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REVIEW ARTICLE-MECHANICAL ENGINEERING

Recent Advances in Unmanned Aerial Vehicles: A Review

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Abstract

In recent decades, aerial robots especially small UAVs and drones have witnessed tremendous improvements in terms of their structure, working methodology, flying features and navigation control. UAVs are highly utilized in a wide range of services such as photography, path planning, search and rescue, inspection of power lines and civil constructions, etc. This manuscript reports a wide overview and comprehensive survey of recent developments in commercially available UAV's and gives a brief note on the progress and research covered in last 10 years. The research presents a roadmap to understand the successive development of advanced drones/ UAVs in terms of their geometric structure, flying mechanism, sensing and vision ability, aviation quality, path planning, intelligent behaviour and adoptability. A literature survey is conducted systematically on 254 retrieved articles published in the last 10 years and scaled down to 96 relevant articles. In these shortlisted articles, path planning, neural network, artificial intelligence, inspection, surveillance, tracking and identification, etc. are the most relevant methodologies or applications presented. The current research is concerned about the growth and impact of UAVs/drones in the society and also inspires the newbies to carry research in this field and propose new methods to select or equip the flying robot for a specific application in various fields. This article also assists researchers in understanding and evaluating their research work in the context of existing solutions. It also helps newcomers and pilots/practitioners to quickly gain an overview of the existing vast literature in the related fields.

Keywords Unmanned Aerial Vehicle (UAV) · Quad-copter · Surveillance and inspection · Coordinated path planning · UAV communication networks

1 Introduction

Unmanned Aerial Vehicle (UAV) or pilotless aircraft operates with advanced components including a physical model, Ground Control Station (GCS), modern sensors and a platform for ease of communication between them. In the past, UAVs are used for civilian and military operations such as rescue and search, climate monitoring, surveillance, weather forecasting and mapping. Since the evolution of modern technology and innovations in internet, UAVs has completely changed. Nowadays, UAVs are also used in emergency evacuations during natural disasters like storms, floods and bush fires, etc.

An expected figure of applications of UAVs from 2010 to 2022 in various fields is represented in Fig. 1. They have better performance in maximum roll angle, turn angle, path length, and flexibility in maneuvering, high scalability, portability and mobility. Apart from this, UAVs are also widely used in civil constructions such as the delivery of materials to an inaccessible location in construction sites and monitoring the constructed buildings for finding damages to achieve the purpose of smart cities. Its usage is also increasing in various domains of real estate management and smart cities. The communication methods have completely evolved from the most advanced platform starting from the first generation (1G) with no data capabilities to the fifth-generation (5G) with end-to-end connectivity and IP networking. 5G presents a cutting-edge future archetype that will ubiquitously and completely link all across the internet as shown in Fig. 2 [1].

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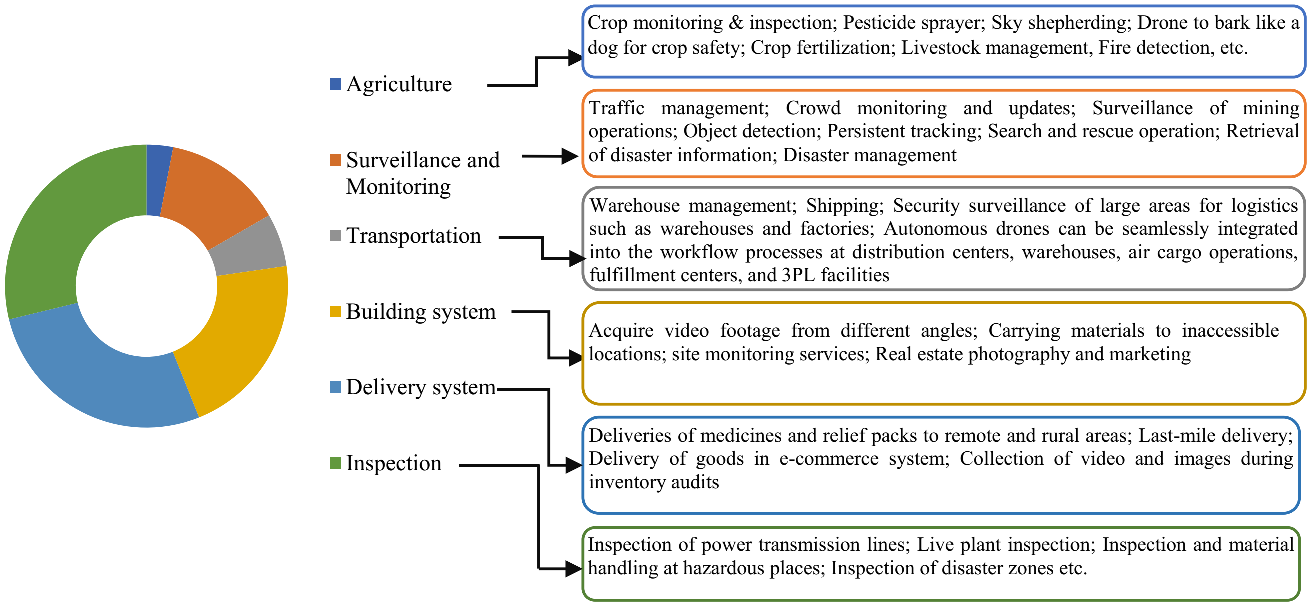


Fig. 1 Expected reach of UAVs in various applications

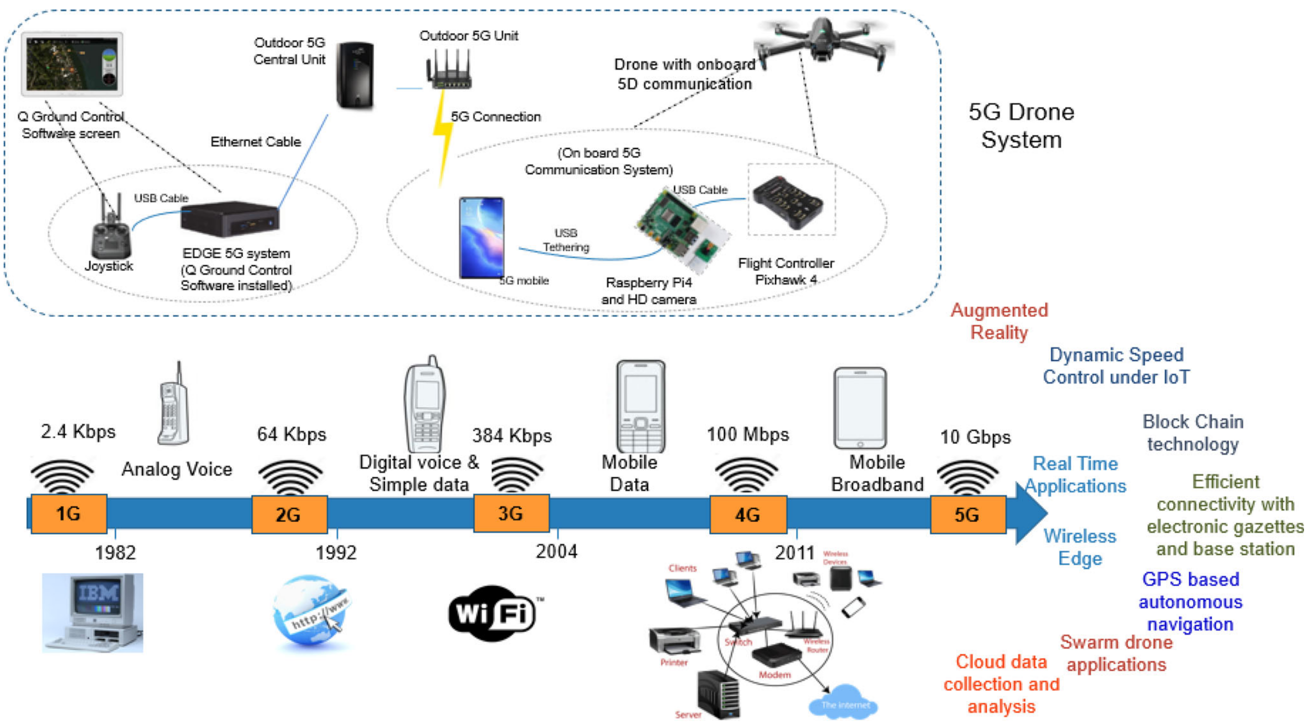


Fig. 2 Evolution of communication technology along with a 5G Drone system and possible upcoming technology/applications for drones [1, 95]

UAVs are classified based on different parameters such as Size, Weight and Power (SWAP). These parameters refer to maximum flight time, altitude, computational speed and communication. Similarly, High Altitude Platform (HAP) refers to better and broader communication with double payload capacity. There must be a fundamental trade-off between the two altitudes platforms for incorporating storage capacity and maximum coverage area. According to the report of the world's second-largest professional services enterprise Price water house-Coopers (PwC) and Interact Analysis, estimates that the global market for UAV applications will exceed $20 billion in 2022 [2]. In the year 2016–17, the United Business Media (UBM) has recorded a 30% growth in UAVs and a hike of 40% in 2017–2018 [3]. According to the forecast yearly report of the Aerospace and Federal Aviation Administration (FAA), in the United States of America, the purchase of UAVs has reached seven million in 2020 [4].

Despite the rapid growth of drone development and marketing, there are very limited reviews showing a road map of step-by-step growth in drone's capabilities distinguishing their types, categories, design and functionality, application, specific developments and major domains of researches [5]. Such reviews are important inputs to select or equip the flying robots for a specific use, to realize the impact of drones in the upcoming society and to grasp important information of its successive growth and current researches and advancements [6]. Thus, for summarizing all such researches, a survey is carried-out over top journals and conference research articles published in the last decade. From the survey, it is observed that the types of UAVs are increasing quickly. This manuscript gives a brief overview of all types of aerial robotics including flapping wing, fixed-wing, spin copter, cyclo-copter, ornithopter, tri-copters, quad-copters, hexa-copters, and octa-copters, etc. along with the structural models of aerial robotics, navigation control and application aspects are also presented comprehensively. In line with the trend of drones, the use of small-scale rotorcraft robotic systems (SRURS) is also in its developing phase [7]. These SRURS are generally weighed less than 25 kg or up to 10 m in dimension and are widely used for the applications of surveillance of environment, photography, the response of nuclear disaster, monitoring of power lines and survey of agriculture, etc. [8]. The research in aerial manipulation also attracted researchers for its wide applications in inspections of bridges and power transmission lines, tool operations, transporting of objects, wall climbing, delivery of goods, etc. [9–11].

1.1 Definition of UAV/Drone

The abbreviation of DRONE is Dynamic Remotely Operated Navigation Equipment. A UAV is also defined as a drone without any onboard pilot and operates autonomously or with the help of a flight controller operated from the ground station [12]. The degree of freedom in UAV is varied for executing the special functions like stabilization and altitude lock, Inertial Measurement Unit (IMU), Global Navigation Satellite System (GNSS) is used for locking the position in mid-air. These additional components and sensors will make the UAV more autonomous and succeed in missions like path planning, obstacle avoidance, and autonomous take-off and landing. From the literature, it is noted that UAVs are named or presented with different names like Aerial-rotor, Vertical take-off and landing aircraft, multi-rotor and rotorcraft, etc. These keywords help in finding the research papers related to UAVs.

1.2 Types/Categories of UAVs/Drones

UAVs are generally classified by their flying principle because of their aerodynamic structure. UAV's having heavier mass will depend on propulsive thrust to fly into the air. Further, they are categorized into two types, i.e., 'rotor' and 'wing' type. Rotor UAV will depend on multiple rotors and propellers attached to them to generate the required amount of thrust to lift upwards. Similarly, UAVs with wing types will depend on their wings to produce the aerodynamic effect for lifting upwards into the air. This is classified further into three sub-categories, i.e., flapping-wing, fixed-wing and flying-wing. The UAV with a light weight like a parachute, balloons and blimps will rely on forces of buoyancy to fly in the air.

Floreano et al. [13] discussed the different categories of UAV/Drones. Wherein, drones are categorized based on their mass and flight time. UAVs with heavier mass will have the capability to carry heavy payload and can perform autonomous and multiple tasks. Fixed-wing and Rotor-type UAVs are heavier in mass and relatively big in structure. Considering the aerodynamic efficiency, fixed-wing UAVs can have more flight time compared to rotor-type.

The structure of this manuscript is organized as follows: Sect. 1 gives a brief introduction to the current study and evaluation of UAV in various applications. In Sect. 2 the methodology followed to identify research articles in the field of UAVs are briefly explained. Section 3 describes the architecture and different components of UAVs. Section 4 shows an overview of UAVs yearly distribution, and types of UAV/drones with growth and need of autonomy. Finally, Sect. 5 concludes the manuscript with a glimpse of upcoming developments.

2 Methodology of Survey

This section explains the methodology and steps carried out in the survey and the scope of research related to UAV/drones. To identify relevant articles towards the scope of research, a well-defined process is carried. The overview of published papers with the methods and concepts are explained and compared with the other types of aerial robotics.

2.1 The Method Followed to Identify UAV Research Papers

To search high impact papers/research concerning aerial robotics or UAV, many titles and keywords are collected from the top journals and conferences which includes IEEE, Web of Science and Scopus index journals [14], etc. The collected list of keywords is grouped and referred to as A1, A2, A3, A4 and A5. A1 refers to the articles focussed on UAV with flapping, fixed wing and aerodynamic structure.

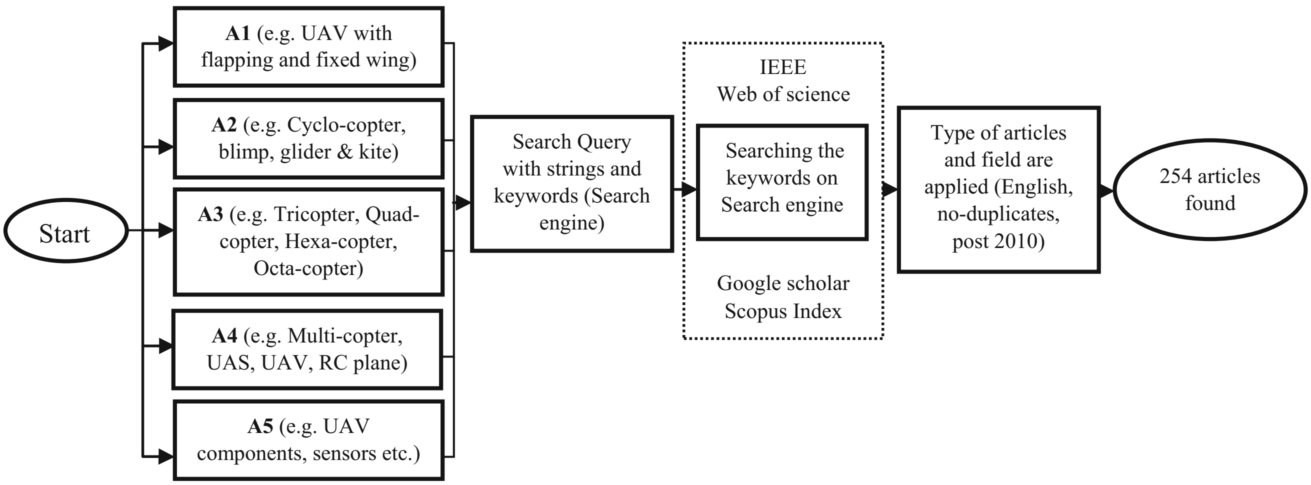


Fig. 3 Retrieval of the articles using keywords

The aim was to retract the articles with domain-specific. The keywords used for A2 are concentrated on UAV's regarding cyclo-copter, blimp, glider and kite, etc. The keywords designed for A3 are used for retracting articles on tricopter, quad-copter, hexacopter and octacopter. The keywords in A4 are used for searching articles on multi-copters, UAS, UAV and Radio Control (RC) planes. Keywords linked to A5 are concerned with different components mounted on UAVs, and sensors attached for various applications. The different stages involved in the retrieval of articles with linked keywords are used in different search engines as shown in Fig. 3.

As an output of this phase, highly cited articles published in high impact factor journals are collected from the search engines. The total number of articles retrieved is 254. As shown in Table 1 keywords are entered with their abbreviation and short-form e.g., UAV and its abbreviation (Unmanned Aerial Vehicle), MAV (Micro Aerial Vehicle), etc. These keywords will find the papers related to words like copter, aerial, robotics, quad-rotor/quad-copter and drones. A screening process is followed to filter the articles to match the relevant keyword. A manual step-by-step process is as follows:

i. In the first step topics presented in posters and workshops are not considered because of the limitations of papers.
ii. The articles or manuscripts should be published on or after January 2010.
iii. Papers that have the most relevant information only on topics related to drones, aerial vehicles and quad-copter, etc. with modelling, methodology, fabrication and results are considered.
iv. Research papers with experimental results of flying and hovering, path planning and surveillance are suggested. (A few papers will not show any experimental results to their method and proposes to implement these methods in UAVs. such papers are not considered.)
v. In research papers like inspections, communication and image processing, it should be noted that the data of images and datasets of inspection should be collected

Table 1 List of keywords collected from the research papers of top journals/conferences

Sl. No	Keywords		
1	Unmanned Aerial Vehicle (UAV)	12	Aerial Manipulating
2	Micro Aerial Vehicle (MAV)	13	Modelling and control
3	Dynamic Remotely Operated Navigation Equipment (DRONE)	14	Flapping
4	Small-Scale Rotorcraft Robotic Systems (SRURS)	15	Rotor craft
5	Vertical Take-off and Landing (VTOL)	16	Fixed-wing
6	Unmanned Aerial Systems (UAS)	17	Gliding
7	Quad-copter	18	Flying
8	Surveillance and monitoring with UAS	19	Dragonfly
9	UAS path planning for disaster management and relief	20	Copter
10	UAS communication networks	21	Multi-copter
11	UAS path planning and trajectory planning	22	Propellers

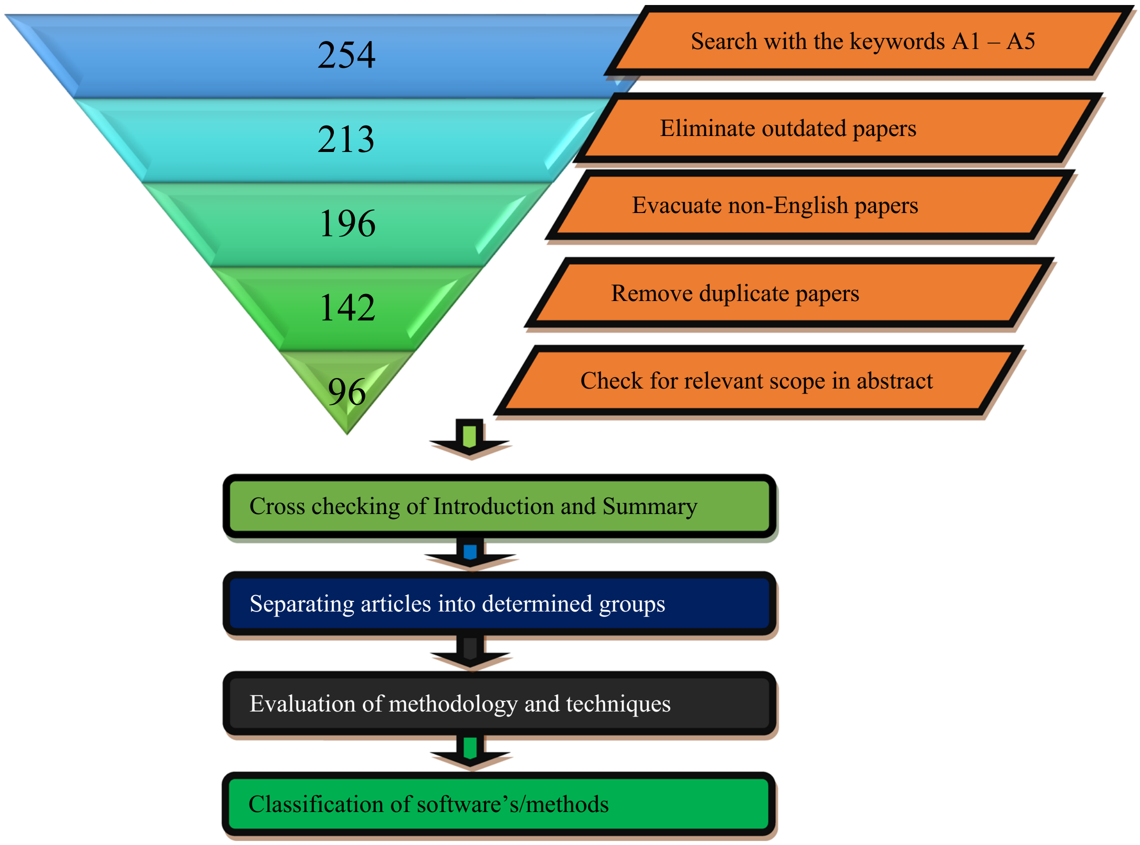


Fig. 4 Methodology of literature survey

by the author. Otherwise, such papers will not be useful for justifying the experimental results shown in the paper.

vi. In the selection of a review paper, it is mostly observed that most of the authors will include methods that are irrelevant and cannot be implemented in UAVs or drones. Such papers are also not considered. Review papers with references or methods of the past five years are considered to be useful.

vii. Modelling and analysis research papers are considered only if the author showed valid results. Otherwise, such papers are also not proposed to be useful.

viii. All manuscripts must be in the English language.

ix. Unique research work articles should be considered leaving duplicate ones.

x. The last step is to categorize the retrieved articles. The introduction and discussion and summary are closely followed to find the domain of the retracted paper. Each step of methodology carried for this retrieval process is shown in Fig. 4.

As discussed in the survey methodology, at first google trends are used to find the search string used in this manuscript. The different keywords used in the trend search are UAV path planning, UAV communication, UAV inspection, UAV surveillance and UAV industry as shown in Fig. 5, and the growth rate in commercial market size of UAVs from 2010 to present and forecasted up to 2025 in terms of commercial drone sales and revenue generation worldwide is shown in Fig. 6. From the figure, it can be observed that there is a spike in UAV communication from 2012 and 2017 onwards. UAV inspection has attained numerous growths since 2010 as it is widely implemented in the inspection of various applications such as power lines, solar panels, civil bridges and windmills, etc. UAVs especially used for surveillance is declining due to the non-availability of long-lasting power. UAV industries are also growing and maintaining consistency from the beginning of a search.

2.2 Topics Covered on UAV

Liew et al. [15] conducted a vast survey on types and categories of UAVs. The information regarding the evolution of UAV is summarized in a pie chart as shown in Fig. 7. It is observed from the pie chart that the number of research papers published is on the topics of hardware development (31%) and control and modelling (28%) as it covers more than 50% of the pie chart. But gradually the growth is

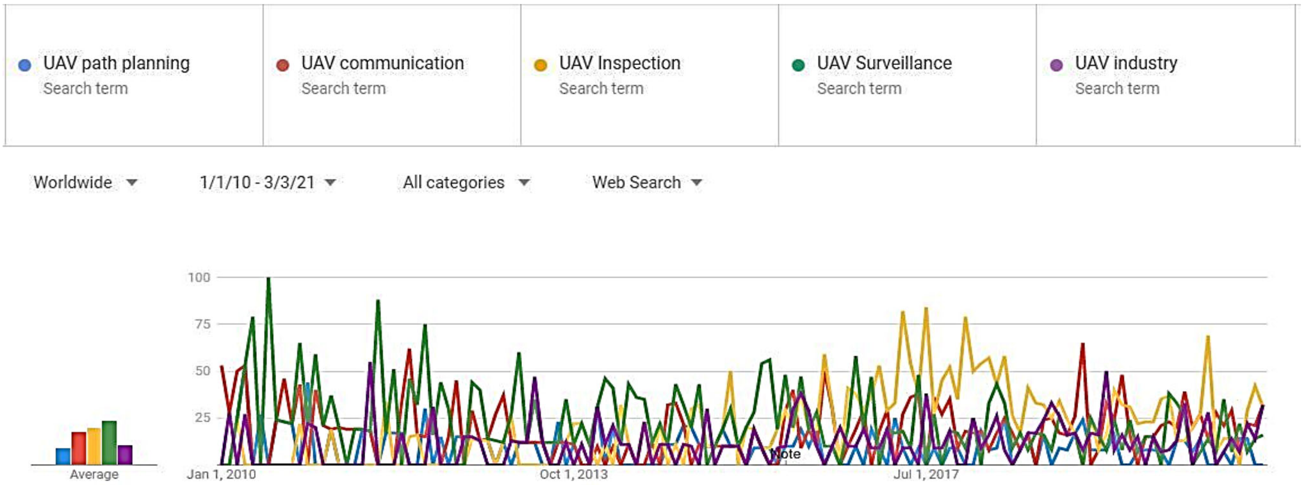


Fig. 5 Analysis of keywords searched in google trends since 2010

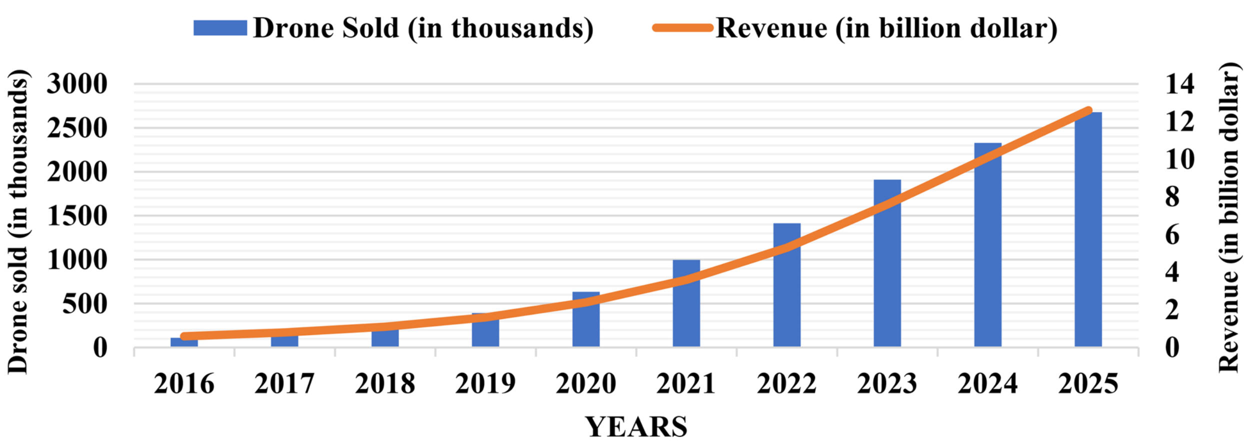


Fig. 6 Projected worldwide market growth for commercial drones [96]

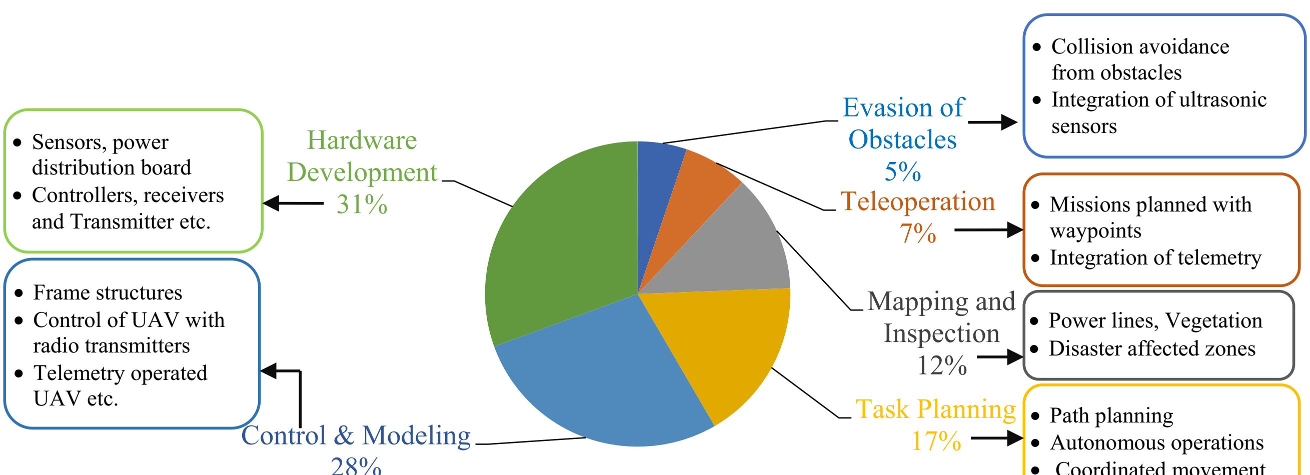


Fig. 7 Research on evolving of UAV [15]

observed in task planning, mapping and inspection as these are the emerging topics in the present era. Beyond this, the research papers also published on navigation, GPS location and collision avoidance. This is the most covered topic after 2016 in the top journals and conferences.

3 Components of UAV and its Architecture

In this section components of UAV and architecture are explained in brief along with their function and applications.

3.1 Drone/Quad-Copter

Drones are also categorized depending on their structure and weight, i.e. Macro aerial Vehicle, Micro Aerial Vehicle (MAV) and Nano Aerial Vehicle (NAV). Kumar et al. [16] carried research on quad-copters and discussed their flight time challenges.

In addition, the main quad-copter is equipped with different components for high-level functioning in different applications such as path and trajectory planning, inspection and evaluation, etc. The structure is mainly divided into data collection, data processing and data actuation or evaluation. The data collection system handles the functioning of onboard sensors, cameras, battery and smart devices. The data collected by these devices is processed by the central core unit of UAV for defined tasks like path planning, surveillance, inspection and detection, localization, etc.

Figure 8 depicts the area covered by components and sensors of UAV. These hardware onboard components cover the area of different applications such as path planning, collision avoidance and inspection, etc. during the hovering of UAV. LIDAR and infrared devices are mainly used for collision avoidance and mapping, whereas camera and GPS are used for surveillance of particular area or path of the UAV in front and rear direction. The central core system actuates the UAV for real-world environment applications as shown in Fig. 9. UAVs are equipped with various components such as Electronic Speed Controller (ESC), Camera & Gimbal, Flight controller and Lithium-ion battery (LiPo), etc. as explained below.

3.1.1 Electronic Speed Controller

ESC is mainly used to offer power and high frequency to the UAV motors. The main function of ESC's is it converts Direct Current (DC) to 3-phase Alternate Current (AC) and is also used for alternating the motors speed.

3.1.2 Battery

In UAVs, Lithium-ion Polymer batteries (LiPo) are used for powering the onboard components and sensors. Drone pilots always prefer to carry an extra battery in case of an emergency during the flight.

3.1.3 Flight and Radio Controllers (FC and RC)

The flight controller plays a key role in UAV during hovering in the mid-air. Improper calibration of flight controllers will lead to crashes or non-stability in the flight of the drone. A highly configured radio controller with switchable sticks will lead to maintaining connectivity for long-range and to attain vertical take-off landing. Lim et. al. [17] discussed the importance of flight controllers in quad-copters and carried a survey of FC's available in the market. According to their survey, the open-source FC's are KK 2.1.5, Arducopter, Aeroquad, Pixhawk, Multiwii, Arduino and Raspberry pi. Apart from the FC's their survey also provides information about the structure and cost estimation of open-source FC's. Development in FC's has gradually increased over the past five years in terms of programming and operation. Pixhawk recently has released a more stable FC into the market known as Pixhawk-cube for Quad, Hexa and Octa-copters. For more information and survey regarding FC & RC for multiple-copters, researchers are suggested to go through this given reference for knowledge on the selection of components and controllers [18, 19].

3.1.4 Camera and Gimbal

Wood et al. [20] discussed the steps involved in building a quad-copter with the different components and also gave a brief note on the various applications of quad-copter. The developed model from their study is used for the application of surveillance and hovering at a particular position. Their copter was much useful in societal applications like surveillance of traffic updates and crowded areas. Fabrication, control, actuation and battery capacity of flapping wing UAV's and their applications are explained in the present field. Thermal cameras are also used in UAS for the inspection of solar panels or power transmission lines. These cameras are also used in agriculture for the detection of disease and the breeding of plants. Gimbal is used to rotate the camera in x, y and z directions without any disturbance in the tilt of the camera. It provides the stabilization for capturing or recording high-definition images and videos.

Besides the frame or the structure, many other system parts in a drone are gradually being improved, i.e., GPS/GNSS (Global Positioning System/Global Navigation Satellite System), motors to rotate propellers, ESC (Electronic Speed Controller); battery and its charging systems,

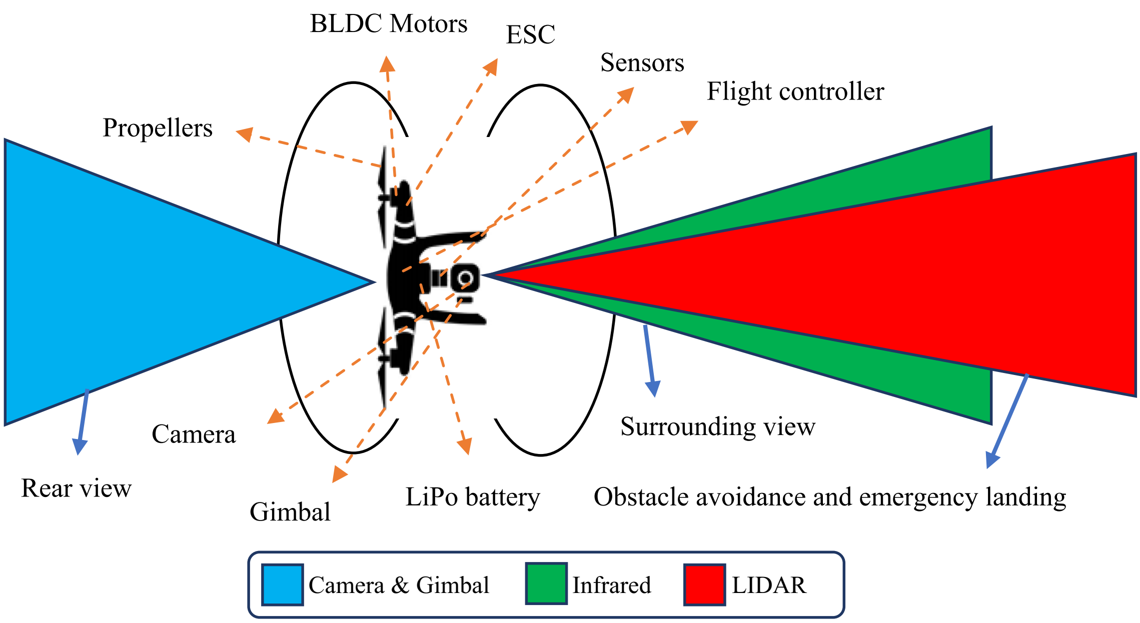


Fig. 8 Components of UAV

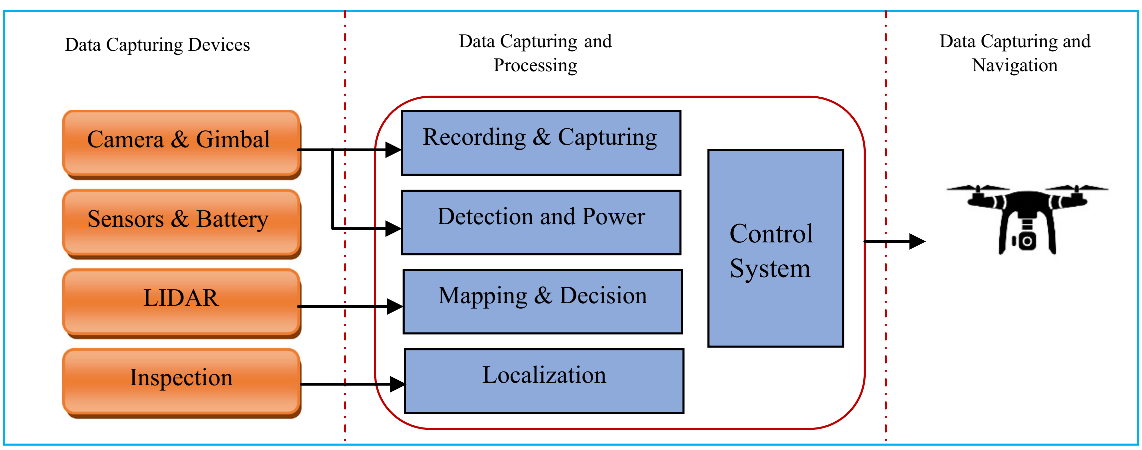


Fig. 9 Functional components of UAV

onboard controller, receivers, transmitters, and propellers. Some commonly used examples of these components are shown in Table 2.

Day by day, gradual improvements are also seen in the development/application of advanced accessories, i.e., camera (infrared, HD cameras and high-speed camera) and gimble system; sensor (gyroscope, Magnetometers, optical, ultra-sonic and accelerometer, etc.) and communication systems (Table 2).

3.1.5 First Person View (FPV) of UAV

Lupashin et al. [21] have demonstrated a video of quad-copters and their motion of flight indoor and outdoor. They have further used the technique of motion capture for explaining the topics of rhythmic flight, aggressive adaptive flight, unstable flight, iterative learning and balance of quad-copter for a perfect flight. Ollero et al. [22] also explained about a video and results of UAV from four European projects. Mellinger et al. [23] discussed the techniques of capturing motion, manipulation, perching and flying through the window with the quad-copter.

3.2 Development of UAV's and Types

The information regarding types of UAV's and growth are collected from the past two decades by observing in the results of Web of Science and Scopus [24]. The information is framed into a graph for better understanding as shown in

Table 2 Some examples of quad-copter system parts and advanced accessories used in modern commercial drones

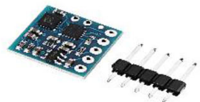
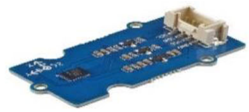
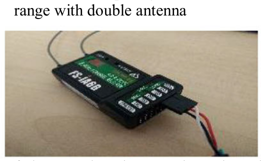
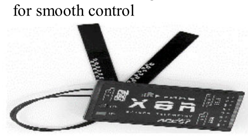
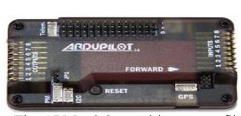
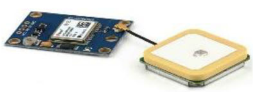
Commonly used accessories in advanced commercial drones				
Camera & Gimbal	 8K Video Resolution; Up to 8000 x 6000 Still Resolution, Gimbal Drone Camera	 Thermal Cam module AiD-MC8 - Electrical Coaxial Octocopter Drone	 10x Zoom Camera gimbal AiD-MC8 - Electrical Coaxial **Octocopter Drone**	 iXM-120 MP Camera and Gimbal for high resolution aerial imaging
Sensors	 Magnetometers are 3-axis devices to determine the magnetic field along each axis, relative to its mount in the UAV	 Ultrasonic sensor: 5V operating voltage, 4500cm maximum sensing range and 40kHz frequency, Obstacle avoidance in drones	 Gyroscope have 6-Axis; 6 DOF inbuilt IMU; BMI088 vibration sensor; used for balancing roll, pitch and yaw	 Lightweight optical flow sensor; short LIDAR and CAN protocol for communication
Communication System	 TS5828L Mini 48CH 600MW Telemetry; Channels: 48CH; Frequency: 5.6GHz-5.9GHz; range: 1-1.5km	 Wireless Telemetry 433Mhz Kit for APM ArduPilot; Frequency: 5.8GHz; range: 5km distance in open area	 RFD 868 is a powerful long-range telemetry; Frequency range: 868 - 869 MHz; range: 10-12km distance in open area	 HereLink HD Digital telemetry with a mavlink input for bi-directional communication; Bandwidth: 20MHz / 10MHz; transmission range: 12-16km
Commonly used UAV system parts				
Propellers	 Propellers provide lift for the aircraft by spinning and creating an airflow. 1045 propellers provide 15° angle design in the end of the propeller to avoid whirlpool multi-copter flying	 Three-bladed propellers are the mostly used for smoother performance, speed and power consumption. Propellers with 4 or 5 blades allow better acceleration and significantly reduce vibrations	 Folding propellers reduce drag while not in use, thereby allowing for more speed or reduced power consumption	 Carbon fiber propellers produce less vibration due to their stiffness, and they are quieter too when spinning. They are lighter and significantly stronger than plastic when crashed, but not indestructible
Transmitters	 FlySky CT6B has 6 channels, 2.4GHz frequency, 20 dBm transmission power	 FlySky FS-i6 has 6 channels, 2.4 – 2.475GHz frequency, 1.6 - 6.4km range with double antenna	 FrSky Taranis Q X7 Access have 16 channels, hall effect gimbal sensors for smooth control	 FrSky Taranis X9D Plus have 24 channels, digital telemetry remote control
Receiver	 fs-r6b receiver have 6 channels and operating range of 500 – 1000m in the air	 fs-iA6 receiver have 6 channels and operating range of 500 – 1000m in the air	 X8R receiver have 16 channels and SBUS smart port telemetry receiver	 L9R receiver have 12 channels and RSSI output with 700 – 1000m range in the air
Onboard controller	 KK 2.1.5 have inbuilt 6050MPU; Atmel 644PA Display Lights; PID settings can be changed by onboard buttons	 The APM 2.8 multi-copter flight controller is a complete open source autopilot system with built-in compass; ATMEGA2560 and ATMEGA32U-2 processor	 Naza is a 32 – bit controller with in built memory card slot for flight logs; MPU6000 as main accelerometer and gyroscope; Spektrum DSM/DSM2/DSM-X satellite input	 Pixhawk orange cube is an advanced beta version in the family of flight controllers; inbuilt IMU and communication ports; built-In ADS-B antenna; carrier board

Table 2 (continued)

Battery	 Single cell Lithium-ion polymer battery; 3.7V	 Three cell (3s) Lithium-ion polymer battery; 11.1V	 Four cell (4s) Lithium-ion polymer battery; 14.8V	 Six cell (6s) Lithium-ion polymer battery; 22.2V
ESC (Electronic Speed Controller)	 Continuous current: 18A; Burst current: 255A; Lipo battery: 2-4S	 Continuous current: 20A; Burst current: 25A; Lipo battery: 2-4S	 Continuous current: 30A; Burst current: 40A; Lipo battery: 2-3S	 Continuous current: 30A; Burst current: 35A; Lipo battery: 2-6S
BLDC (Brushless DC motors)	 Motor KV: 1000; Current Capacity: 12A/ 60S; Li-Po Batteries: 2S-3S; thrust: 700gm	 Motor KV: 920; Li-Po Batteries: 3S-4S; thrust: 500gm	 Motor KV: 935; Li-Po Batteries: 4S-6S; thrust: 850gm	 Motor KV: 750; Li-Po Batteries: 2S-6S; thrust: 1500gm
GPS/GNSS (Global Positioning System/Global Navigation Satellite System)	 NEO-6M GPS is compatible with Arduino; inbuilt antenna & battery for fast signal acquiring; 5Hz position update rate; Operating temperature range: -40 TO 85°	 NEO-7M GPS is compatible with Ardupilot 2.6-2.8; inbuilt antenna; Tracking sensitivity: 161 dBm; Capture sensitivity: 148 dBm	 Here2 GNSS is compatible with pixhawk black or orange cube; HMC5983 MAG, and LIS3MDL Mag; 6CM Ground plane; Supports all satellite augmentation systems	 Here3 GNSS is compatible with pixhawk black or orange cube; RTK supported GNSS chip; Advanced version in its category

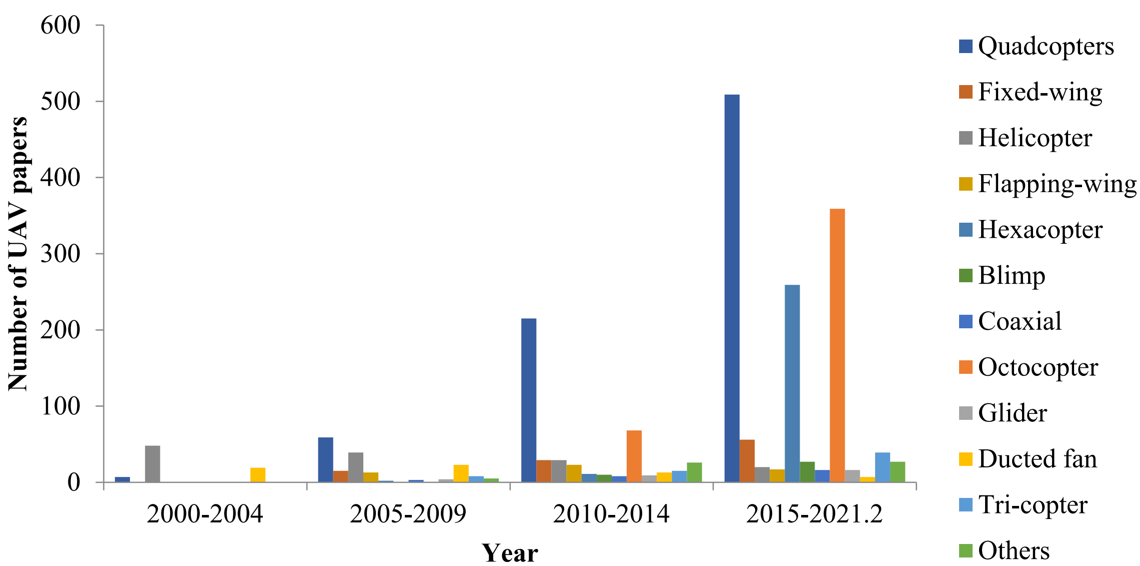


Fig. 10 Overview of distribution of UAV types with the change of research papers over the years (Best viewed in colour)

Fig. 10. It can be observed from the bar graph that the growth of helicopters is gradually decreasing starting from 48, 38, and 28 to 20. It is because of its design and control, maneuverability in air and cost. The number of Tri-copter papers remained 0 up to 2004 and increased to 8 in 2005–2009 and 15 in 2010–2014 and 39 in 2015–2021.2 (Up to 2021 February) because of its limited functions and carrying of payload.

The most impressive transformation in the bar graph is the growth of quad-copters i.e. from 7 in 2000 to 2004 to 509 in 2021.2 because of its flexible design and multi-operational function in various applications. Nowadays, quad-copters are also used for the transportation of goods and medicines in the field of hospitals and firms. Multinational companies like Amazon, E-bay, McDonald's and KFC are planning to use quad-copter as a means of transport for delivering the goods to the customers to save time [25, 26]. Research papers in the field of hexa-copter remained 0 until 2009 and the value increased to 11 in 2010–2014, in 2015–2021.2 it went on increasing to 259. In the same way, the number of papers in octa-copter remained at 68 till 2014 but in the year 2015–2021.2, 359 articles were found on the topic of octa-copters. The reason for the growth of interest in hexa-copters and octa-copters is the mode of control is easy in these copters i.e. if one motor of these copters fails during hovering it does not lead to malfunctioning of the copter and can be landed safely. Further, the control algorithm is not complex. These copters can carry more payload and the researchers can easily attach extra hardware like robotic arms or LIDAR sensors for mapping, inspection and various applications. Researchers are also showing interest in fixed-wing aerial robots as the value reached 56 in 2021.2. The interest in the field of other aerial robotics gradually increased from 2005 to 09 and lost its place as the UAV's were introduced [27, 28].

3.3 Overview of UAV's Yearly Distribution and Types

A survey is conducted in the ten top journals and international conferences from 2010 to date to identify the research papers with broad information on drones and aerial robotics as plotted in Fig. 11. During the survey, it is noticed that the number of research papers has increased from year to year as compared to other topics. Improvements in technology and sensors, flight controllers and receivers have made it easy for the researchers to concentrate more on the field of aerial robotics. A broad area of research is still being carried in this field and the numbers of papers are increasing with the current trends in hobbyist, research and competitions held all across the globe.

The topic of motion capturing system is also increasing rapidly in the field of UAVs or drones since 2009 [29]. This system will help to record the smallest movement of reflective markers mounted on UAV with the help of high-speed action multiple cameras in real-time as shown in Fig. 12.

In this literature survey, research is also carried out on multiple countries mostly publishing the UAV papers in journals and conferences (National and International). Among all of them, the top twelve developed/developing countries such as USA, Switzerland, France, Australia, Japan, Germany, India, China, South Korea, Italy, United Arab Emirates and others are mostly researching on integration of various sensors and modifications in the structure of UAVs for multiple applications. The list of countries in 'Others' are Spain, North Korea, United Kingdom, Canada, Belgium, Mexico, Austria, Venezuela, Slovakia, Portugal, Brazil, Czech Republic, Netherlands, Singapore, Saudi Arabia, Malaysia, Cyprus, Philippines, Iran, Taiwan, Israel, Croatia, Sweden, Hungary, South Africa, Finland, Iran, Turkey, Greece and Denmark.

4 Types of Drones or UAV

In the previous sections, a discussion is carried on the topics of UAV papers and their distribution in terms of percentages and numerical numbers across the world. In this section, a brief discussion is shown on the types of UAVs and their applications presented by the researchers in the past.

i. *UAV with flapping-wing*
   In various domains of robotics, BIOMIMETIC robots are one of the most lucrative domains across the globe. The unique aviation concept used in Flapping-wing micro aerial vehicles (FWMAVs) has received a lot of attention for improving aviation quality. It is being accepted for a wide range of possible uses in military and civic domains, including catastrophe investigation, intelligence collection, anti-terrorism reconnaissance, etc. They are characterized by good maneuverability, camouflage ability and high flight efficiency [30]. Approximately 1000 flapping-wing flying robots with stable flight performance have been produced so far. They were employed for a variety of purposes, including scientific study, flight testing and high-tech entertainment at parties [31].
   UAVs with flapping wings in the shape of insects are most common and they are also known as 'Ornithopter' and are about hand size. Ma et al. [32] have developed a novel based flapping-wing UAV (Fig. 13a) in the shape of Bee with a mass of 380 mg. This mini UAV was hovering with stability in the air. Peterson et al. [33] fabricated a model known as 'BOLT'-flapping-wing UAV and also known as a bipedal robot as it can move on the ground surface and can fly in the air (Fig. 13b). Paranjape et al. [34] have designed a unique type of UAV with wing articulation for controlling the head angles and flight path of UAV. This type of UAV can perch naturally on a human hand or chair (Fig. 13c). Rose et al.

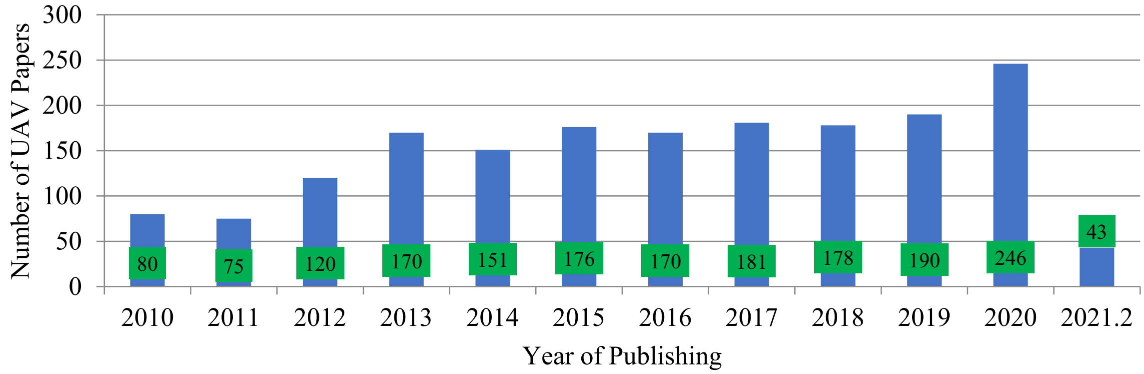


Fig. 11 Number of papers published from top journals and conferences from the year 2010–2021.2 with a moving average curve (Best viewed in colour)

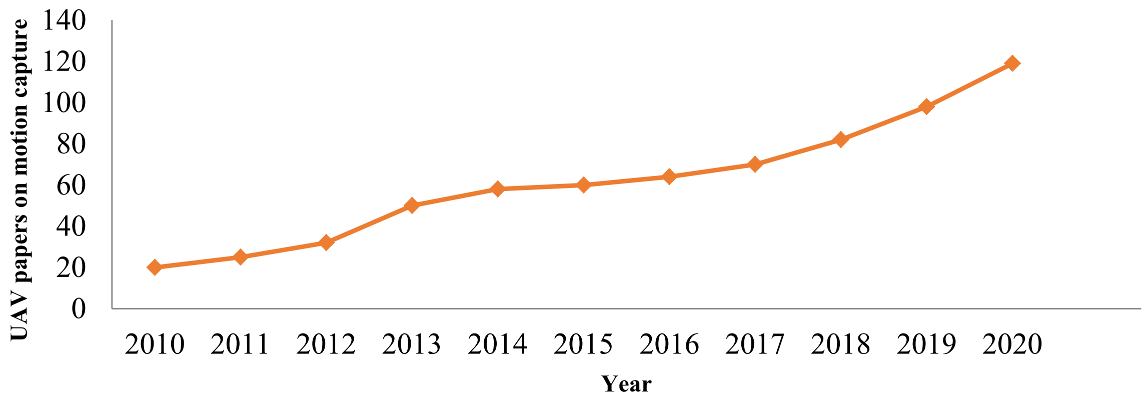


Fig. 12 UAV research papers over the years on motion capture systems

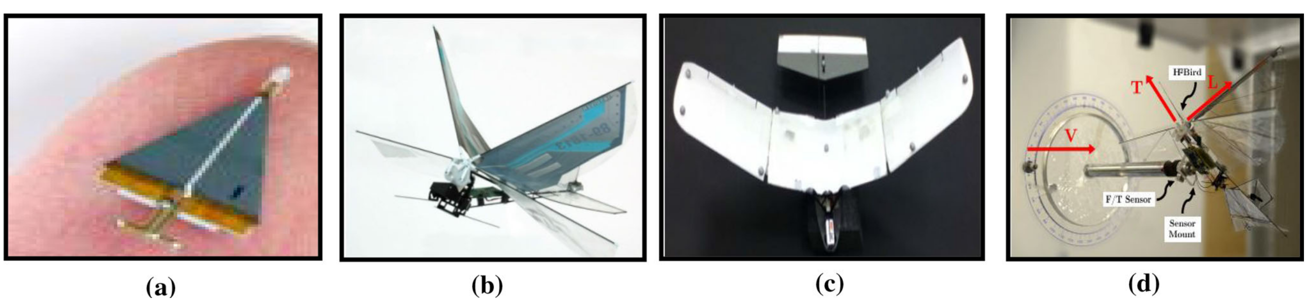


Fig. 13 Models of flapping-wing [**a–d**] [32–35] (Best viewed in colour)

[35] have demonstrated a flapping-wing UAV with a bird shape known as H^2 bird (Fig. 14d). It is widely used for comparing the data from wind tunnels and free flight with aerodynamic modelling.

In general, birds are the inspiration for developing FWMAV and fixed-wing aircraft. When a bird is flying, the actual airspeed experienced by its wings is a mix of forwarding movement of the body and flapping motion of the wings. The airflow over wings will be altered by the combination of these two types of motion, allowing the birds to fully utilize the high lift devices (Fig. 14). The air flow surrounding the birds and FWMAV in-flight differs significantly resulting in improvement of flying efficiency and performance.

He et al. [36] presented a boundary control approach for controlling the two links rigid-flexible wing for FWMAV. It's design is based on the bionics idea to improve aircraft movement and flexibility. The modelling and vibration restraint of a rigid-flexible wing are investigated in this study. The proposed control technique by the author solves these challenges and the controllers are seen to be built to suppress vibrations

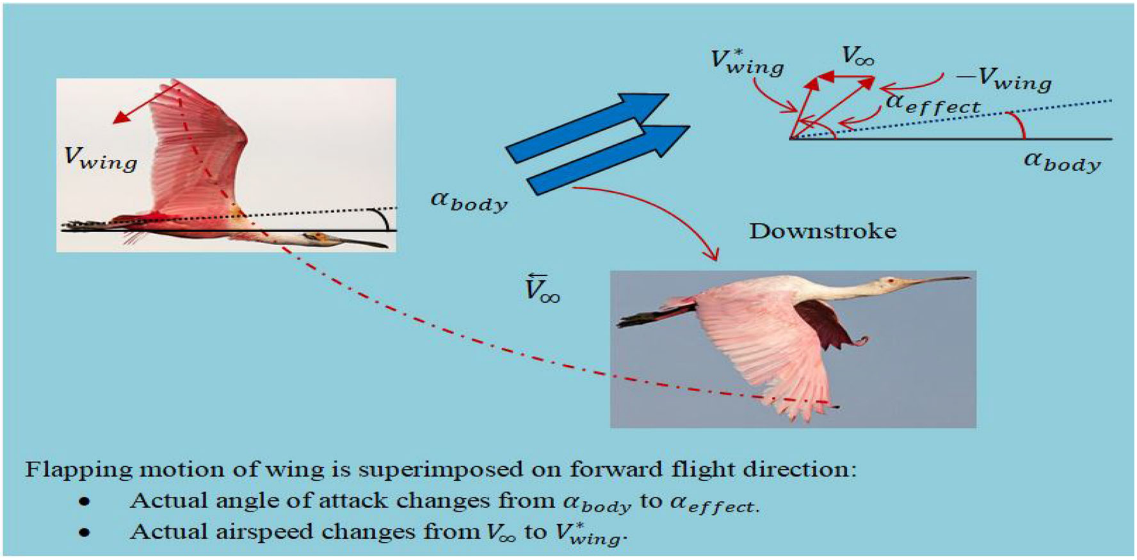


Fig. 14 Angle of attack and air speed of the FWMAVs wing is affected by flapping [36]

and deformations. In addition, the angular error appears to be decreasing.

ii. *UAV with Fixed-wing*

Fixed-wing UAV's are also known as airplanes. Due to their highest flight stability and longer flight time they are considered to be the dominant aircraft in the history of aviation. As compared to conventional multi-rotor aircraft it has the highest efficiency of energy and can stay and glide for a long time in the air irrespective of engine/controller failure. Bapst et al. [37] demonstrated a combination of UAV (Fig. 15a) with their modelling and design to achieve flight of cruise alike fixed-wing and Vertical Take-off and Landing (VTOL) like conventional multi-rotor.

Sa et al. [38] developed a fixed-wing UAV with the configuration of a quad-copter to fly safely in the air and achieve VTOL (Fig. 15b). Zufferey et al. [39] have fabricated a small autonomous fixed-wing UAV that weighs about 30 g (Fig. 15c). With onboard sensors like ultra-sonic, IR and optical flow, this vehicle will navigate safely by avoiding obstacles in the indoor environment. Daler et al. [40] developed a multi-functional UAV that can hover in the air and move on the ground surface by rotating its wings (Fig. 15d). Bryson et al. [41] fabricated a fixed-wing UAV with multiple sensors placed on it such as IMU, GPS, telemetry and monocular camera facing downwards direction for acquiring high-definition images and recording video (Fig. 15e). These vehicles are mainly used for applications like surveillance and mapping. Papachristos et al. [42] also developed a multi-functional fixed-wing UAV that can hover in the midair like a tri-copter and execute cruise flight (Fig. 15f). Kumara et al. [43] proposed a fixed-wing UAV for demonstrating the system identification and learning the model of complex dynamics with Gaussian process (Fig. 15g). Morton et al. [44] developed a solar-powered fixed-wing UAV by giving detailed information regarding modelling, design and development of hardware (Fig. 15h).

iii. *Cyclo-copter, Blimp, Glider and Kite UAV's*

A cyclo-copter is a type of UAV with a cyclo-gyro wing and additional wings fixed on the edges of the cylindrical structure. The required amount of forces is generated by adjusting the angle of attack with a fixed servo motor on it. Hara et al. [45] developed and fabricated a model of cyclo-copter based on the structure of pantograph. In these vehicles, flight control is achieved by contracting or expanding the wings by varying their diameters concerning the rotational axis (Fig. 16a). A blimp is a lightweight UAV (lighter than air) with an envelope structure that depends mostly on helium gas to generate lifting force. This envelope shape helps the blimp to maintain the internal pressure of the helium gas and achieve motion control using the units of actuation. Muller et al. [46] presented a blimp that can navigate autonomously with online motion planning systems in indoor environments (Fig. 16b).

A glider is a type of UAV that uses aerodynamics and its wings to glide freely in the air. It has a structure of fixed-wing UAV but it does not depend on a propulsion system for hovering. Woodward et al. [47] have built a glider inspired by a vampire bat, this glider will bound from the ground and use its wings to fly/hover in the midair (Fig. 16c). Kites are also known as parafoil UAVs, Christoforou et al. [48] introduced a kite UAV

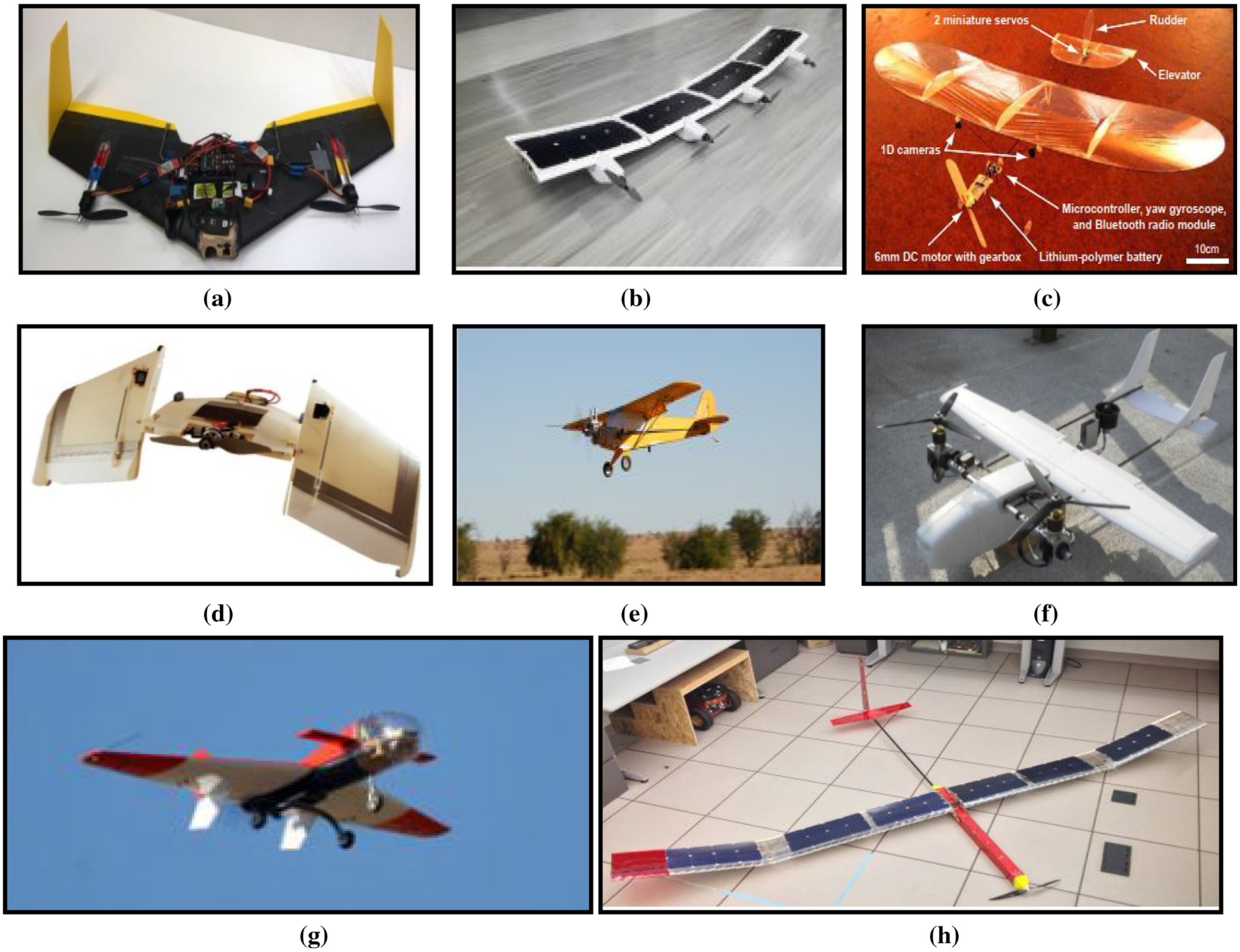


Fig. 15 Models of fixed-wing [**a**–**h**] [37–44] (Best viewed in colour)

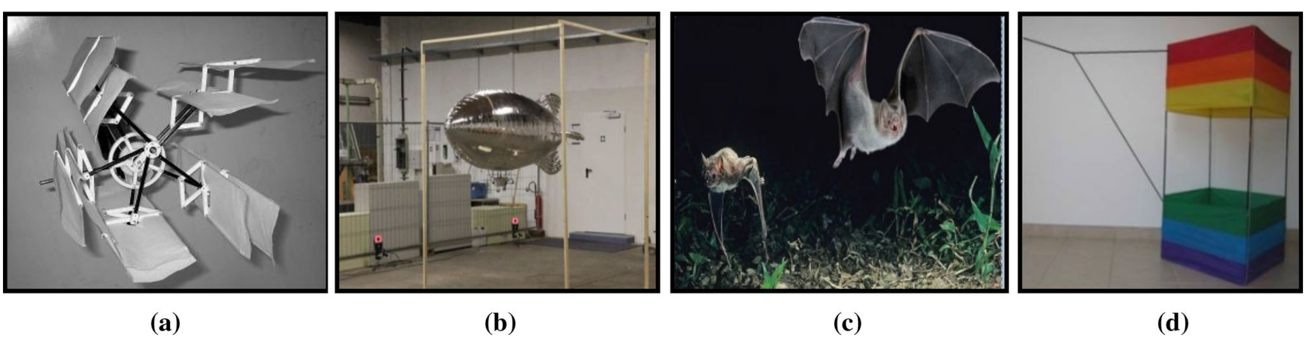


Fig. 16 Models of Cyclo-copter, Blimp, Glider and Kite [**a**–**d**] [45–48] (Best viewed in colour)

with robotic technology to fly autonomously in the air (Fig. 16d) for the application of aerial cargo delivery.

iv. *Tri-copters*

Kastelan et. al. [49] have developed a tricopter with three independent propellers and a rigid body for neglecting the dynamics of the vehicle as shown in Fig. 17a. A method of a pilot supported control scheme is proposed for steering the tri-copter. Belal Sababha et al. [50] has proposed a novel design and control mechanism for tri-copter (Fig. 17b). For stable maneuvering, the results of kinematic and dynamic modelling are simulated and corrected. Ziwei Song et al. [51] (Fig. 17c) have compared three different designs of tri-copter and rotor configurations are selected based on the

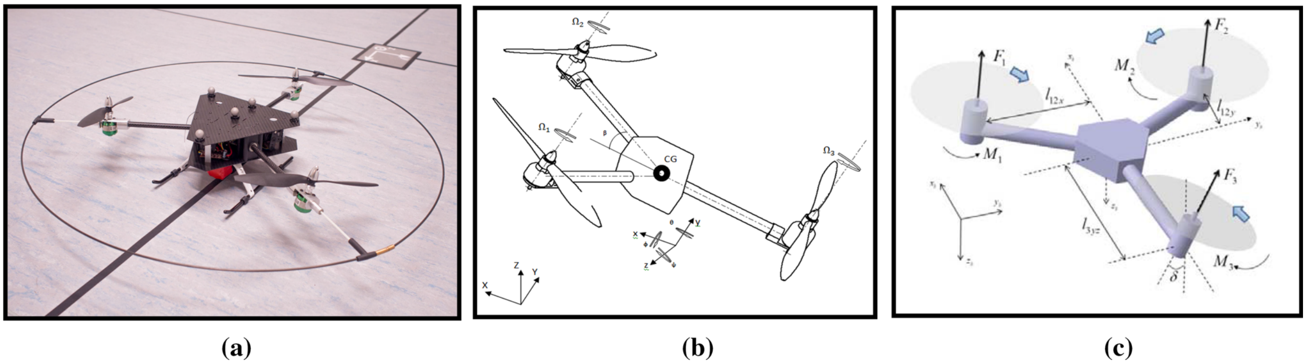


Fig. 17 Models of Tri-copters [**a**–**c**] [50, 51]

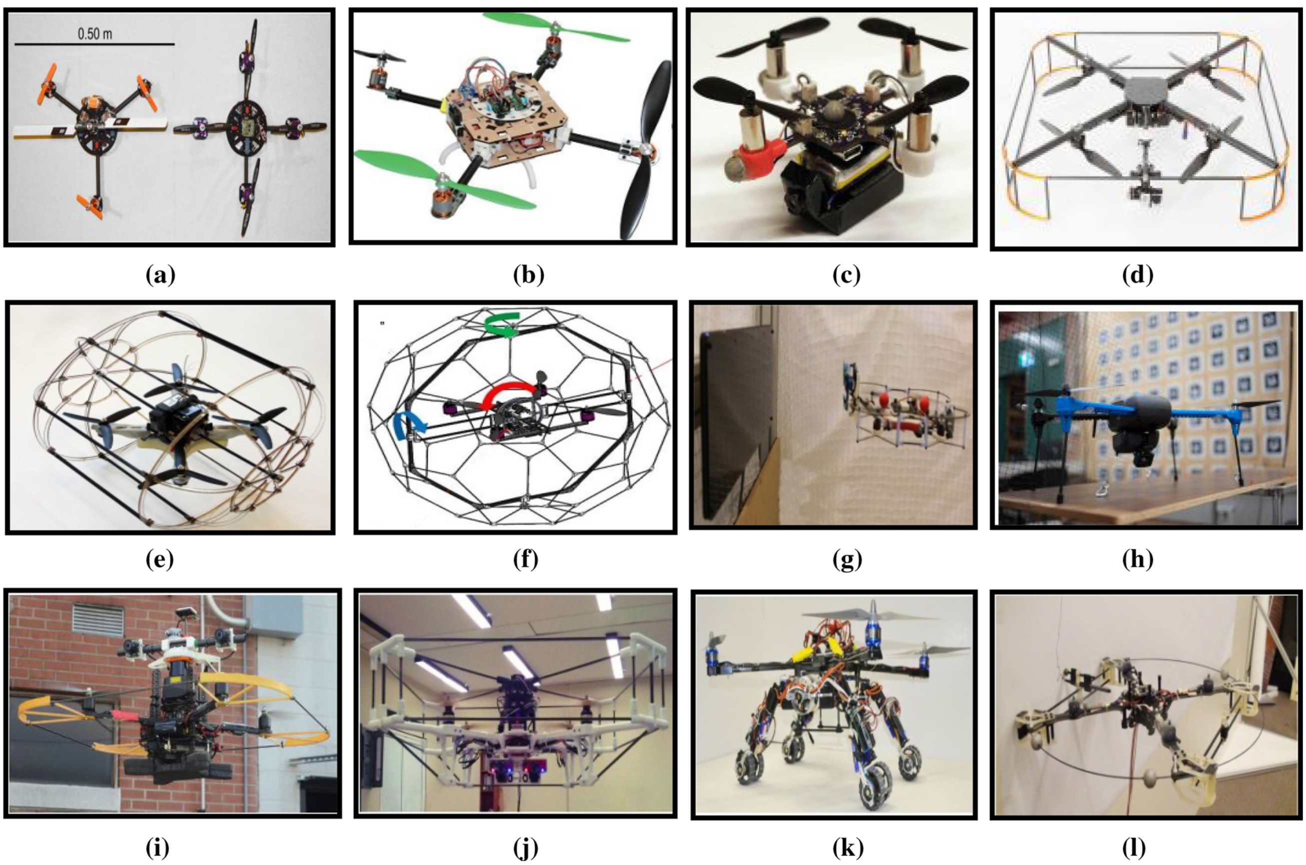


Fig. 18 Models of Quad-copters [**a**–**l**] [53–63] (Best viewed in colour)

performance. PID simulation is carried in MATLAB for reducing the overshoot and peak time.

v. *Quad-copters*

Driessens et al. [52] developed a simplified quadcopter in the name of 'Y4' (Fig. 18a) to mix the energy efficiency of a helicopter with a traditional and conventional quad-copter. Oosedo et al. [53] have proposed a quad-copter of a unique type with various pitch angles for stable hovering in the air with four propellers and motors (Fig. 18b). Mulgaonkar et al. [54] designed and developed a small and low weight quad-copter hardly weighing about twenty five grams (Fig. 18c). Ishiki et al. [55] modelled a quad-copter with an array of microphones (Fig. 18d) for performing localization of sound. Kalantari et al. [56] build the first-ever quad-copter that can hover in the air and can roll on the ground surface (Fig. 18e). Okada et al. [57] showcased a quad-copter with the mechanism of gimbal with rotating shell (Fig. 18f) and helps the vehicle for stable hovering in the air and avoids obstacles. These types of copters are much useful for applications like surveillance and inspection.

Kalantari et al. [58] developed a model of quad-copter with a gripper mechanism for autonomous take-off and perching on walls (Fig. 18g).

Abeywardena et al. [59] demonstrated a quad-copter as shown in Fig. 18h with Kalman filter, IMU sensor and monocular camera for generating high-frequency odometry. Shen et al. [60] is the first person to fly an autonomous quad-copter (Fig. 18i) with a magnetometer, GPS sensor, altimeter, tiltable camera and sensors for hovering inside and outside for the application of surveillance, mission planning, search and rescue. Papachristos et al. [61] have demonstrated a (DIY) Do-It-Yourself quad-copter (Fig. 18j) for avoiding obstacles and collisions, tracking and locating a moving target. Latscha et al. [62] developed a hybrid quad-copter with the combination of two snake structured mobile robots for safety and robustness to monitor the disaster scenarios (Fig. 18k). Darivianakis et al. [63] designed and developed a quad-copter (Fig. 18l) for inspecting the infrastructures and physically interacting with them.

vi. *Hexa-copters*

Nguyen et al. [64] have developed a commercial hexa-copter for path planning, inspection and obstacle avoidance in real-time hovering (Fig. 19a). Park et al. [65] built a hexa-copter (Fig. 19b) with six bi-directional motors aligned asymmetrically for a stable flight. It has many advantages compared to conventional hexa-copter as resistance to wind disturbance, Human Drone Interaction (HDI), and accurate path of flight. Jannoura et al. [66] have developed a small low altitude and cheap hexa-copter for acquiring high-resolution images in agriculture (Fig. 19c). Jeroen et al. [67] have proposed a unique Model Predictive Control (MPC) for hexa-copters (Fig. 19d). A mathematical explanation is given for achieving a stable and fast response in maneuvering with a remote controller. Dmitrijs Lancovs et al. [68] have developed a model for collision avoidance using UGCS software and an aircraft emulator. It helps determining the path of the vehicle with the onboard sensors like IMU and telemetry, etc. (Fig. 19e).

vii. *Octa-copters*

An Octa-copter is a UAV with eight motors and propellers fixed on them. Brescianini et al. [69] fabricated an octa-copter with 6-DOF (Degrees of Freedom) (Fig. 20a) to generate a stable flight in the air. This type of vehicle is widely used for the applications like aerial surveillance and manipulation. Schneider et al. [70] developed an octa-copter with on-board multiple sensors and a fish-eyed camera (Fig. 20b). This type of system is useful in the mapping of vegetation and surveillance of crowded areas.

4.1 Growth of UAVs in Future

In the forthcoming days, UAVs are rapidly emerging in various applications such as path planning, inspection, fire-fighting service, air ambulance, tracing and tracking, delivery and transport, etc. UAV's are going to be equipped with high-definition multiple cameras and sensors to capture heterogeneous data such as ultraviolet and thermal images, video and audio recording in applications like surveillance [71] and monitoring, precision-agriculture, crowd management, transportation, etc. The present technology is not capable to handle such kind of heterogeneous data, so in the future modern algorithms and methods alike (Machine Learning, Artificial Intelligence, Big data, Internet of Things, edge computing and software-defined network) are used to tackle the difficulties and deployment of UAVs in various applications.

4.2 Need of Autonomy in UAVs

In a dynamic environment, UAVs might collide with obstacles while performing different operations in various applications. The present technologies are not capable of overcoming these issues. So there is a need for autonomy implementation in UAV or aerial robotics sector. Autonomy is used in different applications such as inspection, path planning, communication, delivery system, task scheduling, etc. [72]. As mentioned in [73] there are ten levels of autonomy that are used for different applications. These levels are used to define the control levels and autonomy as a metric in UAVs as shown in Fig. 21.

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4.3 Domains of UAV Research

Based on the survey conducted on various research papers on the topic of UAV across the globe and from top international and national journals, conferences it is observed that the current trend is mainly focusing in the field of UAV's. The top most categories or domains concentrated by researchers are shown in Fig. 22. A vast survey and information regarding to drones/UAVs and robotics/aerial manipulation were collected, reviewed and extended from the top journals or international conferences like Journal of Electronics, Journal of Electrical Engineering, Array, Journal of Guidance, International journal of mechanical and production engineering research and development [74], Control and Dynamics [75],

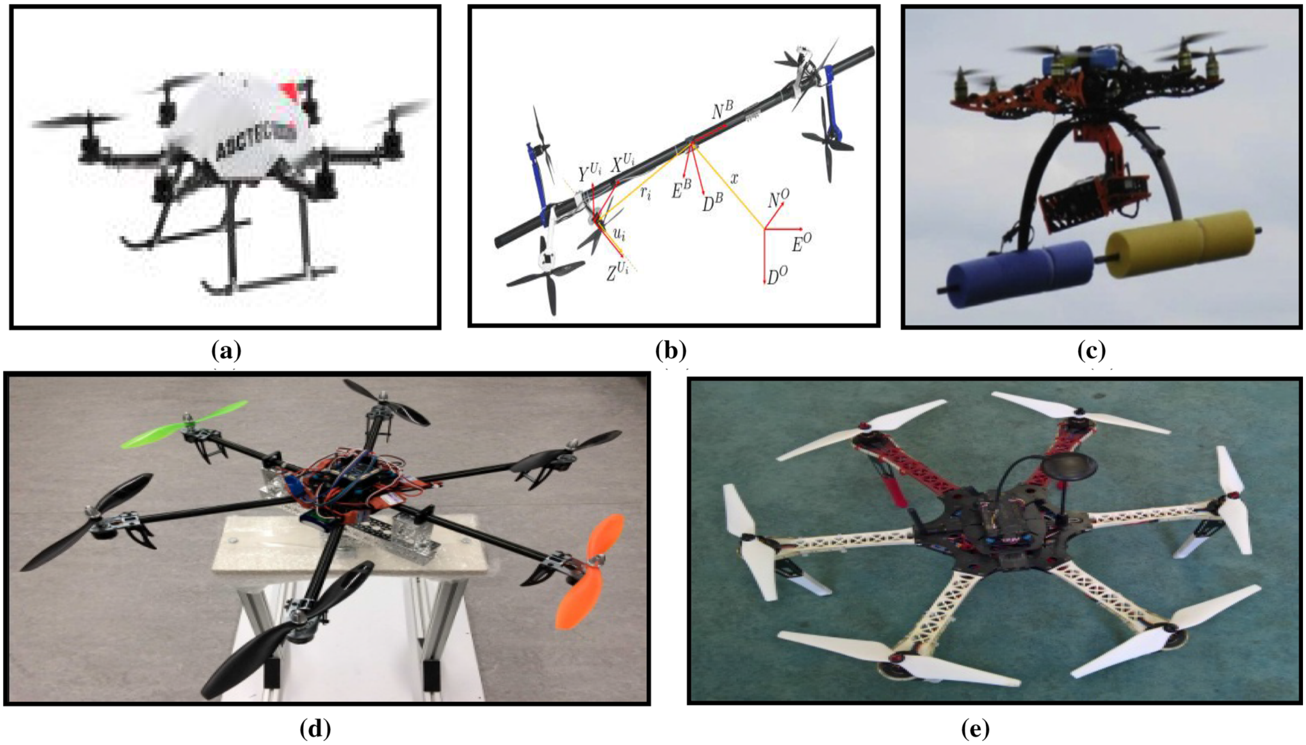

Fig. 19 Models of Hexa-copters [**a**–**e**] [65–68] (Best viewed in colour)

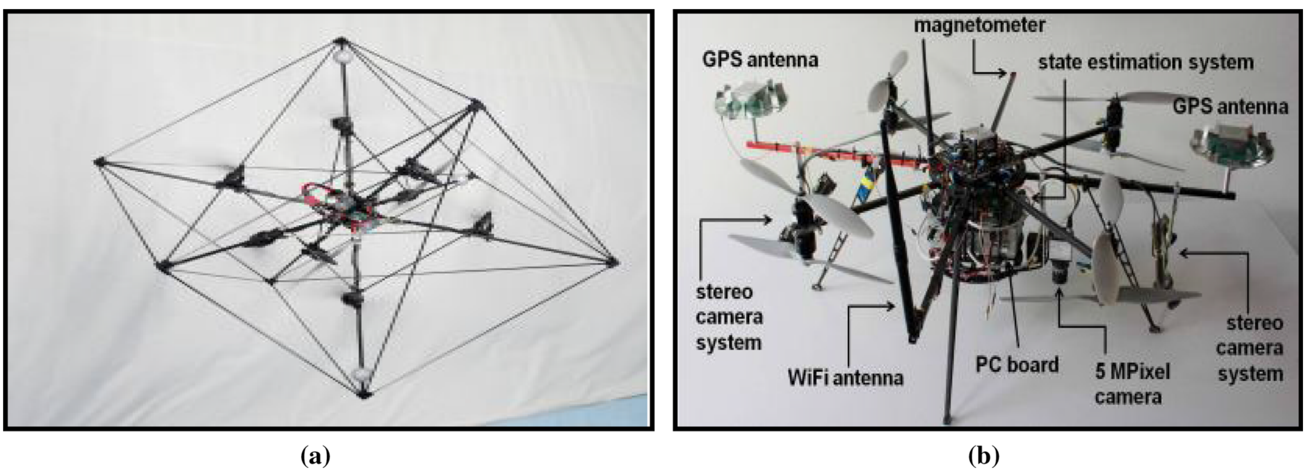

Fig. 20 Models of Octa-copters [**a**–**b**] [69, 70]

International Conference on Unmanned Aircraft Systems [76], International Journal of Robust and Non-linear Control [77]. The plethora of UAV domain research in various fields is briefly explained. Samad et. al. [78] explained a deep role of mapping with UAV in various applications like civil constructions, mapping of vegetation, mapping of power lines, etc. Mahjri et al. [79] has stated various applications of 3D UAV localization and path planning. The algorithm of path planning is divided mainly into five categories: Mathematical model-based, sampling-based, bio-inspired, multi-fusion and node-based. Various approaches are implemented in path planning approaches that include waypoint-based navigation, vision-based navigation and GPS based navigation. Howden et al. [80] has focussed on collective intelligence algorithm on localized control instead of centralized control. Danoy et al. [81] developed a homogeneous network of UAV's carrying an upper layer (altitude, stability) and a lower layer (VTOL, low altitude) to form a swarm with the improved connecting network in a wide range of applications and operations. Roberts et al. [82] demonstrated the tracking position of VTOL UAV. It presents the interference of drone flight and data collecting. Nemra et al. [83] proposed a

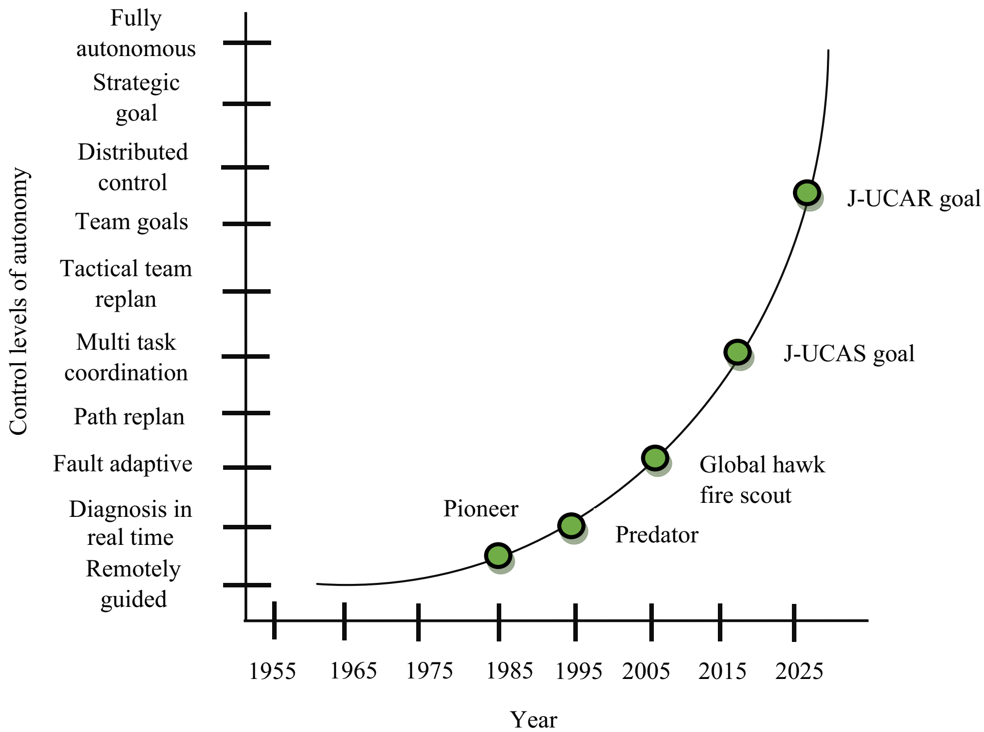

Fig. 21 Control levels of UAV autonomy in future [73]

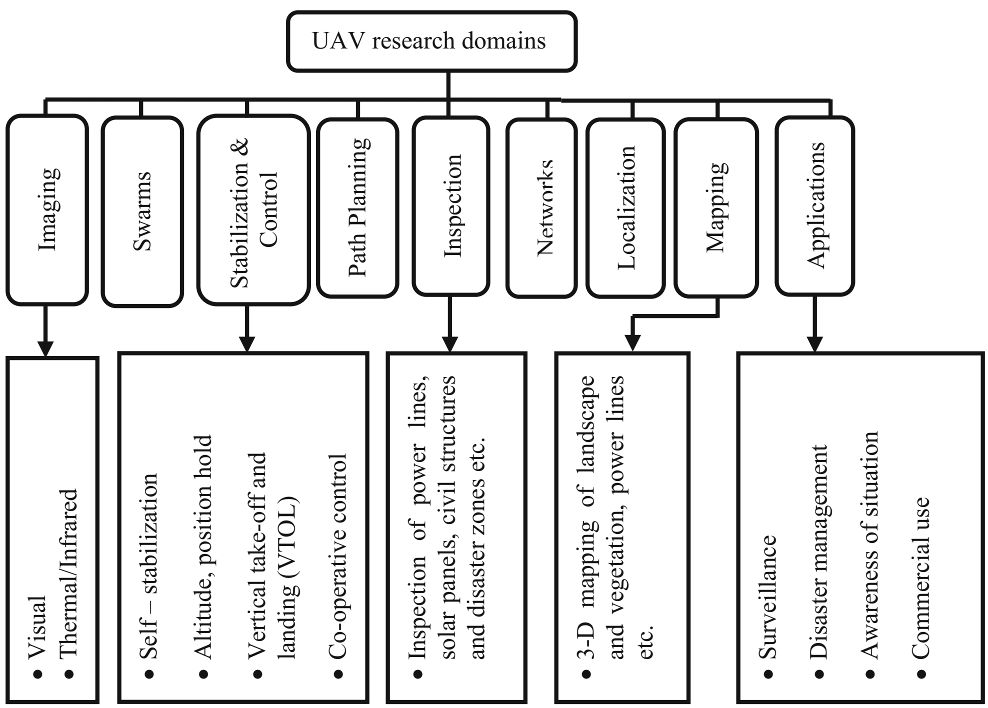

Fig. 22 Domains of UAV research

fusion of inertial navigation sensor and GPS sensor scheme for localization of UAVs with the help of state-dependent Riccati equations.

In [84] a small UAV for collecting hyper-spectral images of vineyards and other crops is explained. The images are transmitted in near real-time to a base distance and are used to assess crop vitality from observations of the reluctance of canopies. Grenzdorffer et al. [85] also explained the potential of UAV's photogrammetry in agriculture and forestry to form a GIS-based data acquisition system with input images. Mauriello et al. [86] also demonstrated the use of drones for thermal imaging on power lines and buildings to locate leakages, defects in conductors and insulators and heat loss. Customization and Applications is a domain with a high level of skills, precision and accuracy. Cho et al. [87] proposed a technique for estimation of wind and air speed with the help of a GPS antenna and a pitot tube. Ferworn et al. [88] have explained a method for the reconstruction of a collapsed building and civil constructions using an approach of game-engine based simulation. This simulation can be used for formulating the search and rescue operations with the help of UAVs. The wide applications of UAV's in various categories include a survey in water with a water proof camera integrated with UAV were proposed by Ruangwiset et al. [89] and detection of water-stress in crops with UAVs by Tejada et al. [90]. The usage of drones in agriculture has got a significant growth such as precision agriculture by Das et al. [91], thermal imaging and monitoring of crop fields by Bellvert et al. [92] and in various aspects are extensively explored.

The top trending drones in society with advanced technology and features will also provide prolific information. For example, UAVs like DJ Mavic Pro, DJ Phantom 4, Matrice 100, 200, 210 and Parrot, etc., will provide featured solutions to many existing problems like inspection, mapping, surveying, tracking, path planning, autonomous hovering, and obstacle avoidance, etc. Conversely, some companies will not provide excessive information to the public regarding their models of UAVs for security and privacy reasons.

Indeed, the COVID-19 pandemic has sped up the drone's consumption in different applications. Peculiarly in logistics and delivery systems, drone applications have found wide utilities [93, 94].

5 Conclusion and Future Scope

The main goal and intent of this paper are to review and present current aerial vehicles literature. In particular, this paper has mostly focussed on journals published from 2010 to till date. Throughout this literature, it has been observed and understood that to have a stable and strong foundation in the advancement of scientific and technical areas of UAVs/drones, a review of relevant literature is required. A review paper leads to identifying challenges and uncovers areas where essential research is needed. Inspired by this idea, an attempt has been made to identify the top approaches and attempts in this area and present them in detail. The data presented in Sect. 4 explains the aforementioned methods and concepts that could be an advantage for researchers to understand the existing technology or can contribute to this domain. An explanation of various drones designed and developed by various researchers is also explained in detail with different techniques, components used and their images. The trends of drones from 2010 to 2021.2 is presented with bar charts and graphs in terms of publishing ratios. A detailed explanation regarding current trends in drones and the interest of researchers in particular drones/UAVs are also explained.

In this study, Google Trends is used to represent various search strings used around the world. The top keywords from Web of Science indexed articles are also mentioned to find the relevant articles. Most of the articles retrieved are determined on the topics of path planning and task scheduling as compared to UAV communications and inspections. The numbers of articles in UAV inspections are found less which leads towards a research gap to be filled in future. Despite this vast survey, a rigorous study is yet to be required in the field of UAVs and new technologies implemented in them across the globe. This review regarding newly developed drones with their components, types of controller used, programming languages and techniques implemented will help the newly emerging researchers to concentrate and carry out their work in the right direction.

The overall approach is about the trend of drones/UAVs and the ratio of researches addressed in this field. It can be forecasted that researchers will continue their research on autonomous aerial vehicles in the future. In reality, a momentous amount of work remains to be carried out in the future. This includes hybrid aerial robotics, air-ground drones, long flight drones with smart technology batteries and VTOL drones with high accuracy, etc. Furthermore, only a small amount of information is presented regarding drones/UAVs with their applications. However, in the domain of UAVs, some issues and constraints need to be addressed properly. A few of these interesting topics are highlighted for future research directions. They are (i) UAVs communication, (ii) Dynamic path planning, (iii) Privacy and security, (iv) Integration of different segments, for network communication between air, ground and space UAVs, (v) Efficient energy for UAVs, (vi) Union of UAVs and AI, (vii) Indigenous programming for UAVs to tackle the multiple issues in inspection, communication and collision avoidance. There are still remains a significant amount of research in future on drones/UAVs and aerial robotics.

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Declarations

Conflicts of interest The authors declare no conflict of interest.

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