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Flight Mechanics and Control of Tilt Rotor/Tilt Wing Unmanned Aerial Vehicles: A Review

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ABSTRACT: A literature review of the Tilt Rotor/Tilt Wing (TR/TW) Unmanned Aerial Vehicles (UAVs) is presented in this paper from the flight mechanics and control points of view. Firstly, the advantages as well as the challenges of the TR/TW UAVs are studied, from the design, aerodynamic, flight dynamic and control viewpoints. Next, a chronicle of the most important researches conducted about the TR/TW UAVs is reported. Then, these TR/TW UAVs are categorized based on the overall configurations, rotor arrangements, engine/rotor positions, and engine/rotor types. Next, a comprehensive flight dynamic modeling of the TR/TW aircraft is introduced that may provide a complete and consistent set of the dynamic equations for any type of the TR/TW regardless of the configurations and rotor arrangements. Afterwards, a survey is carried out about the trim and stability of the TR/TW within the hover and transition phases of flight. Finally, different control methods and control strategies utilized for the attitude and altitude control of the TR/TW UAVs are categorized based on their pros and cons. Since this paper covers the flight mechanics and control of the TR/TW UAVs, it may assist designers in making decisions about the most critical aspects of a new design based on the previous studies.

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1. INTRODUCTION

Nowadays, many engineers and researchers are aimed at making Unmanned Aerial Vehicles (UAVs) more operational for both civilian and military applications. In a majority of cases, the most restrictive aspect of the UAVs is their need for the long take-off and landing runways. Eliminating the need to runways, therefore, can considerably develop the applications of the UAVs, especially in confined environments. The UAVs with the Vertical and/or Short Take-off and Landing (V/STOL) capabilities (e.g., the helicopters, multi-rotors, and ducted-fans) have very limited ranges and endurances due to the drastic battery usage [1]. Also, they cannot fly at high forward speed within the cruise phase [2, 3]. Thus, there are challenges for the development of a UAV with the V/STOL capability as well as the suitable performance and energy efficiency in the cruise phase. To that end, Tilt Rotor/Tilt Wing (TR/TW) UAVs may be excellent solutions. The TR/TW UAVs may be substitutes for other types due to the smaller required power-to-weight ratio, the possibility of proposing a wide variety of configurations, and the operational advantages.

Highlight 1: The TR/TW may be excellent solutions for future UAV developments due to the V/STOL capability as well as the suitable performance and energy efficiency in the cruise phase.

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A TR/TW aircraft can provide the V/STOL and hovering capabilities by tilting the rotors during the terminal phases of flight. These capabilities are required for many applications, such as search and rescue operations [4]. The TR/TWs make compromises between the pros and cons of the rotary- and fixed-wing aircraft [1, 3]. The rotary-wing aircraft have the hover and V/STOL capabilities; nevertheless, they cannot fly at high forward speeds due to the compressibility effects. On the contrary, the fixed-wing aircraft can carry more weight than comparable rotary-wing aircraft; nevertheless, they require high airspeeds during the takeoff and landing phases, and consequently long runways. A TR/TW aircraft can provide the needed lift force by combining the vertical thrust and aerodynamic forces in the transition phase. The take-off procedure of the TR/TW aircraft is divided into the hover, transition, and cruise phases: For the hover phase, the engine pods/nacelles or the entire wings are tilted upwards to provide the V/STOL capability [5, 6]. After reaching a proper altitude, the propellers are gradually rotated forward to increase the aircraft velocity [7]. During the transition phase, the aerodynamic lift is progressively increased due to the increasing airspeed, while the thrust lift is gradually reduced due to the decreasing the engine pod/nacelle or wing angles [8]. The transition phase should be progressed so that the total aerodynamic and thrust lift forces are equal to the aircraft weight. Once the stall speed is reached, the aircraft is able to generate its needed lift force aerodynamically within the cruise phase [9, 10, 11]. The landing procedure is performed in a very similar way: Reducing the speed beyond the aerodynamic stall speed is accessible by tilting the engine pods/nacelles or the entire wings vertically, while the total lift force is progressively altered from the aerodynamic one to the thrust one [12, 13, 14]. Finally, the vertical hover phase can be performed by the thrust lift force generated by the rotors. Since there is no need to take-off and landing fields, the TR/TW aircraft can operate in almost every area [15].

The Tilt Rotor (TR) and Tilt Wing (TW) aircraft are very similar, except that only the engine pods/nacelles are rotated in the former while the entire wing is tilted in the latter. The TRs have higher weight-to-power ratios and smaller disc loading ratios in comparison with the TWs [16]. Therefore, the TR aircraft are more efficient in the hover phase [16]. On the contrary, the TW aircraft are more efficient in the vertical flight due to the smaller wing surfaces against the relative motion. From the operational point of view, a specific forward speed is required by the TR aircraft in the transition phase, while the TW aircraft can begin the transition phase at zero forward speed; therefore, the TWs outperform the TRs, especially at low airspeeds [16]. From the structural point of view, the TRs require less structural strength of the pivot points in comparison with the TWs.

The TR/TW UAVs are faced with several challenges, especially in the transition phase [17]: From the design viewpoint, it is usually problematic to assign a single function (i.e., generating the lift force) to more than one physical component (i.e., the rotors and the wings). This may cause problems when the total lift force is converted from the thrust one into the aerodynamic one, and vice versa. Another design issue of the TR/TW UAVs is the limited wing aspect ratios due to the structural consideration of the rotors placed at the tip of the wings. In that case, a low aspect ratio wing may lead to high angles of attack in the cruise flight. Also, there are aerodynamic challenges regarding the interaction between the rotation of the rotor planes and the free stream. This may lead to sudden decreases in the lift generated by the rotors during the transition phase. Moreover, the transition flight is not steady; therefore, the classical methods for the analysis of the trim conditions, static and dynamic stability, and flying quality are not applicable to this phase. Furthermore, one of the most significant problems is the attitude and altitude control in the hover and transition flight due to the instability of the aircraft, slow response time of the rotors, transmitting delays, non-minimum phase plants [18] and uncertain measurements [12]. There are many other technical considerations such as complicated pod/nacelle rotation system, aeroelasticity, and noise issues. Since this paper is about the flight mechanics and control of the TR/TW UAVs, it is dedicated to the studies conducted about the flight dynamic modeling, simulation, trim, stability, control, guidance, and flight test. Other studies undertaken about the aerodynamics, structure, and propulsion of the TR/TW UAVs are not mentioned in this paper.

Highlight 2: The TR/TW UAVs are faced with several challenges from the design, aerodynamic, flight dynamic and control viewpoints.

2. THE CHRONICLE

While manned TR/TW aircraft are prominent in aviation, the TR/TW UAVs are not extensively used until now. No accurate chronicle of the TR/TW UAVs is available. A lot of researches, designs, development programs, and tests are conducted about the TR/TW UAVs in parallel with the manned TR/TW aircraft. In this section, a brief overview of the most important studies is provided.

The development program of Eagle Eye, the first TR UAV around the world, was started by Bell Helicopter in 1993. Eagle Eye was equipped with a turbo-shaft engine placed in the fuselage and a mechanical system transmitting the power into the TRs positioned at the ends of its wing. The development phase continued for about five years, and the flight tests were conducted in 1998 for both land-based and sea-based operations. There are a few published papers about the flight dynamics and control of Eagle Eye [19].

The first independent study about the TR UAVs was carried out in 1999, where a twin ducted-fan TR UAV concept was developed [20]. In this study, the flight equations of motion and trim conditions in the hover, transition, and cruise phases were obtained. Also, the stability of the TR UAV was investigated. Unfortunately, this study did not calculate the aerodynamic forces and moments acting on the UAV in the hover and transition phases. Moreover, a simplified flight dynamic analysis method based on a semi-steady snapshot concept was utilized. A similar study was carried out by Ref. [21], where the control and simulation of the investigated UAV are considered beyond the modeling of the flight equations of motion.

A TR UAV program was started by the Korea Aerospace Research Institute (KARI) in 2002. During 10 years, several studies were undertaken within this program about the performance analysis [22], flight control [5, 23, 24], autopilot design [25], guidance [26], and flight test [27, 28] of the TRs. The demonstrated UAV called the Smart Unmanned Aerial Vehicle (SUAV) attained an airspeed of 440 km/h at an altitude of about 10000 ft. in late 2011 [22]. These studies are continued, and several prototypes have been built until now.

In 2006, an article was published on the control and modeling of the twin-engine TR UAV called BIROTAN by Université de Technologie de Compiègne [29]. The UAV was able to tilt the propellers independently in the lateral and longitudinal directions. The modeling of the TR UAV was addressed, and a new control strategy was presented for the stabilization and trajectory tracking. Furthermore, simulation studies were made to check the responses in accordance with the parameter uncertainties.

Until 2009, many articles have attempted to control the TR UAVs only with two rotors. For example, a twin-engine TR UAV was built and tested by Nanjing University of Aeronautics and Astronautics (NUAA) [30]. The modeling, development of flight control system and flight tests of the UAVs were carried out and reported by Ref. [30]. The flight test results indicated that the designed controller had acceptable performance in the hover phase. Nevertheless, the paper did not provide any results about the transition phase.

In the following years, several novel ideas were introduced about both the UAV configurations and the number of rotors. For instance, a TR UAV with the flying wing configuration was introduced in 2011 [7]. This UAV was controlled by three engines mounted in the fuselage and the wings, and one rear tilting engine for the UAV transition phase. The research not only presented a mathematical model for the TR UAV within the hover, transition, and cruise modes, but also proposed a nonlinear controller for improvement of the stability in the hover. Nevertheless, the controllers for other flight modes were not presented.

In 2012 and 2013, the number of published articles about the TR/TW UAVs was increased compared to the previous years. Many of these articles were similar to previous studies such as Ref. [31-33]; however, some innovative designs were introduced. For example, quad-plane hybrid TR UAVs were proposed by Ref. [6, 34]. Also, a novel electric-powered quad TW UAV called SUAVI was introduced by Ref. [35, 36]. These articles were of great importance due to the comparisons of the flight simulation and flight test results for the validation. These articles not only covered the theoretical modeling, simulation, and control strategies, but also provided the flight test procedures and results. Furthermore, they approved that quad-rotor TW/TR UAVs have better controllability in comparison with the twin- and tri-rotor ones.

In 2014, many papers were published about the dynamic modeling [37], control [38], simulation [39], and guidance [40] of the TW/TR UAVs. A very interesting UAV was proposed by Ref. [9] in terms of the mission, engine alignment, and control strategy. Designed to fly on Mars, Hyperion was a solar-electric powered TR UAV with a flying wing configuration. The UAV consisted of a pair of fixed coaxial TRs for generating the thrust, and two tip-wing rotors for controlling the roll and pitch angles. The UAV also employed combined control surfaces for the high-speed attitude control. The type of the engine layout intensively changed the UAV dynamic equations of motion and consequently altered the control strategy. It should be noted that the coaxial engine pairs do not necessarily improve the yaw control; nevertheless, they may reduce the battery usage due to smaller trim efforts.

In 2015, several studies were undertaken about the stability and control of the TR/TW UAVs [41-49]. Among these studies, some papers are more notable: For example, a new concept for the TW UAVs was proposed by Ref. [42] in which the outer wing panels were the only tilting parts. This paper covered a wide range of the flight dynamic topics about the TW UAVs, including the aerodynamics, modeling, control, and stability for both the longitudinal and lateral dynamics. A mono-plane with three tilting rotors was proposed by Ref. [43]. In this study, 3D panel method codes were employed to model the aerodynamic interactions, such as the thrust force against the UAV airspeed in the transition phase. A new control method combining the TR and TW strategies was proposed by Ref. [50]. This article was a critical study about the dynamic modeling of the UAVs due to explicit formulation for the thrust and torque against the pitch angle of the rotors. Ref. [51] introduced the concept of the distributed propulsion and tilted lifting surfaces for the first time. In this article, the GL-10 configuration proposed by NASA Langley Research Center was studied, including the tilt wings, tilt tails, ten electric-powered rotors, and nine control surfaces. Due to the large number of the control variables (i.e., the propulsion and control commands), the needed model for this configuration was very complicated; thus, the design of experiment method was utilized to minimize the necessary tests. The optimal design of the TR UAVs was also addressed in 2015 [1, 49].

Among the papers published in 2016 about the flight mechanics and control of the TR/TW UAVs, one can mention Ref. [52-58]. The most noticeable configuration was introduced by Ref. [10]. This TR UAV had a blended wing design with four rotors, namely two rotors mounted on both sides of the fuselage and two coaxial rotors within the fuselage. Also, the configuration employed hybrid winglet-rudders instead of the empennage. In this research, a comprehensive study was undertaken about the dynamic modeling of the TR UAV, the rotation of the rotors in the transition phase, the aerodynamic estimation, and the control strategies.

The most important papers published in 2017 about the TR/TW UAVs were Ref. [59-64]. Among these studies, one of the most interesting configurations was introduced by Ref. [63]. This TW UAV was based on a quad-rotor; nevertheless, two rotors were fixed, and two tilting rotors were mounted on the wings. Therefore, the lift needed for the cruise flight of the tilt-wings-mounted Quad-rotor was produced by both the thrust of the fixed rotors and the lift of the wings. The idea was a combination of the quad-rotor advantages such as the simplicity and low cost, and the benefits of the TW UAVs such as the high cruise speed and long endurance. From the flight dynamics point of view, Ref. [14] was one of the few articles that simultaneously considered the transition phases of the departure and approach phases. In this paper, not only the flight path control system was introduced for a TW UAV, but also the effect of wind on the VTOL phase was also considered. One of the significant challenges for the TR/TW UAVs is the wind, disturbances, and environmental effects. There are a few studies examining these parameters.

In recent three years, many papers have been dedicated to the flight mechanics and control of the TR/TW UAVs [65-89]. Also, some new concepts have been introduced in these years. For example, a quad-tilt tail UAV was introduced by Ref. [90] for VTOL operation on land and water. The tail was designed to generate buoyancy forces for the landing on water. Also, to minimize the altitude loss during the transition phase, a gain-scheduled controller was designed. Another interesting study was undertaken by Ref. [73] in which the performance and life cycle cost of the VTOL and fixed-wing UAVs are compared. In addition, several new concepts for the TR/TW UAVs were proposed by Ref. [73]. Ref. [78] conducted an important study to model the aerodynamic and thrust interferences for

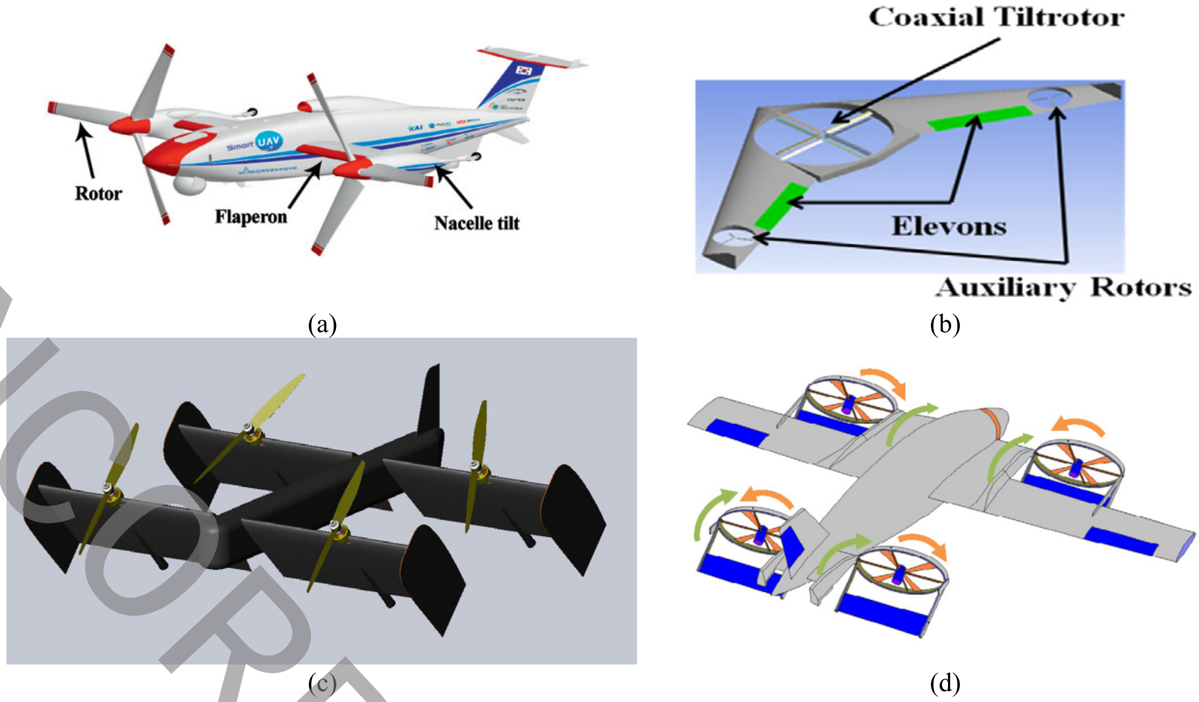

Fig. 1. Some configurations proposed for TR/TW UAVs: (a) monoplane [23], (b) flying wing [9], (c) tandem wing [35], and (d) hybrid [50].

quad TR/TW UAVs using experimental tests in the presence of the ground effect within the hover and transition phase for the first time. The results indicated that the ground effect has significant influences on the design parameters such as the rotor diameter and the control systems.

Highlight 3: Several studies have been undertaken about the flight dynamics and control of TR/TW UAVs in the recent 20 years.

3. CONFIGURATION

Configuration refers to the layout, arrangement, and integration of aircraft components such as the wings, fuselage, empennage, landing gear, power plant, etc. The selection of the overall configuration is critical since any configuration may offer particular advantages and weaknesses. In this section, the overall configurations of the TR/TW UAVs presented in the literature are investigated. After reviewing the articles, one can categorize the TR/TW UAVs into the mono-plane, twin-boom, tandem wing, canard, flying wing and hybrid configurations. Some configurations proposed for TR/TW UAVs are illustrated in Fig. 1.

The mono-plane configuration may have a variety of empennages, including the conventional tail, T-tail, and cruciform tail. This configuration is simple, less costly from the manufacturing perspective, and easy to analyze due to the availability of the classical methods for calculating the stability and control derivatives. Therefore, the mono-plane configuration is widely employed for the TR/TW UAVs in the literature. There are a variety of rotor arrangements for the mono-plane configuration: If there are two rotors, they can be mounted on the wingtips [4, 5]. This is the most common arrangement for the medium-size UAVs. Also, it is possible to position ducted rotors within the wings. Moreover, one can add a fixed horizontal rotor on the vertical tail to increase the cruise speed of the TR/TW UAV and improve its transition phase [93]. If there are four rotors, they should be placed on the struts outside the wings and fuselage. Called a hybrid UAV, the quad-TRs may be the simplest and most popular arrangement for the small-size TR/TW UAVs [39]. In the literature, there are some TR/TW UAVs with the twin-boom configuration [94]. Generally, the mono-plane and twin-boom configurations are similar, except that the latter uses the longitudinal booms to attach the empennage into the fuselage. The twin-boom TR/TW UAVs are advantageous from the weight and balance viewpoint due to the short fuselage; however, this configuration does not offer suitable rotor arrangements. For small TR/TW UAVs, the twin-boom configuration can be easily assembled and disassembled.

To omit the struts required for the quad-rotor mono-plane configuration and consequently its weight and drag, one can employ a tandem wing configuration for the TR/TW UAVs. In the literature, some TR/TW UAVs with the tandem wing configuration are proposed [3, 13, 34, 35, 36, 80]. The tandem wing configuration has a simpler structure and less weight in comparison with the quad-rotor hybrid UAVs. Also, the control of the tandem wing configuration is much easier due to the symmetry of the airframe, engines, and rotors. On the contrary, the interaction of the tandem wing is annoying in the cruise phase due to the increased drag and angle of attack. The canard configuration is also employed for the TR/TW UAVs [38, 47]. The canard configuration is similar to the tandem wings except that the canards are smaller than the front wings

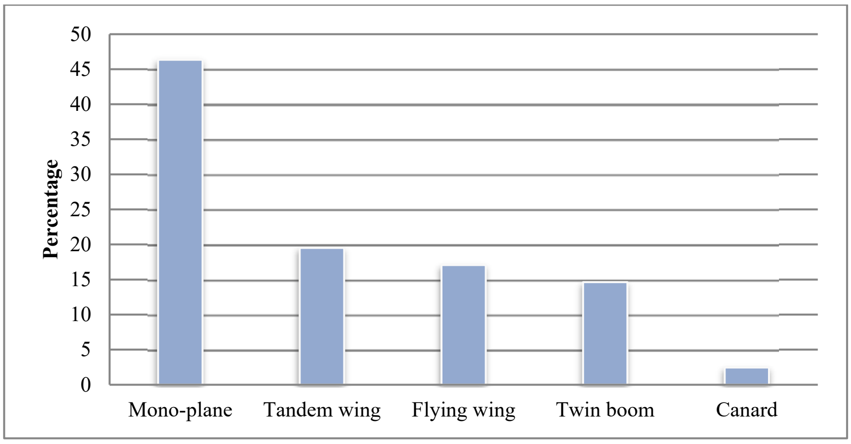

Fig. 2. The classification of the configurations in the studied TR/TW UAVs as percentages.

in the tandem configuration. However, this difference is not negligible. The canards are primarily designed for achieving the stability and control in the cruise phase while they are not used in the hover and transition phases [58]. Eliminating the symmetry of the UAV, the canards do not provide suitable engine/rotor arrangements. Therefore, the canard configuration is rarely employed for the TW/TR UAVs.

The flying wing configuration is usually utilized to maximize the lift to drag ratio in the cruise flight [9]. Nevertheless, the flying wing aircraft are usually statically unstable. Also, it is very sophisticated to model their aerodynamics and flight mechanics due to enormous changes in the aerodynamic forces as well as the aerodynamic center in dissimilar flight conditions. Only a few flying wing aircraft are developed until now. Therefore, employing the flying wing configuration for the TR UAVs is a risk. There are some instances of the flying wing TR/TW UAVs in the literature [9, 10, 40, 72]. Because of the larger integrated body of the flying wing TRs, one can accommodate its engines and tilting ducted rotors inside the body to reduce the drag force [37]. On the contrary, there is a critical disadvantage: If a flying wing UAV is optimized for the cruise phase, it may need a long wingspan that may violate the requirements for the V/STOL phase. This problem is more apparent when a medium to large TR UAV is required.

The classification of the configurations employed for the TR/TW UAVs is expressed in Fig. 2 as percentages. It can be observed that the mono-plane configuration is utilized in about half of the studied cases. This is due to the fact that there are extensive experiences about the mono-plane configuration. Also, this configuration is the simplest from the analysis and design points of view. The tandem configuration is in the second position due to its suitable locations for embedding the engines/rotors. Any of the tandem, twin-boom, and flying wing configurations is employed in less than 20% of the studied case. The canard configuration is rarely used for the TR/TW UAVs because of the improper positioning of the engines/rotors.

Highlight 4: Several configurations are proposed for the TR/TW UAVs, including the mono-plane, twin-boom, tandem wing, canard, and flying wing configurations. Among these configurations, the mono-planes are the most prevalent. The hybrid quad-TRs may be the simplest and most popular arrangement for the small-size TR/TW UAVs.

The engine/rotor arrangement has a vital role in the flight dynamics and control of the TR/TW UAVs. Despite the distributed lift force in the cruise phase, the thrust forces in the hover and transition phases are applied at the rotor points. Increasing the number of engines/rotors may lead to smaller acting forces and consequently more weight; however, it may increase the aerodynamic interference effects between the wing-body and the rotors [77, 78, 90, 95]. The classification of the engine/rotor positions in the studied TR/TW UAVs is expressed in Fig. 3 as percentages. It should be noted that Fig. 3 represents the engine/rotor positions rather than the engine/rotor numbers; therefore, the coaxial engines/rotors are counted once. By studying the literature, one can observe that the twin-rotor arrangement was more prevalent in the first decade of the century; nevertheless, the quad-rotor arrangement has been more common in the current years. Based on Fig. 3, almost half of the studied UAVs use the quad-rotor arrangement. This combination of the rotors and geometry is symmetric in accordance with the Center of Gravity (CG); therefore, easier control strategies are required in the hover and transient phases [6, 46, 70, 87, 88]. Also, the symmetry of the thrust and weight forces leads to less weighty structures. Thus, the selection of the quad-rotor arrangement sounds logical. The tilting tri-rotor arrangement is rarely used; however, there are several tri-rotors with two tilting engines/rotors and one fixed horizontal engine/rotor. Some of these configurations are introduced by Ref. [32, 71, 96, 99, 106]. The single coaxial rotor arrangement is rarely used. The rotor/engine position more than 4 is not frequent due to the asymmetry regarding the CG and drastic battery usage [64]. The classification of the engine/rotor types in the studied TR/TW UAVs are expressed in Fig. 4 in percentage terms. It can be observed that the single-TR type is absolutely common. The coaxial rotors are sometimes used for omitting the yawing moment; however, they cannot vanish the yawing moment, and consequently the yaw control strategy is not simplified.

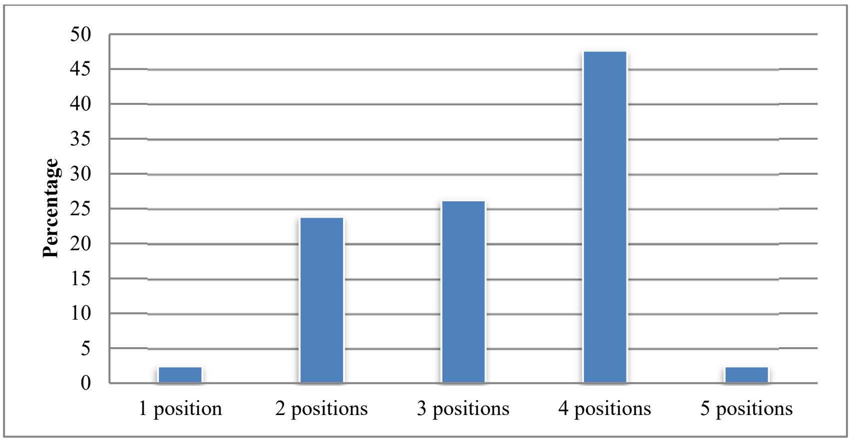

Fig. 3. The classification of the engine/rotor positions in the studied TR/TW UAVs as percentages.

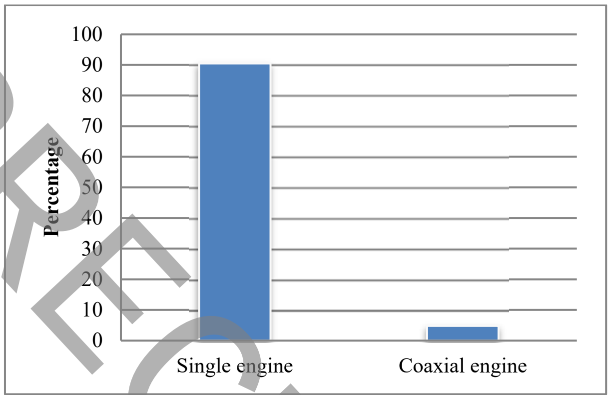

Fig. 4. The classification of the engine/rotor types in the studied TR/TW UAVs as percentages.

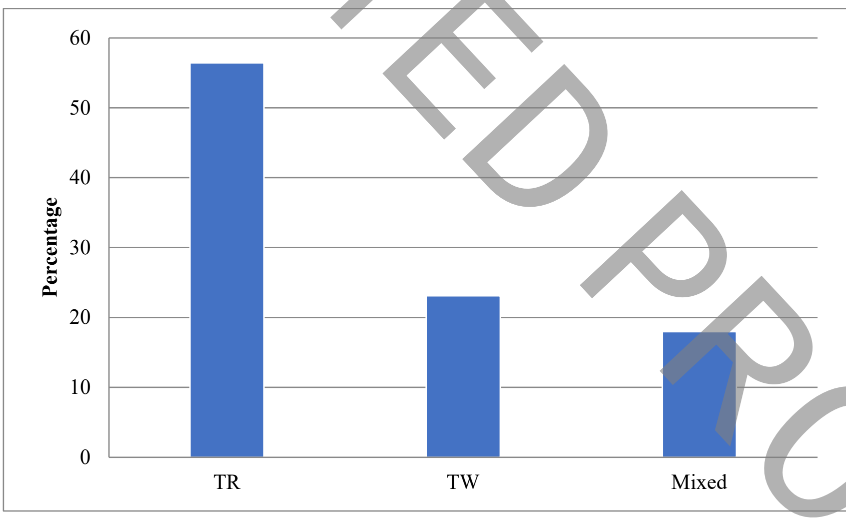

Fig. 5. The classification of the TR and TW in the studied TR/TW UAVs as percentages.

Furthermore, the interactions of the rotors cause a severe loss of the total thrust [90]. Since the battery usage is an essential concern about the TR/TW UAVs [1, 9, 14, 15, 35, 41, 61, 73, 77], the coaxial and combined TRs are not common.

To being TR or TW should also be decided by the designer. There are no absolute pros and cons between the TRs and TWs: The TRs offer advantages such as better controllability, wind resistance, and payload capacity; nevertheless, the TWs have benefits, such as better stability in the transition phase, energy efficiency [96] and more cruise speed [3]. Fig. 5 categorizes the TR and TW in percentage terms. As can be observed, the TRs are more frequent than the TWs.

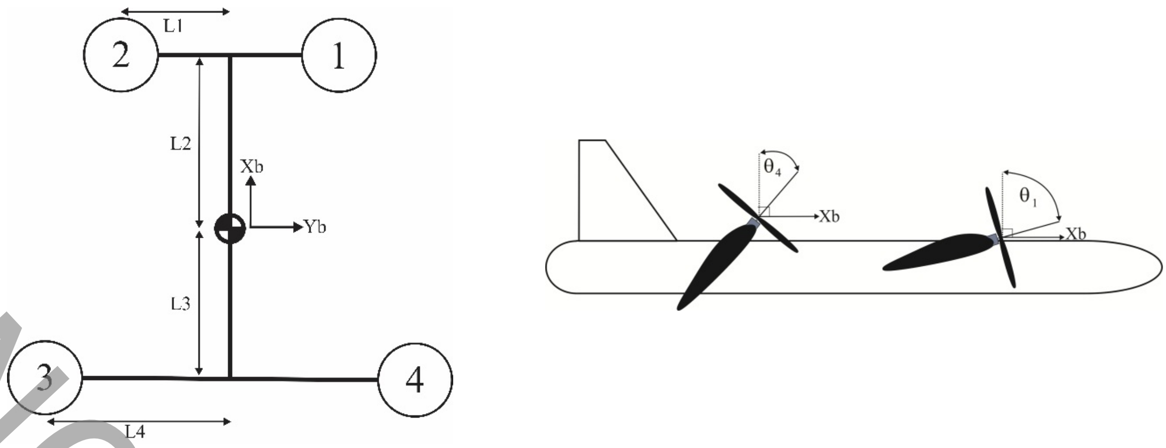

Fig. 6. The quad single TR configuration for the dynamic modeling from (a) the top view, (b) the side view.

Highlight 5: Several rotor arrangements, positions, and types are proposed for the TR/TW UAVs. The quad single TR are the most common arrangement due to its symmetry, easy control strategies, and less weight and cost.

4. FLIGHT DYNAMIC MODELING

To find the responses of an aircraft to the control commands and/or disturbances, the aircraft flight dynamics should be modeled. The flight dynamic models are necessary for many reasons, such as the design of the controllers and Stability Augmentation Systems (SASs). To that end, it is necessary to estimate the forces and moment acting on the aircraft. Then, a set of differential equations describing the 6 Degree Of Freedom (6DOF) equations of motion should be simultaneously solved based on the initial conditions [29, 31]. Finally, the flight parameters should be obtained against time in accordance with the varying flight conditions and control commands. The 6DOF equations of motion can predict the flight parameters in accordance with the internal and/or external excitations without simplifying assumptions such as the linearity around trim points and de-coupling of the longitudinal and lateral dynamics.

The flight dynamic models of the TR/TW UAVs are presented by many of the papers in the literature. In several cases, however, some simplifications are made. Also, it is usually difficult for the readers to find a complete and consistent set of the dynamic equations. In this section, a comprehensive set of flight dynamic models is presented for the TR/TW UAVs. The flight dynamic models of the TR/TW UAVs are very similar to that of other aircraft except that there are some forces and moments due to the tilting rotors and the aerodynamic interactions between the rotors and the wing-body [55, 75, 90]There are several factors simplifying the governing flight dynamics: The TR/TW UAVs usually have small wing aspect ratios in order to decrease the structural bending [56]; therefore, they typically can be assumed rigid bodies. Also, the mass of an electrical-powered TR/TW UAVs is fixed; however, the CG positions and moments of inertia are altering when the pods/nacelles are rotating. Unfortunately, many of the studied papers ignore these effects. Furthermore, many of the TR/TW UAVs have limited airspeeds and altitude [3]. On the contrary, the most difficult tasks for modeling the flight dynamics of the TR/TW UAVs are the estimation of the aerodynamic and thrust forces and moments, and their interactions.

For the TR/TW UAVs, it is very complicated to estimate the aerodynamic force and moments due to the angle of attack of -90 and 90 degrees during the vertical landing and take-off phases, respectively. Also, all the values between -90 to 90 degrees are covered during the transition phase. It should be noted that it is very complicated to estimate the UAV aerodynamics at high angels of attack. While the vertical speed can be neglected at the VTOL phase, it is not usually possible at the transition phases. Semi-empirical methods are not able to predict the aerodynamics at high angles of attack and low dynamic pressures; therefore, exact numerical or experimental methods are needed for the aerodynamic modeling at the transition phases [34, 49, 77]. Furthermore, interactions between the rotors and free stream are very complicated from both the overall aerodynamics and the thrust points of view. The interactions can extremely change the aerodynamic as well as the thrust forces and moments. Usually, the total thrust force is suddenly reduced in the presence of the free stream. No semi-empirical method is able to estimate these interactions; therefore, exact numerical or experimental methods are necessary.

To model the thrust forces and moments, a quad single TR configuration is considered in this section. Other rotor arrangements can similarly be modeled. Fig. 6 illustrates the considered configuration where the rotors #1 and #3 are rotated in the counterclockwise direction, and the rotors #2 and #3 are rotated clockwise. The thrust force and the reaction torque of the i^{th} rotor can be obtained in the rotor coordinate system, as follows [8, 50, 59, 82, 91, 93, 97, 98]:

$$T_i = C_T \omega_i^2 = L_\lambda k \omega_i^2 \tag{1}$$

$$Q_i = -C_Q \omega_i \left|\omega_i\right| \tag{2}$$

where ω represents the rotor angular speed. C_T and C_Q are the blade thrust and torque coefficients, respectively. Also, k is a thrust coefficient, and L_λ is the torque/force ratio [36]. The torque is generated due to the profile drag of the rotor blades when the airflow passes through the rotors. The reaction torque Q_i is applied to the UAV. The thrust force and the reaction torque of all rotors should be transformed into the body coordinate system, as follows [8, 50, 59, 82, 91, 92, 93, 97, 98]:

$$\boldsymbol{T}^b = \begin{bmatrix} \sum_{i=1}^{4} T_i \sin\theta_i & 0 & -\sum_{i=1}^{4} T_i \cos\theta_i \end{bmatrix}^T \tag{3}$$

$$\boldsymbol{MQ}^b = \begin{bmatrix} \sum_{i=1}^{4} -Q_i \sin\theta_i & 0 & \sum_{i=1}^{4} Q_i \cos\theta_i \end{bmatrix}^T \tag{4}$$

in which the superscript b indicates the body coordinate system, and θ_i represents the i^{th} pod/nacelle angle as shown in Fig. 6.

Also, the torque generated by the thrust force and its arm relative to the CG of the UAV should be considered. The arms relative to the CG are shown in Fig. 6. In the body coordinate system, the torque of all rotors can be obtained as follows [8, 40, 50, 59, 82, 85, 93, 97, 98]:

$$\mathbf{MT}^{\mathrm{b}} = \begin{bmatrix} (-\mathrm{T}_1 \cos\theta_1 + \mathrm{T}_2 \cos\theta_2)\, L_1 + (\mathrm{T}_3 \cos\theta_3 - \mathrm{T}_4 \cos\theta_4)\, L_4 \\ (\mathrm{T}_1 \cos\theta_1 + \mathrm{T}_2 \cos\theta_2)\, L_2 + (-\mathrm{T}_3 \cos\theta_3 - \mathrm{T}_4 \cos\theta_4)\, L_3 \\ (\mathrm{T}_2 \sin\theta_2 - \mathrm{T}_1 \sin\theta_1)\, L_1 + (\mathrm{T}_3 \sin\theta_3 - \mathrm{T}_4 \sin\theta_4)\, L_4 \end{bmatrix} \tag{5}$$

Moreover, the gyroscopic torques should be considered. There are two sources for the gyroscopic torques: Firstly, the product of the rotor moment of inertia, the rotor angular speed and the angular rate of the pods/nacelles of the i^{th} rotor generates the gyroscopic torques, as follows [40, 50, 91, 97, 99]:

$$MG_i = j_r \omega_i \dot{\theta}_i \tag{6}$$

where j_r represents the rotor moment of inertia. The torque of all rotors can be obtained in the body coordinate system, as follows [40, 50, 91, 97, 99]:

$$\mathbf{MG}_1{}^{\mathrm{b}} = \begin{bmatrix} \sum_{i=1}^{4} MG_i \cos\theta_i & 0 & \sum_{i=1}^{4} MG_i \sin\theta_i \end{bmatrix}^T \tag{7}$$

Secondly, the product of the rotor moment of inertia, the rotor angular speed and the angular rate of the pod/nacelle for the i^{th} rotor generates the gyroscopic torques. The torque of all rotors can be obtained in the body coordinate system as follows [6, 91, 98]:

$$\boldsymbol{MG}_2{}^b = \begin{bmatrix} \omega_z\, q\, j_r & (\omega_x r - \omega_z p)\, j_r & -\omega_x\, q\, j_r \end{bmatrix}^T \tag{8}$$

where p, q, and r are the UAV angular rates in the body coordinate system, and ω_x and ω_z are defined as follows:

$$\begin{aligned} \omega_x &= -\omega_1 \sin\theta_1 + \omega_2 \sin\theta_2 - \omega_3 \sin\theta_3 + \omega_4 \sin\theta_4 \\ \omega_z &= +\omega_1 \cos\theta_1 - \omega_2 \cos\theta_2 + \omega_3 \cos\theta_3 - \omega_4 \cos\theta_4 \end{aligned} \tag{9}$$

Furthermore, the reaction moments should be considered. There are two sources for the reaction moments: Firstly, a reaction moment is produced due to the angular acceleration of the pods/nacelles. The moments of all rotors can be obtained in the body coordinate system, as follows [50, 97, 99]:

$$\boldsymbol{MR}_1{}^b = \begin{bmatrix} 0 & \left(\ddot{\theta}_1 + \ddot{\theta}_2 + \ddot{\theta}_3 + \ddot{\theta}_4\right) j_t & 0 \end{bmatrix}^T \tag{10}$$

where j_t represents the moment of inertia of the rotor, engine, and pods/nacelles.

Secondly, the product of the rotor moment of inertia and the rotor angular acceleration generates a reaction moment. The moments of all rotors can be obtained in the body coordinate system, as follows:

$$\boldsymbol{MR}_2{}^b = \begin{bmatrix} -j_r.\dot{\omega}_x & 0 & -j_r.\dot{\omega}_z \end{bmatrix}^T \tag{11}$$

Finally, one can obtain the total thrust moments in the body coordinate system as follows:

$$\boldsymbol{M}^b = \boldsymbol{MQ}^b + \mathbf{MT}^{\mathrm{b}} + \mathbf{MG}_1{}^{\mathrm{b}} + \mathbf{MG}_2{}^{\mathrm{b}} + \boldsymbol{MR}_1{}^b + \boldsymbol{MR}_2{}^b \tag{12}$$

Highlight 6: The presented thrust model can be employed within all flight phases. For the aerodynamic modeling as well as the thrust/aerodynamic interactions, no rigorous mathematical model has been introduced until now. In that case, one may need the Computational Fluid Dynamics (CFD) and/or wind tunnel tests.

5. TRIM AND STABILITY

Trim is a condition in which the total forces and moments acting on the aircraft are balanced. A TR/TW UAV should be trimmed within its flight envelope [84]: For the VTOL phase, it is usually straightforward to calculate the required RPMs or blade pitch angles of the rotors in order to generate a total thrust force equal to the UAV weight. Also, in the cruise phase, the trim of the TR/TW UAV is very similar to that of a fixed-wing aircraft where the control surfaces should be deflected to provide the needed lift and moment to balance by altering the angle of attack [66]. For the transition phase, however, it is not the case: If the pods/nacelles are rotated very fast, the UAV cannot achieve a sufficient forward speed. In that case, the UAV may lose the altitude or even crash. Therefore, for every angle of the pods/nacelles, one should find the flight envelope, namely the lowest and highest possible forward speeds in every altitude. To obtain the flight envelope of the transition phase, there are several methods. In the analytical method, one can derive the equations of motion for the TR/TW UAV to find the balanced conditions [94]. Nevertheless, this method is rather intuitive: For example, Ref. [94] divided the transition phase into the low-, mid- and high-speed regimes: At the low- and high-speed regimes, the pitching moment is trimmed by the rotors and the elevator deflections, respectively. At the mid-speed regime of the transition; however, both the rotors and the elevator deflections are employed. Since it is complicated to model the thrust/aerodynamic interactions in the transition phase, the flight test data is usually utilized to trim the UAV. For instance, the pod/nacelle angles can be obtained by the flight tests for the transition flight at dissimilar forward speeds and angles of attack. Then, some experimental combinations of the acceptable pod/nacelle angles and speeds can be achieved and depicted in the speed-tilt angles chart [28]. There are several experimental points in the speed-tilt angles charts, primary due to the fact that the pods/nacelles angles cannot continuously be controlled; however, all the points are positioned within some lower and upper bounds of the charts. To attain the best control, it is necessary to maintain the transition phase within the boundaries of the speed-tilt angles chart [16].

Once the trim conditions are obtained, one should examine the dynamic stability of the TR/TW UAV. In other words, it is necessary to investigate the damping behaviors of the flight parameters around the trim points when the UAV is excited by the control commands or disturbances. It is essential to design the control strategies based on the dynamic stability characteristics. In the classical method, the 6 DOF equations of motion are linearized around the trim points and simplified by the decoupling assumption. Afterwards, the longitudinal and lateral/directional transfer functions can be obtained. Finally, the characteristic equations can be solved to find the corresponding flight modes. There are a few studies that examine the dynamic stability of the TR/TW UAV using the classical method. For example, the dynamic stability of a TW UAV is investigated by Ref. [42]. The longitudinal and lateral/directional flight modes are extracted by the classical method with respect to the tilt angles. The results indicate that the short period mode is stable for all rotor angles; however, the frequency of the short period mode is significantly reduced in the transition and VTOL phases. On the contrary, the phugoid mode is unstable at the VTOL phase. Therefore, one can conclude that the TR/TW UAVs are unstable at the VTOL phase and a wide range of the transition phase. Furthermore, it can be observed that the lateral/directional dynamics is much more unstable since both the Dutch roll and spiral modes are unstable in the hover phase while the relative stability of the Dutch roll is not acceptable in the transition phase. A similar study undertaken by Ref. [100] shows that the TW UAVs are inherently unstable at almost all of the wing angles; however, the SAS can compensate for the small or negative damping ratios for both the longitudinal and lateral/directional dynamics, and improve the responses. Another interesting study is performed by Ref. [94] in which the poles of the longitudinal transfer functions are obtained against the forward speed. The results demonstrate that the phugoid and short period modes are unstable and marginally stable at low speed forward flight, respectively. Nevertheless, the stability of the TR UAV is improved at high forward speeds.

It should be noted that the classical flight dynamics method is not suitable for the analysis of the TR/TW UAVs, especially at the transition phase. This is due to the fact that the transition flight is not steady; therefore, the trim conditions cannot be obtained. Furthermore, the assumption of the linearity around the trim points is not correct because the transition phase is a highly nonlinear regime. Also, in the classical flight dynamics, the decoupling of the longitudinal and lateral/directional dynamics is based on the assumption of the negligible roll angle. For the TR/TW UAVs, however, it has been showed that the amplitudes of the roll and pitch angles are comparable in the transition phase [6, 9, 13, 33, 35, 36]; therefore, the decoupling assumption is not acceptable. All of the mentioned issues indicate that the classical method should be replaced by modern flight dynamics methods. Several coupled flight modes may exist in the transition phase; however, they are ignored by the decoupling, linearity, and steady flight assumptions. The flight test data analysis using the frequency, time, and time-frequency methods may reveal the hidden flight modes, and improve the dynamic stability analysis.

Highlight 7: The hover and transition phases are the most unstable flight phases for the TR/TW UAV. The classical flight dynamics method is not suitable for the analysis of the TR/TW UAVs, especially at the transition phase. The flight test data analysis may reveal the hidden coupled flight modes, and improve the dynamic stability analysis in the transition phase.

6. CONTROL

As can be seen in the previous section, the TR/TW UAVs have unstable behavior in the hover and transition phases; thus, there are severe challenges for the design of the attitude and altitude controllers. For example, the control surfaces are not active at the hover and low-speed transition; therefore, the UAV should be controlled via the thrust forces generated by the tilting rotors. In that case, the differential thrust between the left and right rotors is used for the roll control while the pitch control is performed by the differential thrust between the fore and aft rotors. The yaw control is more challenging: The differential thrust for the roll and pitch controls are caused by altering the RPMs or blade pitch angles of the rotors; therefore, they affect the yaw control and vice versa. This coupling problem is usually resolved in the TW configurations via the control surfaces placed in the slipstream of the rotors [42, 100]. For the TRs, however, the yaw coupling problem cannot be easily resolved.

Highlight 8: For the VTOL phase, the pitch and roll controls are usually performed by the differential thrust. For the TW configuration, the yaw control is performed via the control surfaces placed in the slipstream of the rotors; nevertheless, the yaw coupling problem cannot be easily resolved for the TRs.

If the forward speed is sufficiently developed, the aerodynamic control surfaces will be activated. At lower forward speeds, however, it is necessary to use both the differential thrust and the aerodynamic surfaces to control the UAV. Therefore, a combination of control strategies is required for dissimilar flight conditions. There is a wide variety of configurations and rotor arrangements for the TR/TW UAVs; therefore, different control strategies are investigated in the literature [101]. For example, one can compare the control strategies proposed for the quad TW examined by Ref. [42] and the mono-plane tri-rotor partially-TW studied by Ref. [100]. In addition to different control strategies, a variety of control methods (e.g., the PID, optimal, robust, adaptive, and dynamic inversion methods) are employed until now.

The PID controller is one of the most common examples of the classic feedback control algorithms. The PID controllers are used in many control processes due to their simplicity. The PID controllers calculate the error between the measured output of the plant and the set-point. The purpose of the controller is to minimize the error by adjusting the control commands. The PID controller receives the error signal and computes the control command based on the proportional, integral, and derivative terms. The weighted summation of these terms is used as the control command. Thus, the PID control command is calculated based on the current system error (i.e., the present performance), the sum of system errors (i.e., the past behavior), and the derivative of the current error (i.e., an estimation of future behavior). The PID coefficients can be optimally calculated by known methods such as the Ziegler–Nichols method, Cohen–Coon parameters, and Relay method. In practical applications, nevertheless, they can be acceptably determined by trial and error.

The PID is commonly used for the attitude and altitude control of the TR/TW UAVs because firstly, it is not highly sensitive to the accuracy of the UAV dynamic model, and secondly, the controller parameters can be improved by the flight simulators or flight tests. Different PID control structures can be employed for the attitude and altitude control of the TR/TW UAVs. For the schematic TR UAV illustrated in Fig. 6, one can use the following control structures proposed by Ref. [36, 40, 99, 102]:

$$\boldsymbol{u}=\begin{bmatrix}u_1\\u_2\\u_3\\u_4\end{bmatrix}=\begin{bmatrix}-k & -k & -k & -k\\-kL_1 & kL_1 & kL_4 & -kL_4\\kL_2 & kL_2 & -kL_3 & -kL_3\\kL_\lambda & -kL_\lambda & kL_\lambda & -kL_\lambda\end{bmatrix}\begin{bmatrix}\omega_1^2\\\omega_2^2\\\omega_3^2\\\omega_4^2\end{bmatrix} \tag{13}$$

Also, the following control commands can be proposed:

$$\begin{aligned}
u_1 &= m(-g+k_{pz}e_z+k_{dz}\overset{\ddot{y}}{\left(e_z\right)}+k_{iz}\int e_z\Big)\\
u_2 &= I_{xx}(k_{p\phi}e_\phi+k_{d\phi}\overset{\ddot{y}}{\left(e_\phi\right)}+k_{i\phi}\int e_\phi\Big)\\
u_3 &= I_{yy}(k_{p\theta}e_\theta+k_{d\theta}\overset{\ddot{y}}{\left(e_\theta\right)}+k_{i\theta}\int e_\theta\Big)\\
u_4 &= I_{zz}(k_{p\psi}e_\psi+k_{d\psi}\overset{\ddot{y}}{\left(e_\psi\right)}+k_{i\psi}\int e_\psi\Big)
\end{aligned} \tag{14}$$

in which $e_\psi, e_\theta, e_\phi, e_z$ are the tracking errors for the yaw, pitch, roll and altitude channels. Also, m is the UAV mass, I_{xx}, I_{yy}, I_{zz} are the moments of inertia with respect to the UAV body axes, and k_p, k_i, k_d are the PID controller parameters. Several PID-based controllers are used in the literature for the TR/TW UAVs such as Ref. [2, 30, 33, 35, 36, 40, 41, 63,68, 79, 80, 81, 85, 86, 99, 100, 103-106]. In several cases, the PID-based controllers are combined with other kinds of controllers such as the H-infinity [4, 83], robust [93] and adaptive [67] controllers. Also, the PID controllers are frequently employed in the inner loop of the attitude and altitude controllers [30, 41, 102, 104]. On the contrary, the PID controller has some disadvantages, such as the sensitivity to the measurement uncertainties; therefore, the sensor noise can severely degrade the PID controller performance. Unfortunately, most of the studies in the literature ignore the noise of the gyroscopes, accelerometers, and air data system. Also, they usually ignore the sampling rates of the sensors.

The optimal control is also employed for the control of the hover and transition phases of the TR/TW UAVs [5, 21, 43, 97]. For a given system, the optimal control is going to find a control law so that a certain optimality criterion can be achieved. An optimal control problem has a cost function that should be minimized. The cost function is obtained based on the state and control variables. As its name suggests, the optimal control tries to find an optimal solution for the problem in which the control states should be followed. The fuel consumption or battery usage of the TR/TW UAVs is critical in the hover and transition phases; therefore, the optimal control may be utilized to improve the energy efficiency. The nonlinear optimal control is not widely used because it suffers from an enormous computational burden. On the contrary, the Linear Quadratic Regulation (LQR), a linear optimal control method with quadratic objective function, is more common. In the literature, the LQR method is used for the hover control of the TR/TW UAVs [5, 21, 43]. The definition of the LQR objective function is not unique. The objective function is defined so that the control states are tracked, and the costs are minimized. The LQR problem can be defined as follows:

$$\begin{aligned}
\dot{x}(t) &= \boldsymbol{A}x(t)+\boldsymbol{B}u(t)\\
J &= \frac{1}{2}\int_0^\infty\left(x(t)^T\boldsymbol{Q}x(t)+u(t)^T\boldsymbol{R}u(t)\right)dt
\end{aligned} \tag{15}$$

in which x is the system states, and u is the control commands. Also, the weighting functions Q and R should be selected by the control designer to make a compromise between the tracking errors and costs. The following control command is proposed for the tracking of the states in the hover flight of the TR/TW UAVs [5, 43]:

$$\begin{aligned}
u(t) &= -\boldsymbol{k_a}x(t)\\
k_a &= \boldsymbol{R}^{-1}\boldsymbol{B}^T\boldsymbol{P_R}
\end{aligned} \tag{16}$$

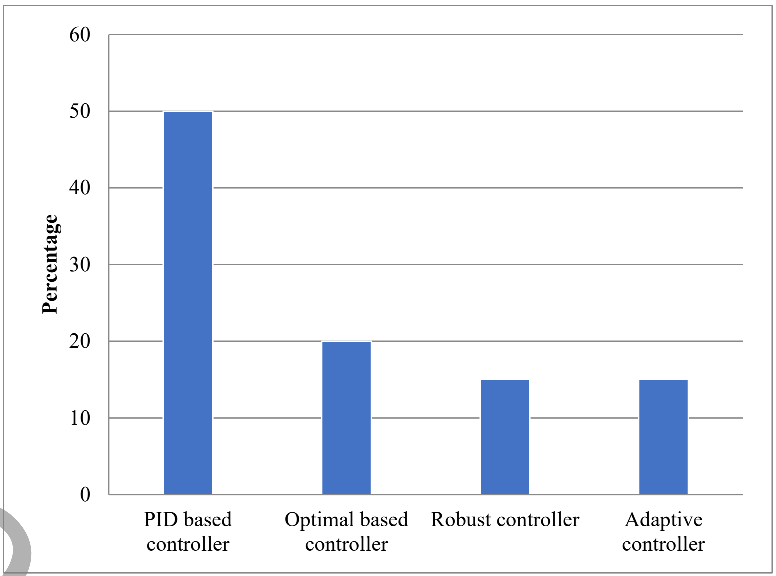

Fig. 7. The control methods used in the investigated simulation studies for the control of the TR/TW UAVs

where k_a is the control feedback gain matrix, and P_R is obtained by solving the Riccati equation as follows [21, 43] .

$$A^T P_R + P_R A - P_R B R^{-1} B^T P_R + Q = 0 \tag{17}$$

There are several sources of uncertainty about the TR/TW UAVs, such as the aerodynamic-thrust interactions at the transition phase, the rotor dynamics in the forward flight, the rotor effects on the stability and control derivatives. For dealing with the uncertainties, the robust control is implemented to the attitude and altitude control of the TR/TW UAVs in some studies [9, 107, 108]. Uncertainty can exist in both the model and the measurements. The control systems are severely affected by uncertainty. In the presence of uncertainty, the performance of the control systems may be degraded, or even the system instability may be occurred. The robust control is an effort to remove this problem so that the acceptable performance of the system is guaranteed in all possible situations.

Sometimes, it is necessary to modify the control laws in order to be consistent with the changing plant or environment. In that case, adaptive control method is needed to track the changes, estimate the system parameters, and adapt the control laws. The adaptive control is based on the parameter estimation techniques. Therefore, the system identification techniques are needed for the adaptive control. The conventional estimation techniques used for the adaptive control are the recursive least squares and the gradient descending. Both of the techniques provide new control rules in real time. The Lyapunov stability criterion is used to extract these rules and update them to ensure the convergence. Since the model of the TR/TW UAVs are highly changing within the VTOL, transition and cruise phases, the adaptive control is used in the literature for the attitude and altitude control [44 ,48 ,89 ,109]. In some cases, also, the adaptive and robust controllers are used together [52, 62]. It is usually challenging to identify the parameters online. In many cases, therefore, the estimated parameters are not directly used by the controller, but they are utilized to calculate the parameters required by the controller.

A summary of the control methods used in the investigated simulation and flight test studies is illustrated in Fig. 7 and 8 for, respectively. Based on the literature review, one can conclude that the PID-based controllers are the most common method for both the simulation and flight test studies. In the flight test case, the percentage of the PID-based controllers is about 80%. This is due to the simplicity and efficiency of the PID-based controllers. In the simulation case, however, about half of the studies use more sophisticated methods such as the optimal, robust, and adaptive controls. A summary of the most important studies in the literature is presented in Table 1.

Highlight 9: Several control methods have been examined for the control of the TR/TW UAVs until now. Among these methods, the PID-based controllers are the most common method. In many cases, however, the plants are assumed ideal. Further studies should consider the sensors noise, actuator delay, wind distribution, and the changing of the CG.

CONCLUSION

The TRs/TWs may be excellent solutions for future UAV developments due to the V/STOL capability, suitable performance characteristics in the cruise phase, and the energy efficiency. Nevertheless, they are faced with several design, aerodynamic, flight dynamic and control challenges, especially in the transition phase. Therefore, several studies are undertaken to deal with the challenges. An overview of the design, flight mechanics and control of the TR/TW UAVs is provided in this paper. Dissimilar configurations and rotor arrangements are studied, and their advantages and disadvantages are discussed. Also, a comprehensive

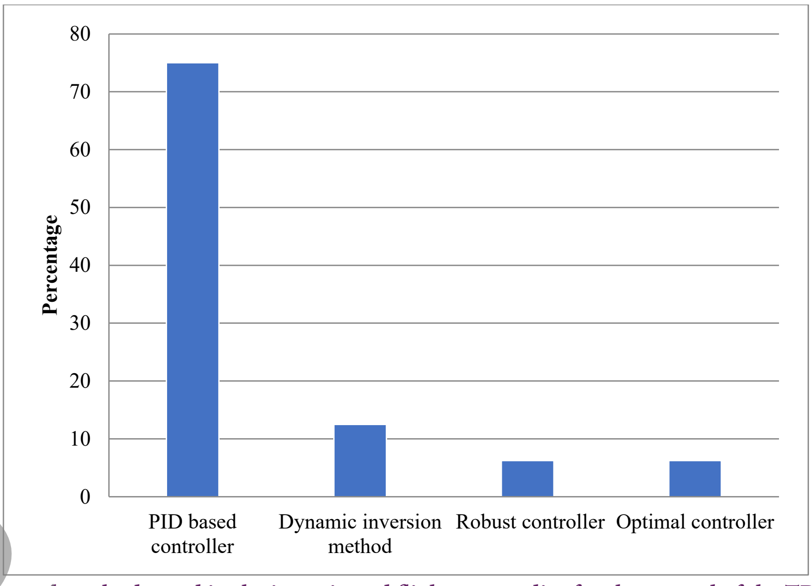

Fig. 8. The control methods used in the investigated flight test studies for the control of the TR/TW UAVs

Table 1. A summary of the most important studies in the literature

Country	Institute	Configuration	Number of engines	Specification	TR/TW	Controller
China	Ninjing university [**Error! Reference source not found.**]	mono-plane	2	span= 1.4 m	TW	PID
	Shanghai aircraft design and research institute [**Error! Reference source not found.**]	mono-plane	3	span= 1 m m= 2.9 kg	TR	robust PID
	National university of defence technology [**Error! Reference source not found.**]	twin boom	5	span=1.7 m m=3.5 kg	TR	PID
Japan	Japan aerospace exploration agency [**Error! Reference source not found.**]	tandem wing	4	span = 2.5 m m= 43 kg	TW	PID (gain scheduling)
	Nagoya & Nan-zan universities & Japan aerospace exploration agency [**Error! Reference source not found.**]	tandem wing	4	span = 1.4 m m= 4.5 kg	TW	LQR
Turkey	Sabanci university [**Error! Reference source not found.**]	tandem wing	4	span = 1.2 m m= 4.5 kg	TW	PID
	Anadolu university [**Error! Reference source not found.**]	twin boom	3 co-axial	span = 1.5 m m= 12.5 kg	TR	PID
South Korea	Seol national university [**Error! Reference source not found.**]	mono-plane	2	span = 4 m m= 1000 kg	TR	LQR

model is presented for the TR/TW UAVs. Moreover, the classical stability methods applied to the TR/TW UAVs are investigated. Finally, different control strategies and control methods proposed for the attitude and altitude control are investigated.

NOMENCLATURE

A, B	State space matrices
C_T	blade thrust coefficient

C_Q	torque coefficient
e	error
g	gravity acceleration
I_{xx}, I_{yy}, I_{zz}	moments of inertia
j_r	rotor moment of inertia
j_t	moment of inertia of the rotor, engine, and pods/nacelles
J	objective function
k	thrust coefficient
k_a	control feedback gain matrix
k_p, k_i and k_d	proportional, integral and derivative control gains
L	engine position
L_λ	torque/force ratio
m	mass
$\boldsymbol{M}$	total thrust moment
MG	the gyroscopic torque
$\boldsymbol{MR}$	reaction moment
MT	torque generated by the thrust force
p, q, and r	angular rates
$\boldsymbol{P_R}$	the Riccati equation results
$\boldsymbol{Q}$, $\boldsymbol{R}$	LQR matrices
Q	reaction torque
T	thrust force
x	control state
$\boldsymbol{u}$	control command

Greek symbols

θ	pod/nacelle angle
ψ, θ, ϕ	Euler angels
ω	rotor angular speed

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