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Design Configuration and Technical Application of Rotary-Wing Unmanned Aerial Vehicles

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Abstract: Due to their advantages in hovering, takeoff and landing adaptability, maneuverability, and other factors, rotary-wing unmanned aerial vehicles (UAVs) are widely applied across many different fields. The UAVs' design and configuration can be quite flexible to fit diverse operation conditions. The major goal of innovations in rotary-wing UAVs is to lower operating risk and expense by optimizing payload and structure layout. This study examines three aspects of rotary-wing UAV design and evolution: the number and arrangement of rotors, hybrid-wing-based UAVs, and configuration and loading structures. The most current advancements of UAV applications in crucial industries, including agriculture, fire rescue, inspection and monitoring, and aerial logistics, are then thoroughly examined. Finally, the authors discussed the prospective uses for rotary-wing UAV design in the future.

Keywords: Rotary-wing unmanned aerial vehicles (UAVs); Configuration design; Hybrid-wing-based UAVs; Application

1. Introduction

Rotary-wing unmanned aerial vehicles (UAVs), also known as unmanned helicopters, are highly common unmanned aircrafts that use a single main rotor with an anti-torque system or multiple rotors to provide lift and change direction. The opposite of rotary-wing UAVs are fixed-wing UAVs, which produce lift by rubbing airflow against surfaces like wings and fuselage. The main benefits of rotary-wing UAVs include the ability to hover, better operating flexibility and maneuverability, and adaptability to various takeoff and landing conditions. Over the years, rotary-wing UAVs have evolved to meet the demands of various industries, including agriculture, search and rescue, inspection and monitoring, logistics, and transportation.

The rotary-wing UAVs were chosen by the Time magazine as one of the top ten technology products in 2014 due to their broad range of industrial applications and quick technological advancements. According to research, the use of UAVs will continue to increase, and by 2022, it is predicted that the market for them will be worth a considerable $20 billion [1]. The "Made in China 2025" government plan, which the State Council of the P.R.C. announced in 2015 [2], encourages the industrialization of UAVs. The desire for novel application scenarios and fierce market rivalry drives the UAVs' continuous technological improvement, but at the same time, the requirements and standards for UAV products get harder to meet. As a result, both the government and the market try to drive the important research on rotary-wing UAVs. Rotor-wing UAV performance and design have greatly advanced in recent years.

To meet various mission needs, rotary-wing UAVs can have a wide range of features and configurations. There is no unified way to categorize the family of rotor-wing UAVs [3]. Rather, they are frequently divided based on factors like the number of rotors, weight, power source, fuselage structure, endurance, flight range, and application. The most typical way to classify rotor-wing UAVs is by the number of rotors: single-rotor, twin-rotor, tri-rotor, quadri-rotor, hexa-rotor, octo-rotor, etc.; the greatest can have up to 18 rotary wings. The classification based on weight is also commonly accepted, but the acceptable weight range varies depending on the industry.

Drones are categorized into three classes in an overview of military drones employed by the UK armed forces based on the minimum take-off weight as well as the intended application and operating conditions. According to

Table 1, the International Affairs and Defense of the UK has classified UAVs into three primary classes, namely Class I, Class II, and Class III. Class I can be further split into f our smaller groups (a, b, c, and d) [4]. UAVs are divided into three categories by the Australian Civil Aviation Authority (CASA), including micro-UAVs, which weigh less than 0.1 kg, small UAVs, which weigh between 0.1 kg and 150 kg, and large UAVs, which weigh more than 100 kg [5]. Cai et al. [6] proposed a more detailed weight-based division for UAVs less than 25 kg based on six different features.

Table 1. Weight-based categorization by the international affairs and defense of the UK [5]

Class	Type	Weight
Class I (a)	Nano	W≤200g
Class I (b)	Micro	200g＜W≤2kg
Class I (c)	Mini	2kg＜W≤20kg
Class I (d)	Small	20kg＜W≤150kg
Class II	Tactical	150kg＜W≤600kg
Class III	MALE/HALE/Strike	W＞600kg

Public interest in the commercial sector has turned to the classification of rotary-wing UAVs as per their power source. Since rotary-wing UAVs' durability and the range of their applications are closely tied to their driven energy source, energy application has always been a crucial area for technological advancement in rotary-wing UAV design. The associated energy and power densities define the majority of modern power sources [7]. In particular for the quadrotor, up to 90% of the rotor-wing UAVs on the market are electrically driven [8]. The electrically powered rotary-wing UAVs utilize a variety of batteries, as indicated in Table 2.

Due to practical limitations on battery pack weight, Li-Po and Li-Ion batteries are frequently used because of their smaller weight and higher specific energy. However, UAVs often have limited endurance; with Li-PO batteries, they can only fly for 90 minutes [9]. Drone fuel comes in a variety of forms, with hydrogen fuel cells now enjoying the most popularity [10]. Fuel cells are more frequently selected for extended endurance circumstances compared to batteries [11]. Although traditional fuels like gasoline and diesel have higher energy densities [12], their fuel engines, which are often big and heavy, have significantly more intricate designs and speed controls. Therefore, conventional fuels are rarely employed in rotor-wing UAVs due to size and weight restrictions.

Table 2. Features of different battery types [7]

Battery type	Pb-acid	NiMH	Li-ion	Nicad	Li-Po	Li-air	Li-SOCl$_2$
Nominal cell voltage (V)	2.1	1.2	3.6-3.85	1.2	2.7-3	2.91	3.5
Energy density (Wh/kg)	30-40	60-120	100-265	40-60	100-265	11140	500-700
Power density (W/kg)	180	250-1000	250-340	150	245-430	11400	18
Cycle life	<350	180-2000	400-1200	2000	500	700	NR *
Charge/Discharge efficiency (%)	50-95	66-92	80-90	70-90	90	93	6-94
Self-discharge rate (%)	3-20	13.9-70.6	0.35-2.5	10	0.3	1-2	0.08
Rating	12V 2Ah	12V 2Ah	3.6V 2Ah	12V 1.8Ah	3.7V 2Ah	NR *	3.6V 2.2Ah

Note: NR means non-rechargeable.

A single power source will always have certain downsides. Hence, it is wise to mix various energy sources to create a hybrid energy driving UAV. This allows the propulsion system to take advantage of both sources' advantages while balancing their disadvantages [13]. The hybrid driven technique is a significant trend for future design and development of rotary-wing UAVs. For many industrial applications today, it is very promising to combine a fuel cell and battery to create a hybrid power supply system. In addition to offering the same stability and maneuverability as electric UAVs, hybrid technology also offers fuel sustainability for missions requiring long endurance and high payloads [14].

Supercapacitor hybrid drives, solar hybrid power, and others are examples of hybrid power sources [15, 16]. There are a few drones on the market that are fueled by different types of energy, such solar, wind, or even biogas. Continuous surveillance has been accomplished by a solar-powered UAV created by Jung et al. [17]. The "Ingenuity," a small twin-rotor unmanned aerial vehicle (UAV) for Mars exploration, has managed to harness solar energy [18]. As a result of their unique energy and power supply mechanism, tethered UAVs require special structure design and application. Both military and commercial applications have employed the tethered systems, which give UAVs limitless flying time over small areas. Tethered drones, for example, are employed on ships to detect offshore oil spills to avoid serious coastal contamination [19, 20] (Figure 1).

Figure 1. Different examples of UAVs on power source (a) Hydrogen UAV HYDrone-1800 [10]; (b) Ingenuity [18]; (c) Tethered UAV [20]

This review paper aims to offer academics and engineers interested in rotary-wing UAVs relevant direction and suggestions by concentrating mostly on the configuration design and commercial applications of rotor-wing UAVs. The rest of this essay is structured as follows: In Section 1, the design and development of rotary-wing UAVs are examined from three angles: the number and arrangement of rotors, hybrid wing-based UAVs, and configuration and loading structures. In Section 2, applications of UAVs in crucial industries like agriculture, fire rescue, inspection and monitoring, and aerial logistics are thoroughly examined. In Section 3, there is a discussion of rotary-wing UAV design trends going forward and prospective uses.

2. Configuration Design

2.1 Number and Structure of Rotors

Changing the quantity and arrangement of rotors is the simplest method of developing a novel UAV structure. If needed, there might be up to 18 rotors. The number of rotors has a significant impact on a UAV's performance. Increased rotary wings, for instance, enhance thrust, combat safety, and maneuverability [21]. The most advanced type of commercial UAVs available today, octa-rotors are primarily utilized for heavy load applications [22]. The newest rideable multi-rotor-wing UAV from Lift Aircraft takes off on 18 rotors, each of which is powered by a separate battery, hence improving cargo capacity [23]. The three rotors of the tri-rotor are employed to generate lift, and one of them is tilted to change the flying direction [24]. A hexa-copter called "Voliro," a UAV with six rotors, moves vertically during takeoff and landing, and integrates the six rotors to allow movement in any direction [25].

After determining the number of rotary-wings, altering the placement of the rotors gives the drones new features. For instance, there are widely dispersed twin-rotor wing UAVs with two rotors that are mostly employed for delivery. For instance, the Chinese MK-400 UAV successfully lifted huge loads on a plateau while reaching a height of 5000 meters for the first time [26]. The twin-rotor-wing UAVs, on the other hand, can be made co-axis to avoid rollover. Chinese Mars exploration UAV employs two rotors on one axis that are operated in opposite directions [27]. The JZ series crossover twin rotor unmanned helicopter created by Tsinghua University is an example of a crossover UAV, which is another variation of coaxial twin-rotor-wing UAVs [28]. The American Eagle-Eye tilt-rotor-wing UAV [29] is another example of twin-rotor design, which combines the benefits of vertical takeoff and landing of rotorcraft with long-endurance flight of fixed-wing aircraft (Figure 2).

Figure 2. (a) Unmanned helicopter [30]; (b) Twin-copter [31]; (c) Tri-copter [24]; (d) Quad-copter [32]; (e) Hexa-copter [25]; (f) Octo-copter [22]; (g) Deca-copter [33]; (h) Lift Aircraft [23]; (i) Mk-400 [26]; (j) Mars exploration Drone [27]; (k) K-MAX [28]; (l) Eagle Eye tilt-rotor-wing UAV [29]

2.2 Hybrid Wing-Based UAV

The hybrid wing-based UAV is a type of UAV that combines fixed and rotary wings for structural improvements. For rotor-wing UAVs, the rapidly rotating rotors push air to provide lift. The energy consumption is relatively significant despite their great maneuverability, which results in restrictions on flying range, speed, and carrying capacity. When fixed wing structures are added to a rotary-wing UAV, the lift produced by the surfaces of the fixed wings can significantly increase the UAV's operational performance [21]. The lifting wing rotor-wing UAV is designed at a fixed installation Angle between the rotor blade plane and the lifting wing, which not only retains the original clean and reliable structure of the rotary-wing UAV, but also improves the forward flight efficiency. A smooth transition from hover to efficient forward flight can be achieved by UAV with this configuration, which allows the maximum lift requirements and optimal power configuration [34].

The hybrid wing UAVs could potentially yet be improved. The HADA-helicopter is built with a second rotor mounted on the tail to create a horizontal thrust, making it possible for horizontal motion without body tilting [35]. The UAS VISION dual-hybrid aircraft has a horizontal rotor attached at the tail and two vertical rotors fastened at the ends of the wings. The UAV is more stable with symmetrical vertical rotors than it is with a single vertical rotor [36]. Latitude's Hq-40 UAV is built with two fixed wings mounted on the quadrotor to achieve great mobility and stability [37].

Different rotor and fixed wing layouts result in various performance characteristics. The rotors mounted around the fuselage of the tail-sitter UAV produce lift. It is head-up during take-off. Once it has ascended to the desired altitude, it moves forward horizontally. The tail-sitter UAV's power system is the same throughout takeoff and cruise flight, allowing for more payload to be held back and preventing rotor disturbance to the wings. During takeoff and landing, however, the bottom airflow is confused and influenced by lateral winds, which may cause tip over instability [38].

The multi-rotor X-hawk tail-sitter UAV can fly autonomously 24 hours a day over vast distances and challenging terrain [39]. It can do vertical takeoff and landing in a small area. The VTOL fixed wing UAV is outfitted with propellers on the front and back of the fixed wing to give the thrust necessary for VTOL, while the thrust or pull propeller put on the tail or nose provides the power for the horizontal flying stage [40]. The VTOL fixed wing UAV can achieve vertical take-off and landing in addition to its efficiency in horizontal flight, just like rotary-wing UAVs. As a result, the requirements for landing circumstances are less stringent, and flying duration is increased (Figure 3).

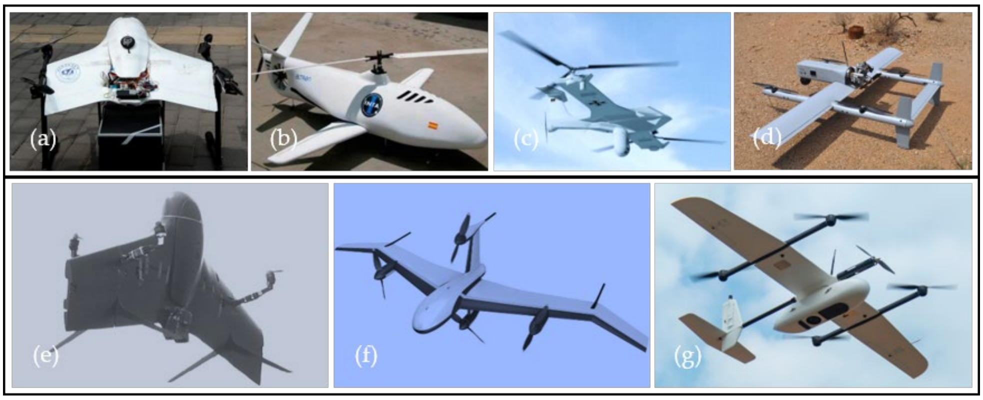

Figure 3. (a) A lifting wing fixed on rotor-wing UAVs [34]; (b) HADA-Helicopter [35]; (c) Hybrid Airborne System [36]; (d) HQ-40 [37]; (e) The tail-sitter UAV [38]; (f) The X-hawk tail-sitter [39]; (g) The VTOL fixed wing UAV [40]

2.3 New Structures

Through airframe designs, a new framework for the rotor-wing UAV can be created. After being launched into the air, UAVs with foldable and flexible structures can conserve space and carry out particular missions. In order to overcome obstacles and withstand external impacts, their construction varies depending on the terrain factors. The University of Zurich and EPFL's adaptive folding UAV can vary its shape by adjusting the angle between the rotor arm and fuselage [41]. The folding UAV can adapt to any new position of the arm in real time since the thrust of the propeller is modified by altering the center of gravity, ensuring steady flying at all times. The safety gear that is built into the foldable quadcopter for freight transportation significantly lowers the possibility of both human harm and propeller damage brought on by the rotors [42]. However, the frame adds to the aircraft's weight, which could affect its mobility and battery performance. To further improve safety and prevent injury from close contact, the rotors of ducted fan UAVs like the Fleye are housed inside the body [43].

Two in-house built mechanical arms are included in the PRODRONE company's Pd6b-aw-arm UAV, which may be used for a variety of tasks right away [44]. A moveable mechanical claw that can automatically bind the intersecting steel bars is a feature of the SkyTy UAV manufactured by the American SkyMul company [45]. These UAVs can eliminate physical labor in high-altitude, high-risk environments, for they are adaptable, steady, and lower in size. The highly developed multi-habitat rotorcraft UAVs can navigate on water and operate on land like vehicles in addition to flying through the air. Robotic Research LLC's Pegasus Mini UAV is a hybrid UAV and land vehicle that can be operated independently in the air and on the ground [46]. The US military has financed the development of Johns Hopkins University's Cracuns amphibious UAV, a quadrotor-winged craft that can move on land and water [47] (Figure 4).

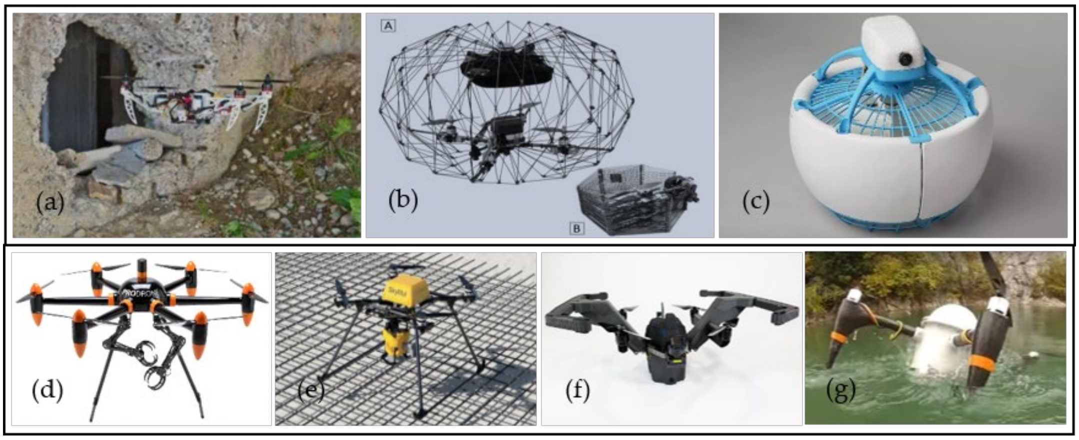

Figure 4. (a) Morphing Quadrotor [41]; (b) Foldable quadcopter for cargo delivery [42]; (c) Fleye [43]; (d) PD6B-AW-ARM [44]; (e) SkyTy UAV [45]; (f) Pegasus Mini [46]; (g) Cracuns [47]

3. Applications and Development of Rotary-Wing UAVs

The technical development levels of rotary-wing UAVs, which have gone through numerous stages, are tightly connected to their uses. The UAVs have currently made outstanding contributions in all spheres of life. In tandem with the growth of the rotorcraft UAV sector, the technology side of UAVs is being further encouraged to enhance their capabilities.

3.1 Applications in Agriculture

To carry out agricultural production operations, the rotary-wing UAVs are mostly operated by ground-based remote systems or devices. The focus of agricultural development has been thought to be their applications in agriculture. Agricultural UAVs have recently received assistance from numerous nations through a variety of government policies [48]. Agricultural UAV companies of all sizes are currently available on the market, and the number of pertinent UAVs is growing. With a holding capacity of more than 55,000 and an operational area of more than 56 million hectares, China produced more than 170 different types of plant protection UAVs by the end of 2019 [49].

For tasks like irrigation scheduling, disease detection, soil texture mapping, weed detection, residue cover, tillage mapping, crops management, cultivations analysis, and other applications in precision agriculture, rotary-wing UAVs are created and brought to use [50, 51]. UAV applications in agriculture clearly outperform conventional farming methods using people and ground machinery. For instance, arduous or dangerous tasks can be completed more simply, working efficiency and production are effectively raised, and seasonal labor shortages are resolved [52]. When compared to manually piloted aircraft, UAVs can concentrate more on the work at hand and manage farms more precisely and at specific locations [53]. In addition to accurate operation and great efficiency, intelligent UAVs in agriculture are also labor- and environmentally-friendly. A current trend in agriculture is centralized, unmanned, precise, and intelligent agricultural production based on UAVs, especially in light of the current worldwide pandemic (Figure 5) (Table 3).

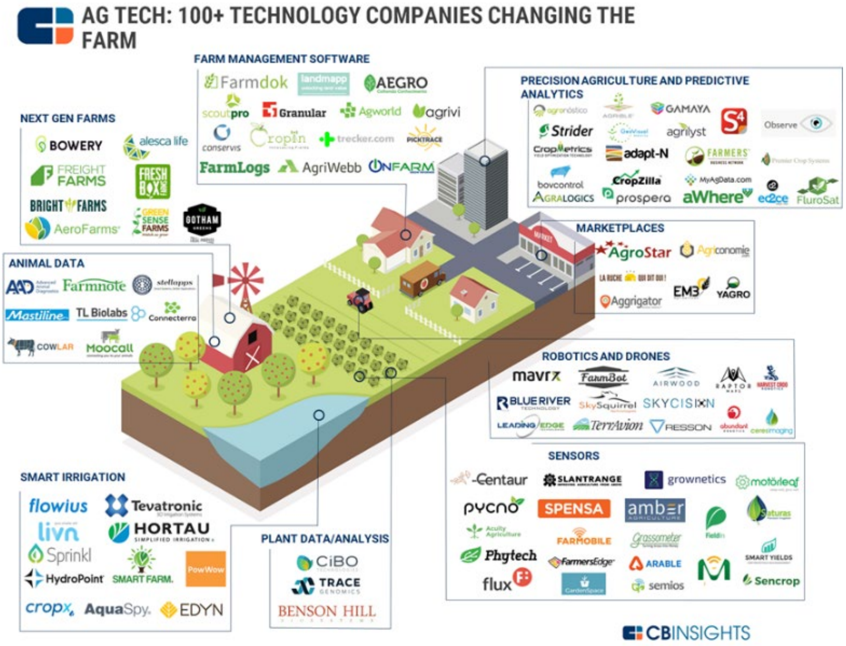

Figure 5. 100 C startups powering the future of farming and agribusiness [54]

Table 3. UAV applications in agriculture

Task	Reference	Focus	Advantages
Irrigation-scheduling	[55]	Aquatic weeds	-Improve monitoring efficiency of irrigation channels
	[56]	Viti	-Real-time updating of irrigation network data
	[57]	crop water evapotranspiration	- Prompt modification of irrigation plans
Disease detection	[58]	Potato	-The precise and automatic diagnosis of diseases
	[59]	Squash	-Quick and affordable early disease detection
	[60]	Viti	-Wide operation area with minimal crop destruction
Soil mapping	[61]	Soil	-Better spatial forecast accuracy for soil maps at various taxonomic levels.
	[62]	Soil	-Cut down on labor, costs, and sampling time.
Spraying pesticides	[63]	Wheat	-Increasing the use of spray
	[64]	Pesticides	-Reduce different problems that affect the human environment
Spraying fertilizers	[65]	Fertilizers	-Decrease crop damage and labor intensity
Crops management	[66]	Remote sensing	-Simplify manual work
	[67]	Region-based UAV control (Multiple UAVs)	-Suit big agricultural areas
	[68]	early season site-specific weed management (ESSWM).	-Improve crop management through precision application of crop production and protection materials
Machine pollination	[69]	Rice	-Support long-distance spraying of parent pollen without harming the plant -Reduce labor intensity and improve efficiency -Adapt to extensive seed planting
Yield estimation	[70]	Sugarcane	-Ignore the plantation's canopy density
	[71]	Grain yield in rice	-Decrease time cost and boost accuracy
	[72]	Soybean yield prediction	-Assess crop maturity across wide areas
	[73]	Corn	
Weed detection	[74]	Oat	-Reduce the cost and environmental impact
	[75]	Image processing	-Achieve more efficiency with high spatial resolution and at a low cost

Companies like DJI (https://www.dji.com/) and Parrot (https://www.parrot.com/) are working harder than ever to develop new agricultural UAV solutions as the demand for UAVs in agricultural applications rises [76]. The DJI T-series and MG series of UAVs are frequently utilized for pollination, ripening, weeding, fertilizing, and pest control. These UAVs mostly target grain, vegetables, and fruit [77]. Due to intelligent design settings and optimization algorithms, DJI series plant protection UAVs can be controlled autonomously in a variety of operating scenarios in large-scale agricultural productions [78]. In addition, UAVs can do various auxiliary tasks for ground machinery in agricultural production. For example, rotary-wing UAVs are deployed to help with crop irrigation [79].

For precision agriculture such as indoor farming, UAVs play very important new roles in auxiliary production. Sensors on the micro-UAV can monitor crop environments such as air temperature, humidity, brightness and carbon dioxide concentration, which allow dynamic management of the indoor crops [80]. However, there are still some unresolved issues about applications of rotary-wing UAVs for agricultural tasks, the most prominent problem is the energy or power constraints [52], which is also a pivotal research and development point for the drone industry (Figure 6).

Figure 6. UAVs in precision agriculture (a) Spraying pesticides; (b) Weed detection; (c) Crop management

3.2 Seek and Rescue

In seek and rescue operations, particularly in the aftermath of fire rescue, hazardous chemical accidents, and major disasters, rotary-wing UAVs have become more prevalent. Unquestionably, utilizing UAVs in these risky settings can minimize human effort and injuries [81], while increasing safety. Additionally, because of their excellent mobility and high flexibility, UAVs can operate in hazardous environments or in places that are inaccessible to people or ground-based equipment, such as during forest fires or search-and-rescue operations in the water. Uncertainty in search and rescue is somewhat diminished by the UAVs' operational effectiveness [82]. The UAVs can conduct a thorough search in a short amount of time thanks to their air superiority and information transmission capabilities. Therefore, quick access to accidents and site monitoring is possible [83, 84]. Furthermore, some UAVs can deliver vital information regarding rescue routes based on tasks and data received [85, 86]. Likewise, as UAVs may transport external equipment like noise sensors [87], binary sensors [88], vibration sensors [89], and heat sensors [90], more rescue-related tasks can be carried out in dire circumstances.

The International Civil Aviation Organization (ICAO) has established guidelines for search and rescue operations following disasters [91]. UAVs should be used to replace humans for field research duties in challenging and hazardous field conditions [92]. Tethered UAVs were utilized to provide lighting in the dark during the rescue operation for China Eastern Airlines' MU5735 accident, and a UAV mobile base station was made available for air-ground communications [93, 94]. UAVs are capable of quick positioning for missing person searches. The Stormpoint UAV organization and the rescue agency launched the UAV equipped with a FLIR thermal imager for the missing teen in Tennessee in order to find the individual using the thermal data that had been received [95]. Poland also employs a similar rescue technique [96].

In the early stages of a fire rescue, using UAVs for reconnaissance and command can considerably increase the effectiveness of the rescue operation. UAVs offer innovative fire safety solutions, particularly for high-rises. For fire rescue in tall buildings, the Altair and Ikhana (Predator-B) UAVs were created by NASA [97] and the theoretical electric six-rotor aircraft by EAC Group [98]. Chinese engineers and researchers have also worked tirelessly on real-world UAV firefighting applications. At an altitude of more than 100 meters, the Chinese Predator UAV can perform rescue and firefighting operations [99]. In a fire simulation, the Guofei business successfully used six high-rise tethered firefighting UAVs to put out the fire [100], validating the idea of fire rescue by a group of UAVs. For rotary-wing UAVs used in fire rescue today, endurance and payload are significant concerns that need to be addressed [72] (Figure 7).

Figure 7. Drone rescues (a) The UAV with a thermal imager [95]; (b) Predator [99]; (c) High-rise fire extinguishing UAVs [100]

3.3 Inspection and Monitoring

For a variety of air-ground tasks, UAVs with external components have tremendous benefits over humans. These duties include traffic inspection [101], bridge inspection [102], grid power line monitoring [103], maritime inspection [104], mine inspection [105], and environmental monitoring [106]. The rotary-wing UAVs may be remotely controlled and autonomously designed to deal with risky inspection settings because of their excellent environmental adaptability. Besides, the sophisticated technology that UAVs are equipped with, such as visible-light imaging equipment, infrared thermal imagers, lidar, and other devices, will enable the acquisition of data and information for more precise and effective operations [107] (Figure 8) (Table 4).

Table 4. Application of UAV in inspection and monitoring

Task	Ref.	Focus	Research Type
Traffic monitoring	[108]	Accident investigation	This study proposes the technique for reconstructing the site of a traffic accident using UAV photogrammetry
	[109]	Traffic flow analysis	This study suggests a brand-new, comprehensive analysis approach for estimating traffic flow parameters from UAV videos.
	[110]	Vehicle detection	Using a program, this study retrieves heterogeneous vehicle flow data, with a focus on motorbikes.
	[111]	Risk assessment	For accurate line-of-sight assessment, this study utilizes UAV video data based on dual grid UAV flights.
Highway infrastructure management	[112]	Bridge inspection	This study examines how UAV infrared thermography can be used to locate subsurface in concrete bridge decks.
	[113]	Railway inspection and monitoring	This study explores the use of UAVs in railroads and computer vision-based-rail infrastructure monitoring.
	[114]	Road distresses monitoring	This study relies on UAV-based images to automatically identify and quantify road distresses.
	[115]	Pavement condition	This study improves the asphalt detection accuracy by combining low-altitude UAV multispectral images with CNN + SVM.
Mining industry inspection	[116]	Three-dimensional mapping of mine environment	This study employs an autonomous flying robot to explore a tunnel environment and creates a 3D map of the environment.
	[117]	Radiological identification of mineral	This study couples low-altitude multi-rotor UAV with state-of-the-art micro-electronics to examine associated radiogenic signatures of surface/near-surface ore deposits.
	[118]	Post-blast rock inspection	This study presents the findings of lab-scale rock fragment measurements made with a UAV.
Power line monitoring	[119]	Clearance detection for transmission line corridors	This study uses UAV-gathered Lidar point clouds to automatically detect clearance anomalies.
	[120]	Power line inspection	This study proposes a power line automatic measurement method based on epipolar constraints (PLAMEC), and uses the method to determine the spatial position of power lines.
Pipeline monitoring	[121]	Gas leak monitoring	This study uses the data on gas (methane) leak gathered by an UAV with a gas sensor and a Lidar.
	[122]	Oil pipeline monitoring	This study presents a filter for UAV point cloud, and effectively identifies unstable areas of oil pipelines.
Environmental monitoring	[123]	Air pollution monitoring	This study designs a UAV with mobile monitoring devices, and applies it to collect 3D data on air pollutant concentration of the vertical profile.
	[124]	Water pollution monitoring	This study applies UAV-borne hyperspectral imagery to grasp the pollution state of the entire river from the surface.
Maritime inspection	[125]	Tidal channel monitoring	Using UAV images, this study estimates the location and shape of tidal channels by observing flood tides exactly at the time zone.
	[126]	Ship monitoring	This study proposed a UAV-based ship monitoring system, and suggests a method to determine ship positions using UAV multi-sensory data.

A wide range of sectors benefit from the inspection and monitoring capabilities of rotary-wing UAVs. Compared to conventional road monitoring technology, UAVs are significantly more flexible and can cover wider regions when monitoring traffic. Guidos et al. [127] adopted UAVs to track cars by capturing and processing the data gathered, and managed to reinforce the advantages of UAVs for traffic management. Furthermore, using drones to record and gather evidence of traffic infractions and road inspections in broad daylight is both practical and efficient [128].

Figure 8. UAV inspection and monitoring (a) UAV-based traffic monitoring [101]; (b) UAV-based mine monitoring [105]; (c) UAV-based environment monitoring [106]

Another emerging trend for electric companies is the use of UAVs for circuit inspection. 85% of the annual inspection operations are now covered by UAVs according to the Inspection Center of Guangdong Power Grid in China. Its efficiency is 2.6 times greater than that of the conventional method, and the UAVs eliminated a big chunk of the operation workload [129]. Rotary-wing UAVs can also be outfitted with infrared (IR) cameras for wire inspections, such as to identify weak conductivity by processing the recorded images [130]. The ability of UAVs to take aerial images allows for real-time monitoring and inspection of mines [131]. UAVs can also be used to monitor smart industrial grids. Some scholars have investigated unlawful mining and gathered evidence by filming the mining site [132]. The cruise network of maritime UAV systems has been built for navigation, investigation, evidence collection, law enforcement, emergency rescue, and other purposes in maritime situations, taking the Yangtze River Basin as an example [133]. Dust accumulation on solar photovoltaic panels can be assessed by drones equipped with radiation sensor and thermal imaging camera [134]. Due to the benefits of UAVs in autonomous operation, remote sensing, vision and thermal detection for dangerous or hard-to-reach locations, they are often used for detecting spills of water, gas and oil in pipelines [135] (Figure 9).

Figure 9. UAV inspection of solar photovoltaic panels [134]

3.4 Logistics and Transportation

The growth of e-commerce has significantly aided the logistics sector's development. UAVs for logistics and transportation have received a lot of interest and investment from related worldwide corporations since Amazon proposed the last mile delivery concept in 2013 [136, 137]. Rotor-wing UAVs are very beneficial for increasing logistical efficiency and lowering operating and environmental costs due to their superior hovering stability and flight speed [138]. The use of UAVs in logistics might increase accessibility and coverage for deliveries to less developed regions, notably in emergency scenarios like distress rescue, medical emergencies, and disaster reconstruction [139]. In light of the global COVID-19 outbreak, cold chain logistics made possible by UAVs offer a significantly safer alternative to traditional grocery purchasing.

Numerous domestic and international businesses have previously created UAV transportation plans and used them to supply practical logistics. Amazon has constructed a "Airborne Fulfillment Center (AFC)" using drones [140], and created Amazon Prime Air, a quick delivery service with a 30-minute turnaround time (maximum delivery distance: 16 km). In addition, DHL [141], Google [142], and Swiss Freight [143] all use rotary-wing UAVs to deliver goods quickly. Domestic businesses, particularly Chinese e-commerce and express delivery companies like Alibaba, JD, SF Express, and ZTO, have finished testing drone delivery, and encouraged the use of UAV delivery [97]. 2015 saw the Federal Aviation Administration (FAA) of the United States carry out the first drone-based medical delivery [144]. In the meanwhile, Apian et al. evaluated the delivery of coronavirus samples using rotary-wing UAVs. The National Health Service (NHS) Air Grid (NAG) is anticipated to receive the service [145] (Table 5).

Table 5. Logistics advantages of UAVs

Scenario	Advantage	Focus	Assessment	Enterprises
Rural areas, e-commerce distribution	Low cost	Distribution	UAVs save cost by 60-70%.	JD, Amazon, Antwork, etc.
Fourth and fifth tier city freight	Low cost, mobility and flexibility	Feeder transport	Compared with manned aircrafts, UAVs cut down the personnel, construction, and facility costs, and relax the constraints on personnel and facilities.	Star UAV, SF Express, etc.
Distribution and integrated logistics systems, warehouses and yards	High efficiency	Distribution, inventory inspection	UAVs support fast delivery in 30 minutes	Amazon
Remote areas, special locations	Accessibility	Delivery	UAVs saves manpower to make up for the lack of ground transportation, and works more flexibly than manned aircrafts.	DHL, SF Express, JD, etc.

Because of their speed and adaptability over short distances, rotary-wing UAVs are particularly popular. By placing orders via mobile phones, Sora Raku drones in Japan may carry food, drinks, and other supplies to golfers at drop-off locations on golf courses [146]. UAVs can drop response equipment for the delivery of emergency supplies. In the first marine UAV rescue event, the UAVs arrived at the target site to deploy the life buoy in under 70 seconds, whereas it would have taken the lifeguards at least five minutes to arrive [147].

Before medical professionals arrive, UAVs can also deliver life-saving supplies like automatic external defibrillators (AEDs) and cardiopulmonary resuscitation (CPR) equipment to patients experiencing medical emergencies. A companion can be instructed to administer the supplies to increase the patient's chance of survival [148]. Industries and the military have shown a great deal of interest in heavy-duty rotary-wing UAVs that can transport over great distances and at great altitudes. In mountainous places, heavy-duty UAVs offer simple construction methods. A UAV transported 300 kg of supplies to engineers working on a mountaintop at the Lijiang power project building site in China [149] (Figure 10).

Figure 10. UAV-based delivery (a) Amazon [97]; (b) DHL [95]; (c) JD; (d) Sora Raku [146]; (e) rescue UAV [147]; (f) Medical UAV [148]; (g) Heavy-duty UAV [149]

Despite their benefits, the use of rotary-wing UAVs in logistics still exhibits some drawbacks. First, advancements in related technologies are required for UAV itself, including payload capacity for hauling bulky goods, weather-resistant stability control, and long-distance flying power endurance [97]. Second, in order to safeguard social security and privacy, comprehensive flight laws and regulations must be adopted by government officials [95]. The integration of costs, resources, and other factors will eventually become crucial components of industrial reorganization from the viewpoint of UAV industries [150].

4. Conclusions

The design and technology of rotary-wing UAVs have steadily improved over the years, laying a strong foundation for commercialization and application. This will draw inspiration from increasingly sophisticated and dependable UAV designs for use in broader and more difficult settings. Rotary-wing UAVs will be used in a variety of businesses and will inevitably become a staple of our culture.

In commercial applications, rotary-wing UAV design and configuration will be far more varied. To meet application requirements, the structure architecture, power source, communication and control network, as well as carry-on devices, may have diverse morphologies. Given the widespread use of rotary-wing UAVs, more criteria for safety and standardization will be proposed, and the market will be subject to legal restrictions. This presents the rotary-wing UAV industry with both a challenge and an opportunity.

Rotor-wing UAV development has reached a relatively mature stage. The development of UAVs will be primarily focused on two factors as new technology evolve: On the one hand, visual perception-based autonomous intelligent control will replace the current control system for individual rotary-wing UAVs, significantly enhancing autonomy. Without a satellite, the UAV can still track objects and avoid obstacles thanks to intelligent autonomous perception. On the other hand, research and applications will increasingly focus on the placement, management, and behavior of a cluster of rotorcraft UAVs. The mission's dependability and the equipment's maintainability will both be significantly enhanced when UAVs work together in groups.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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