2015 International Conference on Unmanned Aircraft Systems (ICUAS)
Denver Marriott Tech Center
Denver, Colorado, USA, June 9-12, 2015

A Review on the Platform Design, Dynamic Modeling and Control of Hybrid UAVs

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***Abstract*— This article presents a review on the platform design, dynamic modeling and control of hybrid Unmanned Aerial Vehicles (UAVs). For now, miniature UAVs which have experienced a tremendous development are dominated by two main types, i.e., fixed-wing UAV and Vertical Take-Off and Landing (VTOL) UAV, each of which, however, has its own inherent limitations on such as flexibility, payload, axnd endurance. Enhanced popularity and interest are recently gained by a newer type of UAVs, named hybrid UAV that integrates the beneficial features of both conventional ones. In this paper, a technical overview of the recent advances of the hybrid UAV is presented. More specifically, the hybrid UAV's platform design together with the associated technical details and features are introduced first. Next, the work on hybrid UAV's flight dynamics modeling is then categorized and explained. As for the flight control system design for the hybrid UAV, several flight control strategies implemented are discussed and compared in terms of theory, linearity and implementation.**

I. Introduction

During the last two to three decades, Unmanned Aerial Vehicles (UAVs) have experienced a tremendous development. For now, miniature UAV platforms are dominated by two main types, i.e., fixed-wing conventional aircraft and Vertical Take-Off and Landing (VTOL) aircraft, and each type has its own inherent limitations on such as flexibility, payload, endurance, and etc. A new and promising trend is to develop fixed-wing VTOL UAV or the so-called Hybrid UAV, which can inherit the advantages of both and thus have the ability of vertical take-off and landing as well as high cruising speed and enhanced endurance. This enables the possibility of performing wider range of missions or same missions with better performance.

Indeed, integrating the advantages of fixed-wing and VTOL aircraft has long been a concern for many aerospace and aviation industries. Over the years, there have been several attempts to build manned hybrid aircraft such as Bell Boeing V-22 Osprey, Vertol VZ-2, Sikorsky X-wing, Convair XFY Pogo and Harrier GR7 as shown in Fig. 1(a) to 1(e), respectively [1][2][3][4][5]. Some of the attempts did succeed and the aircraft are still operating up to the moment such as V22-Osprey and Harrier GR7. Nevertheless, within the last four years, the concept invaded the UAV field as a number of research groups documented their pioneer work in literature and a couple of companies even commercialized the idea. It is believed that the hybrid UAVs will be having a bright future and will promptly dominate the miniature UAV market. Still in its infancy, there is a huge space for the miniature hybrid UAVs to become more mature, in terms of design philosophy, dynamics modeling, control, guidance, navigation, robustness, and etc.

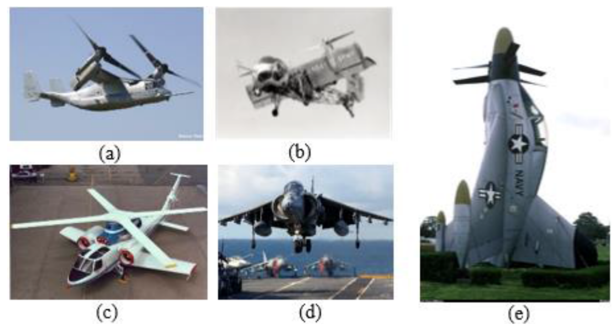

Fig. 1. Examples of Manned Hybrid Aircraft.

The main contribution of this paper is to present an overview on the recent advances of the hybrid UAVs, mainly concentrating on platform design, flight dynamics modeling and control methods. It is the authors desire that this work provides a fairly complete picture of the mini hybrid UAVs and serves as a baseline for further developments of this field.

II. Platform Design

Hybrid UAVs can be generally categorized into two main types: Convertiplanes and Tail-Sitters. Each of them can be further categorized into a few sub-types, depending on the transition mechanism and airframe configuration.

A. Convertiplane

A convertiplane is a type of hybrid aerial vehicle that takes off, cruises, hovers and lands with the aircrafts reference line remaining horizontal (i.e., the main body configuration does not change during flight). A variety of transition mechanisms are applied to achieve the conversion from vertical flight to horizontal flight and vice versa. Based on that, convertiplanes can be further categorized into four sub-types, including 1) Tilt-Rotors, 2) Tilt-Wings, 3) Rotor-Wings, and 4) Dual-Systems.

1) Tilt-Rotor: The primary feature of the Tilt-Rotor aerial vehicle is that the multiple rotors used are mounted on rotating shafts or nacelles. During transition, the rotors tilt gradually towards flight direction providing the aircraft forward speed until level flight mode is achieved. Some Tilt-Rotors might have fixed rotors always directed upwards and

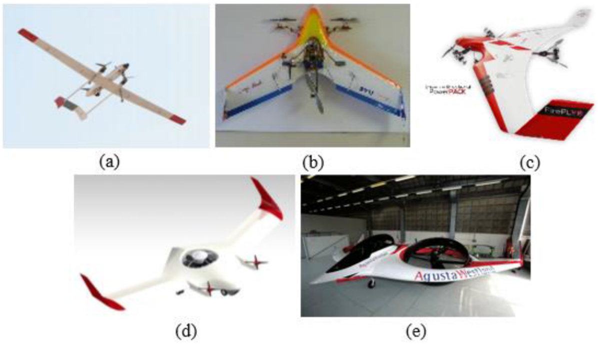

Fig. 2. Examples of Tilt-Rotor UAVs.

operate only during vertical flight to provide extra lift for takeoff, landing and hovering. An example of manned Tilt-Rotor is Bell Boeing V-22 Osprey shown in Fig. 1(a) which has two tilting jet engines to perform the transition [1]. As in V-22 Osprey, Tilt-Rotors usually have their engines mounted at the wing tips forcing shorter wing span and thicker airfoil. This results in lower aspect ratio and increased drag respectively causing poor aerodynamic performance. On the other hand, the shafts and nacelles are only required to rotate rotors instead of wings or other heavy structures which saves power and weight. Moreover, due to their controllability and stability in vertical flight when compared to other hybrid UAVs, Tilt-Rotors are actively researched in academia and there exist several vehicles implementing the idea such as IAI Panther [6][7], TURAC [8][9] [10], Orange Hawk [11], FireFLY6 [12] and AgustaWestland Project Zero [13] shown in Fig. 2(a) to 2(e), respectively.

The most dominant design for Tilt-Rotors is the flying wing configuration as this was utilized in most reviewed works. However, a conventional airplane configuration was also implemented in IAI Panther and Mini Panther. The conventional design is easier to build, analyze and manufacture whereas the flying wing design has a larger wing area to generate lift and therefore better payload capacity. Regarding the propulsion system characteristics, a tricopter configuration is the most common one implied in both configurations which is mainly due to the cost benefit over other multi-copters and the simplicity of the forward flight control system. Also, the tricopter configuration makes the center of gravity of the airplane to be near the center of lift of the tricopter configuration which further enhances stability and controllability [11]. All the works reviewed utilized tricopter configuration except for AgustaWestland Project Zero [13] which has only two tilting rotors that are located in large holes in an otherwise conventional flying wing aircraft. However, few technical details and characteristics for this specific aircraft were found in [13]. In the tricopter design, the differential thrust resulting from the rear motor causing unstable motion can be resolved using a rear coaxial rotor as in TURAC [8] [9] [10] and Orange Hawk [11] or by using all three coaxial rotors as in FireFLY6 [12]. However, IAI Panther with the conventional configuration does not utilize any coaxial rotor because the differential thrust can be canceled using rudder deflections [6] [7]. It is also worthy to note that, although a tilt duct VTOL UAV concept is presented in [14], no actual platform was built by the authors.

2) Tilt-Wing: A Tilt-Wing has a similar concept to Tilt-Rotor except that the assembly of the wing tilts instead of the rotors only. During takeoff, landing and hovering, the wings will be directed upwards which makes the aircraft more vulnerable to cross winds. Consequently, the Tilt-Wing requires complicated control mechanisms and higher use of available power to maintain stability during vertical flight. Furthermore, landing on moving deck environments is relatively more difficult compared to Tilt-Rotors. However, since rotors are fixed to wings, this allows various design options for the wing geometry and therefore enhance the aerodynamic performance of the aircraft. Vertol VZ-2 (Fig. 1b) was a manned Tilt-Wing aircraft built in 1957 by Boeing Vertol, completed several successful flights and was retired in 1965 [2]. Like Tilt-Rotors, Tilt-Wings are also researched actively and there are many examples applying the idea such as AVIGLE (Fig. 3(a)) [15][16][17], Sabanci University UAV (SUAVI) (Fig. 3(b)) [18] [19], AT-10 Responder (Fig. 3(c)) [6], Quad Tilt Wing (QTW) VTOL UAV [20], and HARVee [21].

Due to the requirement of a wing tilting mechanism, conventional configuration design is essential for Tilt-Wings and was utilized in most reviewed works with single main wing favored in AT-10 and AVIGLE and a tandem wing design favored in SUAVI and QTW VTOL UAV. It was found that most of the works implementing the quad Tilt-Wing hybrid UAVs have all the rotors tilt to make the transition to forward flight. Such configuration might not be optimal because two tilting mechanisms will have to equipped, one for the front wing and another for the rear wing, which increases weight as well as the complexity of the design. Moreover, the rear rotors do not contribute much in increasing the forward thrust in level flight, instead the increased drag might as well outweighs the extra forward thrust provided. Therefore, an improvement would be to let the front wing tilt and keep the rear rotors directed upwards (only rotors, not wings) to operate only during vertical flight. On the other hand, the controllability and stability of the single wing Tilt-Wings during vertical flight is somehow questionable because any perturbation that causes a sudden change in the angle of attack will not be countered by any control surface or differential thrust actuation.

3) Rotor-Wing: A Rotor-Wing (or Stop-Rotor) is another type of Convertiplane aircrafts where rotary wings spin to provide lift during vertical flight and stop to act like a fixed wing during horizontal flight. Sikorsky X-wing (Fig. 1c) is a manned aircraft implementing the Rotor-Wing concept but the program was cancelled in 1988 because funds ran out after only three flights [5] [22]. Boeing X-50 Dragon Fly (Fig. 3(d)) developed by DARPA is another Rotor-Wing UAV but was also withdrawn because of some aerodynamic problems [23]. The way the Rotor-Wings work makes the possible design configurations minimal which is why most

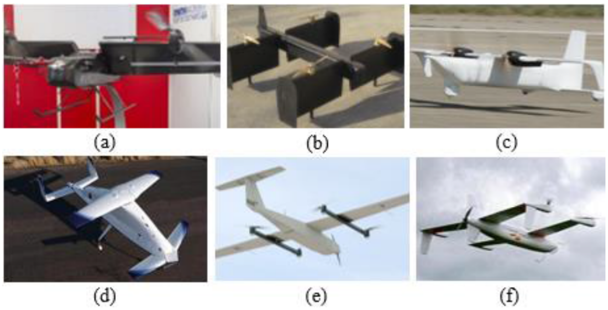

Fig. 3. Examples of Convertiplane UAVs.

of the Rotor-Wing works show similar design configuration which is close to a helicopter. However, a different design configuration in which the whole body tilts during transition was detailed in [24] and [25] but no full envelope powered flight test was conducted. Therefore, the implementation of such design might be suspicious due to the lack of historical successes.

4) Dual-Systems: Another type of Convertiplanes which could be referred to as Dual-System implements multiple rotors always directed upwards for vertical flight and another separate tractor or pusher for level flight. Many possible design configurations are possible for this specific type of UAV but due to the huge weight of the aircraft, quad rotors are the most common. The concept of Dual-Systems is very simple to apply in terms of design, controllability, stability and modeling because the two flight modes could be analyzed separately. However, during horizontal flight, the multiple lifting rotors used for vertical flight are not in operation and add extra weight to the aircraft which results in requiring more power from the tractor or pusher. From the survey conducted, it was found that the idea is employed in Arcturus JUMP (Fig. 3(e)) developed by Arcturus UAV [26] [27] and in Airbus Quadcruiser, shown in Fig. 3(f) [28] [29]. Both designs are quadcopters with a tractor in Arcturus JUMP and a pusher in Quadcruiser. A proof-of-concept 1.50 m wingspan Airbus Quadcruiser successfully performed its maiden flight to test the aircraft's stability, controllability and handling while hovering and low speed cruising [29].

B. Tail-sitter

A Tail-sitter is an aircraft that takes off and lands vertically on its tail and the whole aircraft tilts forward using differential thrust or control surfaces to achieve horizontal flight. This concept could also be denoted as Tilt-Plane since the whole plane tilts to achieve level flight. Due to its ability to make the transition without the need of extra actuators, this concept is mechanically simple and saves a huge amount of weight when compared to Convertiplanes. Moreover, since tail-sitters land on their tails, they require relatively stronger tails to be able to withstand landing impacts. In the last 50 years, Tail-sitters have been analyzed extensively and there were several trials to build manned ones such as Convair XFY Pogo (Fig. 1(e)) and Lockheed XF-V1. However, due to the difficulty of control during transition and landing, none of the projects was successful [4][30]. Tail-sitters can be classified into three types as follows.

1) Ducted-Fan UAVs: Ducted-Fan VTOL UAV is a type of tail-sitter UAVs where a large duct fan usually coaxial forms the main body of the aircraft and several control surfaces are installed for stability, control and transition. The complexity of the control and stability strategies, payload capacity, range, endurance and cruising speed are some drawbacks for this type of design. Several works presented this concept in literature and it was found that this type of UAVs was mainly used for military purposes. RMIT University ducted-fan aimed to aid law enforcement activities [31] and Vertical Bat developed by Brigham Young University partnering with MLB Company [32] are some examples but no prototype was tested in the full flight envelope. Bertin Hovereye and Selex Galileo Asio ((Fig. 4(a)) are other examples that have been marketed since 2005 and 2008 [6].

2) CSTTs and DTTTs: Apart from Ducted-fans, other tail-sitters can be classified into those performing the transition using large control surfaces and those performing that using differential thrust from their multiple rotors. The former can be referred to as Control Surface Transitioning Tail-sitters (CSTT) and the latter as Differential Thrust Transitioning Tail-sitters (DTTT). Both require complicated control mechanisms and higher use of available power to maintain stability during vertical flight because they are more susceptible to cross winds which also makes landing on moving decks difficult. CSTTs usually require only a single or sometimes twin rotors. In contrast, DTTTs require multiple rotors to enable providing sufficient differential thrust to make transitions which results in reduced efficiency in horizontal flight. However, in terms of stability, DTTTs are far more stable in takeoff, hovering, and landing and require simpler control strategies than CSTTs. ITU Tail-sitter with a folding propeller system located on its nose that operates during vertical flight and an electric ducted fan located in the tail that operates during horizontal flight with the propeller blades folded to reduce drag [33] and T-Wing ((Fig. 4(b)) with canard wing and tandem rotors developed by Stone and his colleagues and used for defense and civilian applications [30] [34] are some examples of CSTTs. As mentioned earlier, these tailsitters are based on a fixed wing conventional airplane design configuration and their attitude is controlled by the control surfaces which results in high stability during horizontal flight but low stability and controllability during vertical flight. VertiKUL ((Fig. 4(c)) [35], ATMOS ((Fig. 4(d)) [36] and Quadshot [37] [38] are examples of DTTTs. All three have four rotors to provide differential thrust to make the transition to horizontal flight and back. However, ATMOS and Quadshot have control surfaces or tilting rotors for control during horizontal flight unlike VertiKUL which depends solely on differential thrust.

3) Reconfigurable wings: Reconfigurable wings are another type of Tail-sitters where the wings extend during horizontal flight and retract during vertical flight. This concept is based on the idea that more lift at lower speed is desired in cruising and therefore the wings extend to

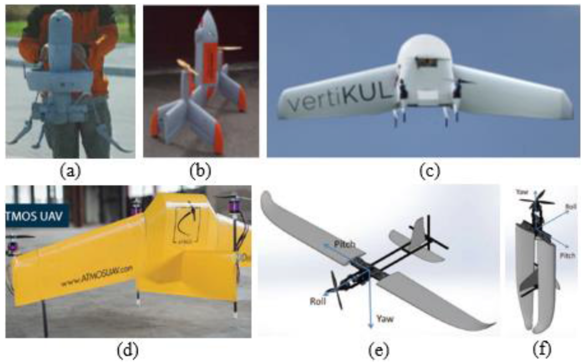

Fig. 4. Examples of Tail-sitter UAVs.

TABLE I
REPRESENTATIVE MODELING RESEARCH WORK.

Aircraft Type	Representative Modeling Work
Tilt-Rotor	[10], [41], [42], [43], [44], [45], [46], [47], [48], [49]
Tilt-Wing	[15], [19], [20], [50], [51]
CSTT	[32], [52], [53], [54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65]
DTTT	[35]

provide larger wing span. Moreover, the wings retract during vertical flight to minimize the effect of wind disturbance and ease maneuverability. The idea is applied in U-Lion ((Fig. 4(e and f)), an aircraft developed by the National University of Singapore in 2014 in which a four bar linkage was designed to make the reconfiguration which in turn minimizes platform weight and keeps the structure simple [39]. [40] also presents the dynamics model of HADA which performs the configuration by unfolding the wings beneath the fuselage. However, no flight experiment was held yet.

III. Flight Dynamics Modeling

A reliable model that can accurately capture the flight dynamics over the flight envelope of interest is critically important for developing the autonomous flight control system. For the hybrid UAVs, the flight envelope can be generally divided into three modes, namely, vertical flight mode, transition mode, and level flight mode. As a result, developing a reliable flight dynamics model becomes more challenging compared with any conventional aircraft. In the recent literature, a number of flight modeling works for the hybrid UAVs have been documented. The representative work are listed in Table I for convenient reference. In what follows of this section, we provide a brief overview of the flight dynamics modeling work via two aspects: 1) model structure of the hybrid UAV dynamics, and 2) representative modeling work.

A. Model Structure

Our survey indicates that the flight dynamics of the hybrid UAVs can be uniformly depicted in Fig. 5, in which six

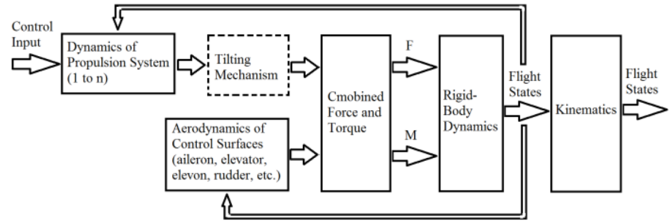

Fig. 5. Block diagram of the flight dynamics model of the hybrid aerial vehicles.

key components are contained. Detailed explanations of these components are given as follows.

First, as the hybrid UAVs are only capable of operating in a relatively confined area, two main Cartesian coordinate systems, i.e., local coordinate (mainly north-east-down) and body-frame coordinate, are generally sufficient for describing the kinematic and dynamic motions of hybrid aerial vehicles. For the level flight mode, the stability coordinate is additionally taking into account the wind effect. The definitions of all these coordinate systems can be easily found in variety of textbooks (see, e.g., [66] and [67]).

With the coordinate systems defined, the kinematics, i.e., orientation and translation relations w.r.t. the operational environment, of hybrid aerial vehicles can be determined. The former can be expressed via two formulations, namely, Euler angles and Quaternion, depending on the specific type of the hybrid vehicles as well as the specified missions. Detailed explanations of both expressions can be found in textbooks such as [66]. Generally, Euler angle representation dominates the convertiplanes and single mode (e.g., hover or cruise with constant speed) of partial tail-sitters because the fuselage does not change with large amplitude. On the other hand, the tail-sitters operating over full flight envelope commonly adopt quaternion representations because the transition between hover and level flight modes leads to approximately 90-degree pitch angle change which has a high chance to raise the singularity of Euler-angle representation. Representative implementation of quaternion expression on hybrid aerial vehicles will be addressed later in Section III-B.

The second component to be addressed is the rigid body dynamics which concerns the translational and rotational equations of the hybrid vehicles. Generally, Newton-Euler and Euler-Lagrange formulations, which involve the combined forces $\mathbf{F}$ and moments $\mathbf{M}$, are employed to achieve this aim. It should be noted that, corresponding to the different orientation expressions (i.e., Euler angle or Quaternion), the expressions of $\mathbf{F}$ and $\mathbf{M}$ differ accordingly. On the other hand, Euler-Lagrange approach does not require a particular identification of the coordinate system and makes use of the conservation of energy to derive the equations of motion instead. Thus, the translational and rotational equations of motions could be derived from Euler-Lagrange equation which involves the generalized coordinates of the system $\mathbf{q}$ and the combined forces and moments $\mathbf{F}$ w.r.t. the C.G of a hybrid UAV. According to our survey, only few research works (i.e., [58], [59], [60]) adopt this formulation without highlighting the particular reason for their selection.

Aerodynamic forces (lift and/or drag) and the associated moments are constantly generated by the various control surfaces and the fuselage of hybrid aerial vehicles in operation. Compared with the conventional fixed-wing or rotary aircrafts, hybrid vehicles dynamic modeling is more complex as the aerodynamic features of the aforementioned components in different flight conditions or envelopes should be taken into account comprehensively. A prevalent method dominantly adopted by the documented works is to express the aerodynamic forces and moments using dimensionless coefficients which are determined via practical flight experimental data as in [62], wind tunnel experimental data as in [18], [19], [49] or CFD results as in [10], [48], [52].

Regarding the dynamics of the propulsion system, two coupled sub components (i.e., the propeller aerodynamics and the motor dynamics) are involved. For the former, the majority of the modeling works on hybrid aerial vehicles adopt highly simplified dynamics model which involves very fundamental aerodynamic analysis. For instance, in [62], [63] only quasi-steady equations are utilized to model the aerodynamic forces and moments. For the latter, according to our survey, no research work has particularly paid attention to the motor dynamics. Thus, the response of propulsion systems to the actuator input is assumed instantaneous.

Finally, the titling mechanism uniquely belongs to convertiplane aircraft. Thus, in Fig. 5 it is put in a dashed block. Similar to the propeller aerodynamics part, the current hybrid aerial vehicle modeling works adopt highly simplified models to account for the titling motion of the propulsion systems. For instance, a common method has been documented in [41], [43], [68] in which two instantaneous shaft tilting angles, α_L and α_R, are defined for the rotation of the left and right front propulsion systems and the tilting motion is reflected by a rotation matrix based on tilting angles defined.

B. Representative Modeling Work

Table I provides a complete list of the documentations related to the dynamics modeling of hybrid aerial vehicles following the categorization method introduced in Section II. According to review conducted, no systematic modeling work on 1) rotor/wing, 2) dual system, and 3) reconfigurable hybrid aircrafts have been documented in the literature, thus in Table I only the remaining four sub-categories are listed. The focus of this section is to analyze some unique features of the modeling work given in Table I.

Starting with the tilt-rotor hybrid aerial vehicles, most of the works (e.g., [41], [42], [43], [68] for bi-rotor convertiplane, [44], [49] for tri-rotor convertiplane, and [46] for quad-rotor convertiplane) employ highly simplified motor dynamics and titling mechanisms to minimize the complexity of the overall model. An exception that can be treated as a benchmark is the modeling work documented in [49], in which a fairly complete flight dynamics model for a bi-rotor convertiplane has been proposed. The propulsion system is modelled in depth by introducing additional coordinate systems (such as Nacelle axis system, hub-axis system, and blade axis system) and including the flapping motion of the propellers. Furthermore, the aerodynamics of the control surfaces and fuselage are carefully determined via variety of wind-tunnel experiments. Model validation in both time- and frequency-domains is presented and the results indicate the relative high fidelity of the proposed model. In another work documented in [47], the essential role of the wind tunnel usage in determining various aerodynamic coefficients is clearly demonstrated via both large amount of data and model validation results. Instead of using the experimental results collected in the wind-tunnel, the authors of [10], [48] have explored the possibility of using CFD to determine the aerodynamic coefficients for a 0.15-scale MV-22 bi-rotor convertiplane and a custom-built tri-rotor convertiplane TURAC respectively. Partial validation results have also been presented in [48] to prove the efficiency of the CFD-based estimation.

Compared with tilt-rotor hybrid aircraft, less interest in modeling tilt-wing hybrid aircraft has been observed. Furthermore, [19], [50], [51] are based on an identical custom-built miniature quad tilt-wing hybrid UAV and only one modeling work on twin tilt-wing hybrid aircraft [15] has been found. All the proposed models adopt Euler-angle expression, Newton-Euler formulation, and highly simplified motor dynamics and tilting mechanisms as mentioned in Section III.A. One distinguished feature shared by all the documented work on tilt-wing hybrid aircraft listed in Table I is that wind tunnels are uniformly used to determine the aerodynamic coefficients involved in the developed models.

A number of research works on CSTTs, which is either single-rotor- or bi-rotor-based, have been carried out and documented in literature. Part of them only focuses on vertical flight mode and attitude stabilization. For instance, in [58], [59], [60], [61], two types of bi-rotor CSTTs have been developed and Euler-Lagrange formulation is adopted in modeling their dynamics. As attitude stabilization in hover model is the focus, Euler angle instead of quaternion is used for more straightforward attitude representation. The rest of the modeling works for CSTTs address the dynamics model covering the full envelope, that is, hover, transition, and level flight. More specifically, [32], [52], [54], [56], [56], [63], [65] concentrate on the modeling of a single-rotor hybrid aerial vehicles. All these works adopt 1) quaternion formulation for avoiding the singularity in pitch angle expression and 2) simple expression for propulsion systems. In order to enhance the accuracy of the proposed model, additional effort has been made in some documented works, mainly on motor dynamics and aerodynamic coefficients determination. For instance, in [52], ducted-fan design code is employed to account for the unique duct fan feature of the custom-made CSTT developed at the KAIST and Navier-Stokes solver integrated in FLUENT toolkit is used to determine aerodynamic control coefficients. In another two documentations [54], [65] based on a miniature single-rotor hybrid UAV developed at BYU, aerodynamic coefficients are determined by maximally matching the flight test data collected in experiments. Furthermore, [54] also addresses a technique of modeling the angular dynamics as a combination of one bias acceleration term and one actuator-based input term which aims at reducing the computational load of physical parameter estimation. However, except the work documented in [56] which provides identification results for the longitudinal motions, none of the aforementioned works have included results on model fidelity validation. On the other hand, research works documented in [55], [57], [62], [64] focus on the modeling of bi-rotor hybrid aerial vehicles. Quaternion expression is dominantly adopted and certain unique features such as variable pitch propeller [69] and motor dynamics [57], [64] are additionally considered aiming at covering the key dynamic features. Validation results and analysis are again rarely addressed with the exception of [62], in which a comparison between the model responses and actual experimental data is conducted and non-ignorable deviations have been observed for all channels which indicates that the model accuracy can be further enhanced.

For DTTT, very rare work on dynamical modeling has been documented in the literature, as DTTT-based UAV is still a relatively new topic to the academia and very less systematic research has yet been conducted. One representative work on DTTT dynamics modeling is presented in [35], in which a quaternion-based Newton-Euler formulation model is proposed for the custom-made quadcopter tail-sitter named VertiKUL. However, no detailed description of the aerodynamic coefficients determination and propeller dynamics is contained, which makes the validation of model fidelity difficult.

IV. Hybrid UAV Flight Control Techniques

The core of the control system depends on the derived dynamics model. As seen in Section III of the paper, the equations of motion are highly complicated and nonlinear. Particularly speaking, the dynamics of the hybrid UAVs can be inherently unstable because it inherits the operation of a fixed-wing and VTOL UAVs. Even if horizontal and vertical modes were analyzed separately, the transition phase remains a critical part of the control system due to the multiple nonlinearities in the model. That is why feedback control is essential which ensures more accurate and quicker response to meet the desired reference command.

A. Flight Control System Theory

Flight control system theory deals with the synthesis and analysis of the logic behind which the flight control system is designed. There are two strategies for that, namely, the classical control theory and the modern control theory. The former, also known as successive loop closure, considers the decomposition of the states derived from the model to form successive control loops such that the output of the innermost loop (low-level) is linked to the actuators of the UAV [69], [70], [71]. It is important to note that the low-level controllers (innermost) should have a quicker response than the higher ones. For a particular case of hybrid UAVs, the decomposition of the states could result in a low-level attitude controller directly linked to the control surfaces of the UAV. It gets the reference commands from a mid-level velocity controller which gets the reference commands from the high-level position controller [70]. This control theory was implemented in Ducted-Fan Tail-sitters as detailed in [32], [52], [72], [73], Tilt-Rotors and Tilt-Wings as detailed in [18], [19], [14], [74], [75] and other tail-sitters, mainly for hovering, as detailed in [35], [56], [76].

For the classical control theory, the reference commands are saturated through the outer loops prior to reaching the innermost loop which mean that this approach is it results in good handling of the flight variables and actuator inputs. Moreover, every single control loop design is simple as it involves few variables and sometimes even single variable. However, the difficulty arises when decomposing and separating the variables for the controllers and also when linking the controllers together especially in terms of determining whether the inner loops are faster than the outer ones. The design algorithms of this classical approach depend on one loop at a time and are very effective for Single-Input Single-Output (SISO) systems. However, complex systems such as hybrid UAVs are Multi-Input Multi-Output (MIMO) systems. Therefore, the success of the classical control system when applied to hybrid UAVs is not guaranteed because it comprises multiple actuators such as elevators, rudders, ailerons, motors and tilting rotors and multiple sensors for attitude, velocity, and position [66] [69] [70] [77].

The second approach, known as modern control, is to design a control system that handles the full dynamics of the UAV. The stability and control specifications can be expressed in terms of a system of first-order differential equations which results in matrix equations that can be solved using commercially available computer software to compute the control gains simultaneously [66] [69] [77]. This means that all the feedback loops are closed at the same time. Therefore, a better performance for MIMO systems is achieved compared to the classical approach in which the control gains are selected individually. This quick and direct modern control approach can be utilized for time varying and time invariant systems, whereas, the classical approach is mainly for time invariant systems [78]. Also, there are many optimal control techniques that could be applied in the modern control theory to improve the controllability and stability of the UAV [72]. However, not all states correspond directly to a single actuator as was the case for the first approach. Therefore, it is difficult to handle actuator saturation [70]. However, modern control theory is also popular in hybrid UAVs as it was employed in Tilt-rotors as described in [41], [42], [68], [79], Tail-sitters as detailed in [54], [57], [76], [80] and Ducted-Fans as detailed in [52], [73], [14].

B. Control Laws Classification

Apart from that, flight control systems can be classified into linear and nonlinear based on the dynamics of the hybrid UAV model. As previously mentioned, hybrid UAVs models are nonlinear. However, those models are commonly linearized using relative equilibrium conditions. Although linear controllers are simple, easy to implement, reduce the computational effort and minimize the design time but their performance degrade when operating away from the local equilibrium point or while performing agile maneuvers. This is very critical during the transition flight for the case of hybrid UAVs because changing from vertical flight mode to horizontal flight mode and vice versa results in operation far away from the relative equilibrium condition. That is the reason behind which some current hybrid UAVs implement nonlinear controllers such as [41], [42], [52], [54], [57], [68], [73], [75], [76], [79], [81], [82] or three separate linear controllers, one for the horizontal mode, one for the vertical mode and one for the transition such as [18], [19], [32], [76], [82], [83].

Nonlinear controllers are extensively studied and investigated theoretically for application in hybrid UAVs but in terms of implementation, linear controllers are far more popular. However, nonlinear controllers operate in a much wider profile than linear ones which are restricted within a specific operating region. Also, they consider the full and true dynamics of the UAV and account for the nonlinear aerodynamic and kinematic effects, actuator saturations and rate limitations [84].

The classical PID controller and the Linear Quadratic Regulator (LQR) are the most common linear control laws applied in hybrid UAVs while the back-stepping, gain-scheduling and dynamic inversion are the common nonlinear laws. Table II shows a summary of the control laws with their advantages, disadvantages and applications.

1) Proportional-Integral-Derivative (PID) Controller: PID controllers are very common in the UAV field. [18], [19], [32], [35], [43], [44], [45], [52], [53], [55], [58], [72], [74], [76], [81], [82], [83], [85] have applied PID controllers in their hybrid UAVs. The PID control law consists of a proportional, integral and derivative elements. When utilizing the PID control law algorithm, it is essential to decide which of these three elements are to be used since each has particular effect on the control signal as given in [69], [70], [72]. Generally, for the hybrid UAVs, three main controllers are implemented: Proportional-Integral-Derivative (PID), Proportional-Integral (PI) and Proportional (P). The controller gain values are determined by empirical tuning until some preconceived ideal response of the system is achieved. Those gains are sometimes estimated theoretically using Ziegler and Nichols method to reduce the amount of tuning [69]. It is important to note that the PID controllers can be implemented in the hybrid UAVs for altitude control, attitude angles control and velocity control by just changing the control gains accordingly. Since PID control strategy only requires appropriate adjustment of the control gains, it serves as a concrete starting design point for many hybrid UAVs as it does not require extensive knowledge of the model. However, PID controller is applicable only for SISO systems, therefore it does not account for the cross coupling effects present in UAVs. For such cases, multiple independent PID controllers are usually utilized in the hybrid UAVs such as in [35], [43], [52], [72], [55], [73], [76], [80], [82], [85].

2) Linear Quadratic Regulator (LQR) Controller: LQR controllers goal is to find a control input of the form, that minimizes the performance index, $\Im$, which is given by

$$\Im = \frac{1}{2}\int_{t_0}^{t_f} [\mathbf{x}^T(t)Q\mathbf{x}(t) + \mathbf{u}^T(t)R\mathbf{u}(t)]dt \tag{1}$$

subject to

$$\dot{\mathbf{x}}(t) = A\mathbf{x}(t) + B\mathbf{u} \tag{2}$$

where $\mathbf{x}(t) \in \mathbb{R}^n$ is the $(n1)$ state vector, $\mathbf{u}(t) \in \mathbb{R}^m$ is the $(m1)$ control input vector, A is the system matrix, B is the control influence matrix, and R and Q are real positive weighting matrices. The feedback control input is of the form

$$\mathbf{u}(t) = -R^{-1}(t)B^T(t)P(t)\mathbf{x}(t) \tag{3}$$

where $P(t)$ is known as the Riccati matrix. The only design freedom in this approach is choosing the weighting matrices. Brysons Rule is usually used to select those weighting matrices based on normalizing the signals [70] [88]. Therefore, LQR easily handles complex dynamic systems and multiple actuators [70]. It is robust with respect to process uncertainty, asymptotically stable given that the system is at least controllable and has very large stability margins to errors in the loop (gain margin of infinity for gain increase and -6 dB for gain decrease and phase margin of 60 for each control signal) [70] [89]. On the other hand, LQR requires access to the full state which is not always possible [70]. Due to their robustness, LQR controllers are extremely suitable for hybrid UAV flight control systems and they are implemented in [56], [57], [14], [76], [86].

3) Backstepping: In Hybrid UAVs, there are several parameters that irregularly change especially during the transition between horizontal and vertical flight modes. Therefore, a controller that handles these parameters changes might be necessary. One example is the back-stepping controller which is based on Lyapunov stability and provides a powerful recursive approach for nonlinear systems that can be transformed into triangular form. The key idea is to let certain states act as virtual controls of others. For a system

$$\dot{x} = f_0(x) + g_0(x)z_1 \tag{4}$$

$$\dot{z}_i = 8f_i(z_1, z_2, \ldots, z_n) + g_i(z_1, z_2, \ldots, z_n)z_{i+1} \tag{5}$$

where z represent the general coordinates of the aircraft for $i = 1, \ldots, n$ and $z_{n+1} = u$ which is the control input. The goal is to design a feedback control law to stabilize z. The detailed back-stepping procedure is described in [84], [90], [91]. This method is beneficial for the hybrid UAVs since it takes into consideration all the states of the system and accounts for the nonlinearities present in the model. From the literature review conducted, it was observed that back-stepping method was mostly coupled with using Euler-Lagrange approach for the dynamic modeling as in [42], [54], [68], [79], [87].

TABLE II
CONTROL LAWS CLASSIFICATION OF THE HYBRID UAVS.

Control Law	Advantages	Disadvantages	Applications
PID	Easy implantation, very common control scheme design in real life applications, does not require the knowledge of the UAV model	Poor robust ability compared with the robust controller when the system encounters to multiple challenges, not optimal solution	[18], [19], [32], [35], [43], [44], [45], [52], [53], [55], [58], [72], [74], [76], [81], [82], [83], [85]
LQR	Handles complex dynamic systems and multiple actuators, robust w.r.t process uncertainty, asymptotically stable for controllable systems, very large stability margins to errors in the loop	Requires access to the full state which is not always possible	[56], [57], [14] [76], [86]
Backstepping	Very robust for external disturbances and irregular parameter uncertainties, deals with all the states of the system and accounts for the nonlinearities	Not optimal, Time inefficient	[42], [54], [68], [79], [87]
Gain-Scheduling	Allows easy understanding and simple implementation of the control laws over the full flight envelope	Time inefficient	[52], [73], [76], [53], [66], [82]
NDI	Closed loops can be easily tuned	Requires a precise knowledge of the aerodynamic coefficients	[41], [52], [73], [81]

4) Gain-Scheduling: As previously mentioned, the UAV dynamics could be linearized by applying relative equilibrium conditions around a steady state operating point and then applying linear controllers such as PID or LQR. However, the controller performance degrades effectively when deviating away from that point. Therefore, a prevailing control design approach, known as gain-scheduling, is to divide the flight envelope into a finite number of small partitions. For each small region, the UAV dynamics is linearized around a corresponding steady state operating point. Then, linear controllers such as PID or LQR each having different consistent control gain values could be applied for each small region effectively. Therefore, this allows easy understanding and simple implementation of the control laws over the full flight envelope. However, since for each small region, a linear controller has to be designed, this method might be tedious and time consuming [70][91]. For the hybrid UAVs, Gain-scheduling was mainly utilized to enhance the control during transition as in [52], [57], [66], [73], [76], [82].

5) Nonlinear Dynamic Inversion (NDI): The dynamic model of a SISO system can be written in companion form as

$$\begin{bmatrix} \dot{x}_1 \\ \vdots \\ \dot{x}_{n-1} \\ \dot{x}_n \end{bmatrix} = \begin{bmatrix} x_2 \\ \vdots \\ x_n \\ b(\mathbf{x}) \end{bmatrix} + \begin{bmatrix} 0 \\ \vdots \\ 0 \\ a(\mathbf{x}) \end{bmatrix} u \tag{6}$$

In this form, $b(\mathbf{x})$and $a(\mathbf{x})$ are functions of the state vector $\mathbf{x}$ which linearize the *nth* state which is the only state affected by the input. All other elements of the state vector derivative are linear. In a similar manner to the back-stepping approach, a virtual control input could be defined as

$$v = b(\mathbf{x}) + a(\mathbf{x})u \tag{7}$$

which is a linear relation and therefore can be used to control the system easily. Here, a SISO system is considered for simplicity, however, the concept could be generalized for MIMO systems as detailed in [92]. An example of this approach is given in fig 8 which illustrates how the NDI linearizes the inner loop making the dashed box a linear system [91].

Unlike Gain-scheduling, a single controller is required for the full flight envelope. Another advantage of this method is that closed loops can be easily tuned as in PID controllers. However, to apply this method a precise knowledge of the aerodynamic coefficients is necessary [91]. From the review, it was noted that NDI was as common and effective as gain scheduling. It was implemented and tested in many hybrid UAVs such as in [41], [52], [73], [81].

6) Other Control Strategies: There are several other controlling methods implemented in the hybrid UAVs. [44], [54], [81] apply adaptive control techniques which account for the nonlinearities and uncertainties present in the model. J.A. Guerrero et al. [93] presents a robust control design based in sliding mode of a mini birotor tail-sitter for the hovering mode. The work in [94] shows the control of hovering flight and vertical landing using optical flow. Fault tolerant flight control system for a tilt-rotor UAV was discussed by S. Park et al. in [86]. Moreover, other control strategies based on Lyapunov stability concepts can be found in [46], [58], [59], [60], [61], [87].

V. CONCLUSION

A technical overview of the hybrid UAVs has been provided in this paper. The common platform design types and technical details are introduced first. The modeling is then explained in terms of model structure, and representative work on the hybrid UAV dynamics modeling is comprehensively addressed. Representative flight control strategies implemented in the hybrid UAVs are then discussed and compared in terms of theory, linearity and implementation. The review presented in this paper is expected to be informative to the researchers who are interested in the promising hybrid UAV development.

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