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# A survey of hybrid Unmanned Aerial Vehicles

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ABSTRACT

This article presents a comprehensive overview on the recent advances of miniature hybrid Unmanned Aerial Vehicles (UAVs). For now, two conventional types, i.e., fixed-wing UAV and Vertical Takeoff and Landing (VTOL) UAV, dominate the miniature UAVs. Each type has its own inherent limitations on flexibility, payload, flight range, cruising speed, takeoff and landing requirements and endurance. Enhanced popularity and interest are recently gained by the newer type, named hybrid UAV, that integrates the beneficial features of both conventional ones. In this survey paper, a systematic categorization method for the hybrid UAV's platform designs is introduced, first presenting the technical features and representative examples. Next, the hybrid UAV's flight dynamics model and flight control strategies are explained addressing several representative modeling and control work. In addition, key observations, existing challenges and conclusive remarks based on the conducted review are discussed accordingly.

## 1. Introduction

During the last several decades, Unmanned Aerial Vehicles (UAVs) have experienced a tremendous development and gained fast-growing popularity worldwide. Nowadays, UAVs are extensively used in various critical military and defence applications such as reconnaissance, surveillance, and security reinforcement. According to [1,2], the total sector sales of the global military UAV market is expected to increase by more than 60% between 2011 and 2020.

Nevertheless, UAVs applications are not limited to military and defence: the market of civilian UAVs has recently grown rapidly, covering a wide range of areas such as traffic surveillance, disaster management, infrastructure inspection, law enforcement, and vegetarian monitoring. Many studies (see, e.g. [1,3,4]) predict that there is a high chance that the utilization of civilian UAVs will eventually dwarf the military demand in the near future. The promising future and unlimited potential of UAVs have also ignited strong interest in academia: numerous research works have been carried out on UAVs that are either commercially available or customized and a large amount of algorithms and techniques has been developed aiming at enhancing the UAVs' intelligence in guidance, navigation, and control.

UAV platforms are currently dominated by two types: fixed-wing UAV and rotorcraft UAV. Each type has advantages but exhibits inherent limitations. The fixed-wing UAV generally advances in cruising speed, payload capacity, flight range, and endurance. However, it requires runways or launching/recovery equipment with special design for reliable takeoff and landing. In addition, it is not applicable to missions requiring ultra low flight speed or confined environment. On the other hand, the rotorcraft UAV has much looser requirements on takeoff and landing spots. It also features the unique hovering capability, which brings much enhanced versatility in executing a mission. However, the speed and endurance limit significantly trunks the rotorcraft UAV's capability in missions requiring wide-range coverage or long endurance. As such, a newly emerging and promising trend of UAV design, particularly for miniature UAVs, is to design an aerial system that integrates the advantages of both, operates in a wider envelope (i.e., vertical takeoff, transition, cruise, and vertical landing), and contributes to a much broader range of applications. Inspired by such demanding need, the hybrid UAV, or fixed-wing Vertical Takeoff and Landing (VTOL) UAV in other words, is born.

Indeed, integrating the advantages of fixed-wing and rotary aircraft has long been a concern for the aerospace and aviation industries. Over the years, there have been quite a number of attempts to build manned hybrid aircraft. Several representative examples are shown in Fig. 1,

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**List of acronyms**

| | |
|---|---|
| UAV | Unmanned Aerial Vehicle |
| VTOL | Vertical Takeoff and Landing |
| LTV | Ling-Temco-Vought |
| RC | Radio-Controlled |
| GL | Greased Lightning |
| QTW | Quad Tilt Wing |
| MTT | Mono Thrust Transitioning |
| CTT | Collective Thrust Transitioning |
| DTT | Differential Thrust Transitioning |
| FDCL | Flight Dynamics and Control Laboratory |
| PID | Proportional-Integral-Derivative |
| LQR | Linear Quadratic Regulator |
| PD | Proportional-Derivative |
| P | Proportional |
| PI | Proportional-Integral |
| SDRE | State Dependent Riccati Equation |

including: Bell-Boeing V-22 Osprey [5,16], Vertol VZ-2 [6,17], Sikorsky X-wing [7,18], Harrier GR7 [8,19], Convair XFY-1 [9,20], Lockheed XFV-1 [10,21], Ling-Temco-Vought (LTV) XC-142 [11,22], and Canadair CL-84 [12,23]. Some of them did achieve remarkable success and a few manned hybrid aircraft such as Bell-Boeing V-22 Osprey and Harrier GR7 are still in service. Within the last five years, the hybrid aircraft design concept has gained increasing popularity in miniature UAV development, given 1) the increasing maturity of miniature UAV design and manufacturing, 2) the steady cost reduction of miniature UAV development, and 3) the saturation of the conventional miniature fixed-wing and rotary UAVs. As a result, a number of pioneer research work has been documented in literature, and a few designs such as BirdsEyeView FireFLY6 [13], X PlusOne [14] and MartinUAV V-Bat [15] have been commercialized successfully. For now, the hybrid UAV development is still in its infancy, and there is a huge space for the hybrid UAVs to become more mature in terms of many critical perspectives such as design philosophy, dynamics modeling, control, guidance, navigation, and robustness. Nevertheless, given their rapidly growing popularity, it is believed that the hybrid UAVs will have a bright future and promptly form an essential pillar of the UAV market.

In this paper, we intend to provide a comprehensive overview on the recent advances of the miniature hybrid UAVs. According to our knowledge, remarkable progress has been mainly achieved in three aspects: platform design, flight dynamics modeling, and flight control. Correspondingly, the remaining content of this paper is organized as follows: Section 2 addresses the platform design, in which a systematic categorization method for the hybrid UAVs is proposed and the technical features as well as the representative hybrid UAV platforms for each type are detailed. In Section 3, an overview of hybrid UAVs' flight dynamics modeling and flight control techniques is presented addressing a comprehensive analysis of the representative modeling and control research work. Finally, key observations, existing challenges and key conclusion remarks are drawn in Section 4. It should be highlighted that the scope of this paper is particularly limited to the miniature hybrid UAVs. Thus, the word ”miniature” will be omitted in the remaining contents.

## 2. Platform design

Generally, hybrid UAVs are categorized into two types: convertiplane and tail-sitter. A convertiplane maintains its airframe orientation in all flight modes, and certain transition or switching mechanisms are employed to achieve mode transfer. On the other hand, a tail-sitter is an aircraft that takes off and lands vertically on its tail, and the entire airframe needs to tilt to accomplish cruise flight. As shown in Fig. 2, both are further categorized into a few sub-types, depending on the specific transition mechanisms and airframe configurations. In what follows of Section 2, we will address all subtypes, analyze their design features, discuss the advantages and disadvantages of every subtype, and introduce representative examples.

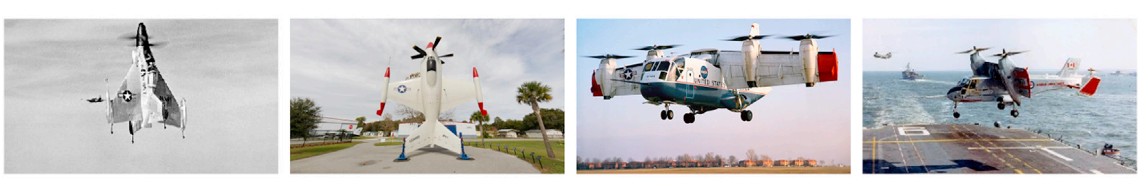
### 2.1. Convertiplane

A variety of mechanisms have been implemented in developing the convertiplane UAVs to achieve the transition between vertical flight and cruise flight. In general, the convertiplane UAVs are classified into four sub-types: 1) tilt-rotor, 2) tilt-wing, 3) rotor-wing, and 4) dual-systems.

#### 2.1.1. Tilt-rotor

A tilt-rotor UAV has multiple rotors mounted on the tilting shafts or nacelles. During the hover-to-cruise transition, partial or all rotors tilt towards flight direction to provide the aircraft forward speed until the cruise flight is achieved. Since the birth of the first tilt-rotor UAV (i.e.,

(a) V-22 Osprey [16] (b) Vertol VZ-2 [17] (c) Sikorsky X-wing [18] (d) Harrier GR7 [19]



(e) Convair XFY-1 [20] (f) Lockheed XFV-1 [21] (g) LTV XC-142 [22] (h) Canadair CL-84[23]

**Fig. 1.** Examples of manned hybrid aircraft.