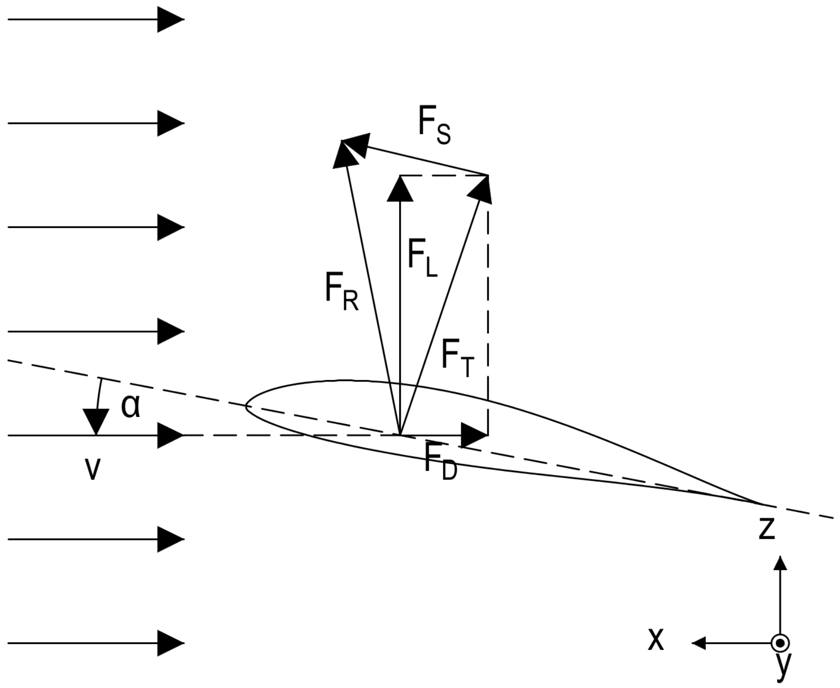

Fig. 3. Distribution of forces in wing during flight

Vector F_R corresponds to force, required by trajectory control to maintain flight on desired path. It consists gravity, centrifugal, trajectory error compensation and actuation force for UAV control from higher-level controller. Aerodynamic forces [3]: lift F_L and drag F_D are generated by airflow around wing. They can be described as follows:

$$F_L = \frac{1}{2} C_L \rho S v^2,$$

$$F_D = \frac{1}{2} C_D \rho S v^2. \tag{5}$$

Coefficients C_L and C_D can be defined in approximate, analytical form:

$$C_L = k_{C_L} \alpha + C_{L_0},$$

$$C_D = k_{C_D} {C_L}^2 + C_{D_0}, \tag{6}$$

or taken from experimental data, as shown on Fig. 4. Presented controller can use any of presented data sources, but quality of control demands as best approximation of real data, as it is possible.

Key idea of presented algorithm is to use pitch control to set optimal AoA in terms of minimization thrust vector F_S – which be required to generate by engines. This demand can be described as optimization problem:

$$L = \min_{\alpha} \| F_R - F_T \|_2, \tag{7}$$

which can be solved analytically on approximation equations or by iteration over data for finding minimal value of L.

Such optimization should cause significant energy savings in terms of flying. Moreover, reduction of required thrust in forward flight will improve maximal speed of designed UAV.

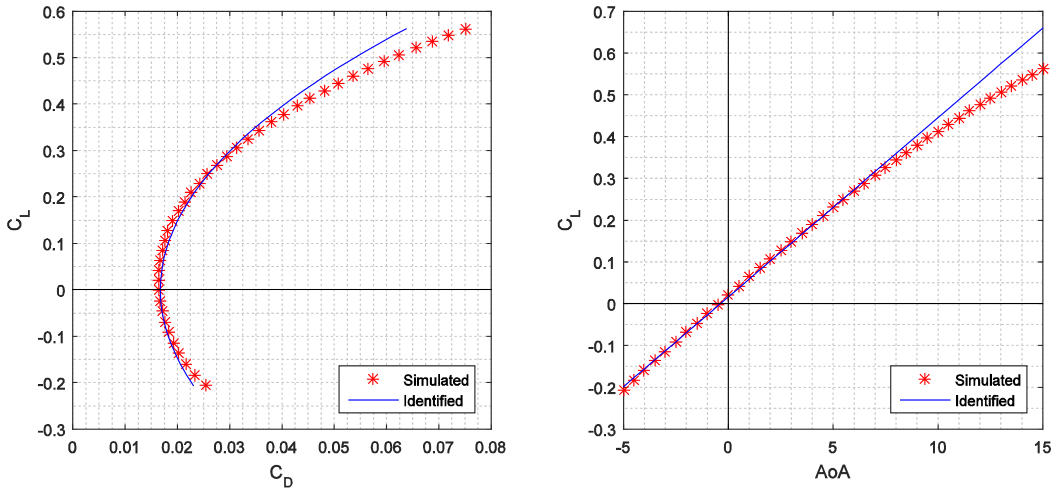

Fig. 4. Characteristics of sample airplane based on simulation and MSE identification: $k_{C_L} = 0.0429$, $C_{L_0} = 0.160$, $k_{C_D} = 0.1487$, $C_{L_D} = 0.167$

6. Conclusion

Nowadays UAVs became very popular in not only military solutions, but also civil aviation. Constructors and designers are pushing to the limit capabilities of existing solutions. Proposed aircraft have significant potential to extend them even further. Fast UAV with ability of hovering can make such tasks, like air inspection, package delivery or car crash reconnaissance and aid delivery cost efficient.

Currently one of the most significant factors, which prevent for further development of small VTOL UAVs, are low energy density in current used power sources. Tiltrotors cannot solve this problem, but they may improve flight energy-efficiency factors. Moreover, they maintain this advantage even when light batteries with huge capacity will be developed.

Presented concepts can inspire people to additional research on tiltrotor concept. Proposed solutions for kinematics, fast and robust tilt mechanism and idea of optimizing AoA to achieve better performance are flash points for further research and development of such aircrafts.

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