

# Advancements in Tilted-Rotor Unmanned Aerial Vehicles: A Comprehensive Review

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**Abstract**—Unmanned Aerial Vehicles (UAVs) have revolutionized various industries by offering versatile capabilities and applications. Among the different types of UAVs, tilted-rotor UAVs have garnered significant attention due to their unique design and operational advantages. This paper presents a comprehensive review of advancements in tilted-rotor UAVs, aiming to provide an in-depth understanding of their design, performance, and applications. Subsequently, the paper explores the underlying principles and mechanisms governing tilted-rotor UAVs, including aerodynamics, control systems, and propulsion technologies. The review also investigates recent advancements in materials, sensors, and autonomy, which have contributed to enhancing the capabilities and efficiency of tilted-rotor UAVs. Moreover, the challenges and limitations associated with tilted-rotor UAVs are discussed, along with potential future research directions. Overall, this comprehensive review serves as a valuable resource for researchers, engineers, and industry professionals seeking to understand the state-of-the-art in tilted-rotor UAV technology and its potential impact on a wide range of applications.

**Index Terms**—tilted-rotor UAV, autonomy, rotor aerodynamics

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## I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) have emerged as a groundbreaking technology with diverse applications spanning surveillance, aerial mapping, delivery services, and disaster management, among others. The rapid advancement in UAV capabilities has spurred research and development efforts to explore novel designs and configurations that can enhance their performance and versatility. Among these designs, tilted-rotor UAVs have garnered significant attention for their potential to combine the benefits of both fixed-wing and rotary-wing aircraft. Tilted-rotor UAVs represent a unique class of aircraft that feature rotors capable of tilting from vertical to horizontal orientations. This design allows them to seamlessly transition between vertical takeoff and landing (VTOL) and efficient horizontal flight, offering a range of advantages over traditional UAV designs. By combining the vertical agility of helicopters with the high-speed capabilities and endurance of fixed-wing aircraft, tilted-rotor UAVs offer enhanced maneuverability, extended range, and increased payload capacity. Over the past few decades, research and development in tilted-rotor UAV technology have witnessed significant advancements. This progress has been driven by advancements in aerodynamics, control systems, materials, sensors, and autonomy. These developments have expanded the potential applications

of tilted-rotor UAVs across various sectors, including military, civilian, and commercial domains. Despite the growing interest and potential of tilted-rotor UAVs, there is a need for a comprehensive review that consolidates the existing knowledge and highlights the latest advancements in this field. Such a review paper can serve as a valuable resource for researchers, engineers, and industry professionals, offering insights into the design principles, performance characteristics, and practical applications of tilted-rotor UAVs. Therefore, the objective of this paper is to provide a comprehensive review of the advancements in tilted-rotor UAV technology. We aim to delve into the historical development of tilted-rotor UAVs, outlining key milestones and breakthroughs. Additionally, we will explore the underlying principles and mechanisms governing their operation, including aerodynamics, control systems, and propulsion technologies. Furthermore, this review will discuss the diverse applications of tilted-rotor UAVs in sectors such as surveillance, cargo transportation, and search and rescue operations. We will also examine recent advancements in materials, sensors, and autonomy, which have contributed to enhancing the capabilities and efficiency of tilted-rotor UAVs. The paper will address the challenges and limitations associated with tilted-rotor UAVs and discuss potential future research directions. By consolidating the existing knowledge and highlighting the potential of tilted-rotor UAVs, this review aims to foster further advancements in this field and inspire new avenues of research and development.

## II. TILTED-ROTOR UAVS

### A. UAVs with Tilted Rotors

Typical multicopters such as most commercial quad-rotors have multiple coplanar rotors, that is, rotors whose thrust axes are parallel to each other. They can hover stably and move back and forth, left and right, by inclining their airframe. However, when one or more rotors are mounted at a tilted angle to the airframe, the UAVs can move without inclining the airframe. In this paper, we focus on the UAVs that have at least one tilted or tiltable rotor to uncover their maneuverability, and call them *tilted-rotor UAVs*.

Tilted-rotor multicopters have attracted the researchers due to their fully-actuated property [1]. For example, conventional hexacopters with coplanar six rotors are regarded as under-actuated systems [2], because the total thrust force generated

by the rotors acts in only one direction with respect to the airframe. On the other hand, if the rotors are appropriately tilted, the combination of the thrust forces by six rotors can generate total force and moment in any direction [3]–[5].

The rotors of tilted-rotor UAVs are fixed to the airframe or tilted variably by servo actuators. Optimal tilt angles of fixed rotors for hexacopters have been examined based on some criterion in the literature [6]–[10]. When the rotors are actively tilted, multiple thrusts and variable tilt angles can also provide full actuation. In [11], it has been shown that this is true in a certain sense even for quad-rotor UAVs.

VTOL UAVs also often have tilted-rotors [12], [13]. VTOL UAVs can take off and land vertically in rotary-wing mode, and can fly fast and energy-efficiently in fixed-wing mode. To achieve the two flight modes, the rotors mounted on them are actively tilted, or some of them are fixed at tilted angles. For example, tilt-rotor UAVs [14]–[18] and tilt-wing UAVs [19]–[22] switch the flight mode by tilting actively the rotors. In dual-propulsion UAVs such as quad-plane UAVs, the rotors for rotary-wing mode and the rotors for fixed-wing mode are independently mounted at different angles relative to the airframe [23]–[25].

### B. Equation of Motion

In this subsection, we present the equations of motion for tilted rotor UAVs, and in the next subsection we will show that tilting rotors enhances the maneuverability of UAVs. We introduce an inertial coordinate frame  $\{\mathbf{a}_0\}$  and a coordinate frame fixed in the body  $\{\mathbf{a}_1\}$  as shown in Fig. 1. The equations of motion can be represented as follows [26], [27].

$$m\dot{\mathbf{V}}_g = -m\boldsymbol{\omega} \times \mathbf{V}_g + \mathbf{F}_g + \mathbf{F}_a + \mathbf{F}_t, \quad (1)$$

$$\mathbf{I}\dot{\boldsymbol{\omega}} = -\boldsymbol{\omega} \times \mathbf{I}\boldsymbol{\omega} + \mathbf{M}_g + \mathbf{M}_a + \mathbf{M}_t, \quad (2)$$

where  $m$  and  $\mathbf{I}$  are the mass and inertia matrix of UAV, respectively.  $\mathbf{V}_g$  and  $\boldsymbol{\omega}$  are the ground speed vector and the angular velocity vector expressed in the body frame  $\{\mathbf{a}_1\}$ , respectively. In the above equations, although it is difficult to accurately model the force and moment applied to the UAV, we simply divide them into three terms, those due to gravity, those due to aerodynamics and those due to rotor thrusts.

The force and moment due to gravity,  $\mathbf{F}_g$  and  $\mathbf{M}_g$ , are written as

$$\mathbf{F}_g = \mathbf{A}[0, 0, mg]^T, \quad \mathbf{M}_g = \mathbf{0}, \quad (3)$$

where  $g$  is the gravitational acceleration and  $\mathbf{A}$  is the coordinate transformation matrix from  $\{\mathbf{a}_0\}$  to  $\{\mathbf{a}_1\}$ . Note that  $\mathbf{M}_g$  is zero because the origin of  $\{\mathbf{a}_1\}$  is the mass center.

The force and moment due to aerodynamics,  $\mathbf{F}_a$  and  $\mathbf{M}_a$ , are often ignored for multi-rotor UAVs, but need to be modeled for VTOL UAVs according to their configuration. When VTOL UAVs have control surfaces such as aileron and elevator,  $\mathbf{F}_a$  and  $\mathbf{M}_a$  depend on the deflection angles of control surfaces. In addition, the aerodynamics may be affected by the tilt angles and the thrust forces of rotors, because the rotor inflow and wake interfere the airframe according to the UAV configuration [28]–[30].

Denoting the position vector of rotor  $i$  as  $\mathbf{R}_i$  and the unit vector along thrust axis as  $\mathbf{e}_i$  ( $i = 1, \dots, n$ ), the force and moment due to the rotor thrusts can be expressed as follows.

$$\mathbf{F}_t = \mathbf{E}_t \mathbf{T}, \quad (4)$$

$$\mathbf{M}_t = (\mathbf{R}_t + \mathbf{E}_t \mathbf{K}_t) \mathbf{T}, \quad (5)$$

where

$$\mathbf{T} = [T_1, T_2, \dots, T_n]^T, \quad (6)$$

$$\mathbf{E}_t = [\mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_n], \quad (7)$$

$$\mathbf{R}_t = [\mathbf{R}_1 \times \mathbf{e}_1, \mathbf{R}_2 \times \mathbf{e}_2, \dots, \mathbf{R}_n \times \mathbf{e}_n], \quad (8)$$

$$\mathbf{K}_t = \text{diag}\{k_1, k_2, \dots, k_n\}. \quad (9)$$

The second term  $\mathbf{E}_t \mathbf{K}_t \mathbf{T}$  on the right side of (5) represents the moment due to the counter-torques caused by the rotors, where  $k_i$  is the counter-torque coefficient for rotor  $i$ .

Denoting the velocity of vehicle as  $\mathbf{v} = [\mathbf{V}_g^T, \boldsymbol{\omega}^T]^T$ , the equations of motion (1) and (2) are summarized as in the following form:

$$\dot{\mathbf{v}} = \mathbf{f}_0(\mathbf{v}) + \mathbf{f}_g(\boldsymbol{\theta}) + \mathbf{f}_a(\boldsymbol{\delta}, \mathbf{v}, \boldsymbol{\theta}, \xi) + \mathbf{f}_t(\mathbf{T}, \mathbf{v}, \boldsymbol{\theta}, \xi), \quad (10)$$

where  $\boldsymbol{\theta}$  is the attitude of UAV and  $\boldsymbol{\delta}$  represents the deflection angles of control surfaces. The terms  $\mathbf{f}_a$  and  $\mathbf{f}_g$  due to aerodynamics and thrust are basically varied by the control inputs  $\boldsymbol{\delta}$  and  $\mathbf{T}$ , respectively. However, they often interfere with each other, and may be influenced by the surrounding environments including wind and distance from the ground or walls. The variable  $\xi$  indicates these effects, although it is difficult to model them accurately.

The acceleration of UAV caused by thrust forces is represented as follows.

$$\mathbf{f}_t = [(1/m)\mathbf{E}_t^T, \{\mathbf{I}^{-1}(\mathbf{R}_t + \mathbf{E}_t \mathbf{K}_t)\}^T]^T \mathbf{T} \equiv \mathbf{B}_t \mathbf{T}. \quad (11)$$

We denote the lower and upper limits of thrust force as  $T_{i \min}$  and  $T_{i \max}$ , that is,

$$T_{i \min} \leq T_i \leq T_{i \max} \quad (i = 1, \dots, n), \quad (12)$$

and introduce the set of allowable thrust forces as

$$\mathcal{T} = \{\mathbf{T} \mid T_{i \min} \leq T_i \leq T_{i \max}\}. \quad (13)$$

It should be noted that  $T_{i \min}$  and  $T_{i \max}$  vary with flight conditions, because the thrust force generated by each rotor depends on the velocity of air inflow into the rotor [30], [31]. Then, we can define the following set of possible acceleration by  $\mathbf{T}$  at each flight condition of UAV:

$$\mathcal{F}_t = \{\mathbf{f}_t \mid \mathbf{T} \in \mathcal{T}\}. \quad (14)$$

Similarly, the set of possible aerodynamic acceleration by  $\boldsymbol{\delta}$  can be defined as

$$\mathcal{F}_a = \{\mathbf{f}_a \mid \boldsymbol{\delta} \in \boldsymbol{\Delta}\}, \quad (15)$$

where, denoting the lower and upper limits of deflection angles as  $\delta_{j \min}$  and  $\delta_{j \max}$  for control surface  $j$ ,

$$\boldsymbol{\Delta} = \{\boldsymbol{\delta} \mid \delta_{j \min} \leq \delta_j \leq \delta_{j \max}\}. \quad (16)$$

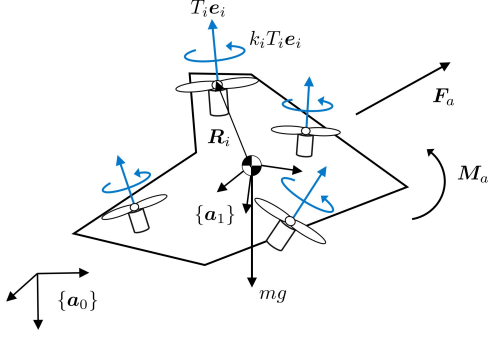


Fig. 1. Forces and moments applied to tilted-rotor UAVs.

Based on the above two sets  $\mathcal{F}_t$  and  $\mathcal{F}_a$ , we can consider the allowable acceleration of UAV at each flight condition as

$$\mathcal{A} = \{\dot{v} \mid T \in \mathcal{T}, \delta \in \Delta\}. \quad (17)$$

The set  $\mathcal{A}$  indicates the maneuverability of the UAV, which corresponds to the dynamic manipulability in robotics [32].

### C. Maneuverability of Tilted Rotor UAVs

From the perspective of maneuverability, we review tilted rotor UAVs again. For conventional multicopters with coplanar rotors, the set  $\mathcal{F}_t$  is restricted on a four-dimensional space, because  $\text{rank}(E_t) = 1$  and  $\text{rank}(B_t) = 4$ . Since multicopters do not have control surfaces, this means that the set  $\mathcal{A}$  is also four-dimensional at each flight condition. Consequently, multicopters with coplanar rotors are underactuated [2].

For multicopters with tilted rotors,  $\text{rank}(E_t)$  can be larger than 1, and  $\text{rank}(B_t)$  can be increased. The sets  $\mathcal{F}_t$  and  $\mathcal{A}$  are not restricted on a four-dimensional space, and the maneuverability of UAV is enhanced due to tilted rotors. In the case of hexarotors with appropriate tilt angles,  $\text{rank}(B_t) = 6$  and the system is fully actuated [1]. Note that, for quad-rotor UAVs,  $\text{rank}(B_t) = 4$  even with tilted angles of rotors. Nevertheless, quad-rotor UAVs with actively tilted rotors are fully actuated in the sense that the jerks of position and attitude can be manipulated in any direction by the time derivatives of thrust forces and tilt angles, as shown in [11]. Even if the tilt angles are fixed with respect to the airframe, tilting rotors can lead to a significant change in maneuverability for quad-rotor UAVs. The reference [33] has shown that quad-rotor UAVs composed of only clockwise rotors can hover if the rotors are appropriately tilted.

For VTOL UAVs, the maneuverability  $\mathcal{A}$  is highly affected by the possible aerodynamic acceleration  $\mathcal{F}_a$  as well as  $\mathcal{F}_t$ . The aerodynamic acceleration  $f_a$  is usually proportional to the squared airspeed  $V_a^2$ , denoting the airspeed as  $V_a$ . When  $V_a$  is zero,  $f_a$  is also zero, and the maneuverability is determined by  $\mathcal{F}_t$  in the same way as for multicopters. Tilted multiple rotors are advantageous in enhancing the maneuverability in rotary-wing mode. When the airspeed  $V_a$  increases, the aerodynamic acceleration  $f_a$  becomes larger. The acceleration of UAV can be generated in the directions that are spanned not only by  $\mathcal{F}_t$  but also  $\mathcal{F}_a$ . However, too large  $f_a$  tends to keep the

total acceleration  $\dot{v}$  away from zero and may make it difficult to control the motion of UAV. For example, when a VTOL UAV flies fast at a large angle of attack, excessively large aerodynamic lift is caused while generating inevitable upward acceleration [25]. The maneuverability of VTOL UAVs should be examined carefully through modeling of  $f_a$  and  $f_t$ .

## III. BASIC TECHNOLOGIES OF TILTED-ROTOR UAVS

This section provides an overview of the basic technologies in aerodynamics, propulsion and control, to better understand the promise and challenges of tilted-rotor UAVs. Studies on the detailed modeling of  $f_a$  and  $f_t$  have been widely tackled, because they play a crucial role in the performance of tilted-rotor UAVs. Along with the studies, controller design for tilted-rotor UAVs has also been extensively studied to exploit the enhanced maneuverability, especially under uncertainty and actuator failure. These advancements in basic technologies would collectively contribute to the further development and improvement of tilted-rotor UAVs.

### A. Aerodynamics

For multicopters without fixed wings, the aerodynamic acceleration  $f_a$  is often modeled as zero, because it is small. However, in crosswinds, the rotor itself is subject to aerodynamic force called *rotor drag* or *H-force*, which is linearly proportional to the airspeed [34]–[36]. In [37], [38], more accurate control has been achieved by taking account of the aerodynamic force in dynamic model. When ducted fans are equipped to a UAV as rotors, larger aerodynamic drag force called *ram drag* or *momentum drag* is applied to the UAV in crosswinds [39]–[41]. It should be noted that these aerodynamic forces depend on the rotor thrust force, or rotor speed, as well as the airspeed. The aerodynamic forces are applied to multicopters whether the rotors are tilted or not. In addition, if the rotors are tilted to a large degree, the airflows induced by the rotors may interfere with each other.

The rotor induced airflows may cause the interference with the surrounding environment such as the ground and walls. Garofano-Soldado et al. [43], [44] have explored the aerodynamic interference effects of tilted propellers in confined environments, such as the wall effect and corner effect. These investigations provide valuable insights into the challenges posed by crosswinds and confined spaces, and offer solutions to improve flight stability and efficiency.

For VTOL UAVs, the aerodynamic force has been an interesting research topic, because it is difficult to build an accurate aerodynamic model due to the complex interaction between propulsion and aerodynamics [28]–[30]. The aforementioned aerodynamic forces caused by the rotors, that are linearly proportional to the airspeed, are applied to VTOL UAVs as well as multicopters. When lift fans are embedded in the wings or fuselage, the ram drag occurs [50], [51]. Thouault et al. [52] have examined the aerodynamic forces applied to a fan-in-wing at various angles of attack by CFD simulations and wind tunnel experiments.

The flow fields in hover and transition depend on a variety of factors such as airframe shape, fan wake, crosswind, and so on [28], [29]. When a lift force is generated in hover by a lift fan embedded near the center of airframe, the airflow entrained along the lower surface of the fixed wings may cause a lift loss. Even in a transition flight, the airflow induced by the fan wake can produce a lift loss and a nose-up moment. If the UAV is close to the ground, the fan wake will impinge on the ground and cause the flow radially outward from the impingement point along the lower surface of wings, which can cause a larger lift loss.

During the transition flight between fixed-wing mode and rotary-wing mode, the aerodynamic characteristics of VTOL UAVs vary with flight conditions such as tilt angle of rotors and airspeed. Muraoka et al. [53] have examined the aerodynamic characteristics of a quad tilt-wing UAV at various tilt angles through wind tunnel experiments, where they constructed an aerodynamic model by interpolating the aerodynamic forces at a number of possible flight conditions. Zhou et al. [54] have developed a dynamic model of a quad tilt-rotor UAV by combining several aerodynamic interference models from prior literature. Mathur et al. [55] have investigated the aerodynamic forces of a quad-plane UAV by wind tunnel tests and have pointed out that unconventional pitch moment and large drag force are caused due to flow interactions. Urakubo et al. [18] conducted an aerodynamic analysis of a tilted-rotor UAV in level flight with varying tilt angles, to investigate the effects of different tilt angles on the aerodynamic performance. The findings of those studies provide valuable insights into the aerodynamic characteristics of tilted-rotor UAVs, aiding in the optimization of tilt angle selection for improved flight performance and efficiency. However, a more comprehensive understanding of aerodynamic forces should be explored, because the aerodynamics is highly complex depending on the flight conditions. For example, Potsdam et al. [56] have shown that, when a tilt-rotor aircraft flies slow at nonzero sideslip angle, pitch-up is caused by an adverse interaction of the rotor wake impinging on the aft fuselage and empennage.

### B. Propulsion

As mentioned in the previous subsection, the interference between propulsion and aerodynamics often exists, and therefore, it is sometimes impossible to divide the force applied to a UAV into  $f_a$  and  $f_t$ . However, the modeling of thrust forces is very important to improve the accuracy of flight control and aerodynamic force identification. The thrust force, drag force and moment applied to a rotor have been modeled so far as in [36], [41], when it is located in an airflow at various angles. The interference with confined spaces such as the ground effect and the wall effect has also been investigated as in [43], [44].

The locations and tilt angles of rotors in the airframe, that are represented by  $R_i$  and  $e_i$ , have a significant effect on the maneuverability  $\mathcal{A}$  through  $f_t$ . The enhanced maneuverability of multicopters with tilted rotors is provided by properly located and tilted thrust forces [7]–[9]. The control effort for

a specific task can also be reduced by choosing the tilt angles appropriately [6], [10]. Based on the progress in the propulsion analysis and modeling, design methods for multicopters with tilted rotors should be further studied.

In the case of VTOL UAVs, the rotors have two roles: to lift the UAVs and to propel the UAVs forward. The energy efficiency of each rotor depends on the inflow speed to the rotor, that is, advance ratio [31]. To keep a high energy efficiency in a wide range of airspeed, variable-pitch propellers can be employed for rotors used during forward flights like an airplane [19]. In addition, the thrust force required to propel the UAV against the aerodynamic drag during high-speed cruise in fixed-wing mode is less than the thrust force to lift the UAV during hover. Therefore, many VTOL UAVs utilize fewer rotors in fixed-wing mode than in rotary-wing mode [18], [19], [23]–[25].

Propulsion systems for tilted-rotor UAVs often incorporate electric motors, internal combustion engines, or hybrid power systems [57]. The choice of propulsion system depends on factors such as payload requirements, flight range, endurance, and efficiency considerations. Currently, engines are advantageous for flight range and endurance due to high energy density of fuel, compared to electric motors with batteries. However, electric propulsion systems would be promising along with progress in battery technologies. Based on the distributed electric propulsion (DEP) concept, multiple electric propulsors are expected to improve the aerodynamic characteristics and the maneuverability [19], [58].

Efforts are underway to enhance the propulsion systems of tilted-rotor UAVs, including the development of more efficient and lightweight electric motors, improved battery technologies, and the integration of advanced power management systems. These advancements aim to increase the endurance, range, and overall efficiency of tilted-rotor UAVs, enabling them to undertake longer missions and carry larger payloads.

### C. Control

For conventional multicopters, all the thrust axes  $e_i$  are parallel to each other. They are underactuated, but still controllable because they are differentially flat [59]. However, it is necessary to incline the airframe in order to cause horizontal translational acceleration. Tilting the rotors can increase  $\text{rank}(B_t)$  and can enhance the maneuverability. Translational acceleration can be obtained without inclining the airframe, and the attitude can be changed without translational acceleration [4]. Further, when the number of rotors  $n$  is more than 6, the control efforts for flight can be reduced by control allocation [46].

Multicopters with tilted rotors can apply a force to an object because of the enhanced maneuverability. Sanchez-Cuevas et al. [5] presented a fully-actuated aerial manipulator for infrastructure contact inspection, encompassing design, modeling, localization, and control aspects. Even when  $\text{rank}(B_t) = 4$  for a quad-rotor UAV, it can apply a force to an object by actively tilting the rotors, that is, by changing the column space of  $B_t$  [60]. Sugihara et al. [49] focused on

the design, control, and motion strategy of TRADY, a tilted-rotor-equipped aerial robot capable of autonomous in-flight assembly and disassembly. Two quad-rotor UAVs with tilted rotors can autonomously dock in the air with each other. The docked UAV is fully actuated, although one quad-rotor UAV is underactuated. These works demonstrated the potential of integrating advanced control and motion planning algorithms in tilted-rotor UAVs.

The aerodynamics of multicopters with tilted rotors may be more uncertain, because the wakes from tilted rotors may interfere with each other. To overcome the aerodynamic uncertainty caused by tilted rotors, Ibuki et al. [45] have proposed a robust tracking control method based on Gaussian processes. Sheng et al. [48] have shown that model reference adaptive control (MRAC) can be applied to fully-actuated multi-rotor UAVs as well as quad-rotors.

The enhanced maneuverability with tilted rotors can also be utilized for fault tolerant control (FTC). Giribet et al. [61] have shown that a fully-actuated hexacopter can achieve FTC when one rotor fails. Shen et al. [47] proposed a design of quad-rotor UAV called Quad-cone-rotor, and discussed its fault tolerant ability.

For VTOL UAVs, the maneuverability highly depends on  $\mathcal{F}_a$  as well as  $\mathcal{F}_t$ , because  $f_a$  increases with airspeed. The control of VTOL UAVs is a critical aspect that enables safe and precise maneuvering under this highly variable maneuverability. VTOL UAVs require sophisticated control systems to manage the transitions between rotary-wing mode and fixed-wing mode, as well as to maintain stability and control during each mode.

Based on the aerodynamic model, flight envelope or conversion corridor is often derived to build a controller for the transition flights [62], [63]. The desired transition has been determined by scheduling the tilt angle at each airspeed in the corridor for a quad tilt-wing UAV in [20] and for a quad tilt-rotor UAV in [54]. Appleton et al. [64] have investigated more accurate conversion corridor for a tilt-rotor aircraft by considering several aerodynamic interaction effects.

The maneuverability changes greatly depending on the flight conditions such as airspeed, angle of attack and so on. Nevertheless, the analysis of maneuverability would be helpful in revealing the flight performance of VTOL UAVs. Kikumoto et al. [25] have derived a control strategy to accomplish back-transition from fixed-wing mode to rotary-wing mode quickly for a quad-plane UAV based on the maneuverability analysis. In [65], the maneuverability of the same UAV has been analyzed to explain optimized forward and backward transition trajectories.

The actuators installed in VTOL UAVs often provide redundancy in control inputs, because a sufficient number of actuators need to be installed in VTOL UAVs to enable rotary-wing mode, fixed-wing mode, and transition between them. If the redundancy is used to its full extent, VTOL UAVs are not just convertible aircraft, but highly maneuverable aircraft. For example, the four upward rotors of a quad-plane UAV are not used during high-speed cruise in the conventional fixed-

wing mode, but can be utilized as redundant control inputs. Urakubo et al. have shown by numerical simulations that the turning radius during high-speed flights can be drastically reduced by using the redundancy for a quad-plane UAV in [66] and for a tilt-rotor UAV in [67]. The redundancy can also be employed to reduce the power or the thrust required during flights through control (and pitch) allocation, as shown for a tilt-rotor UAV in [17] and for a quad-plane UAV in [68].

Dividing the flight envelope into rotary-wing mode, fixed-wing mode and transition between them is currently common, but may lead to inefficient flights. To utilize the redundant control inputs efficiently, unified control approaches for VTOL UAVs have become popular recently, where a controller is designed without dividing the flight envelope. Hartmann et al. [21] have proposed a unified approach for velocity control of a tilt-wing UAV based on its dynamic model. Raab et al. [69] have used incremental nonlinear dynamic inversion to develop a unified controller for a tilt-rotor UAV. Rohr et al. have derived a detailed dynamic model for a tilt-wing UAV, and have designed a controller based on dynamic inversion in [22] and based on nonlinear model predictive control (NMPC) in [70].

Fault tolerant control (FTC) of VTOL UAVs would also benefit from the redundancy in control inputs. A FTC method for a tilt-rotor UAV has been proposed in [71] when the tilt axle is stuck at a fixed angle during transition flights. In [72], [73], it has been shown that a quad-plane UAV can be controlled successfully even if some control surfaces or some rotors for rotary-wing mode fail.

These studies on control of tilted-rotor UAVs have been revealing the advantages of the enhanced maneuverability. Further progress in control studies would contribute to the body of knowledge surrounding tilted-rotor UAVs, addressing various aspects such as maneuverability, motion strategy, and novel designs of aircraft.

#### IV. MODERN TECHNOLOGIES SUPPORTING TILTED-ROTOR UAVS

##### A. Lightweight Composite Materials

Lightweight composite technology has emerged as a significant advancement in the development of tilted-rotor unmanned aerial vehicles (UAVs). These advanced materials offer a range of benefits, including reduced weight, increased strength, improved durability, and enhanced aerodynamic performance. This section will delve deeper into the applications and advantages of lightweight composites for tilted-rotor UAVs. One of the primary advantages of lightweight composites is their exceptional strength-to-weight ratio. Composites, such as carbon fiber composites, fiberglass composites, and advanced polymers, possess high strength characteristics while being significantly lighter than traditional materials like metals. This lightweight property allows tilted-rotor UAVs to carry larger payloads, extend their flight range, and enhance operational capabilities. The use of lightweight composites in the construction of tilted-rotor UAV airframes offers improved structural integrity. These materials exhibit

excellent resistance to fatigue, corrosion, and environmental degradation, ensuring longevity and reliability in demanding operational conditions. Moreover, composite structures can be tailored to specific design requirements, resulting in optimized load distribution, reduced vibrations, and enhanced overall stability. The aerodynamic performance of tilted-rotor UAVs is significantly influenced by the materials used in their construction. Lightweight composites offer design flexibility, allowing for complex and streamlined shapes that minimize drag and improve efficiency. The reduced weight of composites also contributes to improved maneuverability, enabling rapid acceleration, tighter turns, and precise control during flight. Additionally, lightweight composites contribute to reduced energy consumption and increased flight endurance. The lower weight of the airframe translates to reduced power requirements for sustained flight, enabling longer mission durations and extended operational ranges. This benefit is particularly important for applications such as surveillance, mapping, and aerial inspections, where extended flight times are essential. Furthermore, lightweight composites facilitate easier transportation and deployment of tilted-rotor UAVs. The lower weight of the airframe simplifies logistics and reduces the need for specialized equipment or infrastructure during operations. This advantage enhances the mobility and agility of tilted-rotor UAVs, making them suitable for various scenarios and environments. While lightweight composites offer numerous advantages, their implementation in tilted-rotor UAVs does come with challenges. Manufacturing processes, such as composite layup, curing, and quality control, require specialized expertise and stringent quality assurance protocols. Additionally, the cost of composite materials and fabrication techniques may present initial investment challenges. However, advancements in manufacturing techniques and economies of scale are gradually reducing these barriers.

### *B. Improved Battery Technology*

Improved battery technology is a crucial area of development for tilted-rotor unmanned aerial vehicles (UAVs). Advancements in battery technology have significant implications for flight endurance, operational flexibility, and overall performance. This section will explore the applications and advantages of improved battery technology for tilted-rotor UAVs. One of the primary benefits of improved battery technology is increased flight endurance. Tilted-rotor UAVs rely on electric propulsion systems, and advancements in battery technology have led to higher energy densities and improved power-to-weight ratios. This allows UAVs to carry larger battery packs or utilize more efficient batteries, resulting in extended flight durations. Longer flight endurance enables UAVs to cover larger areas, perform longer missions, and collect more data without the need for frequent battery swaps or recharging. Additionally, improved battery technology enhances operational flexibility for tilted-rotor UAVs. UAVs equipped with high-capacity batteries can be deployed for missions in remote or inaccessible areas where recharging infrastructure may be limited. This flexibility allows for increased versatility in

applications such as search and rescue, environmental monitoring, and infrastructure inspection. Moreover, advancements in battery technology contribute to reduced downtime and increased mission efficiency. Faster charging capabilities and improved energy management systems allow tilted-rotor UAVs to spend less time on the ground and more time in the air. This enables higher mission throughput, quicker response times, and improved overall operational effectiveness. Improved battery technology also has implications for payload capacity. Higher energy densities and reduced battery weight allow UAVs to carry larger payloads, such as advanced sensors, cameras, or specialized equipment. This opens up possibilities for a wider range of applications and enables UAVs to perform more demanding tasks while maintaining optimal flight performance.

### *C. Improved Propulsion Efficiency*

Improved propulsion efficiency is a critical focus in the development of tilted-rotor unmanned aerial vehicles (UAVs). Enhancing propulsion efficiency leads to increased flight endurance, improved payload capacity, and overall better performance. This section explores the applications and advantages of improved propulsion efficiency for tilted-rotor UAVs. One of the primary benefits of improved propulsion efficiency is extended flight endurance. Tilted-rotor UAVs rely on propulsion systems that drive both the rotor and propellers, and advancements in propulsion technology can significantly increase the efficiency of these systems. Higher propulsion efficiency results in reduced energy consumption, allowing UAVs to stay airborne for longer durations. Extended flight endurance is especially valuable for applications such as surveillance, mapping, or monitoring, where longer flight times enable more comprehensive data collection and increased mission efficiency. Improved propulsion efficiency also contributes to enhanced payload capacity. More efficient propulsion systems generate greater thrust per unit of power, enabling tilted-rotor UAVs to carry larger payloads. This opens up possibilities for incorporating advanced sensors, cameras, communication equipment, or specialized payloads, allowing UAVs to perform more demanding tasks while maintaining optimal flight performance. Increased payload capacity expands the range of applications and mission capabilities for tilted-rotor UAVs. Furthermore, improved propulsion efficiency leads to reduced energy consumption and increased operational cost-effectiveness. With more efficient propulsion systems, tilted-rotor UAVs require less energy to perform the same tasks, resulting in longer operational range, lower fuel or battery costs, and reduced maintenance requirements. This makes tilted-rotor UAVs more economically viable for various industries, including aerial surveying, delivery services, or infrastructure inspections. Improved propulsion efficiency enhances the overall performance and maneuverability of tilted-rotor UAVs. Higher thrust-to-weight ratios and improved power-to-weight ratios enable faster acceleration, better climb rates, and improved responsiveness. These capabilities enhance the agility and maneuverability of UAVs, allowing them to per-

form dynamic maneuvers, fly in adverse weather conditions, or navigate challenging terrains with precision.

#### *D. Advanced Communication Systems*

An advanced communication system is crucial for the efficient and reliable operation of tilted-rotor unmanned aerial vehicles (UAVs). These systems enable seamless communication between the UAV and ground control, as well as facilitate communication between multiple UAVs in swarming or collaborative operations. This section explores the applications and advantages of advanced communication systems for tilted-rotor UAVs. One of the primary benefits of an advanced communication system is the establishment of robust and reliable communication links between the UAV and ground control. These systems utilize technologies such as long-range data transmission, secure protocols, and advanced modulation schemes to ensure uninterrupted communication over extended distances. Reliable communication is essential for transmitting mission commands, receiving real-time telemetry data, and enabling remote control or monitoring of the UAV. Advanced communication systems also enable high-bandwidth data transfer, allowing tilted-rotor UAVs to transmit large volumes of data in real-time. This capability is particularly valuable for applications such as aerial surveys, remote sensing, or live video streaming, where high-resolution data or video must be transmitted to the ground control station for immediate analysis or decision-making. The high-bandwidth communication system enables efficient data transfer, reducing latency and enabling near-real-time monitoring and response. Additionally, advanced communication systems support collaborative operations and swarming capabilities among multiple tilted-rotor UAVs. These systems enable UAV-to-UAV communication, facilitating coordination, sharing of mission-critical information, and collaborative decision-making. By establishing reliable and low-latency communication links among swarm members, advanced communication systems enable synchronized flight, task distribution, and cooperative mission execution. This capability enhances the efficiency and effectiveness of swarming operations and opens up possibilities for complex missions that require coordinated efforts. Advanced communication systems incorporate features such as anti-jamming capabilities, encryption, and error correction techniques to ensure secure and reliable communication. These systems protect the communication links from interference, unauthorized access, or data corruption, maintaining the integrity and confidentiality of the transmitted information. Secure communication is particularly crucial for applications that involve sensitive data, critical infrastructure inspections, or military operations.

#### *E. Advanced Sensor Integration*

Advanced sensor integration is a key aspect of the development of tilted-rotor unmanned aerial vehicles (UAVs). The integration of sophisticated sensors enhances the UAV's capabilities, enabling it to gather valuable data, perform complex

tasks, and operate safely and effectively in various environments. This section explores the applications and advantages of advanced sensor integration for tilted-rotor UAVs. One of the primary benefits of advanced sensor integration is the enhanced data collection capabilities of tilted-rotor UAVs. These sensors include high-resolution cameras, LiDAR (Light Detection and Ranging) sensors, thermal imaging sensors, multispectral sensors, and more. By integrating these sensors into the UAV's payload, it becomes possible to capture detailed visual information, generate accurate 3D maps, detect temperature variations, and analyze multispectral data for applications such as agriculture, environmental monitoring, and infrastructure inspection. Advanced sensor integration also contributes to improved situational awareness and real-time monitoring. High-resolution cameras and sensor arrays provide operators with detailed visual information about the UAV's surroundings, enabling better decision-making during mission execution. Additionally, real-time data feeds from sensors facilitate immediate detection of changes, anomalies, or critical events, allowing for prompt action or adaptive flight planning. Safety and obstacle avoidance are crucial considerations for tilted-rotor UAV operations, particularly in complex or congested environments. Sensor integration plays a significant role in ensuring safe navigation and obstacle avoidance. LiDAR sensors, radar systems, and computer vision algorithms enable the detection and tracking of obstacles, terrain, and other aircraft, helping the UAV autonomously avoid collisions and navigate through challenging environments. Furthermore, advanced sensor integration facilitates autonomous operations and navigation. By combining sensor inputs with advanced algorithms, tilted-rotor UAVs can perform tasks autonomously, such as waypoint navigation, precision landing, and target tracking. This level of autonomy reduces the dependence on manual control, enhances operational efficiency, and enables UAVs to operate in areas with limited or no GPS signals. The integration of sensors with data fusion algorithms enables the extraction of valuable information from multiple data sources. By combining sensor inputs, such as visual data, thermal data, and LiDAR point clouds, UAVs can generate comprehensive and accurate environmental models, conduct advanced analytics, and make informed decisions in real-time. This information fusion capability enhances the UAV's intelligence, enabling it to perform complex tasks such as object recognition, change detection, and environmental monitoring. Moreover, advancements in miniaturization and power efficiency have made it possible to integrate sensors with smaller form factors and lower power consumption. This enables lightweight and compact sensor payloads for tilted-rotor UAVs, maximizing the available payload capacity for other mission-specific equipment or extending the UAV's flight endurance.

#### *F. Enhanced Autonomy*

Enhanced autonomy is a significant area of development in tilted-rotor unmanned aerial vehicles (UAVs). Advancements in autonomy enable these aircraft to operate with increased

independence, intelligence, and efficiency. This section will delve deeper into the applications and advantages of enhanced autonomy for tilted-rotor UAVs. One of the primary benefits of enhanced autonomy is the ability of tilted-rotor UAVs to perform autonomous takeoff and landing. With advanced flight control algorithms and sensor integration, UAVs can autonomously execute complex maneuvers during the critical phases of flight. This capability enhances safety, reduces reliance on manual control, and enables UAVs to operate from unprepared or confined areas where manual piloting may be challenging. Autonomy also enables tilted-rotor UAVs to perform precise waypoint navigation and mission planning. By integrating GPS, inertial measurement units (IMUs), and sophisticated flight control algorithms, UAVs can autonomously follow pre-defined flight paths, accurately reach designated waypoints, and execute mission-specific tasks. This capability is particularly valuable for applications such as aerial surveys, inspection missions, and search and rescue operations. Furthermore, advanced autonomy allows tilted-rotor UAVs to exhibit obstacle detection and avoidance capabilities. By integrating sensor systems like LiDAR, radar, and computer vision, UAVs can detect and recognize obstacles in real-time, adjust their flight paths, and navigate around obstacles autonomously. This capability enhances safety and enables UAVs to operate in complex and dynamic environments, such as urban areas or industrial sites. Autonomous decision-making is another crucial aspect of enhanced autonomy in tilted-rotor UAVs. With the integration of machine learning algorithms and artificial intelligence, UAVs can analyze sensor data, interpret environmental cues, and make intelligent decisions during flight operations. This capability allows UAVs to adapt to changing conditions, respond to unforeseen events, and optimize mission performance in real-time.

1) *Sense and Avoid*: The implementation of a reliable sense-and-avoid system is crucial for the safe and effective operation of tilted-rotor unmanned aerial vehicles (UAVs). Tilted-rotor UAVs operate in diverse and dynamic environments, often sharing airspace with other aircraft or encountering obstacles. This section explores the applications and advantages of sense-and-avoid systems for tilted-rotor UAVs. One of the primary benefits of a sense-and-avoid system is the ability to detect and track other aircraft, obstacles, or potential hazards in the surrounding airspace. These systems employ a combination of sensors, such as radar, ADS-B (Automatic Dependent Surveillance-Broadcast), LiDAR, or computer vision, to gather real-time data about the UAV's environment. By analyzing this data, the sense-and-avoid system can detect potential collisions or conflicts and initiate appropriate avoidance maneuvers. Sense-and-avoid systems provide tilted-rotor UAVs with increased situational awareness and the ability to make informed decisions during flight. By continuously monitoring the airspace and analyzing sensor inputs, the system can identify potential threats and calculate the optimal course of action. This capability is essential for operations in complex or congested environments, where the UAV must navigate safely and autonomously while avoiding obstacles

or other aircraft. Furthermore, sense-and-avoid systems enable tilted-rotor UAVs to autonomously adjust their flight paths or velocities to avoid potential collisions. Advanced algorithms and flight control systems process the information from the sense-and-avoid system and generate avoidance maneuvers, such as altering the UAV's heading, altitude, or speed. This autonomous response capability enhances safety and reduces the reliance on manual intervention during critical situations. Sense-and-avoid systems also facilitate compliance with aviation regulations and standards. As the airspace becomes more crowded with manned and unmanned aircraft, regulatory bodies require UAVs to possess the capability to detect and avoid potential collisions. By incorporating a robust sense-and-avoid system, tilted-rotor UAVs can meet these requirements and operate within the established rules and guidelines. Additionally, the integration of sense-and-avoid systems enhances the overall operational flexibility and efficiency of tilted-rotor UAVs. By autonomously avoiding obstacles or conflicts, UAVs can maintain their planned flight trajectories, optimize mission performance, and reduce the need for manual intervention or rerouting. This capability is particularly valuable for applications such as aerial surveys, infrastructure inspection, or emergency response, where uninterrupted and efficient flight operations are crucial.

2) *Precision Navigation*: Precision navigation technology is a key area of focus in the development of tilted-rotor unmanned aerial vehicles (UAVs). Accurate and reliable navigation capabilities are essential for these aircraft to perform complex maneuvers, follow precise flight paths, and maintain positional accuracy. This section explores the applications and advantages of precision navigation technology for tilted-rotor UAVs. One of the primary benefits of precision navigation technology is the ability to execute precise flight paths and waypoints. Tilted-rotor UAVs integrate advanced navigation systems, including GPS receivers, inertial navigation systems (INS), and flight control algorithms. These technologies work in conjunction to ensure accurate positioning, precise altitude control, and smooth trajectory following. This capability is vital for applications such as aerial surveys, mapping, and inspections that require precise positioning and repeatable flight paths. Precision navigation technology also enables tilted-rotor UAVs to operate in challenging environments with limited GPS availability or accuracy. Advanced navigation systems incorporate additional sensors, such as altimeters, magnetometers, and barometers, to augment GPS data and improve positioning accuracy. This allows UAVs to navigate through urban canyons, forests, or indoor environments with improved reliability and stability. Furthermore, precision navigation technology facilitates the integration of real-time kinematic (RTK) and differential GPS (DGPS) techniques. These techniques leverage ground-based reference stations to provide centimeter-level positioning accuracy, enabling highly precise aerial mapping, photogrammetry, and surveying applications. The use of RTK and DGPS allows tilted-rotor UAVs to achieve high-accuracy data collection, reducing the need for extensive ground control points and improving data quality. Additionally,

precision navigation technology enhances the ability of tilted-rotor UAVs to perform dynamic maneuvers and autonomous operations. Sophisticated flight control algorithms, sensor fusion techniques, and advanced guidance systems enable UAVs to adapt to changing environmental conditions, execute complex flight patterns, and maintain precise control during critical phases of flight. This capability is particularly valuable for applications such as inspection missions, search and rescue operations, and surveillance tasks that require agility and real-time decision-making. Moreover, precision navigation technology contributes to improved flight safety. Reliable navigation systems, coupled with obstacle detection and avoidance sensors, ensure that tilted-rotor UAVs can navigate safely through congested or complex environments. This capability reduces the risk of collisions, enhances situational awareness, and enables UAVs to operate in urban areas, industrial sites, or other challenging locations with confidence. As precision navigation technology continues to advance, ongoing research focuses on areas such as multi-sensor integration, sensor fusion algorithms, and real-time mapping and localization techniques. These developments aim to further enhance the precision, accuracy, and robustness of navigation systems for tilted-rotor UAVs.

3) *Swarming Capabilities*: Swarming capabilities offer significant advantages for tilted-rotor unmanned aerial vehicles (UAVs) by enabling coordinated and collaborative operations among a group of UAVs. Swarms of tilted-rotor UAVs can work together to accomplish complex tasks, enhance mission efficiency, and provide increased capabilities. This section explores the applications and advantages of swarming capabilities for tilted-rotor UAVs. One of the primary benefits of swarming capabilities is the ability to distribute tasks and collaborate on mission objectives. By working together as a cohesive unit, swarms of tilted-rotor UAVs can divide complex tasks into smaller subtasks, allowing for parallel execution and increased efficiency. This enables the swarm to cover larger areas, perform more extensive surveys, or accomplish time-critical missions with reduced time requirements. Swarming capabilities also provide fault tolerance and redundancy. In a swarm, if one UAV encounters an issue or fails, other UAVs can compensate for the loss, ensuring mission continuity and maximizing system availability. This redundancy enhances the reliability and robustness of the overall operation, making swarming well-suited for critical applications such as search and rescue, surveillance, or disaster response. Furthermore, swarming enables collaborative sensing and data fusion. By sharing information among the swarm members, tilted-rotor UAVs can collectively gather and analyze data from multiple viewpoints. This collaborative sensing approach allows for comprehensive situational awareness, improved object tracking, and enhanced data accuracy. It is particularly valuable for applications such as mapping, monitoring, or target tracking, where multiple perspectives provide a more complete understanding of the environment. Swarming capabilities also offer increased adaptability and flexibility in dynamic environments. Individual UAVs in a swarm can adjust their positions and

flight trajectories in response to changing conditions or emerging situations. This adaptive behavior allows the swarm to dynamically allocate resources, optimize mission performance, and respond to real-time requirements. Swarms of tilted-rotor UAVs can quickly adapt to new information, reconfigure their formation, or dynamically assign roles, enabling them to address evolving mission needs effectively.

## V. CHALLENGES AND FUTURE DIRECTIONS OF TILTED-ROTOR UAVS

### A. Challenges of Titled-rotor UAVs

While tilted-rotor unmanned aerial vehicles (UAVs) offer numerous advantages and capabilities, they also face several challenges and limitations that need to be addressed for their widespread adoption and deployment. This section highlights some of the key challenges and limitations associated with tilted-rotor UAVs.

1) *Complex Design and Engineering*: Tilted-rotor UAVs possess a complex design that involves the integration of both rotor and propeller systems. This complexity adds to the engineering challenges in terms of aerodynamics, structural design, and control systems. Designing and manufacturing tilted-rotor UAVs require specialized expertise and advanced engineering techniques, which can increase development costs and time.

2) *Size and Weight Limitations*: Tilted-rotor UAVs tend to be larger and heavier compared to traditional fixed-wing or multirotor UAVs due to the combined rotor and propeller systems. The size and weight limitations can affect their portability, maneuverability, and ease of deployment in certain environments or applications. Additionally, larger size and weight may result in regulatory restrictions or requirements for specific certifications.

3) *Power and Propulsion Efficiency*: Efficient power and propulsion systems are crucial for the performance and endurance of tilted-rotor UAVs. Achieving high propulsion efficiency while maintaining the necessary thrust can be challenging, especially in larger UAVs. Power requirements and battery capacity are also factors to consider to ensure sufficient flight endurance and payload capabilities.

4) *Noise and Acoustic Signature*: Signature: Tilted-rotor UAVs generate noise due to the combined rotor and propeller systems. The noise produced by these UAVs can be louder compared to other UAV configurations, which may raise concerns in certain operational environments, such as urban areas or noise-sensitive locations. Reducing the acoustic signature and addressing noise-related challenges is important to ensure acceptable noise levels and minimize disturbances.

5) *Control and Stability*: The control and stability of tilted-rotor UAVs require advanced control algorithms and flight control systems. Ensuring precise control during transitions between vertical takeoff and landing (VTOL) and horizontal flight modes can be challenging. Maintaining stability and responsiveness while in different flight configurations and during transitions is crucial for safe and efficient operations.

6) *Regulatory Framework*: The existing regulatory frameworks for UAV operations might not fully address the specific requirements and characteristics of tilted-rotor UAVs. These UAVs introduce unique operational scenarios, including VTOL capabilities, transition phases, and potential collision risks associated with the combined rotor and propeller systems. Developing appropriate regulations and guidelines to ensure the safe integration of tilted-rotor UAVs into the airspace is an ongoing challenge.

7) *Cost*: Tilted-rotor UAVs often involve higher development and manufacturing costs due to their complex design and specialized components. The cost of materials, propulsion systems, control systems, and advanced technologies can be significant. These higher costs can limit the accessibility and affordability of tilted-rotor UAVs for certain applications or organizations.

Addressing these challenges and limitations requires ongoing research, development, and collaboration among various stakeholders, including manufacturers, researchers, regulators, and end-users. Continued advancements in design, engineering, propulsion systems, control algorithms, noise reduction, and regulatory frameworks are essential to overcome these challenges and unlock the full potential of tilted-rotor UAVs in various industries and applications.

#### B. Future Directions of Tilted-rotor UAVs

As tilted-rotor unmanned aerial vehicles (UAVs) continue to evolve, several promising avenues for further exploration and development emerge. This section outlines potential future directions that could shape the trajectory of tilted-rotor UAV technology:

**Multi-Domain Integration**: Tilted-rotor UAVs offer a unique opportunity for seamless transitions between vertical and horizontal flight modes. Exploring the integration of these capabilities into multi-domain operations, such as land-water-air operations, could revolutionize tasks like environmental monitoring, disaster response, and maritime surveillance.

**Optimized Propulsion Systems**: Enhancing the efficiency and reliability of propulsion systems remains a priority. Research into advanced propulsion technologies, including electric and hybrid systems, could lead to improved flight endurance, reduced noise emissions, and greater sustainability.

**Autonomous Decision-Making**: Advancements in artificial intelligence and machine learning can enhance the autonomy of tilted-rotor UAVs. Developing algorithms that enable real-time decision-making, adaptive navigation, and collaboration between swarming UAVs could open doors to complex missions in dynamic environments.

**Advanced Sensing and Perception**: Further integration of advanced sensors, such as LiDAR and hyperspectral imaging, could elevate the sensing capabilities of tilted-rotor UAVs. This would enable high-resolution mapping, detailed environmental analysis, and accurate target detection for applications like precision agriculture and environmental monitoring.

**Urban Air Mobility**: The concept of urban air mobility envisions a future where tilted-rotor UAVs play a crucial

role in intra-city transportation. Research into air traffic management, infrastructure integration, and urban planning for aerial transportation networks could pave the way for this transformative mode of transit.

**Human-Machine Interaction**: Developments in human-machine interaction interfaces, including augmented reality and haptic feedback, could enhance operator control and situational awareness. These advancements would be pivotal for applications requiring precise navigation and interaction in complex environments.

**Energy Storage and Power Distribution**: Continued improvements in energy storage technologies and power distribution systems are essential for extending flight endurance and payload capacities. Exploring alternative energy sources and innovative battery designs could push the boundaries of tilted-rotor UAV capabilities.

**Regulatory Frameworks**: As the technology matures, establishing comprehensive and standardized regulatory frameworks is crucial. Collaborating with regulatory bodies to define guidelines for safe operations, airspace integration, and certification processes will be vital for the widespread adoption of tilted-rotor UAVs.

**Environmental Impact**: Research into minimizing the environmental impact of tilted-rotor UAVs is paramount. This includes developing noise reduction strategies, optimizing flight paths to reduce emissions, and evaluating the ecological effects of increased UAV operations.

**Interdisciplinary Collaboration**: The multidisciplinary nature of tilted-rotor UAVs calls for collaboration between engineers, material scientists, aerodynamicists, AI experts, policy-makers, and more. Encouraging cross-disciplinary partnerships will accelerate innovation and broaden the scope of potential applications.

In essence, the future of tilted-rotor UAVs holds immense promise. By addressing challenges, embracing emerging technologies, and fostering collaborative efforts, we can unlock new dimensions of performance and applications for these transformative aerial vehicles. The journey ahead involves not only technical advancements but also a commitment to responsible and sustainable integration into our ever-evolving airspace ecosystem.

## VI. CONCLUSION

This comprehensive review has illuminated the diverse capabilities and potential applications of tilted-rotor unmanned aerial vehicles (UAVs). These UAVs, encompassing multi-copters and VTOL aircraft, offer a unique fusion of vertical and horizontal flight modes. Their ability to seamlessly transition between these modes makes them adaptable for a wide range of industries, from surveillance to search and rescue.

The review delved into the intricate aspects governing tilted-rotor UAV performance. Aerodynamics challenges in confined spaces were addressed, leading to solutions that enhance flight stability. Advanced control systems and autonomy mechanisms enable precise maneuvering and autonomous operations, vital for complex navigational tasks.

The integration of cutting-edge technologies, such as lightweight composites, advanced sensors, enhanced autonomy, and improved batteries, has significantly boosted tilted-rotor UAV capabilities. Swarming capabilities, precision navigation, sense-and-avoid systems, and augmented reality interfaces have expanded their potential applications.

However, challenges like intricate design, noise mitigation, power efficiency, and regulatory constraints remain. Overcoming these obstacles will require ongoing research and innovation.

The review serves as a valuable resource for researchers and industry professionals, offering insights into the present and future of tilted-rotor UAVs. As these vehicles redefine aerial capabilities, they beckon us to embrace innovation and collaboration to harness their full potential and shape the future of unmanned flight.

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