Architecture, Classification, and Applications of Contemporary Unmanned Aerial Vehicles

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***Abstract*—Unmanned aerial vehicles (UAV) have been gaining significant attention in recent times as they are becoming increasingly accessible and easier to use. UAVs are used in a variety of applications, ranging from civilian tasks, law enforcement, and rescue applications, to military reconnaissance and air strike missions. This article serves as an introduction to UAV systems' architecture, classification, and applications to help researchers and practitioners starting in this field get adequate information to understand the current state of UAV technologies. The article starts by inspecting the UAVs' body configuration styles and explains the physical components and sensors that are necessary to operate and fly a UAV system. The article also provides a comparison of several components for state-of-the-art UAVs. The article further discusses different propulsion methods and various payloads that could be mounted on the UAV. The article then explores the classification of UAVs followed by the application of UAVs in different domains, such as recreational, commercial, and military. Finally, the article provides a discussion of futuristic technologies and applications of UAVs along with their associated challenges.**[1]

I. Introduction

Unmanned aerial vehicles (UAVs) have been gaining significant attention in recent times as they are becoming increasingly accessible and easier to use. The current advancements in flight controllers have enabled users to fly a recreational UAV without any prior flight experience. Hence, the number of recreational UAVs has shown a tremendous surge in recent years. The Federal Aviation Administration (FAA) reports that 990,000 recreational UAVs were registered by December 2019, up from 137,701 in the fourth quarter of 2015 [1]. UAVs are currently used in a variety of applications, ranging from civilian tasks to military reconnaissance and strike missions.

Civilian UAVs can be used for recreational purposes or used in commercial applications, such as aerial cinematography, agriculture to spray pesticides and herbicides, and logistics. UAVs can also be used and in more critical applications, such as search and rescue missions, and delivering medical supplies. UAVs have been used in military applications since the early 1970s, and their role is growing now more than ever. As of 2018, the number of remotely piloted aircraft in the U.S. Air Force rose from 1,366 in 2013 to 2,404 [2].

UAVs have been the subject of considerable research over time and various UAV topics have been covered. Shakhatreh et al. [3] research covered in-depth the civilian applications of UAVs and the key challenges and problems that are facing each application. The authors provided a classification of UAVs based on the communication platform into low altitude platform (LAP) and high altitude platform (HAP). Kim et al. [4] provided a comprehensive study on the use of UAVs in agriculture. They defined a basic UAV architecture based on body type as fixed-wing or rotatory wing. The authors explored the hardware, sensors, and communication systems that are used in agricultural UAVs. The authors further discussed the limitations of UAVs in agricultural applications. Gupte et al. [5] surveyed quadcopter UAVs. The authors discussed the flying mechanism, control systems, and some of the sensors of quadcopter UAVs. The survey, however, did not discuss the applications of UAVs.

This article aims to provide a brief introduction to the UAV systems' architecture, classification, and applications to help researchers and practitioners starting in this field get adequate information to understand the current state of UAV technologies. This article begins the discussion by inspecting the UAVs' body configuration styles and building materials. The article then explores the physical components and sensors that are essential to operate and fly a UAV system as well other components and sensors that could be installed for mission-specific purposes. The article discusses different propulsion methods that are used to power the UAVs and explore various payloads that might be attached to a UAV. The article provides different classifications of UAVs such as that based on the U.S. Department of Defense (DOD) group classification and other classifications based on weight, wingspan, and altitude. The article explores different applications of UAVs in recreational,

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commercial, and military domains.

Our main contributions in this article are as follows:

- Discussion of UAV architecture and components including UAV body styles, sensors, flight controller, propulsion methods, and payload.
- Providing a comparison of several components for state-of-the-art UAVs.
- Examining different classifications of UAVs such as the one based on DOD group classification and the others based on UAV weight, wingspan, and altitude.
- Elaboration of a variety of recreational, commercial, and military applications of UAVs.
- Discussion of futuristic embodiments and applications of UAVs and the challenges associated with these technologies.

II. UAV Architecture

Most UAVs are made up of modular components that fit on and inside the body of UAVs and are powered by an energy supply. Depending on the style of flight and missions to be performed, a UAV can have one of many different body configurations. This section discusses UAV body styles, body material, and different components of UAVs.

A. UAV Body Styles

UAVs can have many different body styles or shapes depending on the flight style and intended usage or missions. UAV body styles mainly fall into one of the following types:

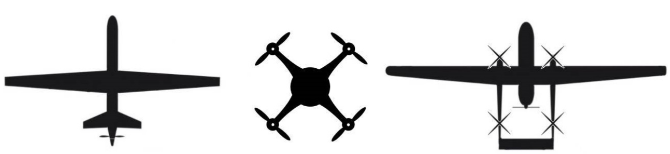

Fig. 1: Examples of UAV body styles.

Fixed-Wing: Fixed-wing UAVs (Fig. 1) are modeled after conventional airplanes and utilize the same flying concepts. Fixed-wing UAVs need a runway or need to be thrown by hand or slung using a catapult to take off. Such UAVs also need a runway or need to be caught by a net or require a landing parachute to land safely. The fixed-wing configuration of UAV has the advantage of having a larger payload capacity and longer flight time due to the low consumption of power needed for gliding. The body style of fixed-wing UAVs might be designed as a normal plane or in a pusher configuration, where the propeller is installed behind the UAV. Another style is a delta wing, which is the simplest build configuration. This style has the propeller at the back like the pusher configuration but there is no rudder and the elevons control the pitch and yaw.

Multirotor: Multirotor UAVs (Fig. 1) can be configured using multiple motors installed on arms. This body type has the advantages of vertical takeoff and landing and can hover in a fixed position. Multirotor UAVs can fly in any direction and change speed, altitude, and direction abruptly, but these UAVs usually tend to have a shorter range and flight duration. The multirotor body can be designed as a traditional helicopter, a tricopter where it has three arms with three motors one on each, or a quadcopter where it has four arms with four motors. Multirotor UAVs can also be configured with a variable number of arms and rotors.

Vertical Takeoff and Landing: Vertical takeoff and landing (VTOL) body type (Fig. 1) is very versatile as it can be a hybrid of the two previously mentioned body styles (i.e., fixed-wing and multirotor). The VTOL UAVs typically use multirotors to takeoff, land, and hover, whereas these UAVs transition to a normal fixed-wing flight style to travel horizontally. The VTOL UAVs can be configured by affixing quadcopter rotors on a fixed-wing like Aerosonde HQ by Textron Systems. Other VTOL body configurations include tiltrotors and tiltwings. In tiltrotor UAVs, some of the rotors on the wing tilt vertically and horizontally like the Bell V-247 Vigilant. Tiltwing UAVs have a wing that is normally horizontal while flying but rotates up in the cases of vertical takeoff and landing.

B. UAV Body Material

The body of UAVs could be made of a plethora of materials, such as foam, plastic, wood, carbon fibers, aluminum, and G-10 (a high-pressure fiberglass laminate). Materials such as foam, plastic, and wood are lightweight and easy to shape and usually used for small and light UAVs running on an electric motor. Carbon fibers and G-10 are very strong and light but an expensive alternative to the aforementioned materials (i.e., foam, plastic, and wood). Aluminum is mostly used in bigger UAVs that have an engine and carry heavier payloads (e.g., packages for delivery, cargo, missiles). Table I compares the density, tensile strength, and pros and cons of some of the UAV body materials.

C. UAV Components

A UAV is made up of modular components that are installed on or inside the body of UAVs. Some

TABLE I: Comparisons of different UAV body materials.

Material	**Density (g/cm)**	**Tensile Strength (MPa)**	**Pros**	**Cons**
Foam	0.05	46 – 60	Easy to shape, Flexible	Weak
Plastic	0.06 – 1.96	2 – 88	Lightweight, Widely available	Varying strength
Wood	0.17	7 – 64		
Carbon Fibers	1.75	2000 – 5600	Very lightweight, Strong	Expensive
G-10	1.80	262 – 310		
Aluminum	2.70	276 – 310	Strong	Heavy

of these components are essential for the operation and flying of UAVs whereas other components are installed for mission-specific purposes. Fig. 2 depicts the main components of a UAV. This section discusses the main components of UAVs focusing on sensors, flight controllers, propulsion subsystem, payloads, and communication subsystem.

1. <u>Sensors:</u> UAVs use a variety of sensors that provide the flight controller with data such as telemetry, attitude measurements, terrain, and obstacles. Sensors are also an integral part of situational awareness of UAVs. The combination of sensors installed on UAVs depends on the complexity and sophistication level of UAVs. The most common sensor suite for UAVs include the following sensors.

Inertial Measurement Unit: An inertial measurement unit (IMU) is an electronic device that provides a measurement of UAV's attitude, specific force (i.e., non-gravitational force per unit mass also called g-force), angular velocity, orientation, and position information. Most of the IMUs consist of a combination of the following sensors:

- *<u>Accelerometer</u>:* measures the linear acceleration a_x, a_y, a_z on the three axes of the body x,y,z.
- *<u>Gyroscope</u>:* measures the angular change rate p, q, r on the three axes of the body x,y,z.
- *<u>Magnetometer</u>:* Determines the heading of a UAV by measuring the earth's magnetic field.
- *<u>Barometer</u>:* Determines the altitude of a UAV by measuring the earth's atmospheric pressure.

Since each one of the IMU components works on 3 axes, by combining the three components (accelerometer, gyroscope, magnetometer) the flight controller can measure the UAV's speed, orientation, and direction along 9 axes. Currently, most professional and military IMUs tend to incorporate redundant IMU sensors. The advantage of this redundancy is to get the most accurate data from the sensors. Furthermore, redundancy is helpful in case of a sensor failure, where the redundant components provide a level of fault tolerance.

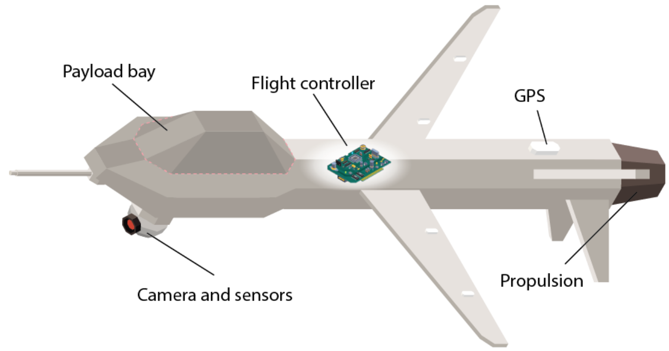

Fig. 2: Main components of a UAV.

Global Positioning System: The global positioning system (GPS) chip is used to get the position of the UAV from multiple satellites, which is how the UAV gets a navigation system. The GPS chip together with the IMU constitutes the navigation system of a UAV, which measures the speed, positioning, and heading of the UAV. The GPS chip can either be a separate receiver chip or part of the flight controller.

Visual, Ultrasonic, and Infrared Sensors: UAVs often incorporate visual, ultrasonic, and infrared sensors to detect obstacles and avoid collisions by measuring the relative distances to the objects in the path of the UAV or surrounding it.

2. <u>Flight Controller:</u> The flight controller is the brain of the UAV. The flight controller is the hardware and the firmware that processes all the information that is collected from the IMU, GPS, and other sensors. The flight controller also controls the payload on the UAV (such as cameras and other sensors). The flight controller can be fully autonomous or just provide some level of navigation assistance in the autopilot mode using the sensed data from the IMUs and other sensors to control the UAV. Some of the flight controllers are capable of being programmed to set a home point from where the UAVs can be launched and land back automatically. The flight controllers provide the ability to fly a UAV through preloaded flight paths utilizing waypoints. Waypoints are a set of predefined location coordinates, which can be set up before the flight by specifying each point's latitude, longitude, and altitude, that creates a route so that a UAV can fly autonomously from one waypoint to the

TABLE II: Example of contemporary flight controllers.

UAV Components		Pixhawk Cube Orange	Lockheed-Martin Kestrel v3.1	CUAV V5 NANO
Processor		32-bit ARM-M7 @ 400MHz	DSP @ 500MHz	32-bit Arm-M7 @ 216MHz
Memory		1 MB RAM, 2 MB flash	32 MB RAM, 32 MB flash	512 KB RAM, 2 MB flash
IMU	Accelerometer	Three 3-axis accelerometers ICM-20948 / ICM-20649 / ICM-20602	One 3-axis accelerometer	Three 3-axis accelerometers ICM-20602 / ICM-20689 / BMI055
	Gyroscope	Three 3-axis gyroscopes ICM-20948 / ICM-20649 / ICM-20602	One 3-axis gyroscope	Three 3-axis gyroscopes ICM-20602 / ICM-20689 / BMI055
	Magnetometer	One 3-axis magnetometer ICM-20948	One 3-axis magnetometer	One 3-axis magnetometer IST8310
	Barometer	MS5611X5	Absolute and differential sensors	MS5611
Cost		$250.00	$5,000.00	$183.42

next. The flight controller can also be programmed to make the UAV loiter in a specific location. The flight controller automates the UAV flight with the help of sensors, throttle, servos, and payloads that are connected to the flight controller. The autopilot capabilities depend on the flight controller's firmware. All the commands are programmed on a computer before the flight and then loaded to the flight controller. Table II shows the processing power, memory, IMU components, and cost of three of the most common flight controllers: the Pixhawk Cube Orange, Lockheed Martin Kestrel v3.1, and CUAV V5 NANO.

3. PROPULSION SUBSYSTEM: UAVs can utilize a variety of propulsion subsystems depending on the size, type, and mission of the UAV.

Fuel Engines: UAVs can utilize the same engine technologies like that of the aircraft. The UAV engine can be a piston engine, whether a two-stroke engine such as the LYCOMING EL-005, or a four-stroke like the Rotax 914. UAVs can also be powered by jet propulsion, such as turbofan and turboprop engines. The Honeywell T76, for instance, is a turboprop engine found in General Atomics's MQ-9 Reaper. The Rolls Royce F137 is an example of a turbofan engine, which is used by the Northrop Grumman's RQ-4 Global Hawk and MQ-4C Triton.

Depending on the engine type, a UAV can be powered by a variety of fuel types such as kerosene, diesel, gasoline, biodiesel, methanol, ethanol, or liquefied petroleum gas (LPG). Engines usually have a higher noise level as compared to electric motors, but they tend to have better endurance. The Aerosonde HQ by Textron Systems with the LYCOMING EL-005 flew over the Atlantic for 26 hours and 45 minutes in stormy weather, using only a gallon and a half of fuel [6]. Table III shows the maximum power, weight, fuel type, and cost for each

TABLE III: Different types of fuel-powered UAV engines.

Attribute	LYCOMING EL-005	Rotax 914	Honeywell T76	Rolls Royce F137
Type	Two-stroke piston engine	Four-stroke piston engine	Turboprop jet engine	Turbofan jet engine
Max Power	900 Watts @ 5,500 RPM	84.5 kW @ 5,800 RPM	700 kW @ 2,000 RPM	44.7 kW @ 16300 RPM
Weight	13.8 lb	140.8 lb	385 lb	641 lb
Fuel	Jet Fuel, Mogas, Unleaded Avgas	100LL Leaded Avgas, Unleaded Regular Gas	Jet Fuel	Jet Fuel
Cost	$150K	$34.9K	$480K	$3.76M

of the aforementioned engine types.

Electric Motors: UAVs that run on electric motors usually fly for a shorter period as compared to those being run on fuel engines, but they have the advantage of being lighter, quieter, and easier to launch. Motorized UAVs use brushed motors that are powered by a battery, mostly lithium-polymer (Li-Po). Additionally, an electronic speed controller (ESC) circuit is required to give the flight controller control over the speed and direction of rotation of an electric motor. An ESC works by adjusting the frequency of the transistors and creating a rotating magnetic field that rotates the motor. The speed of the motor is proportional to the switching frequency of transistors of the ESC circuit.

Hybrid Engines: A hybrid propulsion system consists of two parts: an engine and an electric motor. A hybrid propulsion system can be set up in multiple configurations:

- *Parallel:* In a parallel configuration, either the electric motor can be used alone to drive the propeller, or the engine can be used alone to rotate the propeller and charge the battery. In the latter case, the motor works as a generator powered by the engine. The engine and the electric motor in this setup are mechanically coupled using a gear that is used to drive the propeller.
- *Series:* In a series configuration, the electric motor is connected directly to the propeller and is used to drive it. The engine is not mechanically connected to the propeller, instead, it is connected to a generator that is used to charge the batteries and power the electric motor.
- *Parallel-Series:* This setup uses a planetary gear connected directly to the propeller; both the engine and the electric motor are connected to the planetary gear. The UAV could run on the electric motor or the engine. When the engine is used, the planetary gear transfers most of the energy to the propeller and some to a generator that is used to charge the batteries.

4. PAYLOADS: The payload means the weight that a UAV can carry other than the UAV weight itself. The body style of the UAV is crucial in determining the payload size. Multirotor UAVs can carry small objects for a short-range. On the other hand, fixed-wing UAVs can have a high payload capacity. Depending on the mission type and the purpose of flying a UAV, many different combinations of payloads can be installed on the UAV as described below.

Sensors and Cameras: All the interchangeable sensors that are not part of the flight controller and are not critically related to the UAV flight operations are part of the payload. A UAV can utilize a multitude of payload sensors (e.g., temperature, humidity, pressure, proximity, rangefinder, and LiDAR) and cameras, such as night vision, visual (red, green, blue (RGB)) cameras, and infrared, both near-infrared (NIR) and long-wavelength infrared (LWIR), cameras. Any UAV will have at least one camera (to provide the live feed) or multiple cameras for high-quality images and videos.

Weapons: Weapons are an essential payload in military applications. UAVs can be outfitted with a variety of missiles and bombs such as Hellfire missiles, Stinger missiles, Griffin missiles, Viper strike bombs, laser-guided bombs, or any other combinations.

Tanks and Sprayers: In commercial applications, a UAV can be equipped with a tank and sprayer to help in crop irrigation, pesticide spraying, and firefighting.

Speakers and Lights: In search and rescue and law enforcement applications, UAVs can be outfitted with speakers and lights. A speaker can be installed on UAVs to transmit sounds, and the lights are useful in low light environments.

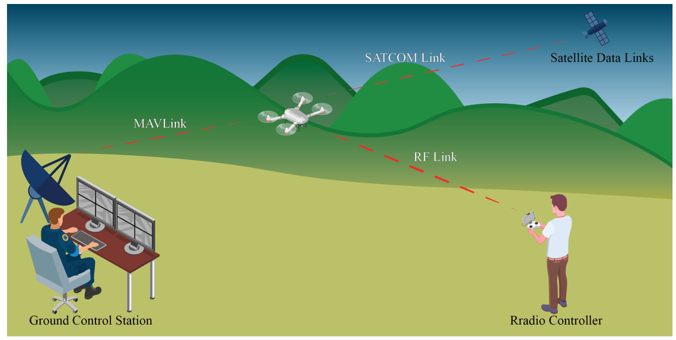

Fig. 3: Different methods for UAV communications.

5. COMMUNICATION SUBSYSTEM: A UAV operator can communicate with the UAV using any of the following: radio controller transmitter, ground control station (GCS), or satellite duplex data links. The GCS communicates with the UAVs by implementing the micro air vehicle link (MAVLink) communication protocol.

The most widely used method of communication in commercial UAVs is the radio frequency (RF). A data link is installed on-board the UAV that contains an uplink to carry the control instructions to the UAV from the operator or command and control (C&C) stations and a downlink to get the video feed and telemetry from the UAV such as speed, orientation, direction, altitude and latitude, power or fuel levels, payload information, and many other parameters. The radio frequencies commonly used for controlling UAVs are 900 MHz, 2.4 GHz, and 5.8 GHz. The 900 MHz frequency has a longer range but smaller data rate as compared to other controlling frequencies for UAVs. On the other hand, the 5.8 GHz frequency has a shorter range, but higher data rate as compared to other controlling frequencies for UAVs. Military UAVs utilize X-band satellite communication (SATCOM) to perform beyond the line-of-sight missions. The X-band SATCOM works at the super-high frequency (SHF) in the range 7.25 GHz to 8.4 GHz which has the advantage of being resilient to weather. Fig. 3 illustrates MAVLink, RF, and SATCOM methods for communication with UAVs.

III. CLASSIFICATIONS OF UAVS

There have been plenty of classifications for UAVs based on a variety of parameters or characteristics, such as size, weight, speed, altitude, and endurance. Commercial and recreational UAVs are classified in a way that is different from military ones. There is not

TABLE IV: U.S. DOD Classification of UAV Groups.

UAV Group	Max Takeoff Weight (lb.)	Operating Altitude (Ft)	Speed (knots)
Group 1	< 20	< 1200	< 100
Group 2	21-55	< 3500	< 250
Group 3	< 1320	$< 18,000$	
Group 4	> 1320		Any Speed
Group 5		$> 18,000$	

TABLE V: UAV classification based on weight and wingspan [9].

Class	Weight	WingSpan
UAV	> 5Kg	> 2m
Small UAV	≤ 5Kg	≤ 2m
MAV (Micro Air Vehicle)	≤ 2Kg	≤ 1m
NAV (Nano Air Vehicle)	≤ 50g	≤ 15m
PAV (Pico Air Vehicle)	≤ 3g	≤ 2.5cm
Smart Dust	≤ 0.5g	≤ 0.25cm

a specific standard classification across all applications and no classification is better than the other.

One way of classifying UAVs is based on their body type and flying style. UAVs can be classified into three distinct classes fixed-wing, multirotor, and VTOL UAVs based on their body type and flying style.

Watts et al. [7] used altitude and endurance to classify UAVs into (i) high altitude long endurance (HALE), (ii) medium altitude long endurance (MALE), (iii) low altitude long endurance (LALE), and (iv) low altitude short endurance (LASE).

The U.S. DOD uses a five group classification [8] that is based on the maximum takeoff weight, operating altitude, and speed of UAVs. Table IV depicts the five groups of the DOD classification. This classification system was created to be uniformly used across all the branches of service (i.e., Air Force, Army, and Navy) instead of tier system classification where each branch of the service had its tiers. For example, the U.S. Air Force had a five-tier system with small and micro UAVs belonging to tier 0 or N/A (not applicable), tier I included LALE UAVs, tier II encompassed MALE UAVs, tier II+ consisted of HALE UAVs, and tier III- included HALE low-observable UAVs. On the other hand, the U.S. Army had a three-tier system where tier I consisted of small UAVs, tier II included short-range tactical UAVs, and tier III comprised of medium-range tactical UAVs. Similarly, U.S. Navy (Marine Corps) had a four-tier system where tier 0 or tier N/A included micro UAVs, tier I consisted of small UAVs, tier II encompassed LALE UAVs, and tier III comprised of medium-range tactical UAVs.

Hassanalian et al. [9] classified UAVs based on their weight and wingspan into UAV, small UAV, micro air vehicle (MAV), nano air vehicle (NAV), pico air vehicle (PAV), and smart dust. Table V shows the classification of UAVs by Hassanalian et al. [9]. This classification, however, is too broad, and the authors did not take into consideration the endurance, range, or the mission type in the classification.

IV. Applications of UAVs

UAV applications can be categorized into three main domains based on the purpose of flying UAVs; recreational, commercial, and military. The application domains of UAVs also provide a means of classification of UAVs. In this section, we elaborate on the applications of UAVs in recreational, commercial, and military domains.

A. *Recreational*

Any UAV flown for the sole purpose of entertainment and fun by hobbyists is categorized as a recreational UAV. Usually, this type of UAV contains the least sophisticated equipment and sensors. Recreational UAVs are sold as ready to fly or bind and fly where most of the UAV components are already installed, programmed, and calibrated. The user just put the parts together and charge the battery to fly. The typical usage for recreational UAVs is mostly aerial photography and first-person-view (FPV) flying, hence the manufacturers focus on the camera quality, gimbal stabilization, and obstacle detection. Some examples of recreational UAVs are DJI Mavic, Parrot FPV Drone, and Skyhunter.

B. *Commercial*

Advanced and specialized UAVs that are made for a specific purpose or task are considered commercial UAVs. Official training and licensing are a requirement to fly a commercial UAV. Some of the applications for commercial UAVs are agriculture, inspection and monitoring, logistics and delivery, surveying and mapping, search and rescue, and professional cinematography. The size and body type of the UAV depends on the specific mission and the payloads to be carried. Fig. 4 illustrates some of the applications of commercial UAVs. Table VI compares some of the most commonly used commercial UAVs in terms of maximum speed, endurance or flight time, payloads, main applications, and cost. In the following, we discuss

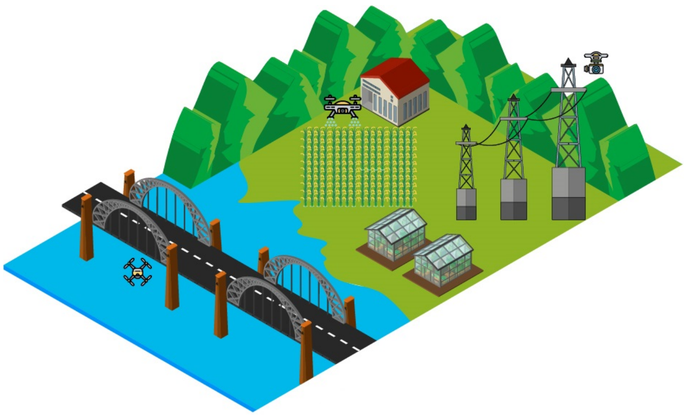

Fig. 4: Applications of commercial UAVs: (i) agricultural UAV spraying pesticides on crops; (ii) inspection and monitoring UAV inspecting bridges and power-lines.

in more detail some of the commercial applications of UAVs.

Agriculture: Agricultural UAVs are typically equipped with FPV cameras, LiDAR, multispectral sensors, obstacle avoidance sensors, and a tank and sprayers. These UAVs are used to monitor crop health and soil quality. Agricultural UAVs are instrumental for precision agriculture. The tanks outfitted on agricultural UAVs are used to supply water and fertilizer to water- and nutrient-stressed areas of crops and pesticides to infested crop portions. The UAVs are also utilized to provide a live feed for livestock monitoring. Some of the common agricultural UAVs are the multirotor DJI Agras MG-1 and the fixed-wing PrecisionHawk Lancaster.

Inspection and Monitoring: Inspection and monitoring applications require that the UAV be equipped with an FPV camera, thermal cameras, proximity sensors, multi-gas detector, and a lighting system. Some of these applications even require a UAV to be equipped with a protective frame. These UAVs are used to inspect objects that are out of reach or areas that might be risky and dangerous, such as power lines, oil pipes, wind turbines, and bridges. Inspection and monitoring UAVs can also be used to inspect confined spaces that are difficult to be inspected by humans, such as smokestacks and ducts. The Flyabilty Elios 2 is an example of a multirotor UAV that is used for beyond-line-of-sight indoor visual inspection. This specific UAV is collision-tolerant due to a spherical cage that encases the entire UAV. The FireFLY6 PRO from BirdsEyeView Aerobotics is an example of a VTOL long-range inspection UAV that is used to inspect power lines and pipes.

Logistics and Delivery: While logistics and package delivery using UAVs are still in the early stages, UAVs can be very advantageous for package delivery as the UAVs can reduce the transport time in big cities to minutes. UAVs are also beneficial for deliveries in rural areas. The Zipline Robin fixed-wing UAV is being used to deliver medical supplies, such as blood, vaccines, and medicine to rural areas in Ghana, Rwanda, India, and the Philippines.

TABLE VI: Comparison of popular commercial UAVs.

Attribute	DJI Mavic 2 Pro	DJI Agras MG-1	Flyabilty Elios 2	FireFly6 Pro
Max speed (mph)	45	49	14.5	18
Max endurance (minutes)	30	24	10	59
Payloads	20MP 4K camera	2.6 gallons tank, Sprayers, Microwave radar, Camera	Thermal camera, 12MP 4K camera, Lighting system	Variable cameras and thermal sensors
Uses	Filming	Agriculture	Indoor inspections	Surveying, Search and rescue
Cost	$1,599.00	$14,999.00	$49,200.00	$7,499.00

Surveying and Mapping: UAVs are being utilized in mapping and surveying applications due to the high-resolution images that can be taken by a low altitude flying UAV and that can be mapped at a closer range as compared to the images obtained from a plane or a satellite. The 3D Robotics Aero is an example of a surveying and mapping commercial UAV. It is a hand-launched electric UAV that can have multiple cameras and customizable payloads.

Search and Rescue: Search and rescue UAVs give first responders the advantage of flying over disaster zones or go to places that are too difficult for humans to reach and search for victims. Some of the applications of search and rescue UAVs are post-disaster evaluation, finding missing persons, and delivering first aid to victims.

Aerial Cinematography: Aerial cinematography is a major commercial application of UAVs. It is easier, faster, and cheaper to fly a UAV to take the aerial shots needed rather than constructing a camera crane or flying a helicopter to take aerial shots. The multirotor DJI Matrice 600 Pro is an example of a UAV that is used in professional cinematography.

TABLE VII: Comparisons of active military UAVs.

Attribute	RQ-4 Global Hawk	MQ-1C Gray Eagle	MQ-1 Predator	ScanEagle
Max Speed (knots)	340	167	120	80
Max Altitude (ft)	60,000	25,000	25,000	19,500
Engine	Rolls Royce F137-RR-100	Lycoming DEL-120	Rotax 914	2-stroke 3W piston
Max Internal Payload (lb.)	3,000	540	450	7.5
Max External Payload (lb.)	NA	1,500	300	NA
Endurance (Hours)	32+	50+	24	24+
Cost	$130M	$21.5M	$40M	$3.2M

C. Military

A UAV is considered a military type if it is flown or manufactured for military purposes, such as intelligence gathering, surveillance, reconnaissance, target acquisition, and battle damage assessment, or if the UAV can carry a variety of weapons and perform air strikes. Some of the types of military UAVs that are being used right now are the General Atomics MQ-1 Predator, Northrop Grumman RQ-4 Global Hawk, General Atomics MQ-1C Gray Eagle, and Boeing Insitu ScanEagle. Table VII shows a comparison of the four above mentioned UAVs in terms of maximum speed, maximum altitude, engine type, maximum internal and external payloads, endurance, and cost.

V. Future of UAVs and Associated Challenges

In future, UAVs will be integrated with emerging technologies such as augmented reality (AR), artificial intelligence (AI), and cellular networking to enable a multitude of innovative applications. Furthermore, advancements and miniaturization of electronics will help realize exciting new applications of UAVs. This section discusses some of the futuristic embodiments and applications of UAVs and the challenges associated with them.

A. UAV Swarms

A swarm of UAVs is a group of UAVs that coordinate with each other to carry out a task. The swarm could be semi-autonomous or fully-autonomous. Semi-autonomous swarms are usually controlled by a GCS which communicates with each UAV simultaneously. Fully-autonomous swarms use flying ad-hoc networks (FANET) to communicate with each other and one leader UAV communicates with the GCS. Utilizing swarms in applications such as surveying and mapping, agricultural, and logistics and delivery has the benefits of saving time and man-hours by distributing the tasks between the UAVs. UAV swarms have gained a lot of attention from the Air Force and the Department of Defense in recent years. UAV swarms can even be used to save lives in the case of search and rescue applications. Deploying a swarm of UAVs in a disaster zone leads to a faster discovery of survivors. The main challenges in UAV swarms are collision avoidance between the UAVs in the swarms and the energy efficiency of swarm operation.

B. Augmented Reality

AR is a technology that allows users to interact with computer-generated objects in a real-world environment [10]. AR has been used in a variety of applications, such as design and manufacturing, tourism, navigation, education, and gaming. By integrating AR technology in UAVs, a multitude of new applications are possible. AR can be used to display real-time overlaying information on the real-world environment like maps, floor plans, and points of interest. These AR maps can be beneficial in the military, and search and rescue operations. Another example of integrated UAV-AR is planning and designing, where architects and engineers can fly over a location and use 3D models to visualize the project. Integrated UAV-AR can also be used in inspection where the AR would overlay and synchronize the building information model (BIM) on the video feed from the UAV. This could be useful in inspecting underground pipes, bridges, power lines, and dams.

C. Artificial Intelligence

UAVs using AI can be utilized in various object detection and recognition applications. Detecting traffic congestion is an example of an application utilizing AI-assisted UAVs [11]. In this example, a UAV takes pictures of traffic in a preplanned route, which are subsequently processed by a convolutional neural network (CNN) to decide if a road is congested or not. The results from the CNN are then sent to the road traffic management center, which can take necessary actions to alleviate the congestion. Another application of UAVs utilizing AI is early forest fire recognition [12]. In this system, a UAV or a group of UAVs use cameras to detect fires. The AI in UAVs is trained to recognize smoke and fire in pictures. The resulting alerts are then sent to the GCS. The integration of AI in UAVs has many challenges, the biggest of which is computational power as UAVs have limited on-board computation ability as well as limited battery energy for battery-operated UAVs. Due to the limited on-board compute capability, AI embedded in UAVs is often not very sophisticated and thus can have a limited accuracy. An incorrect prediction/classification could result in wrong alerts and wasted efforts in case of *false positives* and no response for an emergency situation in case of *false negatives*.

D. Wireless Networking

UAVs are projected to be a major part of the 5G and beyond 5G (B5G) cellular architectures [13]. UAVs can connect to cellular networks which help improve the real-time data stream and extend the maximum range of UAVs. Swarms of UAVs could utilize the existing 5G and B5G networks to enhance communication between the UAVs which leads to better autonomy. Another application is using a swarm of UAVs as flying base stations to provide cellular networks in an area deprived of cellular signal or in disaster zones. Communication reliability, security, privacy, quality of service, and interference management are some of the challenges in wireless networking using UAVs.

E. Nano-UAVs

Highly miniaturized UAVs could be developed and deployed either solo or in swarms and could be used in military applications such as espionage or precision strikes. For example, the FLIR Black Hornet PRS is a nano-UAV with low visual and audible signatures, a size of only 13 grams, and is equipped with the same cameras and sensors as a full-sized UAV. The Black Hornet's small size allows it to carry surveillance and reconnaissance missions covertly and unnoticed. Another application for nano-UAVs is covert lethal force missions and assassinations by equipping a nano-UAV with a small amount of explosives and targeting vital organs. The Swiss Drones and Robotics Center tested the possibility of using 3 grams of explosive charge and a detonator to assassinate a person by landing and detonating on the head; the resulting injuries were fatal with no chances of survival.

F. UAV SLAM

Simultaneous localization and mapping (SLAM) is a computational problem of creating a map of an unknown area, while simultaneously updating the map and tracking the current location of a vehicle within the created map. SLAM is an important topic in unmanned vehicle systems as it is one of the main methods used in creating autonomous vehicles. SLAM is also important for navigating UAVs in GPS-deprived locations or flying UAVs indoor. To obtain sensor data required for developing SLAM for UAVs, a UAV could be outfitted with many sensors, such a LiDAR sensor, an RGB-D camera, a stereo camera, or any combination of these sensors. The SLAM algorithm for autonomous UAVs can be based on Kalman filters or particle filters. The algorithm uses the sensor data to determine the odometry and update the map. High flight speed and real-time response are challenges that currently face SLAM in UAVs.

VI. Conclusion

With the price-to-value of building or buying an unmanned aerial vehicle (UAV) being lower than ever, and with the advancements in flight controllers and payloads, it is now more feasible, even advantageous, to use UAVs for commercial and military missions. This article explored the architecture and components of a modern UAV. The article presented some of the common flight controllers and engine types for contemporary UAVs. The article also discussed different body styles and body material types for UAVs. The article further presented different classification methods for UAVs. Finally, the article elaborated the applications of UAVs in recreational, commercial, and military domains as well as discussed the futuristic embodiments and applications of UAVs along with their associated challenges.

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