In: Unmanned Aerial Vehicles
Editor: Nicholas Barrera
ISBN: 978-1-53618-900-1

Chapter 1

UNMANNED AERIAL VEHICLES: FUNDAMENTALS, COMPONENTS, MECHANICS, AND REGULATIONS

***M. P. Stewart*[*] and S. T. Martin*[†]**
School of Engineering and Applied Sciences and
Department of Earth and Planetary Sciences, Harvard University,
Cambridge, Massachusetts, US

ABSTRACT

Over the last decade, unmanned aerial vehicles (UAVs), colloquially known as drones, have seen rapid adoption within commercial and consumer markets. This market expansion has come with a concomitant increase in the diversity of applications of UAVs, which are now being utilized for everything from aerial photography to measuring gas emissions from volcanoes. Due to the nascent nature of the technology, the UAV landscape is highly dynamic and evolving. There are several important trends and concepts that are informative to the industry professional or

---

[*] Corresponding Author's E-mail: matthew_stewart@g.harvard.edu.

[†] Corresponding Author's E-mail: scot_martin@harvard.edu.

researcher regardless of discipline. This chapter presents background concepts important to any individual endeavoring for the first time to use UAVs in work or research. Such topics include nomenclature and classification, the UAV market, rules and regulations, fundamental components, and flight mechanics. This information affords the reader a deeper understanding of UAV platforms and their capabilities, as well as the relevant sociopolitical, economic, and technological challenges to their use.

1. INTRODUCTION

While the 20th century saw the dawn of manned flight in both the atmosphere and space, the 21st century is experiencing a similar revolution in the realm of unmanned and autonomous flight. Over the past decade, unmanned aerial vehicles (UAVs), often referred to by the general public as drones, have become valuable and ubiquitous assets for use by industry, academia, and hobbyists. Enabled by advances in microcontrollers, sensing technology, and control systems, UAVs have quickly become a ubiquitous feature of the modern world. Although most traditional applications have resided in the military sphere, the broad spectrum of applications afforded by UAVs and their relatively low cost has led to their growing adoption in the commercial market. Technological developments, coupled with economies of scale, suggest that this trend could continue into the near future as platforms become more affordable, acquire additional functionalities, and gain enhanced performance characteristics.

Despite the vast range of applications, several universal aspects transcend individual applications. These aspects are necessary and informative for individuals who plan to use UAVs in their work or research. This chapter introduces the history of the UAV, the present-day UAV market, and a discussion of UAV fundamentals, components, mechanics, and regulations. Different classification systems aim to categorize UAVs based on their propulsion system, structure, size, and mass. A discussion of UAV regulations in an evolving landscape is provided along with the potential ramifications for industry and research applications. The final sections of the chapter focus primarily on rotary-wing UAVs because of their increasing prevalence.

The United States Federal Aviation Administration (FAA) states that "an unmanned aircraft is a device that is used, or is intended to be used, for flight in the air with no onboard pilot" [1].This definition may be considered overly general for the commonly understood applications of a UAV because ballistic and cruise missiles, not commonly regarded as UAVs, could be considered as included in the FAA definition. Thus, in this chapter, a UAV is defined as follows: "an airborne powered vehicle without a human operator capable of operating autonomously, semi-autonomously, or piloted remotely, capable of producing aerodynamic lift and may or may not carry a payload." Missiles and unmanned systems operating using aerostatics, such as radiosondes, do not fall under this definition since they do not produce aerodynamic lift.

New technologies often have dynamic and ambiguous terminology. As an example, the automobile, colloquially known as a car, was originally referred to as a "horseless carriage." Analogies hold for the current terminology of UAVs. There is an aversion to the term "drone" in some parts of society due to its military roots [2]. This aversion, coupled with various terms used by different governments, organizations, and researchers, has led to a long list of alternative names and acronyms (Figure 1). Examples include "unmanned aircraft system" (UAS), "remotely piloted aircraft" (RPA), "remotely piloted vehicle" (RPV), and "remotely operated aircraft" (ROA). The differences among these terms can be subtle. "Remotely piloted" indicates the presence of a human pilot on the ground whereas "unmanned aircraft systems" can be autonomous. "Unmanned aircraft system" is used predominantly by government agencies and international organizations, whereas "unmanned aerial vehicle" is popular in academia.

In contrast to these more technical terms, the word drone has become commonplace in the general public. Consequently, many industries have adopted this word to market their consumer products. For clarity, in this chapter, the terms UAV and drone are used interchangeably to describe the physical vehicle and the term UAS is used to describe the combination of UAV, a ground-based controller, and the synchronous communication system between them. UAVs are often equipped with supporting equipment to augment their functionality, such as cameras, sensing equipment, or other forms of payload.

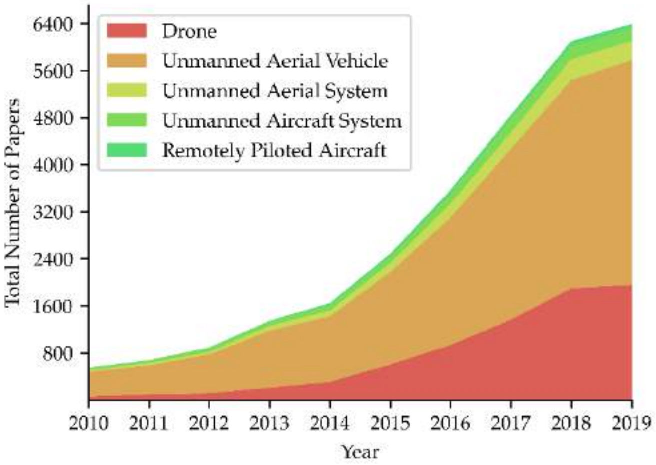

Figure 1. Comparison of the relative frequency of words that are used in research papers to describe unmanned aerial vehicles.

2. HISTORY OF UNMANNED AERIAL VEHICLES

The first known use of an unmanned system occurred in July 1849 during the Austrian siege of Venice by the Hasburgs [3]. Austrian forces launched 200 hot air balloons carrying bombs that were to be dropped with a timed detonation over the city. While at least one of these bombs reached its target, most of these balloons missed due to changing wind conditions following their launch, some even drifting back over Austrian lines. Little immediate further work took place after the ineffectiveness of this effort. In 1903, the advent of fixed-wing aircraft led to renewed developments. During the First World War, the first pilotless aircraft was developed called the Hewitt-Sperry Automatic Airplane, utilizing radio control techniques and the newly invented gyroscope [4,5]. This aircraft served primarily the same purpose as the balloons at the siege of Venice, acting as an aerial torpedo against Zeppelins. After the war, radio-controlled aircraft development continued to be pursued but gradually began to evolve from aerial torpedoes into fully fledged aircraft. In 1931, the United Kingdom developed the radio-controlled "Fairey Queen" UAV adapted from the Fairey IIIF floatplane, a reconnaissance aircraft. This development was followed up in 1935 with the mass production of the "DH.82B Queen Bee," a name derived from the de Havilland Tiger Moth [5]. It is also purported to be the origin of the term "drone" to describe pilotless aircraft.

Around this time, the use of radio-controlled UAVs began to move away from the military and into the private sector. In 1935, the English actor Reginald Denny developed what is possibly the first-ever model aircraft. A former serviceman for the British Royal Air Corps, Denny had emigrated to the USA to pursue a career in acting but was also an avid model aircraft enthusiast. After forming Reginald Denny Industries, he opened a model plane shop in 1934 on Hollywood Boulevard. This store evolved into the Radioplane Company. It demonstrated a UAV prototype to the USA army in 1935 called the RP-1 in the hope of winning a military contract. He was unsuccessful. Subsequently, Denny purchased a design from Walter Righter in 1938, which he developed into the RP-2 and again demonstrated to the USA army. Despite improvements, the RP-2 was still not sufficient to win the contract. Following further developments into the RP-3 and RP-4, Denny finally won the contract in 1940 with the RP-4, which later became the OQ-2 Radioplane. A contract was reached to produce fifteen thousand for the USA army [4]. Reginald Denny received additional military contracts, and he is now considered a UAV pioneer and an influential figure in the history of model aircraft. While hobbyists began to use model aircraft for recreational purposes such as model aircraft racing, several more decades would pass until use for more practical purposes began.

Despite further developments during the Second World War and the post-war era, significant further changes did not occur until the Vietnam War in the 1960s. During this conflict, reconnaissance UAVs were deployed on a large scale. UAVs were also leveraged for new purposes, such as for dropping leaflets, collecting images of enemy territory, and decoys [4]. Following the Vietnam War, other countries outside the United Kingdom and the United States began to explore unmanned aerial technology. New models became more sophisticated. There was improved endurance, and greater altitudes could be maintained. As a result of the maturation and subsequent miniaturization of technology through the 1980s and into the 1990s, the interest of the USA military in UAVs continued to grow. During the 1990s, the USA Department of Defense awarded a contract to AAI Corporation and an Israeli company Malat, and they produced the AAI Pioneer Drone. These UAVs were an important military asset during the 1991 Gulf War and demonstrated the potential capabilities of using relatively low-cost military aircraft without risk to personnel. Initially, the UAV was only used for surveillance missions but was gradually given armaments. The armed UAV known officially as the General Atomics MQ-1 Predator became well known to the public as the Predator drone [4].

Several decades earlier, the development of model aircraft had sparked the emergence of a consumer market from military roots. Despite many technical similarities, the consumer market had substantially different needs from the military market, and as such the two began to diverge. Most model aircraft needed to be lightweight, easily portable, and relatively inexpensive in comparison to military aircraft. The notion that small UAVs might have practical uses arose in the early 1990s. Improvement in propulsion systems such as internal combustion engines and electric motors made the possibility of longer flight times increasingly attainable. The development of miniature radio receivers and control equipment such as gyroscopes had a marked impact on the ability to design a small flying vehicle. Once aerodynamics and control models for small aircraft were developed, the micro air vehicle was born.

The introduction of the micro air vehicle was highlighted in 1992 when DARPA organized a workshop labeled "Future Technology-Driven Revolutions In Military Operations." [6]. One topic discussed at the seminar was "mobile microrobots." The concept of small "microdrones" was discussed with skepticism but slowly started to garner momentum. This seminar was followed in 1994 by a widely circulated paper from the RAND corporation on micro UAVs. DARPA subsequently sponsored a series of idea papers and conducted workshops on the concept over the next two years, leading to early studies at the Massachusetts Institute of Technology (MIT) and the US Naval Research Laboratory (NRL). The studies resulted in the development of the first micro UAV. The following year, DARPA invested in a multi-year micro air vehicle (MAV) program to further develop the technology. The project goal was to develop a low-cost micro UAV. It would be smaller than 15 cm and capable of carrying an imaging device for a flight time of 2 h. The aim was to produce a UAV that could be used in squad-level combat to scout buildings and as part of a survival kit to track for enemy search parties or as an airborne radio relay. The MAV concept represented a paradigm shift in the use of unmanned aerial vehicles, which were now sufficiently small and low-cost to be used for commercial applications. However, several more years passed before these technological innovations entered the consumer market.

Between the late 1990s and early 2000s, the modern quadcopter UAV began to emerge in the form of hobby kits. The most notable of these was the “Draganflyer quad helicopter” in 1999, which became popular among UAV researchers and gained public recognition after its use in the movie *Inspector Gadget*. During the mid-to-late 2000s, quadcopter UAVs continued to grow in popularity among hobbyists.

In May of 2006, the FAA issued the first Certificate of Authorization (COA). This certificate allowed the M/RQ-1 Predator and M/RQ-9 Reaper aircraft to be used in USA civilian airspace to search for survivors of disasters. A perspective article in the Wall Street Journal stated:

> “After distinguished service in war zones in recent years, unmanned planes are hitting turbulence as they battle to join airliners and weekend pilots in America’s civilian skies. Drones face regulatory, safety and technological hurdles – even though demand for them is burgeoning. Government agencies want them for disaster relief, border surveillance and wildfire fighting, while private companies hope to one day use drones for a wide variety of tasks, such as inspecting pipelines and spraying pesticides on farms” [7].

In the same year, the Chinese company DJI, now the leading manufacturer of consumer and many commercial UAVs, was founded by Frank Wang. By 2010, the number of COAs issued each year by the FAA had grown to 298 [8].

The year 2010 saw the release of the first consumer UAV controllable solely by WiFi by the French company Parrot called the "AR.Drone." The WiFi connection allowed users to pilot the UAV using a smartphone. The UAV was a milestone in consumer UAV technology, and the vast demand for this product paved the way for consumer UAVs seen on the market today. In 2013, DJI released its first consumer-driven UAV known as the DJI Phantom. Leveraging similar technology to the AR.Drone, the Phantom had superior hardware and software capabilities compared to other UAVs on the market, and it quickly ascended in market share. They were further adopted for commercial applications such as real estate, mining, farming, and other industries benefiting from aerial imagery. Today, demand for UAVs continues to increase in both the commercial and consumer markets.

UAVs are simpler in construction than human-piloted aircraft. There is no need for life-critical systems onboard. Moreover, since the device is remotely or autonomously piloted, there is no need for a control interface, cockpit, or windows, which reduces weight and increases robustness. Many UAVs carry payloads that are significantly lighter than an adult human, which allows them to be lightweight and highly maneuverable. The presence of multiple propellers means that the average kinetic energy of the blades is relatively low, which reduces the possibility of damage to the UAV or injury to persons when in close proximity. Propellers can also be placed in guards, also known as ducted fans, to further reduce the possibility of damage when near obstacles.

3. UAV CLASSIFICATION

UAVs come in two primary forms: fixed-wing and rotary-wing. Fixed-wing UAVs operate analogously to lightweight unmanned airplanes. Rotary-wing UAVs, also called multirotor, rotorcraft, or multi-copter UAVs depending on their structure, are analogous to lightweight unmanned helicopters. These craft derive their lift from propellers, which are fans that generate thrust through the rotation of rotor blades on a rotor mast. However, while helicopters typically contain a single rotor with two blades, most rotary-wing UAVs require multiple rotors to manage the stresses upon the rotor blades necessary to become airborne. Rotary-wing UAVs are referred to as vertical takeoff and landing (VTOL) vehicles, whereas fixed-wing UAVs are classified as horizontal takeoff and landing (HTOL) vehicles. Often, VTOL vehicles are more convenient because they can become airborne in more enclosed environments and do not require a runway like some HTOL vehicles. On the other hand, HTOL vehicles generally require less power and tend to have larger efficiencies and hence flight times than VTOL vehicles. One major reason for the dominance of rotary-wing UAVs is their ability to produce lift whilst stationary whereas fixed-wing UAVs require movement in order to generate lift via the Kutta-Joukowski theorem. This makes rotary-wing UAVs more maneuverable and movement is generally more controlled. Some examples of fixed- and rotary-wing UAVs are shown in Figure 2.

The most common configurations for rotary-wing UAVs are quadcopter and hexacopter. Rotary-wing UAVs can hover and have high maneuverability. In this sense, the UAV can serve as a stationary floating platform from which images or sensor measurements can be obtained. Fixed-wing UAVs require less power to produce lift and thus tend to have long flight times and distance ranges. Other less commonly encountered UAVs include the hybrid and flapping-wing designs. Hybrid UAVs use a combination of both fixed- and rotary-wings to generate lift. This combination allows the UAV to operate in either fixed-wing or rotary-wing mode, which provides significant flexibility. However, the overall system tends to less reliable than fixed-wing or rotary-wing configurations, and any necessary repair or maintenance can be more complex. They are also typically heavier due to the greater number of required components. Flapping-wing UAVs are designed to mimic the flight mechanics of birds and insects and hence tend to be small. A payload (if any) of sensor or camera is typically directly incorporated in the design, reduced flexibility of applications, and the flight stability is more vulnerable to crosswinds and turbulence compared to other types of UAVs.

Figure 2. Several examples of fixed-wing and rotary-wing UAVs. Adapted from Reference [9]. Creative Commons BY 4.0 license. Copyright (2017), with permission from the *Multidisciplinary Digital Publishing Institute*.

In addition to classification by configuration, there are multiple other classification schemes. The USA Department of Defense (DoD) uses 5 classes based on weight, speed, and altitude (Table 1) [10]. UAVs are also sometimes classified by endurance and altitude, including MAVs (Micro or

Miniature Air Vehicles), NAVs (Nano Air Vehicles), VTOL (Vertical Take-Off & Landing), LASE (Low Altitude, Short-Endurance), LASE Close (LASE requiring a runway), LALE (Low Altitude, Long Endurance), MALE (Medium Altitude, Long Endurance), and HALE (High Altitude, Long Endurance) [11]. Brooke-Holland [12], Weibel and Hansman [13], Gupta et al. [14], and Cavoukian [15] present other complementary classification schemes. One of the most comprehensive classification schemes is provided by Hassanalian and Abdelkefi [16] which begins with weight and wingspan and then further subdivides classes by their propulsion system (Figure 3). In this scheme, from 5 mg/1 mm to 15000 kg/61 m, UAVs are classified into the categories: UAV (5-15000 kg; 2-61 m), micro unmanned air vehicles (μUAV) (2-5 kg; 1-2 m), micro air vehicles (MAV) (0.05-2 kg; 0.15-1 m), nano air vehicles (NAV) (3-50 g; 2.5-15 cm), pico air vehicles (PAV) (0.5-3 g; 0.25-2.5 cm), and smart dusts (SD) (0.005-0.5 g; 0.1-2.5 cm).

Table 1. UAV classes used by the USA Department of Defense

Category	**Size**	**Maximum Takeoff Mass (kg)**	**Operating Altitude (m)**	**Airspeed ($m\ s^{-1}$)**
Class 1	Small	0-9	<366 AGL[a]	<51.4
Class 2	Medium	9-25	<1067 AGL	<128.6
Class 3	Large	<600	<5486 MSL[b]	<128.6
Class 4	Very-Large	>600	<5486 MSL	Any
Class 5	Very-Large	>1,320	>5486 MSL	Any

[a] Above ground level.

[b] Mean sea level.

There are many possible rotary-wing UAV configurations (Figure 4). These configurations are delineated both by the number of propellers and the placement relative to the central unit of the UAV. The most common 8 rotary-wing UAV configurations are illustrated in Figure 4. The naming convention of Figure 4 provides a convenient shorthand for describing these configurations and is often used by UAV vendors. The I- and X-configurations are used when a UAV has evenly distributed rotors in a circle around the central unit. The number after the configuration type refers to the total number of rotor blades present. When the angle of one rotor coincides with the angle of the frontal UAV direction, it is referred to as an I-configuration. When this condition is not met, the UAV is in an X-configuration. The difference between these configurations has little functional impact but can affect pilot control systems and related programming.

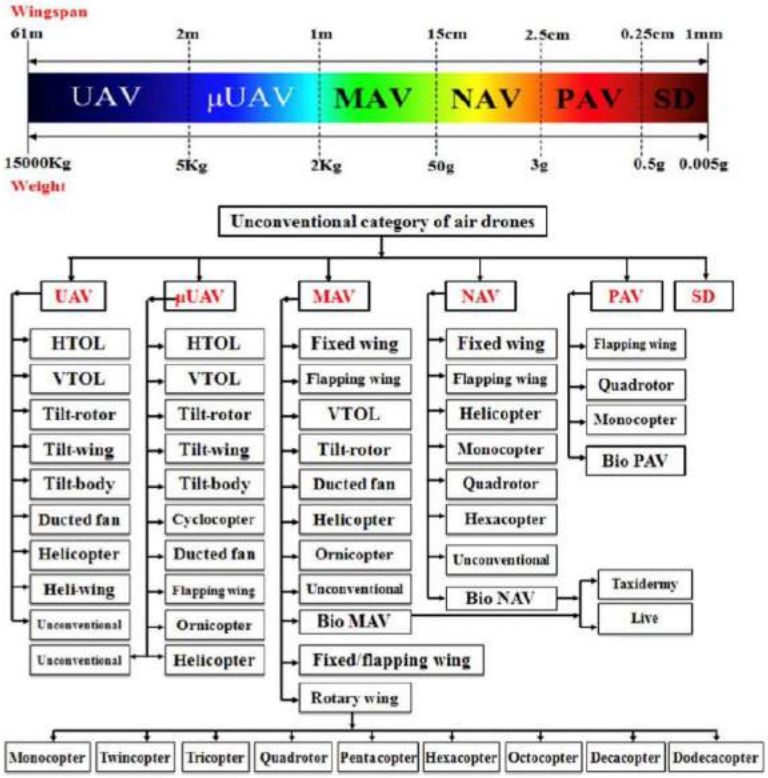

Figure 3. Classification schemes of UAVs based on weight and propulsion. Adapted from Reference [16]. Copyright (2017), wih permission from Elsevier.

The Y-configuration refers to the presence of coaxial rotors, wherein two contra-rotating rotors are concentrically located on a motor shaft. Coaxial rotors have the benefit of reducing flight hazards such as blade stall, vortex ring state, and high-frequency oscillations. Y-configuration UAVs can have substantially different air flow patterns as compared with I- and X-configuration UAVs. The doubling up of rotors localizes thrust generation to fewer rotors. This localization increases the Reynolds numbers of the flow in these regions, which increases turbulence. Flow also becomes more inviscid, which allows simplifying assumptions for modeling. Simultaneous designation as both I- and Y- configurations is also possible.

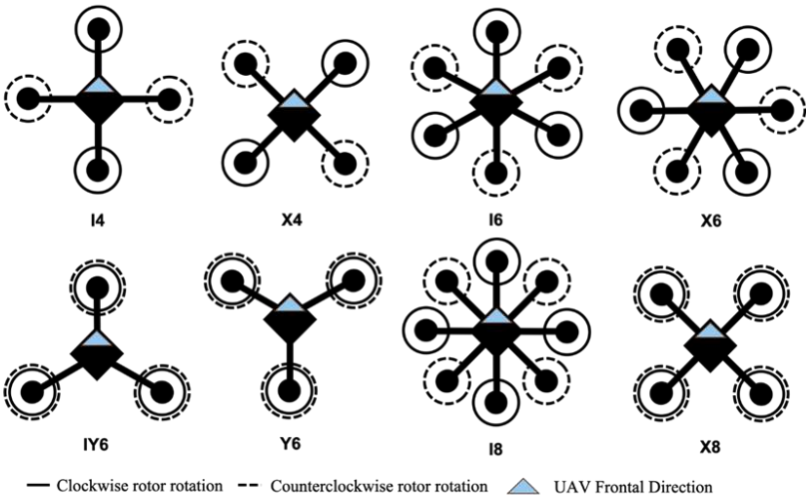

Figure 4. Common rotary-wing UAV configurations. On non-coaxial configurations, clockwise and counterclockwise rotors must be adjacent to maintain flight stability.

4. UAV MARKET

In 2004, 98% of UAV production was for military applications [17]. Since then, there has been a significant upsurge in the use of UAVs both by hobbyists and remote-controlled vehicle enthusiasts and by many commercial and government organizations to augment their operations. The 2019 FAA Aerospace Forecast estimates that the consumer and commercial UAV markets are growing faster than anticipated and could triple by 2023 [18]. More than 900,000 UAVs have been registered with the agency as of 31 December 2018 since online UAV registration was mandated starting 2015. Although the UAV market is still dominated by military use, commercial and consumer market value continues to rapidly expand. Popular commercial applications include aerial photography, disaster management [19,20], agriculture (e.g., crop spraying, monitoring, and irrigation) [21-23], search and rescue [24,25], transportation of goods [26-28], sports recordings [29,30], and entertainment applications [31,32]. Some applications are considered controversial, such as the use of drones by law enforcement, which has created a political divide in the USA [33].

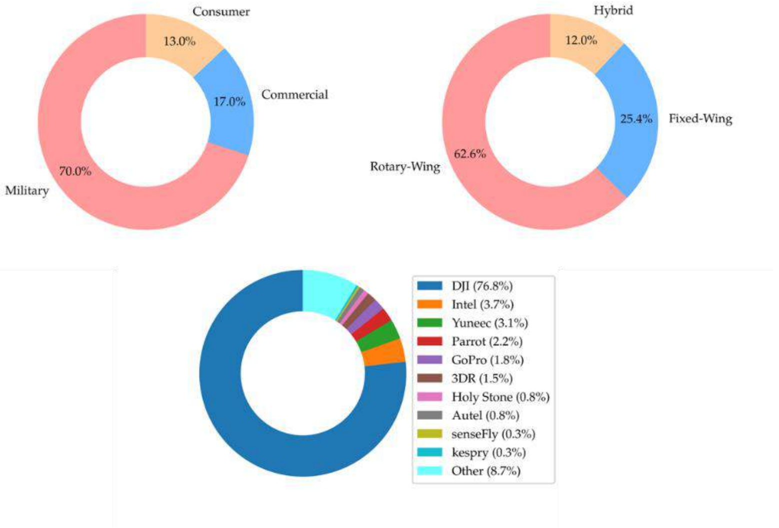

Figure 5. (Top left) USA UAV market share based on major UAV types for year 2019. (Top right) USA UAV market share based on sector. (Bottom) USA commercial UAV market share of the top 10 companies. Data from Drone Industry Insights [34].

Predictions of the future market size of commercial UAVs vary substantially. A 2020 study by Fortune Business Insights [34] estimated that the global commercial UAV market in 2018 stood at USD 1.2 billion and projected it to increase to USD 6.3 billion by 2026. A separate report by Strategy Analytics projected an increase in market size to USD 12 billion for the same year [35]. While there is disagreement in the magnitude of these projections, the directional trend is apparent. There is also consensus suggesting substantial integration of UAVs into the commercial and consumer sectors in the coming decade.

As of 2019, DJI accounted for 76.8% of the USA's market share by number (Figure 5) based on FAA registrations, and no other company accounted for more than 4% according to a report by Drone Industry Insights [36]. The same report also outlined that the USA accounted for the largest drone market in the world and is home to more than half of global drone investments.

Rotary-wing UAVs accounted for two-thirds of the global consumer market share (Figure 5). The low cost and simple construction of rotary-wing UAVs suggests that these UAVs might continue to dominate the consumer market. In contrast, the military market continues to employ fixed-wing UAVs, and market size is projected to remain unchanged in the near future [37]. As of 2019, military applications of UAVs account for 70% of the UAV market (Figure 5). UAVs have also presented new avenues of research for specific scientific fields, especially in the fields of ecology (e.g., wildlife protection) [38], forestry (e.g., tree counting) [39-42], and environmental science (e.g., air quality monitoring) [43-45].

5. REGULATIONS

Many countries have adopted regulations for conducting UAV flights. Both the safety of people on the ground and in air vehicles aloft as well as security against the misuse of UAVs are of concern. The regulations typically relate to UAV classification, airspace and payload restrictions, operator licensing, and UAV registration. Currently, UAV regulations remain largely in the incipient stage, meaning that they continue to change. The ongoing changes can present significant barriers for largescale commercial use of UAVs. Any UAV operator should be fully versed in and comply with the regulations of the operating jurisdiction.

As an example, in the United States under the FAA Modernization and Reform Act of 2012, Congress tasked the FAA with integrating UAVs into the National Airspace System (NAS) [46]. The FAA formulated policies, procedures, and standards to incorporate UAVs safely into the crowded NAS. Some have argued that aircraft design standards and certification procedures must be established for UAVs such that they have similar reliability and safety as conventional aircraft [47]. The regulations currently in place continue to evolve in response to the still emerging technology and its increasingly widespread use. The NAS has six classes of airspaces, within which only specific categories of aircraft may fly. UAVs are generally allowed to fly in class “G” uncontrolled airspace from the surface to 122 m (400 ft). For flights at higher altitudes or close to airports or military areas, prior permission from appropriate authorities is required. All UAVs for commercial usage must be registered with the FAA, and all pilots require a remote pilot certificate rated for small UAS. Flights must also adhere to requirements of maximum speed, visibility, time of day, payload size and rigidity, and total weight (< 25 kg for a small UAS rating).

From 2007 until the creation of the Part 107 Rule, all UAVs either required a COA or a Section 333 exemption to be allowed to operate in the NAS [48]. This COA is provided by the FAA Air Traffic Organization to a public entity to perform a specific operation. Obtaining a COA involves a comprehensive overview and risk analysis of anticipated activities and may involve limitations being imposed as part of the approval process to ensure safe operation in the NAS. The FAA issues a COA based primarily on three criteria. First, the COA authorizes qualified operators associated with the public entity to operate in a defined NAS airspace class and can include special provisions unique to the proposed operation, such as a requirement to operate only under Visual Flight Rules. COAs are issued for a specific time period, typically one year, and for a specified scope of work. Second, many COAs require coordination between the pilot and the air traffic control facilities. They may also require that a transponder be mounted on the UAV to operate in certain types of airspace. Third, due to the inability of UAV to comply with "see-and-avoid" rules, a visual observer or an accompanying aircraft must maintain visual contact with the UAV and provide visual support. COAs are only available to public entities such as government agencies, public schools, and emergency departments and not for privately owned businesses. For companies using UAVs as part of their business operations, a Section 333 exemption was required (now repealed by the 2018 FAA Reauthorization Act and replaced by Section 44807) which essentially allowed the company to operate under COA limitations. This exemption has now been replaced by the newer Part 107 Rule, although COAs are still available for public entities. One of the main benefits of a COA is the ability to self-certify UAV pilots. However, obtaining a COA typically takes 60-120 days, longer than required for a Part 107 license.

In December 2015, the FAA introduced the Part 107 rule to Title 14 Code of Federal Regulations, requiring any individual that wishes to operate a UAV in the NAS for non-recreational purposes to apply for a Part 107 certificate [49]. This rule is often referred to as the "Small UAS Rule." In addition, FAA registration became required for all UAVs weighing more than 0.25 kg and sets a maximum UAV weight limit of 25 kg. This rule states that the non-recreational UAV pilot must pass the FAA's Aeronautical Knowledge Test and must comply with the other requirements listed in the Part 107 Rule. If the individual requires an exemption for any restrictions designated in the Part 107 Rule, they must apply for a waiver under Special Authority for Certain Unmanned Systems (49 U.S.C. §44807). In May 2017, the United States Court of Appeals for the District of Columbia Circuit, in ruling on *Taylor v. Huerta*, reversed the registration requirement [50]. However, in December 2017 the National Defense Authorization Act for Fiscal Year 2018 effectively reinstated the registration requirement [51]. During the following year, the FAA Reauthorization Act of 2018 was passed in the Senate. This repealed Section 336 of the FAA's Special Rule for Model Aircraft, thus requiring recreational UAV pilots to take the Aeronautical Knowledge Test, which previously had been required only for commercial UAV pilots [52]. In December 2019, the FAA proposed a rule to require that consumer UAVs be equipped with an identification device, although this is not expected to come into effect until 2021. This recent history for the USA parallels discussions and developments for many other countries, too [53]. Under current regulations, non-recreational flyers must obtain a Part 107 certificate before operating in the NAS. However, recreational flyers are covered under the Exception for Recreational Flyers and Community-Based Organizations (49 U.S.C. §44809). Thus, recreational flyers do not need to comply with Part 107, just all portions covered under Section 44809. Some educational and research uses of drones are deemed recreational in nature according to a statutory provision (PL 115-254, Section 350).

In the coming years, increasing use of UAVs can be expected to further densify the NAS, especially the class "G" zone. Several challenges must be addressed. These challenges include eventual saturation of the UAV radio spectrum, NAS integration of different types of UAVs [54], landowner airspace rights [55], and privacy [56]. Governments might impose stricter restrictions on UAV usage, which could affect commercial and academic applications of UAVs.

6. COMPONENTS

This section focuses on the components of rotary-wing UAVs. This focus is chosen because of the relative dominance of rotary-wing UAVs in the commercial and consumer UAV markets.

6.1. Chassis

The chassis of a rotary-wing UAV should be lightweight and made from materials resistant to static and dynamic stresses. Common materials are duralumin or carbon fiber. The material should also be suitable for its anticipated operating environment to avoid issues such as heat stress cycling induced from sunlight or brittle fracture in cold environments. The chassis consists of a central unit that houses the main electronics and communications equipment. The central unit is coupled with several evenly spaced arms, each housing a single motor and propeller unit (Figure 6). The number of arms of a rotary-wing UAV is variable, but four (quadcopter), six (hexacopter), eight (octacopter) are common. The arms can be made from trussed beams or tubes. A smaller number of arms can minimize size, weight, and complexity. A larger number of arms, however, can spread the lifting load and provide flight stability.

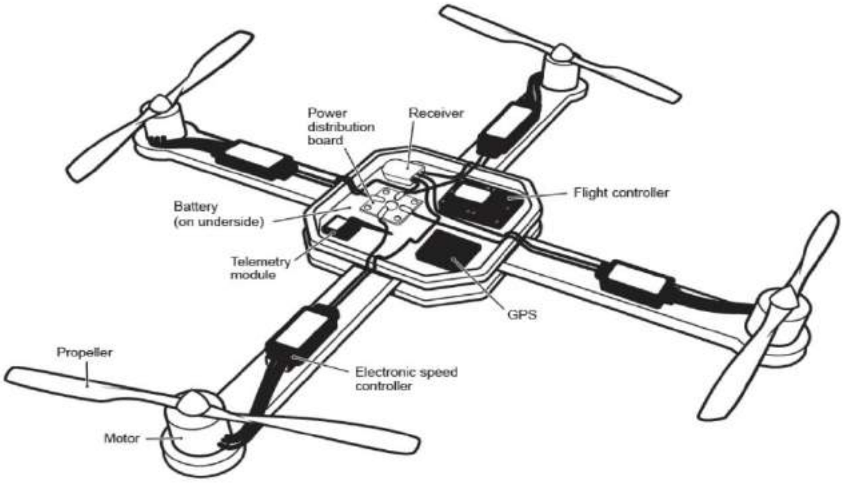

Figure 7. Anatomy of a rotary-wing UAV. Adapted from Reference [57]. Copyright (2017), with permission from the *International Journal of Innovative Research in Computer and Communication Engineering*.

6.2. Propeller

The propellers rotate horizontally and generate thrust orthogonally to the direction of the rotation. Functional parameters of a propeller include blade diameter, blade pitch, and blade number. A higher number of blades, a larger pitch, or a greater diameter correspond to increased thrust and hence power. Propellers of two rotor blades generate more thrust than propellers of three or more blades, which lose a greater fraction of power to turbulence. In respect to larger blade pitch or diameter, the motor must correspondingly produce greater torque. The propeller thrust also depends on several operational variables, including air density, wind speed, and propeller speed. In contrast to helicopters, which have a cyclical pitch (i.e., the pitch changes during rotation of the rotor), UAVs have fixed-pitch propellers. In this case, the lift can be increased only by increasing the propeller speed. Increased propeller pitch results in increased drag. In regard to design parameters, propellers should have the minimum weight that achieves sufficient strength to withstand the stress forces at maximum thrust. Clockwise propellers are placed adjacent to counterclockwise propellers in order to balance torques and prevent rotation about the vertical axis, assuming all propellers operate at the same speed. Without balance, unexpected yaw can occur, leading the vehicle to rotate without any input from the pilot. Some UAVs have rotor blades enclosed in casings built into the chassis. This configuration permits flights in tighter and more challenging environments and thus reduces the risk of damaging the UAV or its surroundings. Many commercial UAVs have foldable propellers to facilitate transport.

Propellers are the main source of audible noise from UAVs. As UAV usage becomes more ubiquitous, there are concerns about the ramifications for residents and wildlife, and studies on propeller noise may become increasingly important as UAVs become more integrated in the NAS. Noise also reflects loss of power from thrust to turbulence. Several UAV manufacturers have focused on improving propeller design toward the twin goals of reducing noise and increasing thrust. Leslie et al. [58] showed the importance of minimizing laminar separation from the blades at low Reynolds number. Altering the diameter, angular velocity, and shape of the propeller can have substantial impacts on produced audible noise and thrust loss.

6.3. Motor

The propulsion system translates electrical energy to mechanical energy. A motor attached to each propeller must be able to respond quickly and reliably to changes in electrical power. The motor shaft is connected to the propeller. Brushless motors reduce friction and thus increase power efficiency (i.e., battery usage).

Brushless motors are characterized by electrical current and rotational speed. The maximum rotational speed ω_0 under no-load conditions is given by $\omega_0 = K_v V$, *where* K_v is a parameter of the motor and V is the applied voltage. When voltage is applied, current is drawn, and the motor exerts torque on the shaft. The shaft is accelerated until the exerted torque equals the load torque, including mechanical losses. At low rotational speeds far from the maximum performance of the motor, the exerted torque is proportional to applied voltage, as quantified by the motor torque constant K_t. The torque is converted into rotational speed and thrust based on the propeller characteristics. The torque produced by the motor is as follows:

$$\tau = K_t(I - I_0) \tag{1}$$

where τ represents the torque produced by the motor, I the input current, I_0 the no-load current, and K_t the torque proportionality constant. Equation (2) shows that the voltage across the motor is the sum of the back-EMF (i.e., because of electrical inductance) and some resistive loss, as follows:

$$V = IR_m + K_v\omega \tag{2}$$

where V is the motor voltage drop, R_m is the motor resistance, ω is the motor angular velocity, and K_v is a motor constant representing back-EMF generated per unit speed. This description can be used to calculate the power consumption of the motor, as follows:

$$P = I\,V = \frac{(\tau + K_t I_0)(K_t I_0 R_m + \tau R_m + K_t K_v \omega)}{K_t^2} \tag{3}$$

In this model, a negligible motor resistance is assumed. Equation (4) shows that the power is proportional to the angular velocity:

$$P = \frac{(\tau + K_t I_0) K_v \omega}{K_t} \tag{4}$$

When $K_t I_0 \ll \tau$ for negligible I_0 at no load, the following holds:

$$P \approx \frac{K_v \tau \omega}{K_t} \tag{5}$$

6.4. Electronic Speed Controller

For brushless motors, an electronic speed controller (ESC) is necessary to achieve electric commutation. The speed of each brushless motor is controlled by a separate ESC, each of which is connected to a master power distribution board (PDB). The ESC transfers the current from the battery to the motor under constant voltage. During the design of a rotary-wing UAV, the ESC should be selected according to the maximum motor current. The PDB is connected to the flight controller, which translates pilot direction into UAV motion (section 6.6). The ESCs also provide telemetry regarding propeller speed, motor current, and temperature.

6.5. Battery

Batteries connected to the PDB provide the needed current and voltage to the electric components onboard the UAV. To obtain the necessary current and voltages for motors and other components onboard the UAV, batteries are connected in series (S) or parallel (P). Batteries are characterized by "mAh" and "C-rate." At constant voltage, the "mAh" capacity refers to the tradeoff between high battery current versus long battery duration. It relates to the total energy E (J) that can be supplied by the battery at its nominal voltage V, for which ($E = 3.6 \times V \times \text{mAh}$). At constant voltage, the "C-rate" (units of h^{-1}) refers to battery usage. A 1C rate means that a battery that is used at its mAh capacity can sustain "mA" for one hour. By comparison, a 2C rate provides a current of 2×"mA" for 30 min, and a C/2 rate provides a current of 0.5×"mA" for 2 h. Conversely, sustaining a current of 2×"mA" for 60 min would require two 2C batteries.

Lithium-polymer (Li-Po) and lithium-ion (Li-ion) batteries are the most widely used on UAVs. In recent years, they have become smaller and more affordable, mainly driven by the computer and mobile phone industries. Although Li-Po and Li-ion batteries have lower volumetric- and mass-specific energy ratings than gasoline or other related fuels (Figure 7), they are rechargeable. Both types of specific energy ratings are important considerations for optimizing the propulsion system and the flight performance to a planned UAV application.

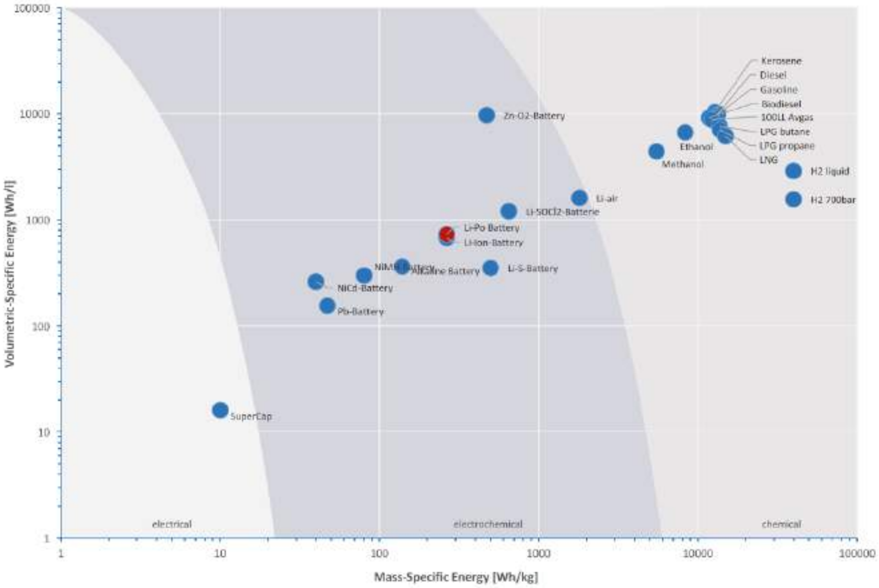

Figure 6. Comparison of power sources for UAVs based on volume and mass parameters [59]. Copyright (2017), with permission from Drone Industry Insights.

Of the two battery types, Li-Po batteries are most widely used for powering rotary-wing UAVs because of their physicochemical properties. They have high energy density (i.e., lower overall UAV weight) and higher current discharge capabilities over both lithium-based (Li-ion, Li-Fe) and nickel-based (NiMh, NiCd) batteries [60]. Battery voltage depends on its type of electrochemistry and its state of charge. For Li-Po batteries, the voltage ranges between 2.7-3.0 V (nearly discharged) and 4.2 V (fully charged). Discharging a Li-Po battery under 3 V leads to permanent damage to the battery. For this reason, the batteries should be discharged to no more than a state of charge of 20%. The nominal voltage of the battery typically corresponds to a state of charge of 50%. This voltage is commonly 3.7 V for Li-Po batteries. Four Li-Po batteries connected in series produces a nominal voltage of 14.8 V.

6.6. Flight Controller

A flight controller translates the high-level commands of a human operator equipped with an interfacing device like a joystick or other technology or alternatively the commands of a software program into the voltages applied to the UAV motor system. The flight controller is necessary for simultaneously controlling the rotational speeds of multiple motors. The flight controller also uses data from onboard sensors, such as a 3-axis gyroscope (providing information about the UAV rotational movement and attitude), a 3-axis accelerometer (providing information about the UAV linear movement and position), and a pressure sensor (providing information on UAV altitude). A Global Positioning System (GPS) is incorporated onto many UAVs, and the flight controller can make use of its data stream for autopilot or as a failsafe in case of communication loss with a ground controller.

The combined information from the set of sensors is used for feedback control to the voltages applied to the motors to maintain flight stability. The controller draws upon the field of control theory, and mathematical models are required to build the control systems used to operate rotary-wing UAVs. Many different methods have been used for quadcopter control such as PID controllers (PID, "proportional integral gain"), back-stepping control, LQR controllers (LQR, "linear quadratic regulator"), and nonlinear H_∞ control (H, "Hardy"). A comprehensive survey of control systems, guidance, and navigation in UAVs is provided by Kendoul [61].

For many years, the difficulty of controlling four or more independent propellers without electronic assistance stalled the technological development of rotary-wing UAVs. The breakthrough electronic control of quadcopters became possible through advances in microprocessor technology that led to miniaturization and reduced costs for flight controllers. Controlling a quadcopter is challenging because the system is under-actuated, which means the following. Quadcopters have six degrees of freedom, corresponding to three translation and three rotational degrees of freedom, yet quadcopters have only four independent controls (i.e., the rotational speed for each propeller). The implication is that the translation and rotational motions are coupled. This coupling results in highly nonlinear dynamics, which are further complicated by the inclusion of additional aerodynamic effects, including exterior factors such as micrometeorology and atmospheric turbulence. Another complication is the absence of a braking mechanism for UAVs, except for the friction of air resistance. Instead, the UAV must provide its own braking mechanism through control of propeller speeds in order to dampen movements and provide stability.

6.7. Communication Link

6.7.1. Radio Frequencies

A ground pilot or computer typically communicates with a UAV through bidirectional radio. Computer and telephone WiFi frequencies such as 2.4 or 5 GHz are often used. This choice simplifies the need for regulatory approvals for use of the electromagnetic spectrum, but it also limits by regulation the maximum allowed radio power. Commercially available UAVs often employ multiple antennas for redundancy, typically in odd numbers such that if one is disabled or fails to receive signal, then an electronic consensus between the remaining antennas is still possible.

An interface between air and ground elements of these UAVs is typically maintained through radio line-of-sight links. Wireless communication is necessary for control and non-payload communication (CNPC) and often for payload communication. Although there are no inherent technical limitations beyond battery restrictions in the maximum distance that a UAV can fly from the controller, most commercially available UAVs are limited to a fixed distance for cost and safety reasons. Accordingly, the distance of commercial UAVs can be increased through various means. This distance is related to the configuration of the communication interface, such as the type and gain of the antenna, as well as the wavelength of the transmission and obstacles between the transmitter and receiver.

Radio communication consists of two antennas connected at two endpoints, which are within range of another. These antennas are operationalized as both transmitters and receivers. The former transforms cyclical voltage information into radio waves. The latter transforms radio waves into cyclical voltages. The communication system between the UAV and its ground controller is referred to as the data link system. The communication range between the UAV and its ground controller largely depends on the radio frequency of the communication and line-of-sight through obstacles at that frequency. Lower frequency signals tend to travel significantly frther than higher frequency signals. In addition, lower frequencies are better able to penetrate dense objects, a characteristic useful for remote control of UAVs. The communications between the UAV and the ground controller can include information related to location, battery levels, airspeed, altitude, GPS coordinates, payload information, distance from controller, and other parameters. Lower operating frequencies (i.e., longer wavelengths) require larger antennas to be able to receive the frequency. The main advantage of using higher frequencies is that faster data transmission is possible, meaning that higher throughput is achievable than at lower frequencies. This higher throughput is ideal for transmitting large amounts of data such as images or videos. Consequently, higher frequencies are commonly used for image-producing payloads, such as aerial photography or photogrammetry.

Unless licensed radios are available, small UAVs typically use open, unlicensed industrial, scientific, and medical (ISM) bands. The bands include the 902-928 MHz, 2.400-2.4835 GHz, and 5.725-5.850 GHz bands, commonly known as different home router frequencies of type 802.11. These bands can support one or several 20 MHz channel bands, and radios that can communicate on these frequencies are readily available. Maximum transmission power is restricted in the USA per Federal Communications Commission (FCC) regulations. The signal range varies significantly depending on antenna gain, path losses, antenna height, and other variables. This topic is discussed further in section 6.7.2. Similar regulations exist in the European Economic Area, where CE (European Conformity) compliance is required. CE compliance for radio communication tends to be stricter than FCC compliance. Most remote-control UAVs use 900 MHz for CNPC. At 900 MHz, mountainous or wooded areas have less influence on range than at 2.4 and 5.8 GHz. Multiple other frequencies are also used in the data link system, which typically depends on the UAV brand and UAV-specific functionality.

The Global Navigation Satellite System (GNSS) refers to the congregate of GPS (USA), GLObal NAvigation Satellite System (GLONASS) (Russia), Galileo (Europe), and Beidou (China). These satellite navigation systems correspond to constellations of satellites. Most modern UAVs use GNSS signals for navigation. GPS signals for UAVs operate on two frequency bands: L1 (1575.42 ± 12 MHz) and L2 (1227.60 ± 12 MHz). In the USA, the L1 band is used for both civilian and military purposes while the L2 band is used solely by the military. L-band frequencies are used for GPS communication because they can penetrate fog, clouds, rain, storm, and light vegetation. However, dense environments (e.g., buildings and forest canopies) can interfere with these frequencies and reduce the accuracy of GPS measurements. Other navigation systems use different frequency bands, such as G1/G2 for GLONASS, B1/B2 for Beidou, and E1/E5b for Galileo, which lie in the frequency range of 1100-1600 MHz. UAVs often have GNSS receivers that are compatible with multiple constellations.

The most popular data link frequencies used historically by UAVs for telemetry are 400 MHz and 900 MHz. Although these relatively low frequencies have limited data transfer capacity, they can travel long distances with relatively little attenuation and hence data loss. This limited data transfer capacity is typically acceptable for temperature, humidity, or wind sensors. Cellular networks frequencies are also sometimes used for telemetry. The most popular of these being 850 MHz, 1700 MHz, and 1900 MHz, but they may be unavailable in remote regions.

The above frequencies used for UAV communication can be summarized as follows:

- 400 MHz. Long-range but low data rates; ideal for telemetry and small data transfers.
- 900 MHz. Able to penetrate through many obstacles but narrow band with relatively slow data rates.

- 1.3 GHz. Able to penetrate through obstacles (inferior to 900 MHz); limited data rates (superior to 900 MHz).
- 1.575 GHz. Wavelength used specifically for GPS signals.
- 2.4 GHz. Widely used WiFi frequency; it can become overcrowded in urban contexts; relatively high data rates.
- 5.8 GHz. Short-range and high data rates; ideal for imaging any other large data transfers.

6.7.2. Link Budget

A link budget allows estimation of the performance of a communications channel for a system. A link budget calculates the received power to ensure that the information is received intelligibly with an adequate signal-to-noise ratio. Consequently, the link budget is a useful tool for comparing multiple radios, antennas, and frequency bands. The link budget is based upon the Friis transmission equation, which can be used to calculate the power received from an antenna of gain G_R when transmitted from a second antenna of gain G_T, separated by a distance R in free space, and operating at frequency f or wavelength λ.

The power provided by the transmitting and receiving antennas is defined as P_T and P_R, respectively. Most common UAVs use omnidirectional, lossless antennas. The receiver antenna is located at the far-field of the transmit antenna. For a transmit antenna of gain G_T in the direction of the receiver antenna, the power density p of the plane wave incident on the receiver antenna a distance R from the transmit antenna is as follows:

$$p = \frac{P_T G_T}{4\pi R^2} \tag{6}$$

The gain term incorporates any losses present in a real antenna and also considers directionality. The power received by the antenna is given as follows:

$$P_R = \frac{P_T G_T A_{ER}}{4\pi R^2} \tag{7}$$

where $A_{ER} = \lambda^2 G / 4\pi$ describes the effective aperture of the receiving antenna. As such, the received power can be written in terms of wavelength or frequency, as follows:

$$P_R = \frac{P_T G_T G_R \lambda^2}{(4\pi R)^2} = \frac{P_T G_T G_R c^2}{(4\pi R f)^2} \tag{8}$$

where c refers to the speed of light This equation can be written in logarithmic form in terms of decibels such that Equation (9) becomes additive, as follows:

$$P_{R,dB} = P_{T,dB} + G_{T,dB} + G_{R,dB} - 20\log_{10}\left(\frac{4Rf}{c}\right) \tag{9}$$

The last term on the right-hand side refers to the path loss in reference to air or other obstacles. This equation demonstrates that higher frequencies have more significant power loss. For a specific gain, an antenna achieves greater energy transfer at lower frequency. A good link margin, which refers to the actual receiver power compared to required receive power, should be above 10 dB to ensure that the signal-to-noise ratio is high enough to easily distinguish the signal from background noise.

The shape of the antenna generates an alignment of the electric field, referred to as polarization. UAVs typically use linear polarization, for which the electric field aligns in a single plane. Pointing loss can occur when the UAV is at a different altitude from the ground controller (i.e., non-zero angle), but the signal can be recovered by a skilled operator who orients the controller in line with UAV position.

Increasing the link margin increases the maximum distance at which a UAV can communicate with the ground controller. A directional antenna can increase the link margin. Whereas omnidirectional antennas commonly used by UAVs have gains of 1-3 dB, directional antennas can achieve 8-15 dB gain. Care must be taken, however, for the operator to keep the UAV within the cone of directionality, which becomes increasingly difficult at longer distances. Autonomously flying UAVs can also extend distance.

Loss of communication between a remote operator and a UAV may occur for reasons such as antenna damage, flying beyond communication range, or background noise. Thus, autonomous safeguards are in place on many commercial UAVs to land in the event of communication loss. Without communication, once the battery is sufficiently depleted to a preset safety level, many UAVs attempt to return autonomously to the GPS coordinates of the takeoff location. For an even more critical battery level, the UAV descends directly to the land surface below it and attempts to land. Depending on what that land surface is, complete UAV damage and loss can occur under these circumstances.

6.8. Component Selection

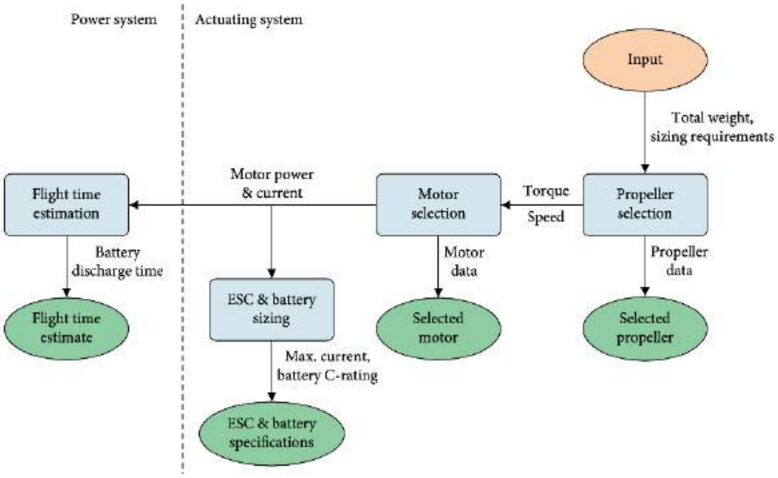

Figure 8. Procedure to select components for a UAV propulsion system. Adapted from Reference [62]. Creative Commons BY 4.0 license. Copyright (2020), with pemission from the *Journal of Advanced Transportation*.

Despite the clear relationships among the purposes of the different UAV components, selecting them based on design criteria, end purpose, and individual needs can be challenging to optimize. Developing a system requires calculations to determine suitable motors, propellers, ESCs, and batteries. Biczyski et al. [62] outline a detailed procedure (Figure 8). A purchase from a UAV manufacturer can simplify the optimization because qualified engineers have already preformed calculations, although the flexibility among options becomes more limited.

7. ASSEMBLED UAV SYSTEM

7.1. Total Weight and Compactness

The assembled UAV can be characterized by weight and compactness. UAV weight (i.e., mass) influences flight mechanics by affecting the gravitational force acting on the UAV and altering the linear and rotational inertia of the body. An increase of weight puts increased stress on the rotor blades as a combined result of these two effects, which must be compensated with increased lift. The increased lift requires additional power from the batteries and thus negatively impacts flight time. Flights at higher altitudes are significantly affected by weight because of the reduced air density, which requires higher rotational speeds of the propellers to maintain the same lift.

UAV compactness and balance are as equally important as weight. In the case that UAV weight, including a possible payload, is distributed non-uniformly, the corresponding load applied to each rotor blade is similarly non-uniform. In commercial UAVs, a single motor is often powered by a single battery, and the flight time is limited by the battery that loses charge the fastest. To minimize heterogeneous loads among the different rotor blades, weight should be centered as close to the UAV center of mass as possible. In doing this, any moments generated by the mass, which must inevitably be compensated by the rotor blades, are minimized.

Budgeting for size is not as simple as budgeting for weight. Instead, components must be placed such that they are not overlapping and are mountable. They should not cause electronic interference and should maintain the center of gravity of the payload close to that of the UAV.

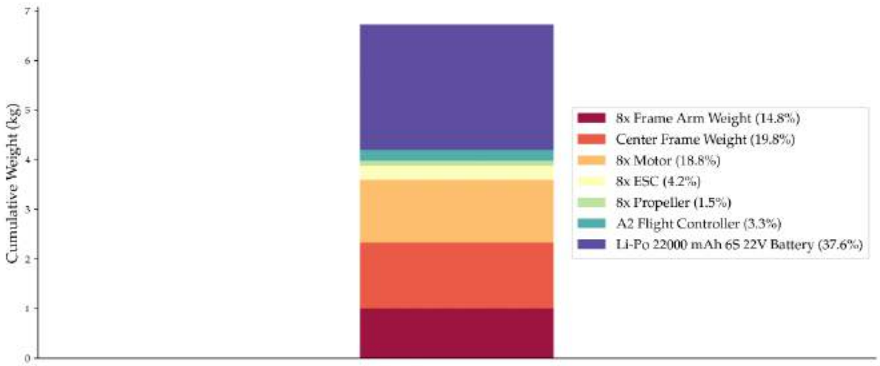

Figure 9. Weight breakdown of a DJI S1000 UAV by component.

As an example of typical weight breakdown, Figure 9 shows that of the DJI S1000 UAV. This barebones UAV is popular in the research community because of the ease for making modifications. The total weight of the UAV without batteries is 4.2 kg. With the addition of a battery pack (single Li-Po 6S; 22,000 mAh; 22.2 V), the weight increases to 6.7 kg. The battery thus constitutes 37.6% of the total UAV weight without payload. The next most significant components are the motors and the chassis, together constituting 38.6% of the total UAV weight. The chassis comprises the landing gear, servos, and main electronics. Since the DJI S1000 is an octocopter, the contribution from the motor arms and their components (39.3%) is higher compared to that of a quadcopter or hexacopter. This example illustrates the relative weight contributions of components and highlights the influence of batteries to the total UAV weight.

7.2. Flight Time

Flight time is a function of the weight of a UAV, its aerodynamics, and the total "mAh" energy available the propulsion system. For example, to illustrate the impact of weight and energy on flight time, a DJI Matrice 600 hexacopter UAV utilizes six batteries (TB48S). Each has an mAh capacity of 5700 mAh. Each battery consists of 6 Li-Po cells connected in series (Li-Po 6S), which provides a nominal voltage of 22.8 V to the battery. However, since Li-Po batteries should not be fully discharged, the advisable mAh use capacity is smaller. For a recommended maximum depth of discharge of 80%, the available capacity drops to 4560 mAh for each battery. With these batteries and without any payload, the total UAV weight is 10 kg and can achieve a hovering flight time of 38 min. This flight time corresponds to an average current draw of 7.2 A for each battery and a power draw of 164 W. For an instructional comparison, a re-build of this UAV to 8 propellers and 8 batteries can be considered. The additional rotors reduce the overall loading to each individual rotor but the additional batteries required also significantly increase the UAV weight. Depending on the marginal gain, this increased weight may or may not increase flight time. There is a diminishing return of adding rotor blades and batteries among weight, lift, and flight time.

The foregoing flight time of 38 min only considered hovering. Horizontal and vertical translations of the UAV, such as arriving at a remote location before the sampling payload is activated, further reduces flight and sampling times. Variable winds of micrometeorology and the UAV movement relative to these winds are hard to predict under realworld scenarios, so a margin of error in estimating battery use prior to flight is advisable. Stationery hovering also progressively draws additional current for wind speeds above 0 m s^{-1} because the UAV is effectively flying against the wind in a relative sense even as it hovers in a single position in an absolute sense. Depending on the application, project management might land the UAV and quickly swap batteries for consecutive flights. In this case, several sets of batteries must be used and charged between flights. The batteries of the DJI Matrice 600 hexacopter UAV can be re-charged in < 2 h using a specialized charger from the vendor.

Addition of a payload comes with additional complexity. For a maximum payload of 5.5 kg, the hovering flight time of the DJI Matrice 600 hexacopter UAV drops from 38 min without payload to 18 min with payload. The current draw is 15.2 A, and the power is 347 W. The relationship between current draw and payload weight is non-linear. The current draw doubled for mounting a payload of 5.5 kg whereas the total UAV weight (including payload) increased by less (+55%). The non-linearity arises from the non-linear motor and propeller characteristics. Another possibility is that the payload can draw power (e.g., a mounted camera or other sensing system). For a 5.5 kg payload that has an additional current draw of 6 A to power a microcontroller and several devices, the current draw shared equally between the six batteries increases from 15.2 A to 16.2 A. Consequently, the flight time drops to 16.8 min. Thus, heavy payloads with high current requirements can significantly impact flight time as compared to non-payload flight times.

In addition to concerns about flight time, an increase in weight also increases the inertia of the UAV. For greater weight yet similar applied force, acceleration is slowed at higher inertia. Slower acceleration presents challenges to the onboard control system that can affect the UAV stability. Critical loss of stability can result from an inability to perform corrective actions quickly enough. For these events, complete UAV damage and loss is typical; damage to nearby property or people is also possible. To avoid these outcomes and maintain stability, the control system is constantly adjusting thrust across the different propellers based on feedback signals, and greater inertia slows the ability of the UAV to respond to changes. Most systems are designed to work up to a specific payload weight. Feedback corrections may become increasingly erratic for heavy payloads. In the presence of strong winds, these stability issues are exacerbated, especially for non-uniformly distributed and heavy payloads. Systems with large power requirements directly connected to the onboard batteries may also present issues if large amounts of power are momentarily required to stabilize the

UAV. Either motors stall or the sensor payload fails if the combined momentary current draw exceeds the capacity of the batteries.

8. FLIGHT MECHANICS

The governing principles of the flight mechanics differ among UAVs. Traditional aerostats such as radiosondes are lighter-than-air systems and work entirely by principles of buoyancy and natural convection. Aerostatics equations describe the buoyancy-driven movement, and no aerodynamic lift is required for the device to remain airborne. Some aerostats fall under this chapter’s definition of a UAV, such as an airship that has a propulsion system in the gondola. Fixed-wing and rotary-wing UAVs are heavier-than-air aircraft, and as such the governing principle of the flight mechanics is aerodynamic lift. These UAVs are classed as aerodynes. Compared to aerostats, aerodynes can have improved maneuverability and greater payload capacity. Flight mechanics, however, are generally more complex.

Within the aerodyne class, rotary-wing UAVs are an important subclass. In many ways, the flight mechanics are analogous to those of a helicopter. Helicopters generate lift through rotating propellers, which force air downwards, creating an upward thrust force by Newton's Third Law. The use of multiple propellers in UAVs allows the rotor blades of each propeller to have a small diameter, minimizing stresses on the transverse arms. The overall kinetic energy is distributed across the rotors. The reduced kinetic energy of each rotor can decrease damage should one of rotors collide with an object. For small UAVs, this design is safer for close interactions and increases flight stability in local turbulent eddies. This reduction in kinetic energy also reduces the Reynolds number of the flow around the UAV as compared to a helicopter. For the low Reynolds numbers typical of UAVs 25 kg and smaller, flows cannot be considered as inviscid, and modeling is correspondingly more complicated.

8.1. Coordinate Systems

For understanding UAV motion, both an inertial frame of reference and a body frame of reference can be useful (Figure 10). The frame of reference attached to the Earth's surface is the inertial reference frame. The frame of reference attached to the center of gravity of the UAV is the body frame of reference. Coordinate transformations between the two frames of reference are often necessary. Some onboard sensors such as the gyroscope and accelerometer measure quantities in the body frame of reference. Other sensors such as for the GPS measure quantities with respect to the inertial frame of reference. The propulsion system and aerodynamic forces act within the body frame of reference. Many UAV applications involve mapping specific locations that are specified in the inertial frame of reference.

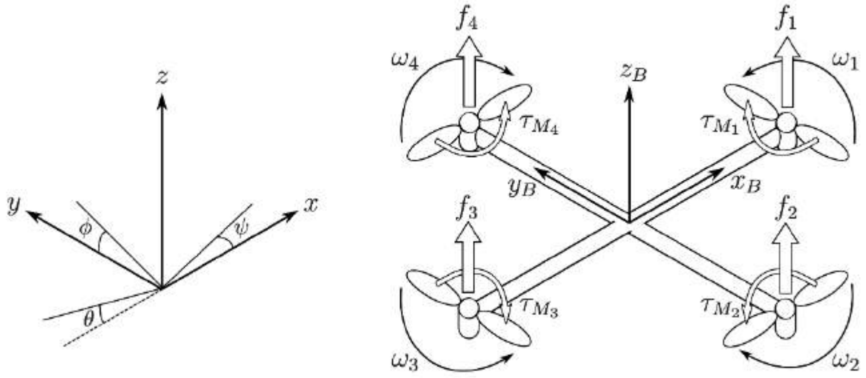

Figure 10. Coordinate system for a quadcopter UAV for (left) an inertial frame of reference and (right) a body frame of reference [63]. Copyright (2011), reproduced with permission from Teppo Luukonen.

The dynamic equations can be derived from both the Newton-Euler equations and the Euler-Lagrange equations. Forces taken to act at fixed points as an acceptably accurate approximation to simplify the mathematics of the propeller mechanics. The structural body and propellers are considered rigid such that deformations are ignored, and motors are assumed to have negligible inertia. Luukonen [63] provides a detailed derivation, which forms the basis of the presentation herein.

For the body frame of reference, the attitude of the UAV is represented by φ, θ, and ψ, as follows. The roll angle about the inertial x-axis is represented by φ, the pitch angle about the inertial y-axis by θ, and the yaw angle about the inertial z-axis by ψ (Figure 10). For the inertial frame of reference, the linear and angular position are given by $\vec{\xi}$ and $\vec{\eta}$, respectively, where the notation of the arrow overhead indicates vector notation. The two frames of reference are related by the transformations $\vec{\xi} = [x, y, z]^T$ and $\vec{\eta} = [\phi, \theta, \psi]^T$. The angular velocity $\vec{v}$ of the entire UAV in the body frame of reference points along the axis of rotation. To convert angular velocities from the inertial frame of reference to that of the body frame, a transformation matrix $\overrightarrow{W}$ can be used, as follows:

$$\overrightarrow{W} = \begin{pmatrix} 1 & 0 & -s_\theta \\ 0 & c_\phi & c_\theta s_\phi \\ 0 & -s_\phi & c_\theta c_\phi \end{pmatrix} \tag{10}$$

where s_x and c_x are shorthand for sin(x) and cos(x), respectively. Thus, the conversion between the angular velocities is given by $\vec{v} = \overrightarrow{W} \cdot \dot{\vec{\eta}}$. Quantities can be converted from the body frame to the inertial frame by the orthogonal rotation matrix $\vec{R}$, as follows:

$$\vec{R} = \begin{pmatrix} c_\phi c_\psi & -c_\psi s_\phi - c_\phi c_\theta s_\psi & s_\theta s_\phi \\ c_\theta c_\psi s_\phi + c_\phi s_\psi & c_\phi c_\theta c_\psi - s_\phi s_\psi & -c_\psi s_\theta \\ s_\phi s_\theta & c_\psi s_\theta & c_\theta \end{pmatrix} \tag{11}$$

For a given vector $\vec{p}$ in the body frame, the corresponding vector is given by $\vec{R} \cdot \vec{p}$ in the inertial frame.

8.2. Thrust

To model the system dynamics, a description of the thrust acting on the UAV is required. The thrusts are generated by the propellers. All propellers on a rotary-wing UAV are considered identical. By conservation of energy, the motor power is equal to the thrust T times the air velocity v_h, as follows: $P = Tv_h$. The air speed velocity relates to thrust, as follows:

$$v_h = \sqrt{\frac{T}{2\rho A}} \tag{12}$$

where ρ is the density of the surrounding air and A is the area swept out by the propeller. The motor constants of section 6.3 relate to the thrust of the UAV, as follows:

$$P = \frac{K_v \tau \omega}{K_t} = \frac{K_v K_\tau T \omega}{K_t} = \frac{T^{3/2}}{\sqrt{2\rho A}} \tag{13}$$

The torque τ is proportional to the thrust T by the ratio K_τ, which is a characteristic of blade configuration and other parameters. Thrust is proportional to the square of angular velocity of the motor, as follows:

$$T = \left(\frac{K_v K_\tau \omega \sqrt{2\rho A}}{K_t} \right)^2 \tag{14}$$

For a rotary-wing UAV with N motors, summing over all the motors, the total thrust in the body frame of reference $\vec{T}_B$ is directly related to angular velocity of the propellers, as follows:

$$\vec{T}_B = \sum_{i=1}^{N} T_i = k \begin{bmatrix} 0 \\ 0 \\ \sum_{i=1}^{N} \omega_i^2 \end{bmatrix} \tag{15}$$

The parameter values in Equation (14) can be subsumed into a single constant *k*. As a result of the model assumptions, the thrust only provides motion in the *z*-direction, and there is no translational component. For translational motion in the *x*-axis and *y*-axis, torques must interact with the vertical component of thrust through the equations of motion. This coupling is how the UAV can be controlled using four inputs even while having six degrees of freedom.

Frictional forces are also present and may become significant at higher speeds. These can be modeled with the addition of a drag force term F_D to the equations of motion, as follows:

$$F_D = \begin{bmatrix} -k_d \dot{x} \\ -k_d \dot{y} \\ -k_d \dot{z} \end{bmatrix} \tag{16}$$

For additional precision, the constant k_d can be separated into three separate friction constants, one for each direction of motion. For consideration of frictional forces, developing the equations in the body frame is necessary [63].

8.3. Moment Mechanics

Moment mechanics can be calculated by consideration of the differential thrust between motors on opposing sides of the same arm. A moment is a force which acts at a distance through a pivot point. Moments describe the forces that lead to movement in a transverse or longitudinal direction relative to the UAV velocity. Each of the propellers generate an amount of torque about the *z*-axis, which is necessary to maintain propeller rotation and therefore thrust. The drag equation from fluid dynamics describes the frictional force, as follows:

$$D = \frac{1}{2} C_D A v^2 \tag{17}$$

where ρ represents the air density, A represents the propeller cross-section, and C_D represents the UAV drag coefficient. This drag can be incorporated into an equation for torque due to drag, as follows:

$$\tau_D = \frac{1}{2} R \rho C_D A v^2 = \frac{1}{2} R \rho C_D A (R\omega)^2 = b\omega^2 \tag{18}$$

where ω refers to the rotational speed of the propeller, R refers to the propeller radius, and b is some constant. The force is applied at the tip of the propeller. The complete torque about the *z*-axis for motor *i* can then be written as follows:

$$\tau_z = b\omega^2 + I_M \frac{d\omega}{dt} \tag{19}$$

where I_M is the moment of inertia about the motor *z*-axis and $d\omega / dt$ is the angular acceleration of the propeller. In steady state flight (i.e., not takeoff or landing), $d\omega / dt \approx 0$ because the propellers are not accelerating (i.e., they are approximately maintaining constant thrust). A simplified expression is obtained, as follows:

$$\tau_z = (-1)^{i+1} b\omega_i^2 \tag{20}$$

where $(-1)^{i+1}$ is positive for propeller *i* for clockwise spin and negative for counterclockwise spin.

As an example, for a quadcopter characterized by two clockwise and two counterclockwise rotors) the total torque about the *z*-axis is as follows:

$$\tau_{\psi} = b(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2) \tag{21}$$

The roll and pitch torques can be derived from standard mechanics. The $i = 1$ and $i = 3$ motors are arbitrarily chosen to be on the roll axis. The torque required to generate this moment is produced by increasing the angular speed of the motor 1 and decreasing the angular speed of the motor 3. This torque generates translational movement in the *x*-direction. The governing equation is as follows:

$$\tau_{\phi} = \sum r \times T = L(k\omega_1^2 - k\omega_3^2) = Lk(\omega_1^2 - \omega_3^2) \tag{22}$$

where L is the distance from the UAV center to a propeller. In a similar fashion, the pitch torque is produced by increasing the angular speed of motor 2 and decreasing the angular speed of motor 4. Translational movement in the *y*-direction occurs based on the following equation:

$$\tau_{\theta} = Lk(\omega_2^2 - \omega_4^2) \tag{23}$$

Altogether, the torques in the body frame of reference are summarized as follows:

$$\overrightarrow{\tau_B} = \begin{bmatrix} Lk(\omega_1^2 - \omega_3^2) \\ Lk(\omega_2^2 - \omega_4^2) \\ b(\omega_1^2 - \omega_2^2 + \omega_3^2 - \omega_4^2) \end{bmatrix} \tag{24}$$

The full set of flight movements for a quadcopter is illustrated in Figure 11.

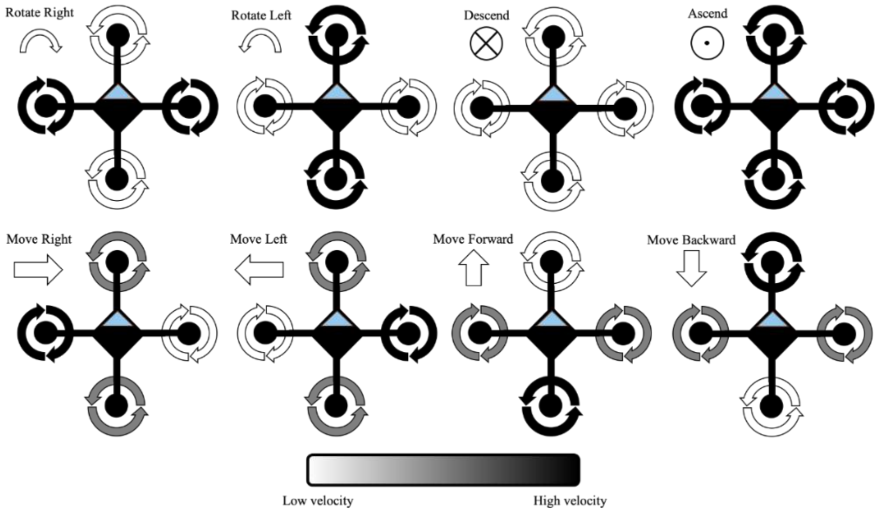

Figure 11. How relative propeller speeds of a quadcopter lead to the named UAV maneuvers, including rotation, horizontal movement, descent, and ascent.

This model omits several important aerodynamic effects that can result in deviations from the model predictions due to the presence of nonlinearities. These nonlinearities include blade flapping (e.g., blade material deformation due to mechanical stresses), bulk fluid movements (e.g., wind), rotational drag forces, and non-zero angles of attack. Under standard flying conditions, most of these factors are negligible except when operating at high velocities or performing aggressive maneuvers.

8.4. Equations of Motion

In the inertial frame of reference, acceleration results from gravity, thrust, and linear friction. The thrust vector in this frame can be obtained using the rotation matrix $\vec{R}$ to map from the body frame of reference. The linear motion can be summarized as follows:

$$\underset{acceleration}{m\vec{\ddot{x}}} = \underbrace{\begin{bmatrix} 0 \\ 0 \\ -mg \end{bmatrix}}_{gravity} + \underset{thrust}{\overrightarrow{R}\cdot\overrightarrow{T_B}} - \underset{drag}{\overrightarrow{F_D}} \tag{25}$$

where g is acceleration due to gravity and m is the UAV mass. These differential equations can be solved for the linear velocity and position in the inertial frame. This equation also allows an estimate of the maximum takeoff weight of the UAV. If the weight component of the equation exceeds the thrust component, then the UAV is over-encumbered and unable to launch.

The linear equations of motion are most convenient to use in the inertial frame, whereas the rotational equations of motion are most useful in the body frame. The body frame allows rotations to be described with reference to the center of mass of the UAV, which is information available to the flight controller via the onboard gyroscope. Expressed in vector form in the body frame of reference, the Newton-Euler equations are as follows:

$$\underset{acceleration}{\vec{I}\dot{\vec{\nu}}} + \underbrace{\vec{\nu}\times(\vec{I}\vec{\nu})}_{centripetal} + \underset{gyroscopic}{\vec{\Gamma}} = \underset{torque}{\vec{\tau}} \tag{26}$$

where $\vec{I}\dot{\vec{\nu}}$ is the product of the inertia matrix and body frame angular acceleration (i.e., the angular acceleration of inertia), $\vec{\nu}\times(\vec{I}\vec{\nu})$ is the centripetal force, $\vec{\Gamma}$ is the gyroscopic force, and $\vec{\tau}$ is the external torque. This equation can be re-cast in terms of the UAV angular velocity, as follows:

$$\dot{\nu} = \begin{bmatrix} \dot{p} \\ \dot{q} \\ \dot{r} \end{bmatrix} = \overrightarrow{I^{-1}}(\dot{\tau} - \dot{\nu}\times(\dot{I}\dot{\nu})) \tag{27}$$

For these equations, the quadcopter can be taken as a specific example. It can be modeled as two thin uniform rods intersecting perpendicularly through the centers. There is a point mass at both ends of each rod corresponding to the motors. There is a point mass at the center corresponding to the body and any added payload. This setup results in lines of symmetry on all axes. As a result, the system can be described by a diagonal matrix for which inertia is constant in each rotational direction, as follows:

$$\vec{I} = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \tag{28}$$

The equation for the UAV angular velocity in the body frame of reference is thus as follows:

$$\dot{\vec{v}} = \begin{bmatrix} \tau_\phi I_{xx}^{-1} \\ \tau_\theta I_{yy}^{-1} \\ \tau_\psi I_{zz}^{-1} \end{bmatrix} - \begin{bmatrix} \dfrac{I_{yy} - I_{zz}}{I_{xx}} v_y v_z \\ \dfrac{I_{zz} - I_{xx}}{I_{yy}} v_x v_z \\ \dfrac{I_{xx} - I_{yy}}{I_{zz}} v_x v_y \end{bmatrix} \tag{29}$$

Altogether, the set of equations (25) and (29) for the linear and rotational dynamics constitutes the equations of motion for the system. This set of equations can be solved to determine both linear and angular positions and velocities of the UAV. This model is useful for the design of UAVs for specific applications and operating conditions.

8.5. Scaling Laws

As UAVs become ever smaller, a consideration of scaling laws can be helpful for accelerating new designs. Flight mechanics are significantly influenced by UAV scaling. Scaling can be assessed by similitude [64]. For a UAV of characteristic length *L*, the rotor radius *R* scales linearly with *L*. The mass and moment of inertia scale with L^3 and L^5, respectively. Equations (14) and (17) show that the thrust and drag forces are both proportional to the cross-sectional area and the square of the blade-tip velocity. Since $v = R\omega$, the scaling for both these forces is $T, D \sim \omega^2 L^4$. The linear acceleration is given by the ratio of this force and mass, leading $\ddot{x} \sim \omega^2 L^4 / L^3 \sim \omega^2 L$. Similarly, the angular acceleration is given by the ratio of rotational force and moment of inertia. However, the rotational force is the linear force scaled by a moment arm *L*, and thus the contribution cancels out, leading to $\ddot{\eta} \sim \omega^2 L^5 / L^5 \sim \omega^2$. The rotor speed also scales with length since smaller rotors must rotate at higher speeds to produce the same thrust as a larger rotor. By assuming blade tip velocities to be constant, Mach scaling for a compressible flow can be used, leading to $\omega \sim L^{-1}$.

Consequently, the torque required by the motors is expected to scale approximately with $\tau \sim L^3$. With thrust and drag forces scaling with $T, D \sim L^2$, linear acceleration with $\ddot{x} \sim L^{-1}$, and rotational acceleration with $\ddot{\eta} \sim L^{-2}$. The inverse relation between length and accelerations demonstrates that smaller UAVs are significantly more agile than larger UAVs. Mass and rotational inertia rapidly increase with length, and as a result, additional force is needed to propel the UAV. The amount of torque required from the motor scales linearly with mass. This result suggests that a doubling of mass would require a corresponding doubling of the motor torque. This scaling analysis omits consideration of blade inertia and rotor efficiency and assumes that rotors are rigid, which may not be reflected in some systems. For incompressible flow, Froude scaling is more appropriate in the analysis than Mach scaling, yielding slightly different scaling laws.

8.6. Flight Hazards

As a result of their flight mechanics, multiple flight hazards exist for UAVs. The main hazards are dynamic rollover, vortex ring state, and retreating blade stall. Development of these hazards can be related both to the UAV design and to the environmental conditions in which the UAV is operating.

8.6.1. Dynamic Rollover

Dynamic rollover is a hazard associated with taking off and landing and can occur when one of the landing skids touches the ground at a banked angle while the UAV is undergoing translational motion (Figure 12). Dynamic rollover can be exacerbated by landing on sloped ground. The point of contact of the landing skid acts as a pivot, which asserts a resistive force. The combination of the propeller thrust and translational motion results in a net rotation. Given sufficient force, this rotation can increase the bank angle until it reaches a critical rollover angle. Beyond this point, corrective action is not possible by the UAV control system or through pilot intervention, causing the UAV to roll and possibly damage components or the surroundings. Asymmetrically loaded UAVs have increased susceptibility to dynamic rollover since they have reduced stability and may tend to lean towards one of the landing skids. A static rollover is also possible, which refers to the same condition even in the absence of motion of the rotor blades. This condition may occur in high wind conditions or if rotor blades are prematurely halted before landing. The critical rollover angle is a byproduct of the center of gravity. This angle is the point where the force of weight acts through the pivot and is no longer able to counteract other rotational forces. The possibility of dynamic rollover can be reduced by lowering the UAV center of gravity as well as by avoiding takeoff and landing on sloped surfaces and in the presence of strong crosswinds.

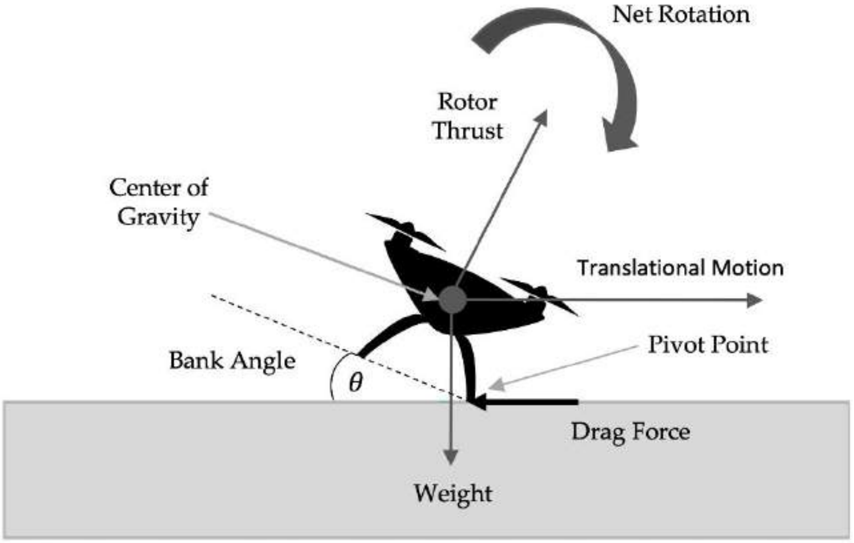

Figure 12. Illustration of UAV failure by dynamic rollover. The UAV rolls over once the bank angle is sufficiently large that the weight force acts through the pivot point.

8.6.2. Vortex Ring State

A vortex ring state, sometimes referred to as settling with power, is a hazardous flight condition wherein a UAV descends at a moderately fast rate, causing the propellers to be fed by their downwash, resulting in substantial loss of lift. This condition arises when the rotor blades form a vortex ring. During regular operation, induced air is pulled downwards by the rotors, generating an upward force. However, this force is not constant across the rotor. The airspeed close to the rotor hub moves more slowly than at the wingtip, which results in a smaller downward flow close to the hub. When there is a sufficient upflow of air, the induced air close to the rotor hub is overcome, and the blade stalls near the hub. This stalling stimulates the generation of a second set of vortices similar to wingtip vortices. In combination with the outer vortices, these additional vortices result in the formation of a vortex ring (Figure 13). At such a point, there is instability and loss of lift. Once a vortex is generated, increasing the rotor speed can feed the vortex without providing additional lift, thus further exacerbating the issue. The vortex can induce pitch and roll oscillations, which can affect UAV stability during descent. Descending at sufficiently low speeds ensures that there is no stalling or airflow reversal at the inner blade sections, thus inhibiting vortex formation. Some UAVs have altitude hold and can automatically control descent, thus avoiding the formation of a vortex. At sufficiently high speeds, the windmill-brake state or autorotation state is entered. Although this state can still result in oscillations, it is more stable than the vortex ring state because the high upflow of air provides enough lift such that the aircraft can be controlled.

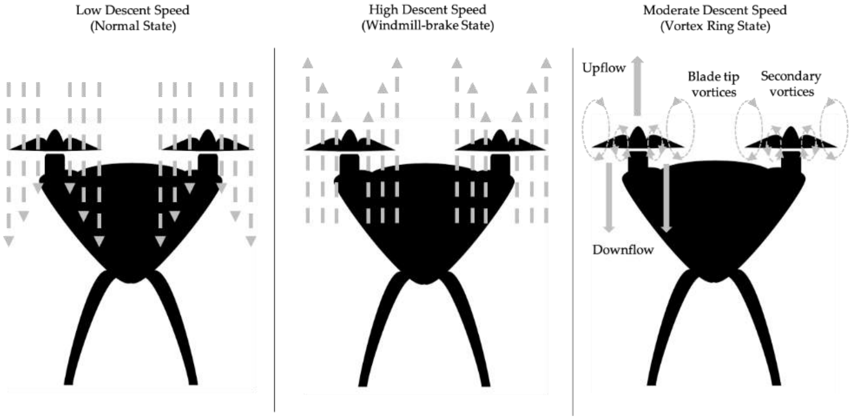

Figure 13. Influence of descent speed on flow state. UAV instability can occur at moderate descent speeds when a vortex ring forms from the interaction between blade tip vortices and secondary vortices at the hub. At high descent speed the vortex ring rises above the rotor, extracting more energy from the air than required for flight, similar to the operation of a windmill.

8.6.3. Retreating Blade Stall

Retreating blade stall refers to differences in lift produced by a propeller across its full rotation. During forward UAV motion, any component of the propeller movement that moves in the same direction as the UAV motion is referred to as the advancing blade side. Conversely, any component of the propeller movement in the opposite direction of UAV motion is referred to as the retreating blade side (Figure 14). At sufficiently high forward speeds, this asymmetry can result in substantially lower relative blade speeds on the retreating blade side. This asymmetry results in differences in lift across the full rotation of the propeller. In combination with an increased angle of attack, the differences can result in loss of lift (i.e., UAV stall). The hazard of a retreating blade stall is less pronounced in most rotary-wing UAVs than in helicopters because of the presence of multiple rotors, half of which rotate in a counter direction, which helps to even out this effect. As such, this hazard is of primary concern in UAVs that have a small number of rotors. The hazard of retreating blade stall is more common for heavier UAVs when operating at lower rotor speeds or during high-speed translational motion, steep climbs, and abrupt turns.

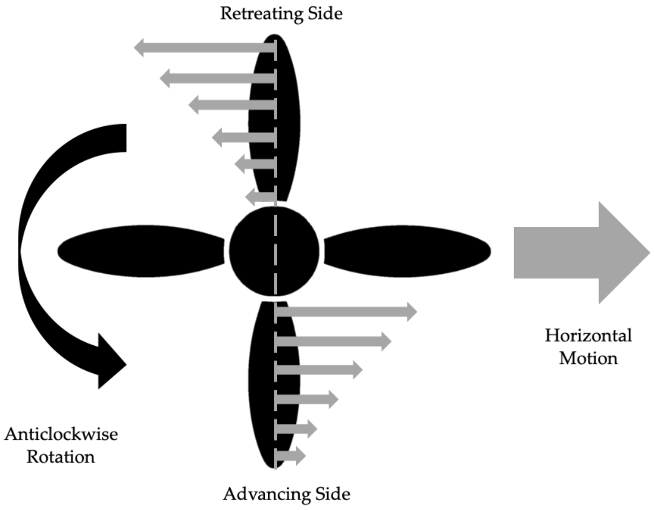

Figure 14. Illustration of UAV instability by retreating blade stall. Airflow on the advancing side meets the rotor at a higher speed than on the retreating side due to the relative motion of the UAV, resulting in a dissymmetry of lift across the rotor.

8.6.4. Environmental Robustness

Assurance that a UAV can function adequately in the anticipated operating environment is important.

8.6.4.1. Wind

Small-scale UAVs are sensitive to wind conditions as a result of their size and weight. For example, micro air vehicles (0.1-0.5 m in length, 0.1-0.5 kg in mass) operate in a sensitive Reynolds number regime. Many complex flow phenomena occur within the planetary boundary layer in this regime. Separation, transition, and reattachment can all occur within a short distance along the chord line of a wing or rotor and can strongly affect the lift. Designing small-scale UAVs to fly efficiently represents a challenge to aerospace design engineers. For larger UAVs (e.g., 5 kg and greater), the influence of wind is less important because these UAVs operate in a less sensitive Reynolds number regime. Even so, high-speed winds may still present stability issues, especially in the presence of heavy and non-uniformly distributed payloads.

8.6.4.2. Temperature

The temperatures experienced by a UAV as a whole and by its components individually depend not only on ambient atmospheric temperature but also on solar irradiation (especially if components are black) and on heat produced by onboard electric components, batteries, and motors. Temperature can significantly impact many of the components of a UAV. Electrical components typically specify a temperature range within which devices can be expected to operate normally. Temperature also significantly affects battery electrochemistry and efficiency. Specifically, higher temperatures usually result in reduced efficiency, represented by achievable mAh. Very high temperatures can also damage the chassis. For certain materials, such as polymers having relatively low glass transition temperatures, heat stress can result in plastic deformation of the structure, which reduces the load-bearing capacity of the material. Cyclical heat stresses can result in thermal creep of components that are otherwise stable to exposure at a single rated temperature. Cold temperatures, such as those that may be encountered at high altitudes or high latitudes, can also lead to severe problems, such as the brittle fracture of materials related to decreased strength or toughness.

8.6.4.3. Moisture

High humidity can strongly and detrimentally affect onboard electronics. Small-scale commercially available UAVs often use cheap, lightweight materials and components that leave electronics exposed to atmospheric humidity. High humidity can lead to leakage currents, which can result in the short-circuiting of some electric components. High humidity can also increase the oxidation rate of materials, influencing physical properties including load-bearing capacity. Batteries are typically the most critical components to shield from moisture. Any infiltration of water in the battery casing causes rapid oxidation of the metal contacts.

Rain presents a range of issues, especially to exposed components like the rotor blades and motors. Many vendors provide an Ingress Protection (IP) code for components. This code indicates the protection of mechanical and electrical casings against water, dust, and accidental contact. A high IP code indicates reduced susceptibility to moisture. Commercially available UAVs are often rated by an overall IP code for the vehicle, including all components. Most commercial UAVs are classified as “water-resistant” and are covered by IP codes between IPX3 and IPX6. This code implies a limited capacity to repel water for short periods. Many laptops or smartphones have a similar rating, implying that they can withstand light rain but not total submergence in water. UAVs of IPX3 to IPX6 are able to navigate back to the pilot and land in light rain but should not be exposed to conditions such as rain, fog, or snow for long periods. Certain UAVs, however, are certified to fly in rain (e.g., IPX7/IPX8). Flying in the rain raises other complications that should be considered, too, such as reduced lift at the same rotor speeds and possible communication issues with the ground controller.

9. FUTURE TRENDS

Despite significant advances over the last decade, there remain some strong limitations for UAV use. These limitations present broad technical challenges to engineers and scientists, and they could shape future research trends. At present time, the primary engineering limitations presented by UAVs lie in limits on flight time, flight range, and structural mechanics. The limitations result from a combination of weight, power, compactness, environmental robustness, and communication requirements. These different variables are interrelated because improvement in one can come at the detriment of another. Environmental robustness refers to UAV endurance to adverse weather and environmental conditions. Communication requirements affect the maximum distance a UAV can fly from a ground controller before requiring an autonomous capability. In this section, current technical challenges and possible solutions under active research are presented. In particular, current trends in artificial intelligence for autonomous systems are described for so-called possible future “UAV swarms,” “internet of drones,” and “smart dust.”

9.1. Design

9.1.1. Components, Materials, and Manufacture

Propulsion technologies are the primary limit related to weight, compactness, and power requirement of rotary-wing UAVs [44]. More specifically, battery storage capacity is the main limit for most UAVs (section 6.5) (Figure 15). One suggested idea is that battery life could be extended through the use of solar energy in fixed-wing UAVs [11], but the charging rate is not fast enough for the geometries and power requirements of typical rotary-wing UAVs [65].

The maximum technical takeoff weight is a design constraint determined by the UAV equations of motion (section 8.4). There is also a weight limit determined by the Part 107 “Small UAS Rule” (section 5). The heaviest components present in rotary-wing UAVs are the batteries, which can account for almost half of the total weight (section 7.1). Consequently, a reduction in battery weight and the ability to miniaturize batteries are both highly desirable. For this reason, improving battery energy density and not just battery storage capacity is an ongoing technological challenge for the UAV community. Although weight can also be reduced in other ways, such as replacing body materials with carbon fiber and minimizing payload weight, these gains are marginal in comparison to improvements in battery technology. Improved battery energy density is also desirable for increasing the compactness of UAVs.

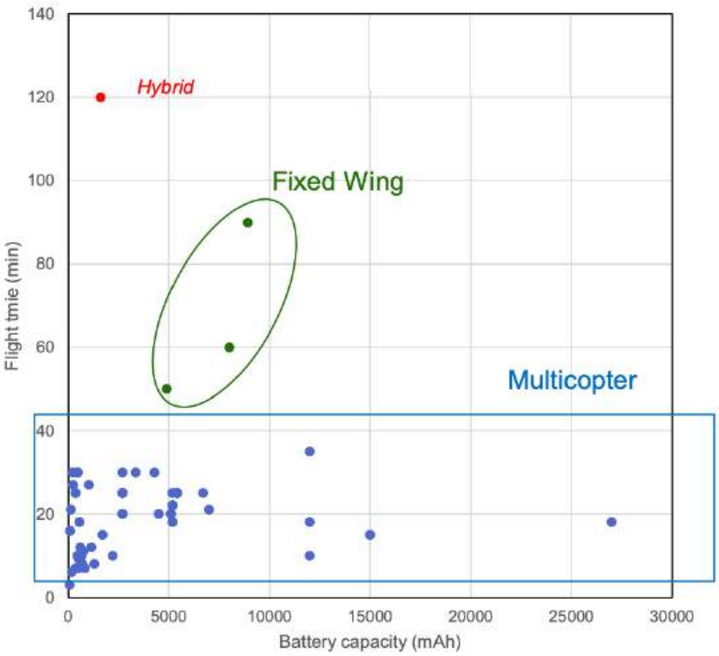

Figure 15. Flight time of commercially available UAVs as a function of battery capacity [66]. Copyright (2018), with permission from IDTechEx.

Additive manufacturing (i.e., "3D printing") is another possibility for weight reduction. Several studies have explored the potential of additive manufacturing for customized UAVs that have strong structures [67-69]. The strength-to-weight ratio is an essential characteristic for the UAV to ensure structural integrity [70]. Additive manufacturing seeks to maximize the strength-to-weight ratio, thereby minimizing overall UAV weight, for a UAV that is targeted to a particular purpose. In addition, additive manufacturing can allow the production of more compact structures that have similar strength to existing structures, resulting in increasingly compact UAV designs. Technological advances in additive manufacturing, as well as cost reductions and the ability to process increasingly lightweight and strong materials, might lead to greater usage of this technique for the production of UAVs in the future.

9.1.2. Miniaturization

There is currently an increasing trend toward UAV miniaturization. Reduced power consumption, improved transportability, and greater maneuverability are all possible through miniaturization. A challenge, however, is that the miniaturization of both rotary-wing and fixed-wing aircraft is fundamentally limited by the laws of physics. Shrinking the size of propellers is only possible up to a point, beyond which friction overtakes the lift force. For rotary-wing aircraft, in this limit motors overheat in an attempt to maintain lift. For fixed-wing aircraft, at smaller scales lift drops on miniaturized airfoils, and there is increased sensitivity of flight stability to small scale perturbations in the wind. Some researchers study insects for inspiration on how to achieve flight for a lightweight aircraft while maintaining high levels of control and in the presence of atmospheric turbulence [71,72].

The development of a bio-inspired “flapping wing” UAV presents significant aerodynamic and control challenges. Some UAVs, like the eBee and AR.Drone 2.0, are bio-inspired yet still based on rotary-wing or fixed-wing design (i.e., not flapping wing). Flapping-wing UAVs that closely mimic insect flight are still in the developmental stage. Two notable examples of existing flapping-wing designs are the Nano Hummingbird [73]and the RoboBee [74] (Figure 16). Floreano and Wood [75] suggest that bio-inspired UAVs might be increasingly important in future markets because of their potential simplicity. Even so, their applications can be expected to be limited to those that do not require a substantial payload.

Bio-inspired UAVs have several additional possible advantages. The wings of bio-inspired UAVs can produce less noise than rotary-wing UAVs [72]. Flapping wings also allow for sharp turns and abrupt flight arrest without loss of stability. These capabilities coupled with miniaturization could make the use of UAVs in indoor environments increasingly feasible [77]. Such UAVs might also be less invasive in applications such as wildlife monitoring, photography, and surveillance.

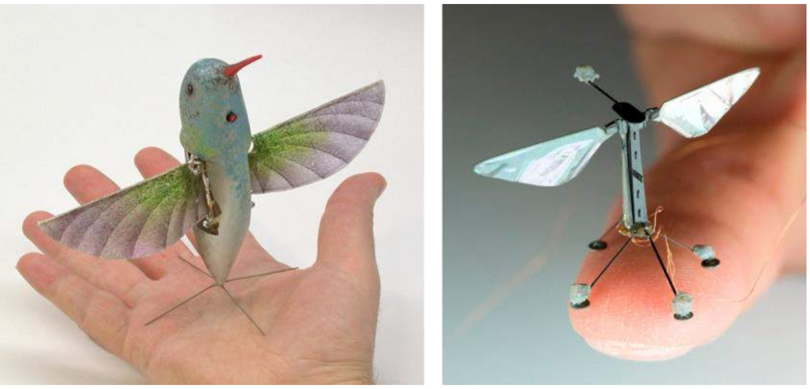

Figure 16. Examples of flapping-wing UAVs. (left) The Nano Hummingbird. (right) The RoboBee [76].

"Smart dust" is an aspirational goal that represents the limit of the miniaturization trend [78-81]. Smart dust refers to micrometer-sized UAVs. Recent advances in microelectromechanical (MEMS)-based sensors and systems are enabling the development of UAVs on this length scale. The possibility of visually undetectable UAVs that are the size of dust particles and equipped with cameras and other sensors could find many applications and benefits. Still, many social and political dilemmas related to privacy and health can be expected to complicate widespread use and early adoption of smart dusts.

9.2. Communication

9.2.1. Identification and Control

Since UAV systems are operated remotely, there is the possibility for compromise by malicious actors. The data link portion of the UAV communication system is the most vulnerable part of the UAV control system. Attacks by bad actors may be done covertly, such as stealing onboard data, or overtly whereby control of the UAV is overridden. To help prevent this scenario, devices use a unique identification code to identify the origin of a transmission. Transmitters and receivers are paired using a radio frequency identifier (RFID). This receiver identifies the origin of the information. To prevent the malicious actor from copying this RFID, signals between the transmitter and receiver can be encrypted. For example, DJI UAVs connect to their controller using the OcuSync 2.0 protocol. The Advanced Encryption Standard (AES)-256 is used for information exchange between the UAV and its controller. Some UAVs may also feature password protection for UAV activation, linking to a new controller, or providing access to onboard data.

UAV jammers present an additional challenge. Radio jammers are able to generate high-power signals that block or interfere other radio communications through decreasing the signal-to-noise ratio of existing signals or by mimicking these signals. The frequencies targeted by UAV jammers typically focus around the 2.4 GHz and 5.8 GHz bands due to their high usage for UAV communication. Civilian use of jammers is illegal in most countries [82]. Jammers are being increasingly used by authorities in response to criminal use of UAVs such as near airports and prisons [82,83]. Jammers are able to halt communication between the controller and UAV. Although jammers are intended for public safety, bad actors can also use them to hijack UAVs, track a UAV back to its pilot, force the UAV to land, or merely block communication between the UAV and pilot. UAVs can themselves be used as jammers [84,85]. Geofencing by UAV manufacturers adds software-level functionality that prevents flight near sensitive airspace such as airports, prisons, and nuclear power plants. Geofencing is not foolproof, however. It can be bypassed by using aluminum foil to block GPS signals or by using a custom-built UAV without built-in geofencing.

Another potential attack on UAVs is through GPS spoofing. A radio transmitter interferes with the GPS signals by feeding false GPS coordinates. Autonomous UAVs, which often navigate directly using this GPS information, are especially susceptible to this kind of attack. Waveforms used by the military are designed to be unpredictable and are resistant to spoofing. For consumer applications, however, waveforms are unencrypted and unauthenticated [86]. UAV capture is also possible using GPS spoofing, whereby the bad actor is able to specify the position and velocity estimates to manipulate the state of the UAV, effectively taking control of UAV flight [86]. GPS spoofing is difficult to prevent, but it can be efficiently detected.

The best-known countermeasures are using encrypted GPS information and using machine learning to detect spoofing attacks.

The FAA has proposed to integrate RFID identifiers on UAVs. This change may also have substantial impacts on UAV communication and navigation. The proposal suggests the creation of a UAS Data Exchange, which would be a collaborative data-sharing effort between government and private agencies for airspace information. The UAS Data Exchange aims to cover multiple partnerships, the first of which is named the Low Altitude Authorization and Notification Capability (LAANC). LAANC would provide a simpler framework than currently exists for the integration of UAVs into the NAS by providing information to air traffic control on where current UAV flights are taking place. This information can also be used by UAV pilots to know where they may and may not fly. The information could further enhance geofencing capabilities by vendors to ensure that pilots do not encroach upon controlled airspace. The integrated nature of this FAA proposal could provide UAV users with real-time authorization for flights. At the same time, law enforcement and airspace authorities can monitor controlled airspace and identify any unusual activity to facilitate public safety. As such, according to the proposal, this system would simultaneously provide increased freedom to business and recreational UAV users while aiding authorities to prevent UAV-related security threats, such as those that have occurred in recent years [87].

9.2.2. Autonomous UAVs

Fully autonomous UAVs are under development. Many commercial UAVs allow the user to program flight paths using GPS coordinates. This capability can be described as “automated” or “semi-autonomous.” By comparison, an “autonomous” UAV (i.e., “self-driving”) must be capable of following and updating its flight path based on real-time data without human input. Fully autonomous UAVs are expected to be useful for many applications, such as package delivery, policing, or environmental monitoring.

At present time, machine learning algorithms are focusing on data extracted from UAV flights. The goal of these efforts is to develop UAV systems that can respond in real-time to high-resolution onboard measurements. More data continue to become available as sensors become smaller, more accurate, and more reliable. The use of built-in machine learning algorithms on UAVs, however, presents new processing and storage challenges because many such algorithms can be data- or compute-intensive. Optimization under this constraint is sometimes called “tiny machine learning.” Decisions must be made whether (i) data are stored and processed onboard, (ii) data are communicated to a ground station, cloud, or other computing platform, or (iii) a combination of both.

9.2.2.1. UAV Swarms

Orchestrating the coordinated movements of tens of UAVs or more in a simultaneous fashion is considerably more complicated than direction of a single system. Such orchestration, which is a research topic of multi-agent systems, has led to the term “UAV swarms.” These swarms can require rapid communication and coordination to avoid collisions among UAVs. Even when more widely spaced, communication and coordination can still be important for sharing data and coordinating flight paths. Communication among too many devices can quickly cause a network to reach the Shannon capacity, becoming saturated and halting all communications.

UAV swarms have been demonstrated at several public events. In the opening ceremony of the 2018 Winter Olympics, 1,218 UAVs were used in a single display. In the future, an array of coordinated UAVs could be equipped with gas sensors to monitor pollution levels across an entire city or equivalently in a large warehouse to assess indoor air quality. A similar approach could be used to form an airborne surveillance system for security of buildings and public events. UAV swarms might be able to use artificial intelligence for autonomous operations. Recent interest from industry, military, and academic bodies suggests that UAV swarms may become more prevalent in the coming years.

9.2.2.2. Internet of Drones

Related to UAV swarms, the Internet of Drones (IoD) extends the concept of the Internet of Things (IoT) to UAV-based end devices [88-90].

An IoD could be used to create airborne sensor networks [91-93]. The resulting distributed sensor networks could provide useful data and great flexibility of a mobile sensor platform. The Facebook Loon project intends to provide internet connectivity in remote locations that lack connectivity, and UAVs could serve as an important access point in the technology hierarchy.

Interest in using IoT-connected drones is expected to increase substantially in the next five years. One prediction is that the number of connected devices might reach 75 billion by 2025 [93]. A lack of regulations and oversight by the government, coupled with increased demand for low-cost sensors, has given rise to multiple IoT communication protocols by private companies. Some of the most popular of these are narrowband-IoT (NB-IoT), Sigfox, low-power wide-area network (LP-WAN), long-range LPWAN (LoRaWAN), Bluetooth Low Energy (BLE), Zigbee, and Z-Wave. These protocols operate at various frequencies, mostly within the ISM bands. However, these frequencies vary depending on location and may consist of multiple bands. For example, Zigbee operates on unlicensed ISM bands (868 MHz in Europe, 915 MHz in North America, and 433 MHz in Asia), and NB-IoT utilizes five different bands in North America (B4, 1700 MHz; B12, 700 MHz; B26, 850 MHz; B66, 1700 MHz; and B71, 600 MHz). As such, frequency considerations, among other characteristics such as weight and power requirements, must be taken into account when combining UAVs with other IoT devices.

CONCLUSION

Although the first UAVs have existed for more than a century, especially for military uses, the modern version has become possible by the development of lightweight radio receivers, advancements in propulsion systems, and microcontrollers. More recently, commercial and consumer versions of UAVs have emerged. Today, the prolific use of lightweight and portable UAVs by industry, researchers, and hobbyists has led to a paradigm shift in aviation. While the UAV market is burgeoning, its size is still small, and substantial growth is anticipated for the coming years. Technological developments and market expansion could result in economies of scale, making UAVs more affordable and, in turn, further increasing market size. Rapid growth of the market and use of UAVs is meeting increasing legal and regulatory requirements. Concerns are related to individual privacy, saturation of communication bands, integration into the national airspace, and nefarious uses by bad actors. Despite the many capabilities afforded by modern UAVs, there are still substantial limitations related to weight, size, environmental robustness, communication, and payloads. These limitations present scientific and engineering challenges that must be managed by prospective users in a variety of applications.

ACKNOWLEDGMENTS

Support from the Division of Atmospheric and Geospace Sciences (AGS) of the USA National Science Foundation (AGS-1829025) is gratefully acknowledged.

REFERENCES

[1] FAA. *Unmanned Aircraft Operations in the National Airspace System*. (Federal Register: Office of the Federal Register, 2007). https://www.federalregister.gov/documents/2007/02/13/E7-2402/unmanned-aircraft-operations-in-the-national-airspace-system (accessed 22 August 2020).

[2] Chapman, Andrew. "It's okay to call them drones." *Journal of Unmanned Vehicle Systems* (2014): iii-v. doi:10.1139/juvs-2014-0009.

[3] Kozera, Cyprian. "Military use of unmanned aerial vehicles – a historical study." *Safety & Defense* (2018): 17-21. doi:10.37105/sd.4.

[4] Blom, John David. *Unmanned Aerial Systems: A Historical Perspective*. (Washington D.C.: Combat Studies Institute Press, 2010).

[5] Keane, John F., and Stephen Scott Carr. 2013. "A Brief History of Early Unmanned Aircraft." In *Johns Hopkins APL Technical Digest*, 559-570.

[6] Hundley, R., E. Gritton. *Future Technology-Driven Revolutions in Military Operations: Results of a Workshop.* (Santa Monica, CA: RAND Corporation, 1994). https://www.rand.org/pubs/documented_briefings/DB110.html (accessed August 22, 2020).

[7] Karp, Jonathan; Pasztor, Andy. "Drones in domestic skies?" *Wall Street Journal* (2006). https://www.wsj.com/articles/SB115491642950528436 (accessed June 7, 2020).

[8] Wolf, H. G. *Drones: safety risk management for the next evolution of flight*. (Abingdon-on-Thames: Routledge, 2017).

[9] Schuyler, J. Travis, C. C. Sean Bailey, and I. Marcelo Guzman. "Monitoring tropospheric gases with small unmanned aerial systems (sUAS) during the second CLOUDMAP flight campaign." *Atmosphere* (2019). doi:10.3390/atmos10080434.

[10] United States Department of Defense. *Unmanned Aircraft System Airspace Integration Plan*. (Washington D.C.: GPO, 2011). https://info.publicintelligence.net/DoD-UAS-AirspaceIntegration.pdf (accessed August 22, 2020).

[11] Watts, Adam, Vincent Ambrosia, and Everett Hinkley. "Unmanned aircraft systems in remote sensing and scientific research: classification and considerations of use." *RS* (2012): 1671-1692. doi:10.3390/rs4061671.

[12] Brooke-Holland, Louisa. *Unmanned Aerial Vehicles (drones): an introduction.* (London: House of Commons Library, 2012). https://www.files.ethz.ch/isn/157096/SN06493.pdf (accessed August 22, 2020).

[13] Weibel, Roland, and R. Hansman. *Safety considerations for operation of different classes of UAVs in the NAS*. (2004). doi:10.2514/6.2004-6421.

[14] Gupta, Suraj, Mangesh Ghonge, and Pradip Jawandhiya. "Review of unmanned aircraft system (UAS)." *International Journal of Advanced Research in Computer Engineering & Technology* (2013). doi:10.2139/ssrn.3451039.

[15] Cavoukian, Ann. *Privacy and drones: unmanned aerial vehicles*. (Toronto, Ontario: Information and Privacy Commissioner of Ontario, Canada, 2012).

[16] Hassanalian, Mostafa, and Abdessattar Abdelkefi. "Classifications, applications, and design challenges of drones: A review." *Progress in Aerospace Sciences* (2017). doi:10.1016/j.paerosci.2017.04.003.

[17] Rango, Albert, Andrea Laliberte, Jeffrey Herrick, Craig Winters, Kris Havstad, Caiti Steele, and Dawn Browning. "Unmanned aerial vehicle-based remote sensing for rangeland assessment, monitoring, and management." *Journal of Applied Remote Sensing* (2009). doi:10.1117/1.3216822.

[18] Federal Aviation Administration. *FAA Aerospace Forecast 2019-2039*. (Washington, D.C.: GPO, 2019). https://www.faa.gov/data_research/aviation/aerospace_forecasts/media/FY2019-39_FAA_Aerospace_Forecast.pdf (accessed August 22, 2020).

[19] Restas, Agoston. "Drone applications for supporting disaster management." *World Journal of Engineering and Technology* (2015): 316-321. doi:10.4236/wjet.2015.33C047.

[20] Restas, A. "Disaster management supported by unmanned aerial systems (UAS) focusing especially on natural disasters." *Zeszyty Naukowe SGSP / Szkoła Główna Służby Pożarniczej* (2017): 25-34.

[21] Veroustraete, Frank. "The rise of the drones in agriculture." *EC Agriculture* (2015).

[22] Puri, Vikram, Anand Nayyar, and Linesh Raja. "Agriculture drones: a modern breakthrough in precision agriculture." *Journal of Statistics and Management Systems* (2017): 507-518. doi:10.1080/09720510.2017.1395171.

[23] Liuzza, Davide, Giuseppe Silano, Francesco Picariello, Luigi Iannelli, Luigi Glielmo, Luca De Vito, and P. Daponte. "A review on the use of

drones for precision agriculture." *IOP Conference Series: Earth and Environmental Science,* (2018).

[24] Naidoo, Yogianandh, Riaan Stopforth, and Glen Bright. "Development of an UAV for search & rescue applications." *IEEE Africon Conference,* (2011).

[25] Rémy, Guillaume, Sidi-Mohammed Senouci, François Jan, and Yvon Gourhant. "SAR.Drones: drones for advanced search and rescue missions." *Journées Nationales des Communications dans les Transports,* (2013).

[26] Jung, Sunghun, and Hyunsu Kim. "Analysis of Amazon Prime Air UAV delivery service." *Journal of Knowledge Information Technology and Systems* (2017): 253-266. doi:10.34163/jkits. 2017.12.2.005.

[27] Scott, Judy, and Carlton Scott. 2017. "Drone delivery models for healthcare." *Proceedings of the 50th Hawaii international conference on system sciences*.

[28] Dorling, Kevin, Jordan Heinrichs, Geoffrey G Messier, and Sebastian Magierowski. "Vehicle routing problems for drone delivery." *IEEE Transactions on Systems, Man, and Cybernetics: Systems* (2016): 70-85. doi:10.1109/TSMC.2016.2582745.

[29] Ayranci, Zehra Betul. "Use of drones in sports broadcasting." *Ent. & Sports Law.* (2016): 79.

[30] Zachariadis, Orestis, Vasileios Mygdalis, Ioannis Mademlis, Nikos Nikolaidis, and Ioannis Pitas. 2017. "2D visual tracking for sports UAV cinematography applications." *2017 IEEE Global Conference on Signal and Information Processing* (GlobalSIP).

[31] Kaufmann, Elia, Mathias Gehrig, Philipp Foehn, René Ranftl, Alexey Dosovitskiy, Vladlen Koltun, and Davide Scaramuzza. 2019. "Beauty and the beast: optimal methods meet learning for drone racing." *2019 International Conference on Robotics and Automation (ICRA).*

[32] Kaufmann, Elia, Antonio Loquercio, Rene Ranftl, Alexey Dosovitskiy, Vladlen Koltun, and Davide Scaramuzza. "Deep drone racing: learning agile flight in dynamic environments." *arXiv preprint arXiv:1806.08548* (2018).

[33] Stelmack, Kyle. "Weaponized police drones and their effect on police use of force." *Pittsburgh Journal of Technology Law and Policy* (2015): 276. doi:10.5195/tlp.2015.172.

[34] Commercial Drone Market Size, Share & Industry Analysis, By Product (Fixed Wing Drone, Rotary Blade Drone, and Hybrid Drone), By Technology (Remotely Operated, Semi-Autonomous, and Autonomous), By System (UAV Structure, UAV Payloads, UAV Avionics, UAV Propulsion, and UAV Software), By Industry (Infrastructure, Transport & Delivery, Insurance, Media, Telecommunication, Agriculture, Security, and Mining) and Regional Forecast, 2020-2027. (*Fortune Business Insights*, 2020). https://www.fortunebusinessinsights.com/commercial-drone-market-102171 (accessed August 22, 2020).

[35] Anwar, A. *Commercial UAS Market Outlook 2017-2027*. (Strategy Analytics, 2018). https://www.strategyanalytics.com/access-services/components/defense/reports/report-detail/commercial-uas-market-outlook-2017-2027 (accessed August 22, 2020).

[36] Wackwitz, Kay. *The Drone Market Report 2019-2024*. (Drone Industry Insights, 2019). https://www.droneii.com/project/drone-market-report (accessed August 22, 2020).

[37] Cai, Guowei, Jorge Dias, and Lakmal Seneviratne. "A survey of small-scale unmanned aerial vehicles: recent advances and future development trends." *Unmanned Systems* (2014): 175-199. doi:10.1142/S2301385014300017.

[38] Ivosevic, Bojana, Yong-Gu Han, Youngho Cho, and Ohseok Kwon. "The use of conservation drones in ecology and wildlife research." *Journal of Ecology and Environment* (2015): 113-118. doi:10.5141/ecoenv.2015.012.

[39] Banu, Tiberiu, Gheorghe Borlea, and Constantin Banu. "The use of drones in forestry." *Journal of Environmental Science and Engineering B* (2016). doi:10.17265/2162-5263/2016.11.007.

[40] Tang, Lina, and Guofan Shao. "Drone remote sensing for forestry research and practices." *Journal of Forestry Research* (2015): 791-797. doi:10.1007/s11676-015-0088-y.

[41] Zhang, Jian, Jianbo Hu, Juyu Lian, Zongji Fan, Xuejun Ouyang, and Wanhui Ye. "Seeing the forest from drones: testing the potential of lightweight drones as a tool for long-term forest monitoring." *Biological Conservation* (2016). doi:10.1016/j.biocon.2016.03.027.

[42] Paneque-Gálvez, Jaime, K. Michael McCall, M. Brian Napoletano, A. Serge Wich, and P. Lian Koh. "Small drones for community-based forest monitoring: an assessment of their feasibility and potential in tropical areas." *Forests* (2014). doi:10.3390/f5061481.

[43] Manfreda, Salvatore, F. Matthew McCabe, E. Pauline Miller, Richard Lucas, Victor Pajuelo Madrigal, Giorgos Mallinis, Eyal Ben Dor, David Helman, Lyndon Estes, Giuseppe Ciraolo, Jana Müllerová, Flavia Tauro, I. M. De Lima, L. M. P. João De Lima, Antonino Maltese, Felix Frances, Kelly Caylor, Marko Kohv, Matthew Perks, Guiomar Ruiz-Pérez, Zhongbo Su, Giulia Vico, and Brigitta Toth. "On the use of unmanned aerial systems for environmental monitoring." *Remote Sensing* (2018). doi:10.3390/rs10040641.

[44] Villa, F. Tommaso, Felipe Gonzalez, Branka Miljievic, D. Zoran Ristovski, and Lidia Morawska. "An overview of small unmanned aerial vehicles for air quality measurements: present applications and future prospectives." *Sensors* (2016). doi:10.3390/s16071072.

[45] Hardin, Perry, and Ryan Jensen. "Small-scale unmanned aerial vehicles in environmental remote sensing: challenges and opportunities." *GIScience & Remote Sensing* (2011). doi:10.2747/1548-1603.48.1.99.

[46] *FAA Modernization and Reform Act of 2012*. 112 P.L. 95. 126 Stat. 11.

[47] Maddalon, Jeffrey, Kelly Hayhurst, Allan Morris, and Harry Verstynen. "Considerations of unmanned aircraft classification for civil airworthiness standards." *Infotech@Aerospace Conference*, (2013).

[48] Federal Aviation Administration. *Unmanned Aircraft Operations in the National Airspace System*. (Washington D.C.: GPO, 2006). https://www.faa.gov/uas/resources/policy_library/media/frnotice_uas.pdf (accessed August 22, 2020).

[49] "Small Unmanned Aircraft Systems." *Code of Federal Regulations*, title 14 (2016): 925-933. https://www.govinfo.gov/content/pkg/CFR-2020-title14-vol2/pdf/CFR-2020-title14-vol2-part107.pdf.

[50] Taylor v. Huerta, 856 F.3d 1089 (D.C. Cir. 2017).

[51] *National Defense Authorization Act for Fiscal Year 2018*. 115 P.L. 91. 131 Stat. 1332.

[52] *FAA Reauthorization Act of 2018*. 115 P.L. 254. 132 Stat. 3186.

[53] European Aviation Safety Agency. *UAS ATM Integration.* (2018). https://www.eurocontrol.int/sites/default/files/publication/files/uas-atm-integration-operational-concept-v1.0-release%2020181128.pdf (accessed August 22, 2020).

[54] Simonite, Tom. "Air traffic control for drones." (*MIT Technology Review*, 2014). https://www.technologyreview.com/2014/10/17/170928/air-traffic-control-for-drones/ (accessed August 22, 2020).

[55] Rule, Troy A. "Drone zoning." *North Carolina Law Review* (2016).

[56] Calo, Ryan. "The drone as privacy catalyst." *Stanford Law Review Online* (2011): 29-33.

[57] Pothuganti, Karunakar, Mesfin Jariso, and Pradeep Kale. "A review on geo mapping with unmanned aerial vehicles." *International Journal of Innovative Research in Computer and Communication Engineering* (2017).

[58] Leslie, Angus, Kee Choon Wong, and Doug Auld. "Experimental analysis of the radiated noise from a small propeller." *Applied Acoustics* (2010). doi:10.1016/j.apacoust.2012.06.011.

[59] Schroth, Frank. "Drone Energy Sources – Pushing the Boundaries of Electric Flight." (*Drone Industry Insights*, 2017). https://www.droneii.com/drone-energy-sources (accessed August 22, 2020).

[60] Gatti, Mauro. "Complete preliminary design methodology for electric multirotor." *Journal of Aerospace Engineering* (2017). doi:10.1061/(ASCE)AS.1943-5525.0000752.

[61] Kendoul, Farid. "Survey of advances in guidance, navigation, and control of unmanned rotorcraft systems." *Journal of Field Robotics* (2012): 315-378. doi:10.1002/rob.20414.

[62] Biczyski, Marcin, Rabia Sehab, James Whidborne, Guillaume Krebs, and Patrick Luk. "Multirotor sizing methodology with flight time estimation." *Journal of Advanced Transportation* (2020): 1-14. doi:10.1155/2020/9689604.

[63] Luukkonen, Teppo. *Modelling and control of quadcopter*. (2011). https://sal.aalto.fi/publications/pdf-files/eluu11_public.pdf.

[64] Kumar, Vijay, and Nathan Michael. "Opportunities and challenges with autonomous micro aerial vehicles." *The International Journal of Robotics Research* (2012): 1279-1291. doi:10.1177/02783649 12455954.

[65] Lussier, Marc, Justin Bradley, and Carrick Detweiler. *Extending endurance of multicopters: The current state-of-the-art*. (2019).

[66] Ghaffarzadeh, Khasha; Harrop, Peter. *Drones 2018-2038: Components, Technologies, Roadmaps, Market Forecasts.* (IDTechEx: 2018). (accessed August 22, 2020).

[67] Balasubramanian, Esakki, N. Sagar, Udayagiri Chandrasekhar, and Sachin Salunkhe. "Development of light weight multi-rotor UAV structures through synergistic application of design analysis and fused deposition modelling." *International Journal of Materials and Product Technology* (2019): 229-238. doi:10.1504/IJMPT. 2019.10024474.

[68] Goh, Guo Dong, Shweta Agarwala, Goh Guo Liang, Vishwesh Dikshit, Swee Leong Sing, and Wai Yee Yeong. "Additive manufacturing in unmanned aerial vehicles (UAVs): Challenges and potential." *Aerospace Science and Technology* (2017): 140-151. doi:10.1016/j.ast.2016.12.019.

[69] Moon, Seung, Yu Tan, Jihong Hwang, and Yong-jin Yoon. "Application of 3D printing technology for designing light-weight unmanned aerial vehicle wing structures." *International Journal of Precision Engineering and Manufacturing-Green Technology* (2014): 223-228. doi:10.1007/s40684-014-0028-x.

[70] Kushleyev, Alex, Daniel Mellinger, Caitlin Powers, and Vijay Kumar. "Towards a swarm of agile micro quadrotors." *Autonomous Robots* (2013). doi:10.1007/s10514-013-9349-9.

[71] Sane, Sanjay. "The aerodynamics of insect flight." *The Journal of experimental biology* (2004): 4191-208. doi:10.1242/jeb.00663.

[72] Dickinson, Michael H., Fritz-Olaf Lehmann, and Sanjay P. Sane. "Wing Rotation and the Aerodynamic Basis of Insect Flight." *Science* (1999): 1954. doi:10.1126/science.284.5422.1954.

[73] Keennon, Matthew, Karl Klingebiel, and Henry Won. "Development of the Nano Hummingbird: A Tailless Flapping Wing Micro Air Vehicle." 5*0th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition*, (2012).

[74] Wood, Robert, Radhika Nagpal, and Gu-Yeon Wei. "Flight of the RoboBees." *Scientific American* (2013): 60-5. doi:10.1038/scientific american0313-60.

[75] Floreano, Dario, and Robert Wood. "Science, technology and the future of small autonomous drones." *Nature* (2015): 460-6. doi:10.1038/nature14542.

[76] Chin, Yao-Wei, Jia Ming Kok, Yong-Qiang Zhu, Woei-Leong Chan, Javaan S. Chahl, Boo Cheong Khoo, and Gih-Keong Lau. "Efficient flapping wing drone arrests high-speed flight using post-stall soaring." *Science Robotics* (2020): eaba2386. doi:10.1126/scirobotics.aba2386.

[77] Warneke, Brett, Matt Last, Brian Liebowitz, and Kristofer SJ Pister. "Smart dust: communicating with a cubic-millimeter computer." *Computer* (2001): 44-51. doi:10.1109/2.895117.

[78] Kahn, Joseph M, Randy H Katz, and Kristofer SJ Pister. 1999. "Next century challenges: mobile networking for “smart dust.” *Proceedings of the 5th annual ACM/IEEE international conference on Mobile computing and networking*.

[79] Kahn, Joseph M, Randy Howard Katz, and Kristofer SJ Pister. "Emerging challenges: mobile networking for “smart dust.” *Journal of Communications and Networks* (2000): 188-196. doi:10.1109/ JCN.2000.6596708.

[80] Ilyas, Mohammad, and Imad Mahgoub. *Smart dust: sensor network applications, architecture and design*. (CRC press, 2018).

[81] Lykou, Georgia, Dimitrios Moustakas, and Dimitris Gritzalis. "Defending Airports from UAS: A Survey on Cyber-Attacks and

Counter-Drone Sensing Technologies." *Sensors (Basel)* (2020): 3537. doi:10.3390/s20123537.

[82] Pärlin, Karel, Muhammad Alam, and Yannick Le Moullec. "Jamming of UAV Remote Control Systems Using Software Defined Radio." 2018 International Conference on Military Communications and Information Systems, (2018).

[83] Wu, Q., W. Mei, and R. Zhang. "Safeguarding Wireless Network with UAVs: A Physical Layer Security Perspective." *IEEE Wireless Communications* (2019): 12-18. doi:10.1109/MWC.001.1900050.

[84] Wu, Qingqing, Weidong Mei, and Rui Zhang. "Safeguarding Wireless Network with UAVs: A Physical Layer Security Perspective." *IEEE Wireless Communications* (2019): 5. doi:10.1109/MWC.001. 1900050.

[85] Kerns, Andrew, Daniel Shepard, Jahshan Bhatti, and Todd Humphreys. "Unmanned aircraft capture and control via GPS spoofing." *Journal of Field Robotics* (2014). doi:10.1002/rob.21513.

[86] Pyrgies, John. "The UAVs threat to airport security: risk analysis and mitigation." *Journal of Airline and Airport Management* (2019): 63. doi:10.3926/jairm.127.

[87] Nayyar, Anand, Bao-Le Nguyen, and Nguyen Nhu. 2020. "The Internet of drone things (IoDT): future envision of smart drones." In *First International Conference on Sustainable Technologies for Computational Intelligence*, 563-580. Springer Nature Singapore.

[88] Hall, Robert. "An internet of drones." *IEEE Internet Computing* (2016): 68-73. doi:10.1109/MIC.2016.59.

[89] Loke, S. "The Internet of flying-things: opportunities and challenges with airborne fog computing and mobile cloud in the clouds." *ArXiv* (2015).

[90] Popescu, Dan, Cristian Dragana, Florin Stoican, Loretta Ichim, and Grigore Stamatescu. "A collaborative UAV-WSN network for monitoring large areas." *Sensors (Basel)* (2018): 4202. doi:10.3390/s18124202.

[91] Wang, Chengliang, Fei Ma, Junhui Yan, Debraj De, and Sajal K. Das. "Efficient aerial data collection with UAV in large-scale wireless

sensor networks." *International Journal of Distributed Sensor Networks* (2015): 286080. doi:10.1155/2015/286080.

[92] Costa, F. G., J. Ueyama, T. Braun, G. Pessin, F. S. Osório, and P. A. Vargas. 2012. "The use of unmanned aerial vehicles and wireless sensor network in agricultural applications." *2012 IEEE International Geoscience and Remote Sensing Symposium*, 22-27 July 2012.

[93] *Internet of things - number of connected devices worldwide 2015-2025*. (New York: Statista Research Department, 2016). https://www.statista.com/statistics/471264/iot-number-of-connected-devices-worldwide/ (accessed August 22, 2020).

[94] Bansod, Babankumar, R. Singh, Ritula Thakur, and Gaurav Singhal. "A comparision between satellite based and drone based remote sensing technology to achieve sustainable development: A review." *Journal of Agriculture and Environment for International Development* (2017): 383-407. doi:10.12895/jaeid.20172.690.