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Preventive Arms Control for Small and Very Small Armed Aircraft and Missiles

Report No. 1

Survey of the Status of Small Armed and Unarmed Uninhabited Aircraft

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Contents

Abbreviations and Acronyms

AGL	Above ground level
AMSL	Above mean sea level
BAV	Biomimetic air vehicle
BDS	BeiDou navigation satellite system
C-UAS	Counter uninhabited aircraft system
COMINT	Communications intelligence
COTS	Commercial off-the-shelf
DARPA	Defense Advanced Research Projects Agency
EFP	Explosively formed penetrator
EO	Electro-optical
GCS	Ground control system
GLONASS	Global navigation satellite system
GNSS	Global navigation satellite system
GPS	Global positioning system
HTOL	Horizontal take-off and landing
ICAO	International Civil Aviation Organization
IMU	Inertial measurement unit
INS	Inertial navigation system
IR	Infrared
ISR	Intelligence, surveillance and reconnaissance
LiDAR	Light detection and ranging
LOCUST	Low-cost UAV swarming technology
LWIR	Long-wave infrared
MAV	Micro air vehicle
MEMS	Microelectromechanical systems
MTOW	Maximum take-off weight
MWIR	Midwave infrared
NAV	Nano Air Vehicle
NIR	Near infrared
PEO	Program Executive Office
R&D	Research and development
RF	Radio frequency
RPG	Rocket-propelled grenade
SCO	Strategic Capabilities Office
SWIR	Short-wave infrared
UA	Uninhabited aircraft
UAS	Uninhabited aerial system
UAV	Uninhabited aerial vehicle
VTOL	Vertical take-off and landing

1 Introduction

The project 'Preventive Arms Control for Small and Very Small Armed Aircraft and Missiles', funded by the German Foundation for Peace Research DSF, is investigating the properties to be expected of ever smaller aircraft and missiles, including their use in swarms (`https://url.tu-dortmund.de/pacsam`). Small and very small aircraft as covered here are uninhabited by their size, thus the designation uninhabited aerial vehicle (UAV) or uninhabited aircraft (UA) applies. While the focus is on armed systems, unarmed ones will be covered as well, since modifications for carrying or acting as a weapon are possible. This report no. 1 covers the status of UAVs. Further reports will deal with missiles and consider dangers and preventive arms control.

Uninhabited vehicles are increasingly being deployed and used by armed forces, with UAVs most advanced. Since 2001 UAVs have been armed and used for attacks by a few states, the number of countries with armed UAVs is rising dramatically. In 2017, there were 28 (World of Drones, 2017), while in 2020 the number rose to 39 (World of Drones, 2020). These UAVs have wingspans of many metres.

The principal possibility of small and very small armed UAVs and missiles was mentioned early, fuelled by emerging microsystems technology and nanotechnology, but proposals for limits or prohibitions[1] have not been taken up so far. In the meantime, the first small armed UAVs with a size of only very few metres, down to centimetres, have arrived. Although small UAVs are far more limited in their capabilities than large UAVs, they can be a considered a cheap alternative to larger systems that nevertheless provides a basic level of aircraft capabilities.

A rapid increase in popularity, availability, variety and capability of commercial off-the-shelf (COTS) small UAVs over the past decade has led to an increase in usage of these systems by non-state actors and armed groups. Usually much less sophisticated than their military counterparts, improvised armed UAVs have been built and used by non-state actors using commercial and hobby multicopters as well as home-built fixed-wing UAVs. Because non-state actors are not the drivers of technology development, their activities are mentioned only in this introduction. Activities by non-state actors using small (here: mass $< 25\,\mathrm{kg}$) COTS UAVs are covered in (Friese et al., 2016). The authors conclude that historically, the use of UAVs by non-state actors has been sporadic and rudimentary. However, recent jumps in capabilities and availability of small COTS UAVs, including smaller size and easier piloting, are leading to an increased use of these systems by non-state actors. Non-state actors which have used COTS small UAVs include, among others, Syrian militants, e.g. attacking Russian air and naval bases in Syria (MacFarquhar, 2018; Binnie, 2018), the so-called Islamic State using them as scouts or for attacks with explosive charges (Hambling, 2016), and non-state actors in the Ukraine (Friese et al., 2016). Criminals have used small commercial UAVs to illicitly transport narcotics between Mexico and the USA (Friese et al., 2016), as well

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[1] Mainly by (Altmann, 2001; Altmann, 2006): prohibition of missiles and 'mobile micro-robots' below 0.2-0.5 m size.

as weaponised modified versions for gang wars (Hambling, 2020b).

In military small armed UAs a next step could be equipping them with missiles. Traditional missiles such as the AGM-114 *Hellfire* (length: 163–175 cm, mass: 45-48 kg (FAS, 2012)) are far too large and heavy for smaller UAVs. However, smaller missiles have been developed, too, one intent being the wish to arm smaller UAVs. Small and very small missiles will be covered in the next report.

To assess the potential effects to be expected from small and very small armed aircraft and missiles, including dangers to military stability and international security, as well as options for preventive arms control, the first precondition is reliable information about already existing systems and current trends in research and development.

Based on databases, scientific and internet publications, this report lists small armed UAVs deployed and used worldwide, as well as systems under research and development, with their properties. Non-armed systems are included to investigate the global usage of small UAVs and thus overall interest in smaller systems. This comprises non-armed systems which could be provided with or used as weapons.

In order to minimise a contribution to proliferation of these systems, only public sources were investigated, i.e. the internet as well as publicly available databases and catalogues. Furthermore, where information is incomplete, no estimates based on the laws of physics or stemming from engineering expertise are given. Improvised or modified versions of UAVs or missiles, already in use by non-state actors, are left out for the same reason.

The results of our research are collected in two databases, one each for the UAVs and the missiles; here the one for the UAVs is covered. As far as has been available, their basic properties with the year of introduction are listed to allow statements on trends of UAV capabilities in recent years. Due to the sheer number of UAV types available today, we focused mainly on UAVs intended to fulfil military roles, such as reconnaissance or combat. An exception are UAVs that fall under the very small category. There, most UAVs are still in the research or development stages and not in military service nor designed for military use. However, research and development (R&D) of some systems had been funded originally by military institutions (sections 5.1 and 5.11). In any case, these projects are important indicators of the future potential of these small-sized aircraft.

Similar work has been done by the Center for the Study of the Drone at Bard College in the USA. In 2019, it released the Drone Databook (Gettinger, 2019) (with an update in March 2020 (Gettinger, 2020)), evaluating the military drone capabilities of over 100 countries known to possess or operate uninhabited aircraft. It includes lists of military UAV infrastructures and technical specifications of over 170 UAVs of all sizes.

Technical specifications of so-called loitering munitions, a special variant of UAVs equipped with a warhead and the ability to loiter in the air for an extended amount of time before attacking with self-destruction, were collected in (Gettinger & Michel, 2017).

An overview of countries that have conducted UAV attacks, that possess and develop armed UAVs, including non-state-actor activities, is given in the World of Drones database (World of Drones, 2020).

In 2014, Cai et al. published a survey of ‘small-scale’ UAVs with a total of 132 civilian and military models (Cai et al., 2014). The UAVs collected vary in size from less than ten metres down to centimetres. UAV properties are given only for a few examples and far less detailed than in our database. The development of key UAV elements, such as on-board processing units, sensors, communication modules etc. is presented and analysed as well. Among the predictions for the near-term future (2-5 years) are an increased popularity in flapping-wing UAVs in research, as well as an increasing demand of small-scale UAVs for military applications.

In 2015, Ward et al. presented a bibliometric review of engineering and biology articles published between 1984 and 2014 on so-called biomimetic air vehicles (BAVs), flapping-wing UAVs that mimic the kinematics of flying organisms (Ward, Rezadad et al., 2015). The general focus of articles is aerodynamics, guidance and control, mechanisms, structures and materials, and system design, with a rapid increase in publications since 2005. Most research was done in the United States, South Korea, Japan, the United Kingdom and China. The authors expect an increase in numbers and variety of bio-mimicry species as technological challenges are overcome.

This article was followed by Ward et al. in 2017 with a bibilometric review on micro air vehicles (MAVs) between the years 1998 and 2015 (Ward, Fearday et al., 2017). The majority of research articles were written in the USA, China, UK, France and South Korea. The authors conclude that biomimetic MAVs are most popular, rivalled by a growing popularity of rotary-wing MAVs.

The focus of the present report is on small and very small UAVs. Before we present the results of the data collection, we need to establish a technical background and factual information. Chapter 2 lays a terminology basis and chapter 3 presents basic aspects of aerodynamics. Chapter 4 gives a technical overview, with subchapters on airframe configurations, materials and manufacturing, power and propulsion, guidance, launch and recovery and payloads.[1] Research and development in the USA are the subject of chapter 5. Swarms and countermeasures are treated in Chapters chapter 6 and chapter 7, respectively. Chapter 8 presents summary properties of the database which itself is presented in the appendix A and at an internet location.[2]

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[1] Since many aspects of communication to and from UAVs apply in general and are not specific to small UAVs, they are not discussed here; they are covered in (Gundlach, 2012, ch. 12). MAV communication is treated in (Michelson, 2015).

[2] `https://url.tu-dortmund.de/pacsam` for the project description and `https://url.tu-dortmund.de/pacsam-db` for a description of the databases. The small and very small aircraft database is available at `https://url.tu-dortmund.de/pacsam-db-sa`.

2 Definitions and Classifications

2.1 Uninhabited Aircraft

There exist many different definitions of a UA given by institutions, policymakers or by individual scientists in research articles. We use the term UA and UAV synonymously for an uninhabited aircraft, following the definitions of the International Civil Aviation Organization (ICAO) (definitions 2.1.1 and 2.1.2). However, instead of the ICAO's use of the term 'unmanned' we prefer the gender-neutral and more precise 'uninhabited' since uninhabited aircraft that are remotely piloted can still be considered 'manned'.

Definition 2.1.1: Aircraft

Any machine that can derive support in the atmosphere from the reactions of the air other than the reactions of the air against the earth's surface (ICAO, 2010, p. I-1). Consequently cruise and other guided or unguided missiles count as (uninhabited) aircraft, except ballistic missiles not using aerodynamic lift when travelling in the atmosphere.

Definition 2.1.2: Uninhabited Aircraft

Aircraft intended to be flown without a pilot on board (ICAO, 2020).

The UA itself is part of an uninhabited aerial system (UAS), which in addition to the aircraft includes all key elements required for a UA mission. These additional elements are the payload, the communication data link, the launch and recovery element, the human element and a command and control structure.

Definition 2.1.1 includes so-called 'loitering munitions', which can be considered as both a UA and a guided missile. Their purpose is to attack a target in the same manner as a missile, e.g. with an explosive warhead. However, in contrast to a missile, a loitering munition can spend an extended amount of time in the target zone and fly a search pattern before attacking. Therefore, as long as the loitering munition is in flight, the attack can still be called off, with the aircraft either returning back to base or self-destructing in a chosen area, a capability that does not exist with most missiles.

Definition 2.1.3: Loitering Munition

An uninhabited aircraft with its main purpose to attack targets with a fixed built-in warhead (usually explosive) that leads to self-destruction of the aircraft. In contrast to missiles, it has the ability to loiter above a designated area before striking its target.

Loitering munitions can appear in the same configurations as other UAs, i.e. as rotary-wing, fixed-wing or any other aircraft type. A rotary-wing example is the IAI

ROTEM, the WB Group *Warmate* uses fixed wings (figures 2.1 and 2.2).

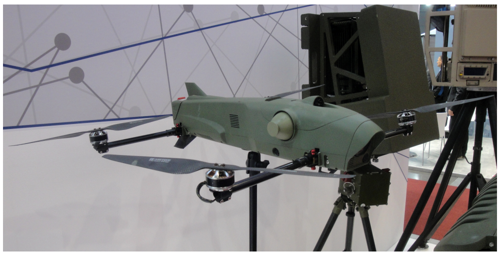

Figure 2.1: IAI *ROTEM*, exact size unknown (public domain) (Reise Reise, 2019).

Figure 2.2: WB Group *Warmate*, Poland (public domain) (VoidWanderer, 2016). Wingspan: 1.4 m (WB Group, 2019).

2.2 Small and Very Small (Uninhabited) Aircraft

There is no single standard of UA classification. Manufacturers, defence agencies and civilian organizations all use their own terminologies and classification systems. Uninhabited aircraft can be classified e.g. by size, mass, maximum flight altitude and range. A combination of these can be used to define a tier system. Even among researchers, no consensus exists, thus all terms describing the size or mass of an UA are always understood in the context of a pre-defined classification system. Comprehensive overviews of various UA classifications are given in (Hassanalian & Abdelkefi, 2017; Dalamagkidis, 2015).

Our classification system is based only on the size of the aircraft. The size is defined by the length, wingspan or rotor diameter of the aircraft. For multicopters this means the diameter over all rotors. We define every aircraft below a size of 2 m as *small*, and below 0.2 m as *very small* (table 2.1). We choose these limits because aircraft of this size and below are typically much more limited in endurance, range, armament and payload mass compared to larger aircraft. Often the notion of MAV is used.

Table 2.1: Definitions of ‘small’ and ‘very small’ sizes of UAs.

	Defining property	‘Small’	‘Very small’
Aircraft	Wingspan, rotor diameter and length	$\leq 2\,\text{m}$ and $> 0.2\,\text{m}$	$\leq 0.2\,\text{m}$

3 Aerodynamics

Conditions of flight change as aircraft size decreases. For some understanding, this chapter gives an elementary introduction into aerodynamics (for an in-depth introduction, see (Anderson, 1999) and (McCormick, 1979)). Non-technical readers may skip it.

If some body moves through air – or, equivalently, if air flows in the opposite direction toward and around the body – the body experiences a force. In case of level flight at constant velocity (figure 3.1), the lift force L points vertically upward and is equal and opposite to the weight force W of the aircraft. The drag force D points backward; in order to prevent its slowing down the movement, an equal and opposite thrust force T is needed that points in the forward direction – it is provided e.g. by a propeller or a jet engine. If lift and weight do not balance, the aircraft climbs or descends. If thrust is not equal to drag, the aircraft accelerates or decelerates.

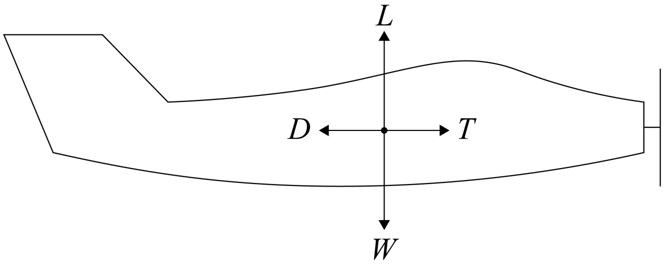

Figure 3.1: Balance of forces for level flight at constant velocity: The lift force L has to compensate the weight force W, the thrust force T has to compensate the drag force D.

If the force is referred to an axis of rotation, a moment exists around that axis (figure 3.2).

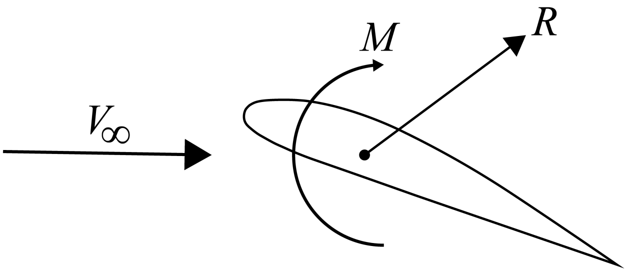

Figure 3.2: Resultant aerodynamic force R and moment M on the body. V_∞ is the freestream velocity.

For flight the most relevant body is the wing. The resultant force on the wing R is the sum of the partial forces exerted on all parts of the total wing surface, and similarly for the total moment M. Due to the wing form and the angle between the air flow and the wing, usually overpressure develops at the bottom side of the wing and underpressure at the upper side. Thus the force R contains a component orthogonal to the velocity through the air, the lift L. The air flow against the wing induces friction that exerts a force opposite to the air flow, the drag D. The free-stream velocity V_∞ holds at large distance from the wing (close to the wing, the velocity varies in magnitude and direction). Figure 3.3 shows the splitting of the resultant force R into the lift L perpendicular to V_∞ and the drag D parallel to V_∞. L and D depend on the angle of attack α between the chord c, that is the line connecting the extreme points of the wing profile, and V_∞.

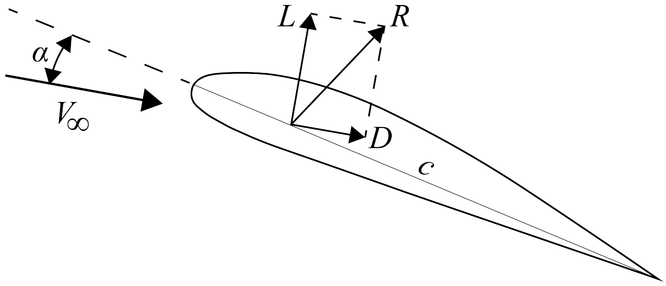

Figure 3.3: Resulting aerodynamic force R split into its components L perpendicular to the freestream velocity V_∞ and D parallel to it. The angle of attack α is measured between the freestream velocity and the chord c of the wing.

Both forces scale linearly with the area S of the wing projection and the so-called dynamic pressure q_∞ which is one half of the air density ρ_∞ times the free-stream velocity V_∞ squared. The dimensionless proportionality constants are the lift coefficient C_L and the drag coefficient C_D, respectively. Thus

$$L = q_\infty S C_\mathrm{L}, \tag{3.1}$$

$$D = q_\infty S C_\mathrm{D}, \tag{3.2}$$

with the dynamic pressure q_∞:

$$q_\infty = \frac{1}{2}\rho_\infty V_\infty^2, \tag{3.3}$$

and ρ_∞ is the density of the freestream far ahead of the body. S is the reference wing area defined as the planform area of the main wing including the area of the wing extended through the fuselage (figure 3.4).

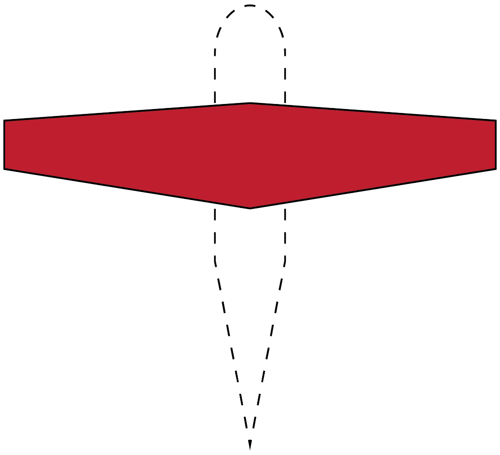

Figure 3.4: Aircraft fuselage (dashed line) and reference wing area S in red.

The coefficients C_L and C_D are functions of the angle of attack α, the freestream velocity (figures 3.5a and 3.5b) and the Reynolds number. C_L at first increases with angle of attack α, but beyond a critical angle the flow separates from the upper wing surface, severely reducing the underpressure there and thus the lift – the aircraft stalls. C_D increases with the angle of attack. The lift and drag characteristics are highly dependent on the shape of the airfoil, the Mach number and the Reynolds number.

For very high velocities the lift and drag coefficients are no longer constant, but are functions of the Mach number M, that is defined as the ratio of the body's velocity to the speed of sound a:

$$M = \frac{V_\infty}{a}. \tag{3.4}$$

The other extreme is more relevant in the present context. For very low velocity and/or small wings, lift and drag are functions of the Reynolds number Re. This number is given by

$$Re = \frac{\rho_\infty V_\infty c}{\mu}, \tag{3.5}$$

where c is the length of the wing chord (figure 3.3) and μ is the dynamic viscosity of the air, causing friction when moving past the wing.

The Reynolds number is a key parameter that represents the influence of inertial versus viscous forces. Due to their size, very small UAs operate in a Reynolds number regime much lower than habited aircraft. We give an example and calculate the Reynolds number of a typical passenger jet, assuming a mean aerodynamic chord of 4.0 m, a flight altitude of 9000 m and a cruise speed of 250 m/s. At an altitude of 9000 m, and assuming an air temperature of $-45\,^{\circ}\mathrm{C}$, the air density ρ and the viscosity μ are:[1]

$$\rho = 0.469\,\mathrm{kg/m^3}, \quad \mu = 1.497 \times 10^{-5}\,\mathrm{Pa\,s}. \tag{3.6}$$

Inserting all values into equation (3.5) yields:

$$Re \approx 3.1 \times 10^7. \tag{3.7}$$

In contrast, a much smaller aircraft with a chord length of 5.5 cm flying at the same altitude with a flight velocity of 30 m/s yields

$$Re_{\mathrm{small}} \approx 5.2 \times 10^4, \tag{3.8}$$

which is three orders of magnitude below the previous results. However, small UAs typically fly only several hundred metres above ground level (AGL). Assuming flight at ground level and a temperature of 23 °C, the air density and viscosity values increase to

$$\rho_{\mathrm{GL}} = 1.192\,\mathrm{kg/m^3}, \quad \mu_{\mathrm{GL}} = 1.852 \times 10^{-5}\,\mathrm{Pa\,s}, \tag{3.9}$$

and the Reynolds number decreases to

$$Re_{\mathrm{small,GL}} \approx 4.2 \times 10^4. \tag{3.10}$$

Figures 3.5a and 3.5b show the lift and drag coefficients c_ℓ and c_d versus the angle of attack α for Reynolds numbers 3×10^7 and 5×10^4 for a NACA 2411 airfoil (figure 3.6). The lower case notation of the coefficients indicates that calculations are valid only for a purely two-dimensional shape (of theoretically infinite span) such as an airfoil.

Figure 3.5c shows the ratio c_ℓ/c_d; in general, a decrease of the Reynolds number leads to a substantial reduction in the lift to drag ratio L/D. Note however, that airfoils are designed to operate in certain Reynolds number regimes, and that the NACA 2411 airfoil is not optimized to operate in low-Reynolds-number regimes. The lift-to-drag ratio L/D is used as a measure of aerodynamic efficiency and creating lift efficiently means generating as little drag as possible (Anderson, 1999, p. 105).

From figure 3.5c, we see that the maximum ratios are 164 at $Re = 3 \times 10^7$ and 34 at $Re = 5 \times 10^4$. However, these values only hold for wings with infinite span. Finite wings suffer from additional drag due to strong vortices produced at the wing tips. Furthermore, a complete aircraft shows more drag components, they stem from the fuselage and the tail, plus other parts in the air stream. As a consequence, the maximum lift-to-drag ratio is 13-16 for (normal-size) propeller aircraft, 17-20 for jet airliners (Loftin, 1985, chs. 6, 13). Typically the ratio decreases with size, very small UAVs may have ratios in the range of small birds and insects, i.e. below 10 (Mueller, 1999), e.g. 6 for the *Black Widow* (wingspan: 15.2 cm) (Grasmeyer & Keennon, 2001, table 5, p. 524).

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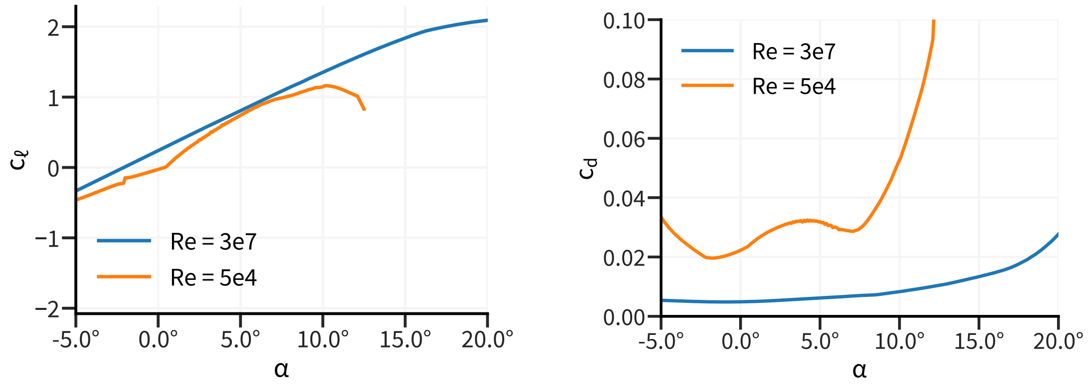
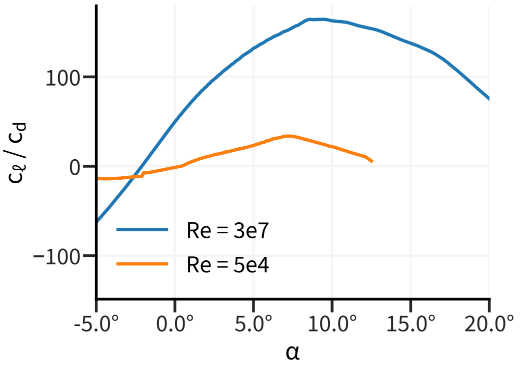
[1] ρ and μ were calculated using the AeroToolbox Standard Atmosphere Calculator (AeroToolbox, 2020).

Furthermore, small flyers are highly susceptible to environmental effects due to their low mass and slower flight speed. These challenges are typically overcome by using flapping wings and wing-tail coordination (Shyy et al., 2013, p. 40). Also, airfoil profiles that optimize aerodynamic behaviour for a specific Reynolds number regime are used.



(a) Typical dependence of lift coefficient c_ℓ with angle of attack α. C_ℓ decreases beyond a critical angle.

(b) Typical dependence of drag coefficient c_d with angle of attack α.



(c) Ratio c_ℓ/c_d, or ratio of lift L over drag D, versus angle of attack α.

Figure 3.5: Two-dimensional lift and drag coefficients dependent on the angle of attack α of a NACA 2411 airfoil (shown in figure 3.6) calculated with XFOIL 6.99 (Drela, 2013) at $M = 0$ for Reynolds numbers of $Re = 3 \times 10^7$ and 5×10^4.

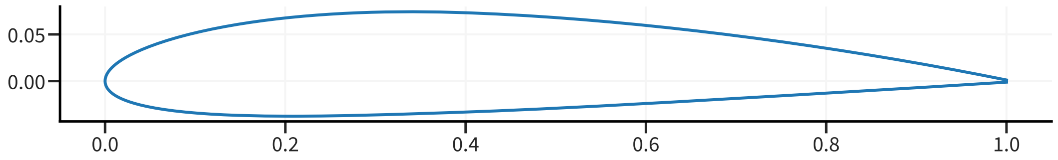


Figure 3.6: NACA 2411 airfoil generated with XFOIL 6.99 (Drela, 2013). The lengths are normalized relative to the chord.

Aircraft with fixed/variable-geometry wings have to move with a certain velocity to stay airborne. Their direction of movement usually is controlled by control flaps (small additional wings) that by aerodynamic forces create a moment around the vertical axis (rudder) or a horizontal axis in wing direction (elevator). The velocity, climbing or descent can be controlled by varying the engine thrust.

In rotary-wing aircraft, the above considerations about lift and drag apply to each individual blade of the rotor(s). Because the velocity through the air increases along the blade, the blade is twisted to keep the lift distribution approximately constant. The blade pitch can be varied during one rotation; in case of one main rotor, if the blade pitch is increased when the blades are in the backward half circle, the craft is tilted up at the back and some component of the total rotor force points forward, creating forward thrust. In order to compensate for the torque, often a small tail rotor is used. Since multiple rotors can counter-rotate, no special counter-torque mechanism is needed. Tilting the craft in some direction for thrust does not need varying the blade pitch during rotation, but can be achieved by varying the rotation rates among the rotors.

4 Technical Overview

4.1 Airframe Configurations

In general aircraft are divided into three categories (Austin, 2010, ch. 3.5):

1. horizontal take-off and landing (HTOL),
2. vertical take-off and landing (VTOL),
3. HTOL / VTOL hybrids.

The acronym HTOL designates aircraft which require a horizontal acceleration to achieve flight speed. HTOL aircraft are typically in fixed-wing configuration, while VTOL aircraft use rotary or flapping wings. The range of airframe configurations for UAs is the same as for crewed aircraft. Most common for small UAVs are fixed- and rotary-wing configurations. Very small UAVs typically use flapping wings.

4.1.1 Fixed-wing Configurations

The three fundamental types of fixed-wing aircraft are the 'tailplane aft', the 'tailplane forward' and the 'tailless' configuration. Almost all UAs in our database use a pusher-propeller configuration with the power-plant at the rear of the fuselage. This allows payload placement in front of the aircraft and an unobstructed forward view. Payload placement in front of the engine also prevents contamination of the payload with leaked fluids from the forward engine exhaust (Gundlach, 2012, p. 134). A typical example is shown in figure 4.1.

From an aerodynamic viewpoint, if a propeller is used, the induced air velocity of the rear-mounted propeller does not increase the friction drag of the fuselage as much as the slipstream would from a front-mounted tractor propeller (Austin, 2010, p. 34). However, tractor propellers have clean airflow to the propeller, which leads to higher propeller efficiency (Gundlach, 2012, p. 134). Gundlach adds that tractors can also be quieter because there is no wake impingement upon the propeller and that tractors allow a large tail moment arm due to the forward engine location.

Flying-wing (including delta-wing) aircraft are tailless and suffer from a reduced effective tail arm in both pitch and yaw axes,[1] although the rearward sweep of the wing adds to directional stability (Austin, 2010, p. 36). An argument in favour of the flying-wing configuration is that the removal of the horizontal stabiliser avoids the additional profile drag due to that surface. However, the poorer lift distribution of the flying wing can result in negative lift at the tip sections and result in high induced drag (Austin, 2010, p. 36). An example of a flying-wing UAV is the Spaitech *Sparrow* shown in figure 4.2.

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[1] An aircraft in flight can rotate around three axes with their origins at the centre of gravity. The pitch axis is parallel to the wings of a winged aircraft, the roll axis is drawn through the aircraft's body from tail to nose in forward direction, and the yaw axis is directed towards the bottom of the aircraft, perpendicular to the other two axes.

Figure 4.1: Conventional fixed-wing configuration: IAI *GreenDragon* ((C) IAI, reprinted by permission) (IAI, 2019a). Wingspan: 1.7 m (IAI, 2019b).

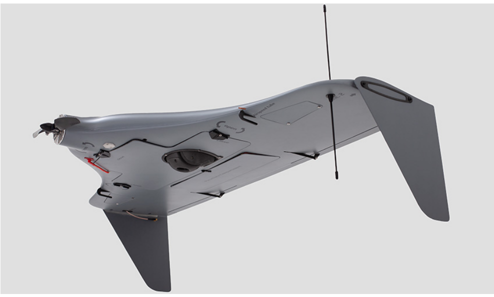


Figure 4.2: Flying wing with tractor propeller: Spaitech *Sparrow*. Wingspan: 0.98 m ((C) Spaitech, reprinted by permission) (Spaitech, 2019).

Another typical form is the tandem-wing configuration. It uses two wings of similar areas with one at the front and one in the back of the aircraft. The advantage is that in case of wing folding along the fuselage, for the same total wing area the stowage space is reduced. The maximum wingspan is then twice the fuselage length. However, the forward wing produces a downwash field on the rear wing, leading to a higher induced drag, so that tandem-wing configurations usually have lower aerodynamic efficiency than conventional configurations (Gundlach, 2012, p. 118). Tandem-wing UAVs can easily be deployed from the stowed state, typically from tube launchers, and unfold their wings after launch (figure 4.11). An example is the Raytheon *Coyote* shown in figure 4.3.

Figure 4.3: Tandem-wing configuration: Raytheon *Coyote* (public domain, cropped) (NOAA, 2016). Wingspan: 1.47 m (Streetly & Bernadi, 2018).

Figure 4.4: Custom wing configuration: UVision *HERO-30* (public domain, cropped) (Swadim, 2019). Exact size unknown.

An alternative to increase the wing area while still allowing a folding mechanism is to use four primary and four secondary wings as shown on the UVision *Hero-30* (figure 4.4). This design allows a shorter fuselage length compared to a tandem-wing configuration while maintaining a large wing area.

Advantages of HTOL UAs are typically a higher endurance compared to rotary-wing aircraft, while they lack the manoeuvrability and VTOL ability of rotorcraft. A major disadvantage is the reliance on an extended space to launch and land and the necessity for constant forward movement to stay airborne.

4.1.2 Rotary-wing Configurations

Rotary-wing aircraft or rotorcraft use one or more main rotors to generate lift (figure 4.5). Designs using multiple rotors are called multi-rotors, or e.g. tri- or quadrotors (-copters) indicating the number of rotors used. In case of multiple rotors, their blades are fixed in pitch and horizontal thrust is generated by changing the speed of rotation of each rotor, tilting the craft in the intended direction. An example of a quadrotor is the Bitcraze *Crazyflie* (figure 4.6).

Their main advantage over fixed-wing aircraft is their VTOL capability, allowing them to access spaces unavailable to fixed-wing aircraft. Moreover their ability to hover allows them to remain stationary which simplifies surveillance, even allowing them to land during a mission to save fuel or battery capacity. Compared to fixed-wing aircraft, no additional equipment such as airbags or a parachute is required for recovery. However, rotary-wing aircraft usually have a lower endurance (Gundlach, 2012, pp. 47–50), a lower cruise speed and thus longer response time, and achieve lower altitudes (Austin, 2010, p. 181), which makes them more suitable for short ranges.

Figure 4.5: Helicopter configuration: AeroVironment *VAPOR35*. Rotor diameter: 1.7 m ((C) AeroVironment, reprinted by permission) (AeroVironment, 2019).

Figure 4.6: Quadrotor Bitcraze *Crazyflie 2.1*. Width (motor-to-motor and including motor mount feet): 9.2 cm ((C) Bitcraze, reprinted by permission) (Bitcraze, 2020).

4.1.3 Hybrid Configurations

Hybrid configurations intend to combine the capabilities of both HTOL and VTOL aircraft. In the tilt-rotor configuration, rotors are mounted onto the front tip of the main wing and can be rotated forward by 90° to act as propellers for cruise flight (figure 4.7). An special combination of a tri- and tiltrotor is the Skyborne Technologies *Cerberus* with one rotor at its tail and two main lift fans at the front that can tilt forward (Skyborne Technologies, 2019).

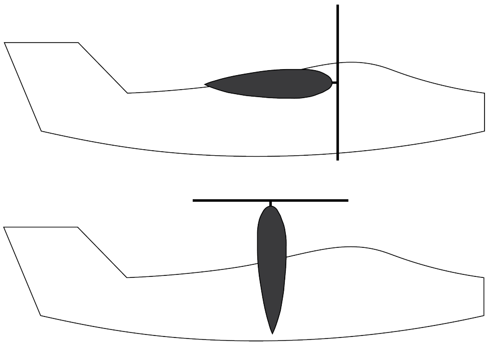


Figure 4.7: Tilt-rotor configuration during cruise and hover flight.

4.1.4 Flapping Wings

Flapping-wing aerial vehicles use their wings to generate thrust in addition to lift. Flapping wings can significantly increase the manoeuvrability of an aircraft. A combination of flapping motion, wing deformation, body contour and tail adjustment allows a precise trajectory control at high speeds (Shyy et al., 2013, p. 7). Flapping wings are used almost always by UAVs of very small sizes.

Current very small flapping-wing UAVs face the challenge of relatively high design complexity, low endurance and low payload mass.

Figure 4.8: *DelFly Nimble*. Wingspan: 33 cm (public domain) (MAVLab TU Delft, 2018; de Croon et al., 2016).

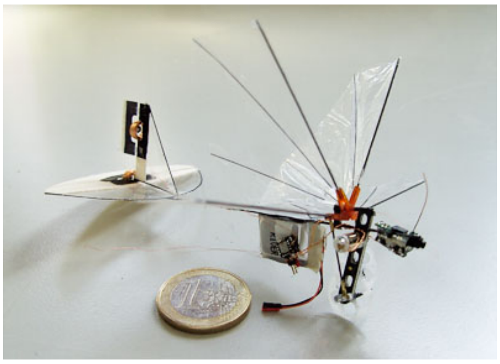


Figure 4.9: *DelFly Micro*. Wingspan: 10 cm (public domain) (de Wagter, 2008; de Croon et al., 2016).

We divide flapping-wing UAVs into the tailless and 'with tail' categories, since the former are less conventional as the tail is typically used as an important control structure. Tailless flapping-wing UAVs have to use the same wings for lift generation as well as control. An example of a tailless design is the *DelFly Nimble* (mass: 29 g) (figure 4.8) as well as the *Nano Hummingbird* (figure 5.1) (mass: 19.0 g). A design with tail is the *DelFly Micro* (mass: 3.07 g) (figure 4.9).

4.1.5 Tethering

Tethered UAVs are VTOL aircraft connected to a power-supply ground unit. Their radius of action is limited for a stationary ground unit, but is much larger if the power supply is transported on a ground vehicle. For example, the *HoverMast 100* can reach an altitude of 100 m (SCR, 2019) and operate along a moving pick-up truck (figure 4.13 below). As long as a steady power supply is ensured, tethered configurations offer basically limitless flight time until maintenance is required. Since the on-board battery can be much smaller and lighter compared to non-tethered rotary-wing aircraft, the remaining aircraft components can be much heavier, increasing overall aircraft performance. Tethered UAVs are typically used for surveillance missions such as border control or for guarding infrastructure.

However, a UA might simply be tethered because it would not fly or achieve a certain flight performance with the increased weight of an on-board power supply unit. An example is the research system *RoboBee*, which would otherwise not achieve flight due to its extremely small size (mass: 80 mg) (Ma et al., 2013).

4.2 Materials and Manufacturing

Small UAs developed by professional institutions tend to use modern materials and manufacturing methods (Gundlach, 2012, sec. 7.3). Various types of plastics, foam and sandwich structures are used, metal only for special parts. Composite materials provide high strength at low weight; the load is borne by fibres, sometimes woven, often with plies of unidirectional fibre sheets in different directions. Fibres of graphite (carbon) provide higher strength than fibres of glass or aramid. They are supported and bonded together by a matrix material, sometimes thermoplastic, often a resin such as epoxy that polymerises. With two components this happens at normal temperature; for higher requirements a thermoset resin is used that has to be cured at high temperature. Consolidation and better fit to a mould can be supported by pressure, often from the air by a vacuum under an airtight film. Wings and fuselages can be made with integrated ribs and from fewer pieces, requiring fewer fasteners. Tapered wings and rounded shapes can be made easily.

Additive manufacturing (often called 3-D printing) provides much more flexibility, moulds are not needed and complex forms, e.g. with inner cavities, can be produced. Several methods and materials can be used to print parts or complete structures (Goh et al., 2017). Beside wings and fuselages mechanical parts have been made, e.g. in gears.

In very lightweight UAs, special work has been done to produce the flapping wings, often emulating insect wings. Various methods have been described how stiffeners, membranes and links can be made and bonded, e.g. by laser cutting (Liu et al., 2017) or microsystems technology (also called microelectromechanical systems (MEMS) technology) (Bao et al., 2011); carbon nanotubes have been added for strength (Kumar et al., 2019). For driving, beside electrical motors with transmissions, 'artificial muscles' are made from piezoelectric materials, dielectric or electrostatic elastomers (Chen & Zhang, 2019).

A special concept can make manufacture easier and allow series production, potentially at low cost: producing structures in two dimensions and then folding them up, creating a three-dimensional object, as in Japanese paper folding (origami) (Sreetharan et al., 2012; Dufour et al., 2018). Laser cutting, lamination and microsystems technology have been used; the latter can produce integrated electronic circuits in the same process. Rigid and flexible materials have been combined for movable elements. Actuation for moving elements out of the plane can use shape-memory materials, flapping wings can be driven by piezoelectric or dielectric elastomers. Used for mass production such methods may enable swarms of immense numbers of disposable MAVs.

4.3 Power and Propulsion

The vast majority (89 %) of the 129 UAVs in our database uses electric power, mostly from batteries; for one type a fuel cell is stated, the few tethered ones receive external power. For one very small (80 mg) tethered, flapping-wing UAV, *RoboBee*, an upgraded version has been equipped with solar cells (*RoboBee X-Wing*, 259 mg, that can fly as long as it is under intense light.

The advantage of using electric motors is their low acoustic signature compared to combustion and jet engines. In addition, depleted batteries may be replaced with fully charged ones in a few seconds, so-called 'hotswapping'. Furthermore, the UAV mass stays constant throughout the flight, unlike with engines that use fuel, simplifying centre-of-gravity considerations in the initial UAV design phase. The disadvantage of using batteries is their lower energy density compared to fuel, leading to a shorter flight time.

Nine UAVs use combustion engines, and two can use either electric or combustion power. The eleven types with (optional) combustion have maximum take-off masses of 2.5 to 13 kg, with the exception of the rotary-wing *Comandor* with 110 kg that is an outlier in many respects.

There is one type with turbojet propulsion (*Futura*) with 70 kg mass, also an outlier.

Propulsion is by propeller for all others of the 65 fixed-wing UAVs, for two thirds in the pusher arrangement (propeller in the back). Two types use tilt-rotors. The rotary-wing UAVs have one main rotor or several rotors.

Flapping wings, with or without tail, are used with very lightweight UAVs only; the masses of the twelve types lie between 80 mg and 29 g.

4.4 Guidance and Navigation

4.4.1 Navigation and Autopilots

Most small UASs use a global navigation satellite system (GNSS) to determine the aircraft's position and to navigate between waypoints. A GNSS consists of a collection of satellites orbiting the Earth at an altitude of approximately 20 000 km (Austin, 2010, ch. 11.1). Each satellite transmits radio signals that contain the start time of the signal and travel at the speed of light. A receiver can then calculate the range to the satellite by using the arrival time. Determining the exact position in three dimensions, however, requires signals from four or more satellites. The result is a sequence of discrete aircraft positions. GNSS signals can be jammed by emitting a radio-frequency signal strong enough so that the satellite's signals are outweighed. To avoid the loss of the aircraft, usually an additional, so-called dead-reckoning system, is used. It uses the aircraft's position at the start of the mission and time, speed and direction measurements to calculate the current position. These calculations can be combined with the data provided by the GNSS to receive a smoothing between calculated positions and to continue navigation in case of a GNSS signal loss. Current GNSSs in use are the US-owned global positioning system (GPS), the Russian global navigation satellite system (GLONASS), the European Galileo and the Chinese BeiDou navigation satellite system (BDS).

In addition to jamming, GNSS signals can be spoofed, i.e. the satellite's transmissions are mimicked and false location information is fed to the receiver. This can be used to either completely deny the use of GNSS by feeding obviously wrong information or by slowly directing the aircraft away from the original route. For these reasons, navigational systems independent of external inputs, such as an inertial measurement unit (IMU), may be used. An IMU functions independently of external signals. Using inertial forces, accelerometers measure the change of the velocity in three dimensions. To refer these measurement to fixed coordinate directions the rotations of the system are measured e.g. by gyroscopes. With knowledge of the starting velocity, the acceleration is integrated over time to yield the changed velocity. With the given start location, integrating the velocity gives the changed location. IMUs have the disadvantage that their estimates drift over time. For high-grade accelerometers and gyroscopes the drift can be low, but for miniaturized systems used by small UAVs which tend to use MEMS devices that have very high drift and can provide nonsense estimates in seconds or minutes (Gundlach, 2012, p. 392).

An IMU and GNSS system can be combined to an inertial navigation system (INS), where the IMU provides state estimates at a high rate, while the GNSS provides discrete positions at a lower rate, allowing for correction of the IMU drift.

Inertial measurement systems are sometimes complemented with magnetic-field sensors for orientation in the earth magnetic field and barometric sensors for altitude. Autopilots – systems for controlling the trajectory of aircraft, often including waypoint-navigation – can integrate such systems. Miniaturization in particular of microelectromechanical sensors has been advanced greatly by their introduction in every-day electronics such as smart phones. One exemplary device with three-axis accelerometer, three-axis gyroscope and three-axis magnetometer measures $3 \times 3 \times 3$ mm^3 with a mass of 0.14 g (TDK, 2021). University researchers have built autopilots of extremely small size and extremely light weight. One example including telemetry and remote control had 2.8 g mass on a 2×2 cm^2 board (Remes et al., 2014), another had 1.3 g including communication (Runco et al., 2019).

A different method of navigation uses optical flow, that is the apparent motion of (parts of) a camera image as the camera moves and/or changes its view angles. This motion can be derived from the time sequence of the pictures, e.g. by identifying landmarks or by image correlation. In order to provide coordinates in an external reference system, additional information is needed, e.g. the UAV attitude and its altitude. In particular for small UAVs, optical flow can be combined with IMUs and an altimeter (e.g. Santamaria-Navarro et al., 2018).

4.4.2 Control Stations

The control station is a human-machine interface allowing communication with the UAV as well as its control. The control station may be based aboard ships or aboard another aircraft (‘mothership’) or based on the ground. Almost all small and very small UAVs in our database use a ground control system (GCS). GCSs typically consist of ruggedized laptops or tablets, displaying the UAV’s attitude, altitude, airspeed and position or video and camera feed from the payloads. Remote controls with joysticks and switches may be included for manual control.

Using the GCS the UAV’s flight path can either be directly controlled, e.g. by using a remote control and video feed, or by using a pre-progammed waypoint system that may also be updated during flight. The UAV may also have on-board programs that allow it to execute tasks without operator control, such as orbiting at a given speed, radius and altitude for loitering (e.g. WB Group, 2019) or returning home automatically (IAI, 2020). These in-built functions lower the number of direct inputs necessary for flight and thus reduce pilot workload.

4.5 Launch and Recovery

Launch methods include hand-launching the vehicle by throwing it forward, launch from a catapult via e.g. a bungee rope, from a pneumatic tube (figure 4.10), multiple tube launchers in quick succession (figure 4.11) or a grenade launcher (figure 4.12b).

Figure 4.10: AeroVironment *Switchblade* (AeroVironment, 2021b) ((C) AeroVironment, reprinted by permission).

Figure 4.11: Raytheon *Coyote* launched from low-cost UAV swarming technology (LOCUST) launcher (public domain, cropped) (Smalley, 2015).

A hand launch can influence the UA configuration to avoid injury of the person throwing the UAV (Gundlach, 2012, p. 442). Tube launchers can be very compact and prepared in a short amount of time. However, they can only be used with UAVs that can unfold their wings and propeller after deployment. The UAVs launched from tubes usually have a pusher propeller at the back of the aircraft, that has a small shield protecting it from the launch and which is lost after launch (figure 4.11).

Launches from aircraft are also possible, allowing a transport of the UAVs close to the mission area, thus increasing their mission range. An example is the *Perdix* UAV deployment from a F/A-18 *Super Hornet* fighter jet (figure 4.14). The *Perdix* UAVs use containers similar in size to flare canisters so that the flare ejection mechanism already available on the aircraft can be used for a UAV launch instead. An aircraft can also be used as a mothership with an aircraft recovery function as in the Defense Advanced Research Projects Agency (DARPA) Gremlins project (figure 4.15). The ability to recover UAVs removes the necessity for ground landings or UAV loss after a completed mission.

Launch from ground vehicles, such as the autonomous Rheinmetall *Mission Master* (Monroy, 2019), is also possible. UAVs can also be tethered to a moving ground vehicle such as the SkySapience *HoverMast* (figure 4.13).

(a) After launch, the rotor arms extract and the UAV acts as a quadcopter.

(b) *Drone-40* inserted into M320 40 mm grenade launcher.

Figure 4.12: DefendTex *Drone-40* rotary-wing UAV with integrated warhead, launched from a hand-held 40 mm grenade launcher (US DoD photos, public domain) (Soldier Systems, 2019).

Figure 4.13: Sky Sapience *HoverMast* tethered to power supply unit transported on a pick-up truck ((C) SkySapience, reprinted by permission) (Sky Sapience, 2020).

The conventional landing with a landing gear with wheels and a (small) airstrip is rare for small and very small fixed-wing aircraft. They usually come without a landing gear due to weight and volume limitations, but also because it is not needed. They are so lightweight that simpler mechanisms can be used, such as a deep-stall or belly landing.

During a deep-stall landing, the aircraft flies at a low altitude and its nose is pulled up to induce a stall, so that the aircraft falls onto the ground.

A skid or belly landing is only applicable to UAV rugged enough to survive the landing or cheap enough as to be considered expendable.

In other cases where these simpler methods are not viable, a parachute or an airbag may be used instead. The airbag acts as an energy absorbing system that reduces the severity of ground impact. Both the parachute and the airbag have the disadvantage of adding to the overall weight and taking additional space inside the aircraft.

Another option is a guided flight into a net, by which the UAV is captured and stopped mid-air. However, the net has to be placed on the ground beforehand, thus limiting the landing location to a specific area.

Figure 4.14: Swarm deployment from three F/A-18 *Super Hornets* in October 2016 (public domain) (TIME, 2018).

Figure 4.15: DARPA Gremlins project (artist's concept, public domain) (DARPA, 2018).

4.6 Payloads

Austin defines payload as the part of an aircraft specifically carried to achieve a mission or to fulfil a certain role. The aircraft should be capable of flight with the payload removed (Austin, 2010, ch. 8, p. 127). The mission requirements determine the optimal configuration of payload and aircraft to perform a specific role.

Payloads can be divided into two basic categories:

1. sensors, cameras, weapons, etc. which remain attached to the aircraft,
2. dispensable loads such as missiles, bombs, fluids, etc.

In the following, we give a brief overview of the sensor and offensive payloads found in the UAV database.

4.6.1 Sensor Payloads

Payloads meant for intelligence, surveillance and reconnaissance (ISR) purposes are mainly cameras with variable viewing direction. They contain both electro-optical (EO) and infrared (IR) sensors.

EO sensors operate in the visible (wavelength 0.4 µm to 0.8 µm) or near-infrared (NIR) band, ranging from 0.7 µm to 1.0 µm (Gundlach, 2012, p. 519). Usually the output is colour video if the camera records in the visible band, or greyscale for increased contrast and for low light (Gundlach, 2012, p. 558). Usually there are zoom capabilities.

IR sensors typically operate in three different wavelength bands: short-wave infrared (SWIR) ranging between 1 µm to 1.7 µm, midwave infrared (MWIR) ranging between 3 µm to 6 µm and long-wave infrared (LWIR) ranging between 6 µm to 14 µm (Gundlach, 2012, p. 520). SWIR sensors have good resolution in low light conditions and do not require cooling, but are not thermal imagers like MWIR and LWIR sensors. Their detection relies on energy reflected by the object. MWIR sensors can detect both reflected and emitted energy, while LWIR sensors primarily detect energy emitted by the object, making them especially useful to detect heat signatures.

EO and IR sensor systems are usually combined to so-called EO/IR balls. These may additionally include laser illuminators, designators and rangefinders (Gundlach, 2012, p. 557). A laser illuminator illuminates a target in the band of the night-vision sensor, which may be seen by the EO/IR ball or external night-vision equipment. Laser designators are used to point towards targets in the wavelength band of the detector, similar to laser pointers but not necessarily in a visible band.

EO payloads are usually mounted in two ways:

1. Forward looking from a mounting in the nose, with the sensors mounted on gimbals with actuators. The range can be upwards and forwards to above the horizon or upwards and rearwards. Capabilities for a pan in azimuth and image stabilisation may be present (Austin, 2010, p. 132).
2. A rotatable turret mounted beneath the aircraft to cover a 360° azimuth field of view, with sensors, elevation and roll gimbals and their actuators (Austin, 2010, p. 132) (e.g. as seen in figures 4.1 and 4.2).

Positioning the EO/IR ball below or in front of the aircraft provides an unobstructed view. Internal payloads, in contrast to external ones such as turrets, reduce aerodynamic drag and thus increase the aircraft's endurance, range and speed. A gimbal allows an independent movement of the payload, the simplest are able to pan and tilt while more advanced gimbals may include inertial stabilisation to mitigate effects of manoeuvring, vibration and air turbulence (Friese et al., 2016).

Further non-standard non-weapon payloads used by small and very small UAs as listed in our database are:

- gas (Streetly & Bernadi, 2018, pp. 59-60) and fire detector (IAI, 2020),
- radiological detector (Streetly & Bernadi, 2018, pp. 124-125), spectrometer (Streetly & Bernadi, 2018, pp. 59-60), dosimeter (Spaitech, 2019),
- communications intelligence (COMINT) equipment (IAI, 2020),
- radar (Sky Sapience, 2019); (Streetly & Bernadi, 2018, pp. 216–217),
- light detection and ranging (LiDAR) (AeroVironment, 2019),
- (radio) relay (Sky Sapience, 2019); (Streetly & Bernadi, 2018, pp. 278-280),
- hyperspectral sensor (AeroVironment, 2019).

4.6.2 Offensive Payloads

Offensive payloads for small UAs include lethal and non-lethal weapons. The UA may function as a either a weapons platform or as a guided weapon itself. A list of lethal weapons and UAV types they are carried by is given in table 4.1 (see also section 8.3).

Most prominent are warheads integrated into the aircraft's fuselage. The UAV then acts similar to a missile or guided munition and is destroyed by the warhead's detonation. These are usually designed to work against specific targets, such as fragmentation or anti-personnel warheads, e.g. the Polish *Warmate* (WB Group, 2019), anti-tank (Israeli *Green Dragon* (IAI, 2019b)) or a high-explosive charge (Australian *Drone-40* (N., 2019)).

Lethal weapons not destroying the aircraft during the attack are a rocket-propelled grenade launcher, a 40 mm grenade launcher or free-falling bombs ejected from the UAV.

Small UAVs armed with missiles or precision-guided munitions do not appear to have been developed yet. The manufacturers of the *Comandor* and *Cerberus* mention the possibility of using missiles (table 4.1, but have not shown or mentioned any existing missile to be used.

Non-lethal weapons used are an (anti-UAV) net launcher (Delft Dynamics BV, 2016), a kinetic anti-UAV tip (Soldier Systems, 2019), as well as smoke grenades (Soldier Systems, 2019) and tear gas released from a canister mounted under the UAV (ISPRA, 2019).

Table 4.1: Offensive payloads and UAV types using them. Some types can use a variety of weapons and are thus listed multiple times. The most prominent armament is an integrated warhead, with a total of 20 UAV types. For references, see the UAV database in appendix A.

Armament	Types
Integrated warhead	Alpagu, Alpagu Block II, CH-901, Coyote, Demon, Drone-40, Futura, Green Dragon, HERO-20, HERO-30, HERO-70, KYB-UAV, Kargu, ROTEM, Spike Firefly, Switchblade, Warmate, Warmate TL, Warmate V, ZALA LANCET-1
Shotgun	Cerberus
40 mm grenade launcher	Cerberus
Rocket-propelled grenade (RPG)	Demon
Bombs	Comandor
Missile	Comandor, Cerberus

5 Research and Development Programmes in the USA

As our database indicates, several countries are active in developing small and very small UAVs; research probably is being done by a smaller number. Future possibilities and possible trends in military technology can be assessed by considering present activities in R&D. Because the USA spends by far the most for military R&D – its expenses cover nearly two thirds of the world total (while its overall military expenditure is about 40 % of the world total) – the USA is the technological leader and sets precedents for other countries, a consequence of its permanent goal of maintaining military-technological superiority (Altmann, 2017; Altmann, 2020). Here we present a cursory overview about US military R&D for small and very small UAVs; this is made easier because the USA is much more transparent about its activities than any other country.

5.1 The DARPA Nano Air Vehicle (NAV)

In 2005 DARPA announced the Nano Air Vehicle (NAV) programme with the objective to develop and demonstrate very small, i.e. < 7.5 cm in any dimension, lightweight (gross take-off mass: < 10 grams, payload: 2 g) air vehicle systems with the potential to perform challenging indoor and outdoor military missions (Hylton et al., 2012; Keennon et al., 2012). The most prominent result is the AeroVironment *Nano Hummingbird* tailless flapping-wing UAV biologically inspired by a hummingbird (figure 5.1).

Figure 5.1: AeroVironment *Nano Hummingbird* prototype with right body panel removed. Total mass: 19.0 g, Flap rate: 30 Hz, wingspan: 16.5 cm, speed: from hover to 6.7 m/s, endurance: 4.0 min (Keennon et al., 2012, p. 4, fig. 11, table 2). Image source: (AeroVironment, 2021a) ((C) AeroVironment, reprinted by permission).

The main technical challenges include low-Reynolds-number aerodynamic performance, navigation in complex, confined environments, radio communication through buildings and extreme constraints on size, weight and power (Hylton et al., 2012, p. 2).

5.2 Lethal Miniature Aerial Missile System (LMAMS)

The Lethal Miniature Aerial Missile System (LMAMS) is an active programme run by the US Army. It seeks to provide a small tactical unit with the capability to engage threat targets beyond current line-of-sight weapons or indirect fire. Required properties include (US Programs Executive Office Missiles and Space, 2020):

- launcher: single man-portable / operable,
- munition: small visual and thermal signature,
- modular warhead: $< 0.315\,\mathrm{kg}$,
- weight of munition and warhead: $2.475\,\mathrm{kg}$,
- endurance: $\geq 15\,\mathrm{min}$,
- range: $\geq 10\,\mathrm{km}$,
- loitering and wave-off capability,
- automatic tracking of targets,
- assembly in two minutes.

The system currently in use by the US Army is the AeroVironment *Switchblade* (AeroVironment, 2020) (figure 4.10).

5.3 Gremlins

Launched in 2016, the DARPA Gremlins programme seeks to develop technologies enabling aircraft to launch volleys of low-cost, reusable UAS which can be launched and recovered by manned aircraft. Dynetics first demonstrated a launch of its *X-61A Gremlins Air Vehicle* (GAV) (wingspan: 3.48 m, mass: 680 kg (Dynetics, 2020c)) in November 2019 (Dynetics, 2020b). In 2020, a second flight test was conducted to demonstrate formation flight with the Lockheed C-130 *Hercules* functioning as mothership (figure 5.2). However, an airborne recovery has not been achieved yet (Dynetics, 2020a), even in a third flight test in the same year (DARPA, 2020a). Although the size of the UA is larger than the 2 m size of our definition of a ‘small’ UA, the principle can be used with small UAs as well.

Figure 5.2: Third flight of the Dynetics *X-61A Gremlins Air Vehicle* launched from a customized Lockheed C-130 *Hercules* (public domain) (DARPA, 2020a).

5.4 Perdix

Perdix is a small (wingspan: 30 cm, mass: 290 g) UA intended for ISR missions, capable of swarm flight (US SCO, 2019). It was first developed in 2012 at MIT (Tao, 2012) and then was upgraded by the Strategic Capabilities Office (SCO), US Department of Defense. *Perdix* was first air-launched from F-16 *Fighting Falcon* flare canisters in 2014. In 2016, three F/A-18 *Super Hornets* launched 103 *Perdix* UAs which then flew in swarm formation (figures 4.14 and 5.3) (US SCO, 2019). The SCO claims that the Perdix are not preprogrammed, synchronized individuals but instead share a distributed brain for decision making. Each UA communicates with each other. *Perdix* is produced via additive manufacturing.

Figure 5.3: SCO *Perdix* with swarm-flight capability (public domain) (Dyndal et al., 2017).

5.5 Low-Cost UAV Swarming Technology (LOCUST)

The LOCUST of the Office of Naval Research (ONR) is launched from a tube canister that sends UAs into the air in rapid succession (figure 4.11) (Smalley, 2015). It was first demonstrated in 2015. In 2016 30 ship-based autonomous swarming UAVs were launched. The UA currently in use is the Raytheon *Coyote* armed with an integrated warhead (figure 4.3).

5.6 Anubis

In 2008 the US Air Force started the research project 'Anubis' to develop a small loitering munition designed to strike high-value individuals. The research phase of the project was completed, but no information on the actual system or status of the project is available (Hambling, 2010; Gettinger & Michel, 2017).

5.7 Cluster UAS Smart Munition for Missile Deployment

In 2016, the US Army announced a programme that seeks to develop a cluster payload that is launched and deployed from a MGM-140 Army Tactical Missile System (ATACMS) surface-to-surface missile or the Guided Multiple Launch Rocket System (GMLRS). The payload should consist of multiple deployable smart quadcopters delivering small explosively formed penetrators (EFPs) to designated targets (SBIR, 2016; Gettinger & Michel, 2017). The missile releases the quadcopter payload during flight. The quadcopters shall be able to identify potential targets, land on them and detonate their EFP charges. Targets include tanks and large-calibre-gun barrels, fuel storage barrels, vehicle roofs and ammunition storage sites.

5.8 Short Range Reconnaissance (SRR)

In 2019, the US Army Program Executive Office (PEO) Aviation announced the Short Range Reconnaissance (SRR) programme (PEO Aviation, 2019). It seeks to develop a small, inexpensive, rucksack-portable VTOL UAV with a focus on open-source tools for reconnaissance missions. The PEO awarded six commercial companies with $11 million to prototype new UAV capabilities (Defence Procurement International, 2020).

5.9 Offensive Swarm-Enabled Tactics (OFFSET)

The DARPA Offensive Swarm-Enabled Tactics (OFFSET) programme seeks to provide small-unit infantry forces with upwards of 250 small UAVs and/or small uninhabited ground systems. Goals include an advanced human-swarm interface that allows direct control of the swarm in real time and a real-time networked virtual environment to support a swarm-tactics game which allows players to determine the best tactical swarm approach (Chung, 2020; DARPA, 2020b).

5.10 Air Launch Effects (ALE)

The US Army's Air Launch Effects (ALE) programme seeks to provide an autonomous or semi-autonomous UAS working together with other UAVs as well as manned aircraft (PEO Aviation, 2020). Its goal is to increase the aircraft's operational reach by using expendable, low-cost systems that are e.g. launched directly from the aircraft. In September 2020, the US Army demonstrated the launch of an Area-I *ALTIUS-600* UAV (wingspan: 2.54 m, mass: 12.3 kg (Area-I, 2020)) from a UH-60 *Black Hawk* helicopter (Roque, 2020) (figure 5.4). In total, six UAVs were launched simultaneously from Black Hawks, ground-rail launchers and a truck. Again, although the *ALTIUS-600* is larger than 2 m the principle can be used with small UAs as well.

Figure 5.4: UH-60 *Black Hawk* launching a Area-I *ALTIUS-600* UAV during flight (public domain) (PEO Aviation, 2020).

5.11 Air Force and Army MAV Programmes

From 2007 to 2012 the Air Force Office of Scientific Research had a programme for a 'Micro-Robotic Fly'. Carried out at Harvard University, a flapping-wing UAV of 3 cm wingspan was built, with power supplied via wires (Callier, 2010; AFOSR, 2013, p. 73). The Harvard work was then continued under the name 'RoboBee' with funding from the National Science Foundation (Ma et al., 2013) (see also section 4.1.5). Much of the Air-Force research had transitioned to the US Army, which had a big programme ‘Micro Autonomous Systems and Technology’ from 2008 to 2017. Here many aspects of small autonomous systems were studied by 19 partners from industry and academia, including wings, navigation, sensors and communications (McNally, 2017; MAST, 2016).

6 UAV Swarms

A UAV swarm is a group of uninhabited aircraft acting together in flight to achieve a common goal, in a military context often attack(s). Through their potentially large numbers, they are intended to overwhelm their targets, while the communication between the individual elements allows highly coordinated, multidirectional and simultaneous attacks. A swarm can be directly controlled by a human as a whole, while its full effectiveness is reached if the swarm is completely autonomous (e.g. Scharre, 2018). Together with a decentralized command structure, a swarm cannot be defeated by destroying e.g. a leader or group of leader units. Furthermore, initiative can be taken by single units, i.e. they can take the 'lead' of the swarm once an opportunity arises and give it away once another member signals a more effective way to attack. Thus, the flat-hierarchy command structure inside the swarm makes each member expendable for the swarm to achieve its goal. Developing algorithms for swarm behaviour and control poses very high requirements, in particular if 'intelligent' reaction to changes is intended.

The limited endurance and range of these small systems are typically overcome by transporting the swarm to the mission area in a larger vehicle. This vehicle can either be an aircraft or a maritime ship, a so-called 'mothership', or a ground vehicle as shown in section 4.5.

A coordinated swarm flight of 20 *Perdix* UAs, already mentioned in section 5.4, was demonstrated in 2015, followed by a swarm of 103 in 2016. Although no information on the payloads used during both exercises is available, the aircraft were most likely unarmed, since *Perdix* has not been advertised or described as an armed system so far. In the same year, Raytheon announced a coordinated flight of 24 of their *Coyote* UAs, which are able to perform strikes using an integrated warhead (figures 4.3 and 4.11).

In 2017, DARPA held a small-UAV swarms competition, in which teams of the US Military, Naval and Air Force Academies competed in a game of Capture the Flag swarm-vs-swarm matches using self-developed swarm tactics (DARPA, 2017). The swarms consisted of a mixture of fixed- and rotary-wing UAVs, with a total of up to 25 UAVs each.

Significant advances in UAV swarming outside the United States have been made in China. In 2016, the Chinese company CETC demonstrated a swarm flight of 67 small fixed-wing UAVs, followed by another demonstration in 2017 with 119 UAVs (Kania, 2017, p. 23).

A tube-launch system similar to LOCUST mentioned in section 5.5 has been demonstrated by CETC in September 2020 (Hambling, 2020a). Their launcher is mounted on a ground vehicle and consists of 48 tubes. Information on the UAVs is not given, but pictures show that they have tandem wings and unfold after launch in the same way as the Raytheon *Coyote* (figure 4.11).

7 UAV Countermeasures

The increasing number of small and inexpensive UAS worldwide has given states as well as non-state actors the capability to perform airborne attacks, which was previously restricted to states with a sophisticated aircraft programme (Michel, 2019). Thus the demand for countermeasures that can detect, disable or destroy uninhabited aircraft has risen as well. Current air-defence systems are designed with inhabited aircraft in mind, with higher speeds and bigger sizes, making them ineffective in detecting, tracking and shooting down small UAVs (Michel, 2019) as well as cost-inefficient (Schlegel, 2018).

Between 2015 and 2019, the number of counter uninhabited aircraft systems (C-UASs) available increased from a dozen to 537 systems (Michel, 2019). A list of detection, tracking and identification methods is given in table 7.1, a list of interdiction methods in table 7.2 and a list of platform types in table 7.3.

Table 7.1: Detection, tracking and identification methods (Michel, 2019, p. 3).

Radar	Detects the presence of small uninhabited aircraft by their radar echo. These systems often employ algorithms to distinguish between drones and other small, low-flying objects, such as birds.
Radio frequency (RF)	Detects, locates, and in some cases identifies nearby drones by scanning for the frequencies on which most drones are known to operate.
EO	Identifies and tracks drones based on their visual signature.
IR	Identifies and tracks drones based on their heat signature.
Acoustic	Detects drones by recognizing the unique sounds produced by their motors.
Combined sensors	Integration of different sensor types in order to provide a more robust detection, tracking, and identification capability.

Table 7.2: Interdiction methods (Michel, 2019, p. 4).

Radio-frequency jamming	Disrupts the radio-frequency link between the drone and its operator by RF interference. With a broken RF link a drone will usually descend to the ground or return to a specified location.
GNSS jamming	Disrupts the link to navigation satellites, such as GPS or GLONASS. With a lost link, the drone will usually hover in place, land, or return to home.
Spoofing	Allows one to take control of or misdirect the targeted drone by feeding it spurious communications or navigation signals.
Dazzling	Employs a high-intensity light beam or laser to temporarily 'blind' the camera on a drone.
Laser	Destroys vital segments of the drone airframe using directed energy.
High power microwave	Directs pulses of high intensity microwave energy at the drone, disabling the aircraft's electronic systems.
Nets	Designed to entangle the targeted drone and/or its rotors.
Projectile	Regular or custom-designed ammunition.
Collision drone	Destroy by collision.
Combined interdiction elements	Combination for higher interdiction likelihood. E.g. RF and GNSS jamming, or an electronic system with a kinetic backup.

Table 7.3: C-UAS platform types after (Michel, 2019, p. 4).

Ground-based: fixed	Systems to be used from stationary positions or mobile on the ground.
Ground-based: mobile	Systems mounted on vehicles.
Hand-held	Systems to be operated by a single individual by hand. Many of these systems resemble rifles or other small arms.
UAV-based	Systems mounted on drones.

8 Small and Very Small UAV Database

8.1 Database Properties

The small and very small aircraft (and missile) databases are publicly available via `https://url.tu-dortmund.de/pacsam-db` as HTML tables. The tables are fully searchable and columns can be sorted. The data can be downloaded in .csv or .JSON file format by clicking on the CSV or JSON button. Empty cells indicate that no information was found. A screenshot of the web page is shown in figure 8.1. The complete database is shown in appendix A. Additionally, all data files, including the interactive HTML file, are available under `https://doi.org/10.5281/zenodo.4537704` (Pilch et al., 2021). The printed version here was updated on 5th February 2021.

All UAV types listed have a size below or equal to 2 m.[1] The UAV database contains 26 categories, listed in table 8.1. In addition to basic properties such as size, mass and payload, we also included the category *In Service*, with the names of countries whose militaries adopted the system into their service, which allows statements on the proliferation of these systems.

As mentioned in the introduction only public sources were investigated, consisting mainly of fact sheets published by manufacturers or catalogues such as (Streetly & Bernadi, 2018). The focus of our investigation was mainly on systems designed to be used in a military context. An exception are very small UAVs still in the research or development phase. In general, these are not in military service or intended for military use, although some systems had been funded originally by military institutions (sections 5.1 and 5.11). We include them because they are are important indicators for trends and future capabilities of very small UAVs. The amount of effort put into collecting systems still in research was thus limited, and only a representative number of systems was included in our database.

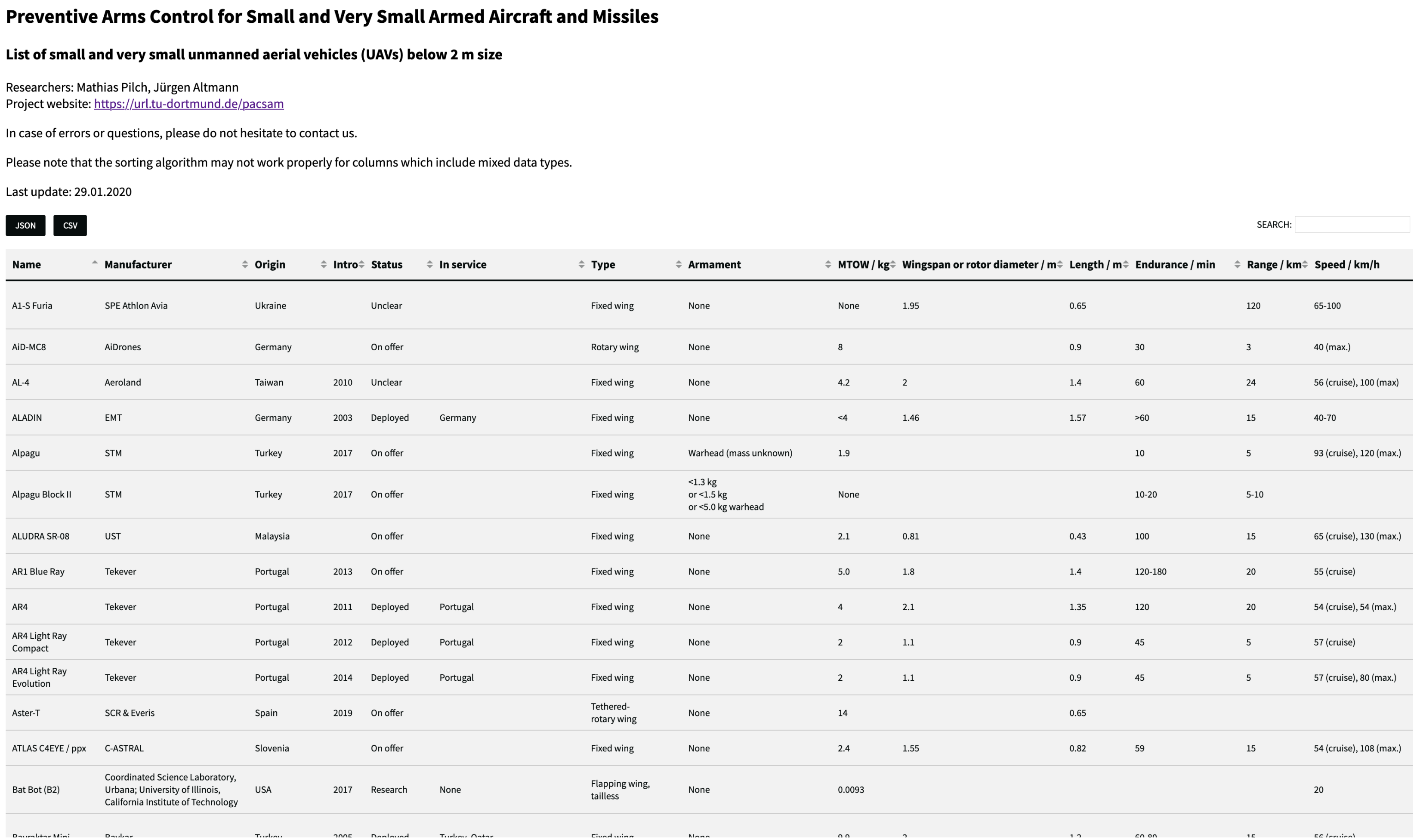
In the next section, we give a general overview of the data, with a special look on armed UAs in section 8.3. In section 8.4 we present parameter distributions and correlations of technical parameters.

---

[1] There exist UAVs with wingspans slightly above that, like the Aeronautics *Orbiter 1K* with a wingspan of 2.2 m (Aeronautics Defense Systems, 2019) and the Tekever *AR4* with a wingspan of 2.1 m (Tekever, 2019). The *Orbiter 1K* was used by Azerbaijan in the war against Armenia in autumn 2020 (Frantzman, 2020). In early 2021, version 2 of the *Orbiter 1K* is listed with 2.9 m wingspan (Aeronautics Defense Systems, 2021).

Table 8.1: The 26 categories used in the small and very small aircraft database.

Category	Description
Name	Name of the UAV
Manufacturer	Name of the UAV's manufacturer
Origin	Manufacturer's origin country
Intro	Year aircraft is first mentioned in media
Status	Includes commercial availability, development, military deployment or already ordered by a nation for service, legacy (no longer produced by manufacturer), advertised by manufacturer, research stage and unclear if status information is missing or outdated
In service	Nations with military usage
Configuration	Aircraft configuration
Armament	Type of weaponry with mass (if available)
Maximum take-off weight (MTOW)	Maximum take-off weight (mass) in kilograms
Wingspan or rotor diameter	Given in metres. In case of a fixed-wing or flying-wing UAV, the wingspan is given. For rotary-wing aircraft, the diameter of the main rotor is given instead. For multicopters, the overall diameter is used. Aircraft with ducted fans are actually larger, because of the shroud or duct that contains the propeller
Length	Aircraft length in metres
Endurance	Maximum flight time in minutes
Range	Flight range in kilometres
Speed	Aircraft speed as given by the manufacturer. Can be a range of values or cruise, dive and maximum speed, in km/h
Cruise speed	Speed of normal cruise once the aircraft has reached its cruise altitude in km/h
Maximum speed	Includes the maximum speed achieved through diving in km/h
Altitude AGL	Maximum altitude above ground level in metres
Altitude above mean sea level (AMSL)	Maximum altitude above mean sea level in metres
Power	Form of power supply
Propulsion	Method of thrust generation
Guidance	Navigation systems
Targeting	Targeting capabilities, e.g. object tracking, detection, classification
Payload	Payload type with mass in kilograms
Launch	Launch methods
Recovery	Recovery methods
References	Data sources



Preventive Arms Control for Small and Very Small Armed Aircraft and Missiles

List of small and very small unmanned aerial vehicles (UAVs) below 2 m size

Researchers: Mathias Pilch, Jürgen Altmann
Project website: https://url.tu-dortmund.de/pacsam

In case of errors or questions, please do not hesitate to contact us.

Please note that the sorting algorithm may not work properly for columns which include mixed data types.

Last update: 29.01.2020

Name	Manufacturer	Origin	Intro	Status	In service	Type	Armament	MTOW / kg	Wingspan or rotor diameter / m	Length / m	Endurance / min	Range / km	Speed / km/h
A1-S Furia	SPE Athlon Avia	Ukraine		Unclear		Fixed wing	None	None	1.95	0.65		120	65-100
AiD-MC8	AiDrones	Germany		On offer		Rotary wing	None	8		0.9	30	3	40 (max.)
AL-4	Aeroland	Taiwan	2010	Unclear		Fixed wing	None	4.2	2	1.4	60	24	56 (cruise), 100 (max)
ALADIN	EMT	Germany	2003	Deployed	Germany	Fixed wing	None	<4	1.46	1.57	>60	15	40-70
Alpagu	STM	Turkey	2017	On offer		Fixed wing	Warhead (mass unknown)	1.9			10	5	93 (cruise), 120 (max.)
Alpagu Block II	STM	Turkey	2017	On offer		Fixed wing	<1.3 kg or <1.5 kg or <5.0 kg warhead	None			10-20	5-10	
ALUDRA SR-08	UST	Malaysia		On offer		Fixed wing	None	2.1	0.81	0.43	100	15	65 (cruise), 130 (max.)
AR1 Blue Ray	Tekever	Portugal	2013	On offer		Fixed wing	None	5.0	1.8	1.4	120-180	20	55 (cruise)
AR4	Tekever	Portugal	2011	Deployed	Portugal	Fixed wing	None	4	2.1	1.35	120	20	54 (cruise), 54 (max.)
AR4 Light Ray Compact	Tekever	Portugal	2012	Deployed	Portugal	Fixed wing	None	2	1.1	0.9	45	5	57 (cruise)
AR4 Light Ray Evolution	Tekever	Portugal	2014	Deployed	Portugal	Fixed wing	None	2	1.1	0.9	45	5	57 (cruise), 80 (max.)
Aster-T	SCR & Everis	Spain	2019	On offer		Tethered-rotary wing	None	14		0.65			
ATLAS C4EYE / ppx	C-ASTRAL	Slovenia		On offer		Fixed wing	None	2.4	1.55	0.82	59	15	54 (cruise), 108 (max.)
Bat Bot (B2)	Coordinated Science Laboratory, Urbana; University of Illinois, California Institute of Technology	USA	2017	Research	None	Flapping wing, tailless	None	0.0093					20

Figure 8.1: Screenshot of the small and very small aircraft database available at `https://url.tu-dortmund.de/pacsam-db-sa`.

8.2 General Overview

A general overview is given in figure 8.2. Here, we see that the majority of UAVs is either of fixed- or rotary-wing configuration. Out of all 129 UAVs types produced in 27 different countries, only 25 are armed and produced in ten countries.

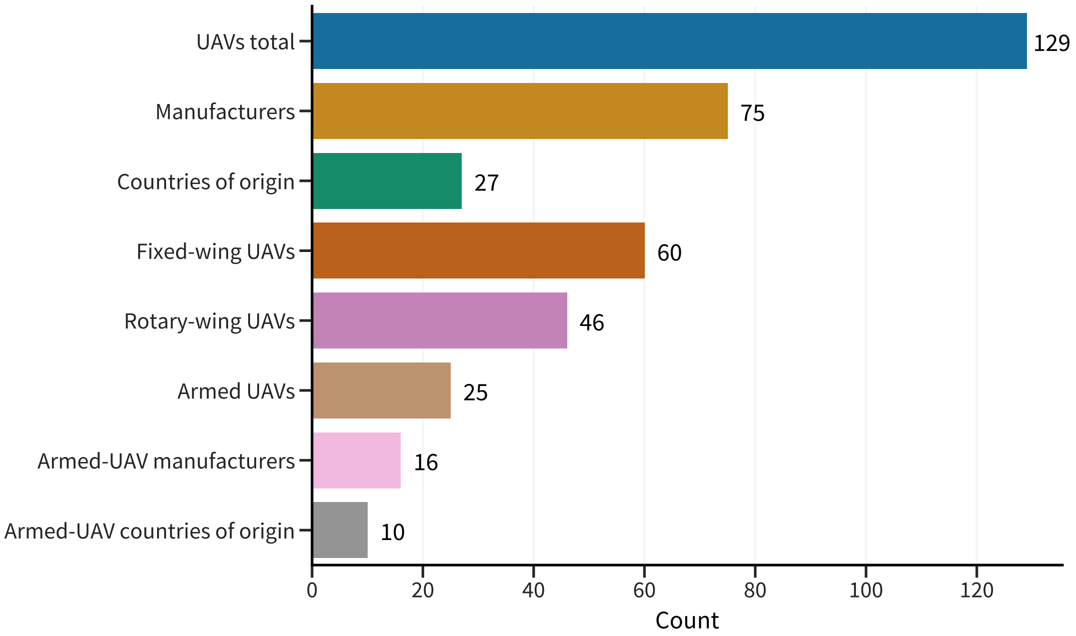


Figure 8.2: General database properties.

All of the diagrams shown in this and the following sections present data on all UAVs listed in our database. This does not necessarily mean that these systems are currently in use, especially for systems that were developed in the early 2000s. Figure 8.3 shows the UAV status distribution.

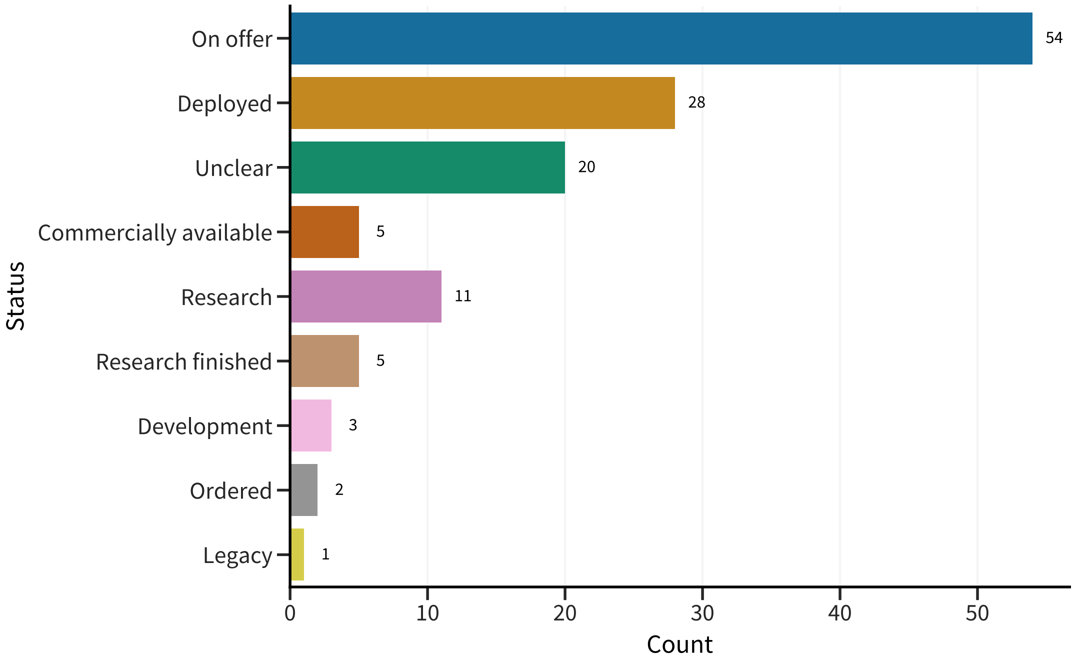


Figure 8.3: Status of small and very small UAV types.

Figure 8.4 shows the number of small and very small UAV types introduced per year, beginning in 2000. Between the years 2000 and 2011, the average number of UAVs introduced is 2.5, between 2011 and 2019 this number nearly quadrupled to 9.9 per year. The highest number of newly introduced systems was reached in 2014 with 17. In the following years, the numbers per year decreased to single digits. In general, we see a great increase of small and very small systems in the last decade.

In figure 8.5 we present the number of UAVs types for each country of origin. Out of the 129 systems collected, the USA produced the highest number of types with a total of 30, followed by Israel with 15. In all other countries the UAV-type count is in the single digits. As expected, the USA is leading in numbers, however, only two out of 30 are armed (AeroVironment *Switchblade* and Raytheon *Coyote*).

Figure 8.6 shows the number of UAV types in the different configurations, with the fixed-wing category leading with 60 UAVs followed by rotary-wing aircraft with 46. Tethered types are counted in their own categories, since their movement radius is restricted and thus can only fulfil a specific role such as area protection or surveillance.

In table 8.2 we list the countries exporting and importing small and very small UAVs. The USA is leading by far in the number of countries it exports to, followed by Norway. For a much more detailed analysis of import and export of UAVs in general we refer to (World of Drones, 2020).

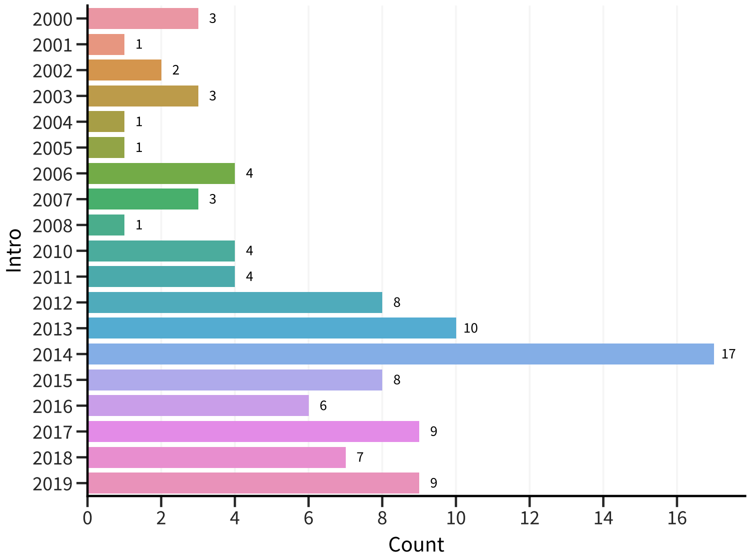


Figure 8.4: Number of small and very small UAV types introduced per year. Here, the total number is 101 out of 129, since in some cases it was not possible to determine a year of introduction.

Table 8.2: List of countries exporting small and very small UAVs based on our database. The total number of recipient countries is 39.

Origin	Exports to
Germany	South Africa, USA
Israel	Peru
Italy	Brazil
Norway	Australia, France, Germany, India, Netherlands, New Zealand, Poland, Spain, Turkey, USA, United Kingdom
Poland	Peru, Ukraine
Taiwan	China
Turkey	Qatar
USA	Australia, Belgium, Bulgaria, Burundi, Canada, Colombia, Czechia, Estonia, Hungary, Iraq, Kenya, Lebanon, Lithuania, Luxembourg, Netherlands, Norway, Philippines, Poland, Portugal, Romania, Spain, Sweden, Thailand, Uganda, Ukraine, United Kingdom, Uzbekistan

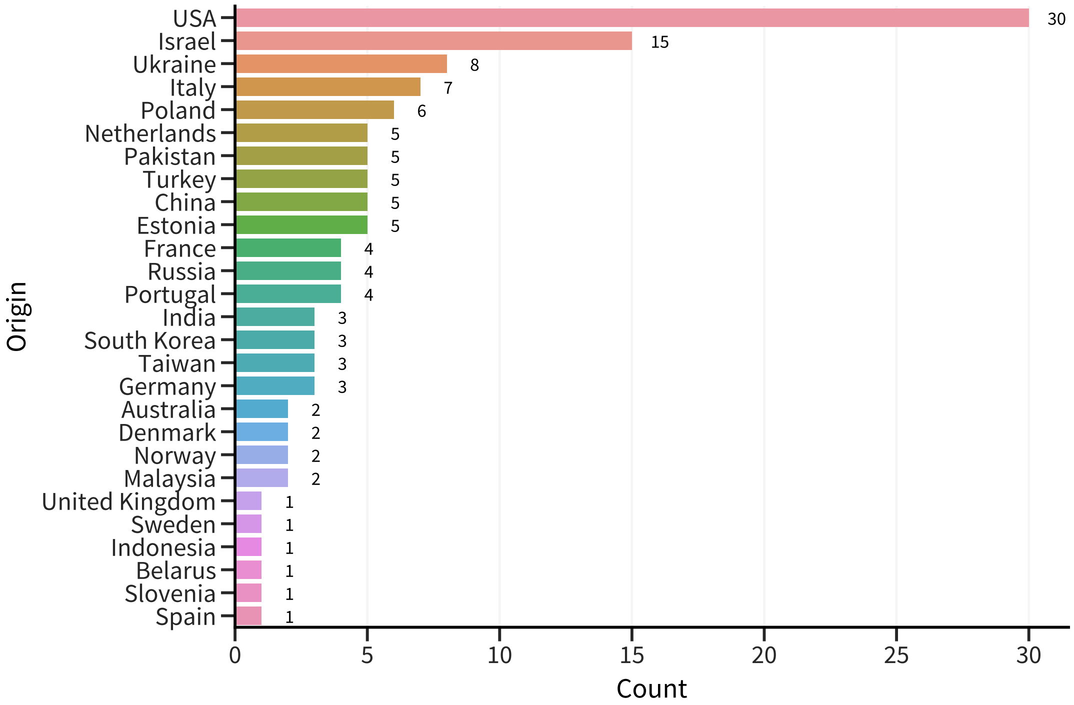


Figure 8.5: Number of small and very small UAV types per country of origin. The total number of countries is 27.

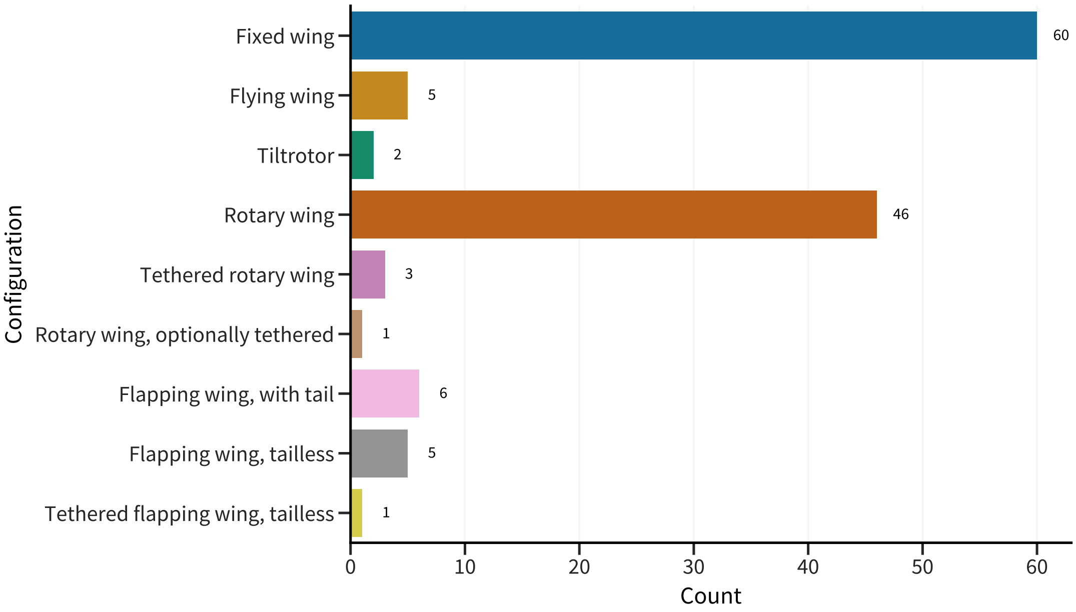


Figure 8.6: Number of small and very small UAV configurations. Here, flying-wing UAVs are counted separately.

8.3 Armed UAVs

A shortened overview of technical properties of armed UAVs is presented in table 8.5. The full data are given in the database in appendix A. Except for the *Cerberus*, which is a tiltrotor aircraft, all armed UAVs are of either rotary-wing or fixed-wing configuration. For armed UAVs, we see from figure 8.7 that the first armed small system was introduced in 2000, but a general trend towards small armed systems started in 2015.

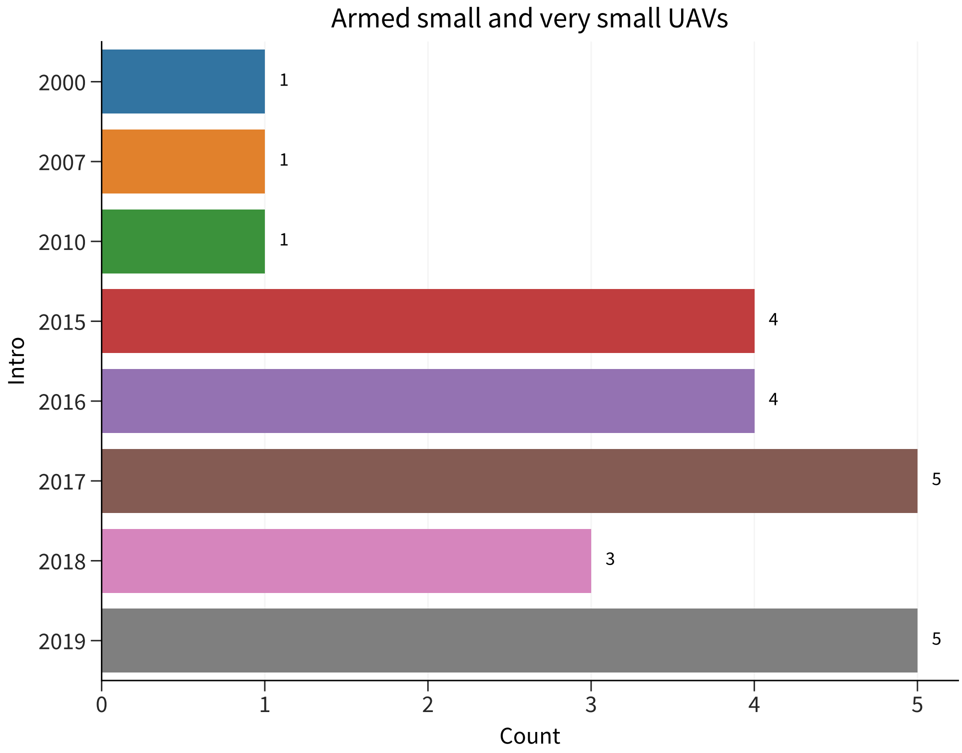


Figure 8.7: Number of small and very small armed UAV types introduced per year. Here, we list all 24 armed UAV types.

Figure 8.8 shows the count of armed UAV types per country. Here, we see that Israel is leading with seven systems. At the second and third place with three systems each are Turkey (STM's *Alpagu* series and *Kargu*) and Poland (WB Group's *Warmate* series), all loitering-munition systems.

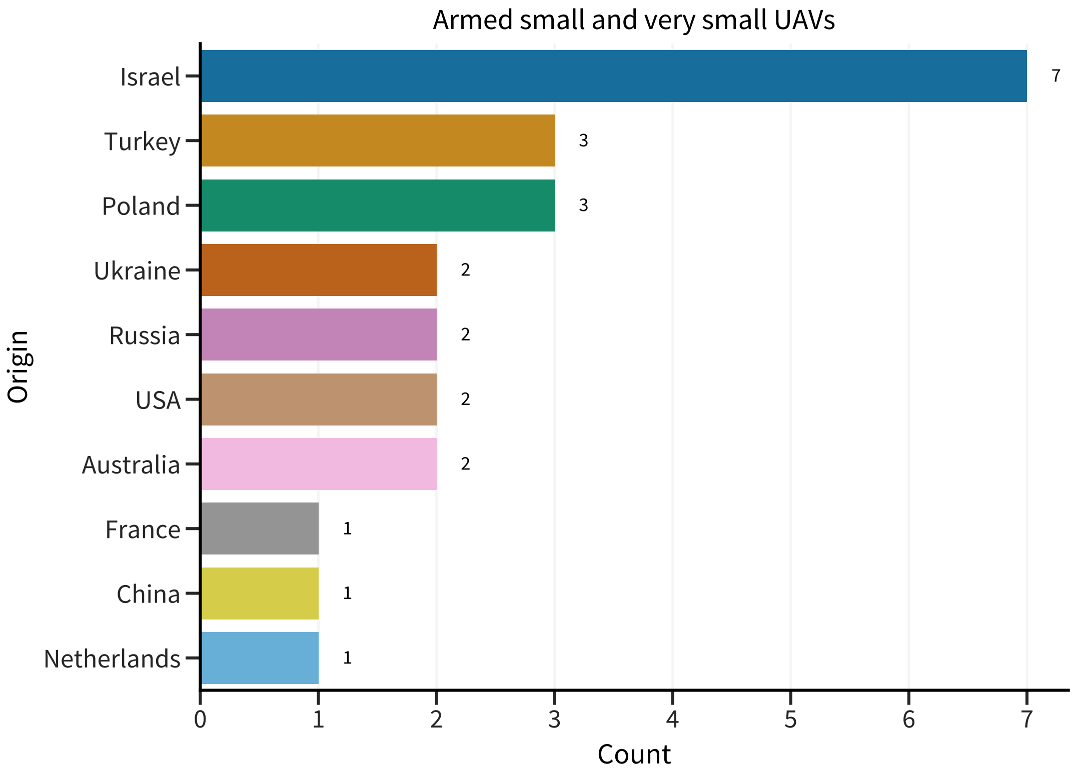


Figure 8.8: Number of armed small and very small UAV types per country of origin. The total number is 24 from 16 different manufacturers and ten countries.

As already discussed in section 4.6.2, most armed UAVs use integrated warheads. The relationship between warhead mass and MTOW is shown in figure 8.9. Table 8.3 lists the data points used in figure 8.9 as well as the percentage of the warhead mass relative to the MTOW. On average, warhead mass equals 19 % of the MTOW.

Table 8.3: List of UAV types with integrated warheads for which the warhead mass and MTOW were stated by the manufacturer (10 out of 20 armed with a warhead).

Name	Type	Wingspan or rotor diameter / m	Warhead mass / kg	MTOW / kg	Warhead mass/MTOW
Hero-20	Fixed wing		0.2	1.8	0.11
Spike Firefly	Rotary wing		<0.35	3	0.12
Hero-30	Fixed wing		0.5	3	0.17
Coyote	Fixed wing	1.47	<0.9	6.4	0.14
Hero-70	Fixed wing		1.2	7	0.17
ROTEM	Rotary wing		1.2	5.8	0.21
Warmate	Fixed wing	1.4	<1.4	5.3	0.26
Warmate TL	Fixed wing	1.7	1.4	4.5	0.31
Warmate V	Rotary wing		1.6	7.0	0.23
Green Dragon	Fixed wing	1.7	2.5	15	0.17

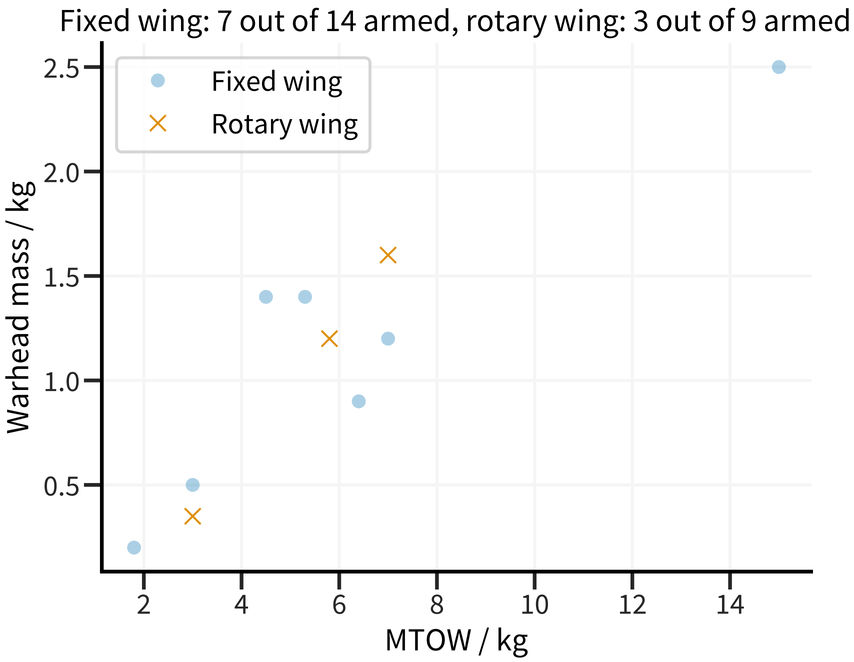


Figure 8.9: Warhead mass versus MTOW of armed fixed- and rotary-wing UAVs. Other types of UAVs do not carry any warheads. In case only an upper limit of the warhead mass is given by the manufacturer, we choose this value.

Of the very small UAs (i.e. < 0.2 m wingspan or rotor diameter) in our database none have been armed. The heaviest among them is the flying-wing *Black Widow* with 0.15 m wingspan, it has 0.80 kg mass. Assuming that a similar armed system could carry a warhead of 11 to 31 % of the total UA mass as in table 8.3, the warhead mass could be between 0.08 and 0.25 kg. This is in the range of anti-personnel mines (ICRC, 1996, p. 10), and the latter value is similar to the one of the most lightweight small armed UAs of table 8.3. Thus, very small UAs near 0.2 m size could be used for attacking personnel and light vehicles. Much smaller UAs could still kill humans; in order to check whether the attacks in the fictitious video ‘Slaughterbots’ (Russell, 2017) would be feasible, the Swiss Federal Office for Defence Procurement built a shape charge of 3 g of explosive and conical copper foil that penetrated a skull simulant (Drapela, 2018). An unspecified attack against a human sniper by an MAV of centimetres size had already been shown in 2009 in a video animation by the U.S. Air Force Research Laboratory (US AFRL, 2009). Of course, chemical or biological agents could kill with a mass much below 1 g.

A description of the methods for targeting is only given in few cases, but in general targets can be tracked in real-time. ‘Autonomous tracking’ or ‘autonomous targeting’ is mentioned for *Alpagu Block II* and *Kargu*. The actual degree of autonomy in target selection and engagement in these and the other armed UAVs is unclear. A list of armed UAVs in the database that potentially target autonomously is given in table 8.4.

Table 8.4: List of armed UAVs in the database that potentially target autonomously.

Type	Targeting
Alpagu	Embedded and real-time object tracking, detection and classification
Alpagu Block II	Autonomous, real-time object tracking, detection and classification
Kargu	Autonomous targeting
Patriot R2	Real-time air vehicle location tracking
Sparrow	Automatic tracking of moving targets, target aiming and artillery fire correction
Warmate R	Automatic target lock
Warmate TL	Automated videotracker even under communication loss
ZALA 421-08M	Active target tracking unit

Table 8.5: Excerpt of the UAV database listing only armed types and 12 out of 26 categories, with a focus on technical properties. For a complete list and references see the UAV database in appendix A.

Name	Type	Armament	MTOW / kg	Wingspan or rotor diameter / m	Endurance / min	Range / km	Speed / km/h	Cruise speed / km/h	Max. speed / km/h	Targeting
Alpagu	Fixed wing	Warhead (mass unknown)	1.9		10	5		93	120	Embedded and real-time object tracking, detection and classification
Alpagu Block II	Fixed wing	<1.3 kg or <1.5 kg or <5.0 kg warhead			10-20	5-10				Autonomous, real-time object tracking, detection and classification
CH-901	Fixed wing	Warhead (mass unknown)	9		120	15	64-113			
Cerberus	Tiltrotor	40 mm grenade launcher or 12-gauge shotgun or micro munitions or net launcher	6.0		22 (3 x 40mm Grenades), 28-32 (no payload)	5	60-80			
Comandor	Rotary wing	Anti-tank missile or free-fall bombs	110	1.5	210	200			60	
Coyote	Fixed wing	<0.9 kg warhead	6.4	1.47	90	37		111	157	
Cyclone	Rotary wing	Tear gas	1.5							
Demon	Rotary wing	RPG-22/26 or RPG-7 or 5 kg bomb or 7 kg high-explosive fragmentation warhead				10-20				
Drone-40	Rotary wing	Kinetic anti-UAV or high-explosive warhead or anti-armour warhead or smoke grenade				10		72		
DroneCatcher	Rotary wing	Net launcher	<6		30				72	
Futura	Fixed wing	Fragmentation warhead (mass unknown)	70.0	2	70	400	130 (loitering)	341	359	
Green Dragon	Fixed wing	2.5 kg warhead: anti-personnel or anti-tank or both combined	15	1.7	75	40	120-157 (loitering)		370	
HERO-20	Fixed wing	0.2 kg anti-personnel warhead	1.8		20	10				
HERO-30	Fixed wing	0.5 kg anti-personnel warhead	3		30	5-10-40				
HERO-70	Fixed wing	1.2 kg anti-light-vehicle warhead	7		45	40			185	
KYB-UAV	Fixed wing	<3 kg warhead		1.21	30		80-130			
Kargu	Rotary wing	Multiple warhead configurations (mass unknown)								Autonomous targeting
ROTEM	Rotary wing	1.2 kg warhead, <1 m strike precision	5.8		30	10		102-157	370	Strike precision <1 m
Spike Firefly	Rotary wing	<0.35 kg omnidirectional fragmentation warhead	3		15	5-10	70 (diving)	60	70	Proximity sensors, tracker designed for agile targets
Switchblade	Fixed wing	Warhead (mass unknown)	2.5	0.61	>15	10-45		101	161	Target selection by operator
Warmate	Fixed wing	<1.4 kg fragmentation or shaped fragmentation warhead	5.3	1.4	50	10				
Warmate TL	Fixed wing	1.4 kg warhead	4.5	1.7	40	10		75	120	Automated videotracker even under communication loss
Warmate V	Rotary wing	1.6 kg warhead	7		30	12		27		
ZALA LANCET-1	Fixed wing	Warhead (mass unknown)	5		30	40	80-110			

8.4 Parameter Distributions and Correlations

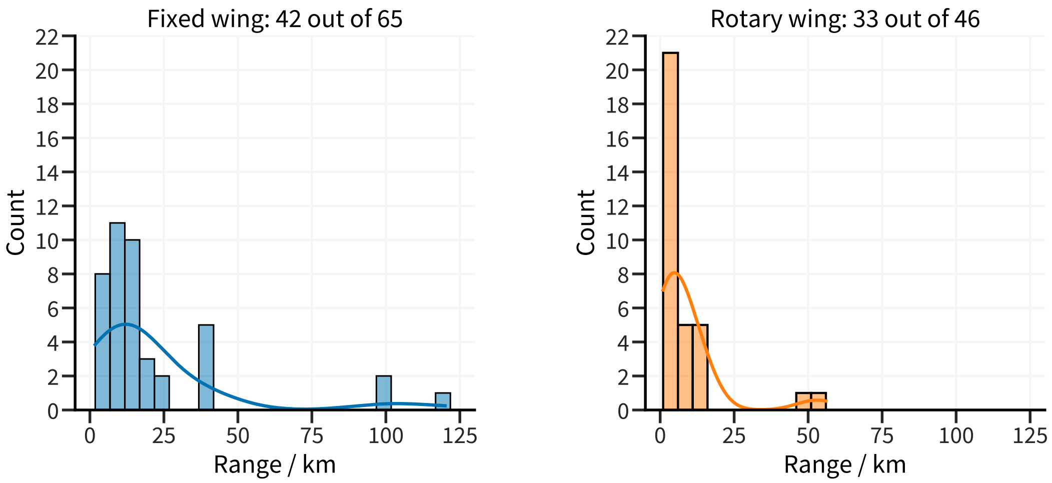
In this section we present distributions of important parameters singly as well as one versus another, first for fixed- and rotary-wing UAVs, then for flapping-wing ones. Since flying-wing UAVs are technically also fixed-wing UAVs, we include them in the fixed-wing category in the diagrams. Altitude is not presented here since the data acquired are poor: in many cases, only the maximum flight altitude is given but not the typical one for cruising. In other cases, altitude ranges were given or it was not clear whether altitude was given as measured from ground or mean sea level.

In general, note that because of missing data, the number of data points in the diagrams is lower than the total of UAV types. The actual number is given in the title of each diagram.

A detailed analysis is beyond this report, but the general tendency fits to what one would expect: bigger UAVs are heavier, can carry higher payloads, have longer endurances and ranges. Rotary-wing UAVs tend to have lower speeds and smaller ranges. Flapping wings are exclusively used with very small aircraft with correspondingly lower take-off masses and shorter endurances.

Of all UAVs listed in the database, two exhibit properties far beyond all other UAVs. These are the Alcore *Futura* and the Matrix UAV *Comandor*. The *Futura* is the only small UAV with a turbojet engine, allowing a cruise speed of 341 km/h and a range of 400 km at an MTOW of 70 kg (Streetly & Bernadi, 2018, p. 73). The rotary-wing *Comandor* UAV uses either 12 electric or 2 piston engines, with an MTOW of 110 kg, an endurance of 210 min and a range of 200 km (Streetly & Bernadi, 2018, pp. 216–217). However the status of both the *Futura* and the *Comandor* is unclear. For the other UAV types, a typical value for the MTOW is $<$ 15 kg as can be seen from figure 8.12.

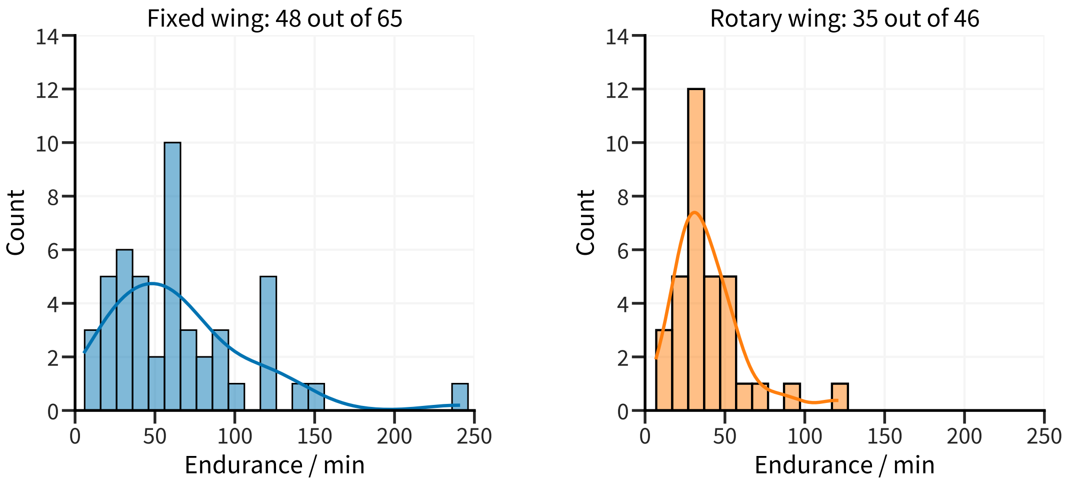
8.4.1 Fixed- and rotary-wing UAVs



(a) Fixed-wing UAVs.

(b) Rotary-wing UAVs.

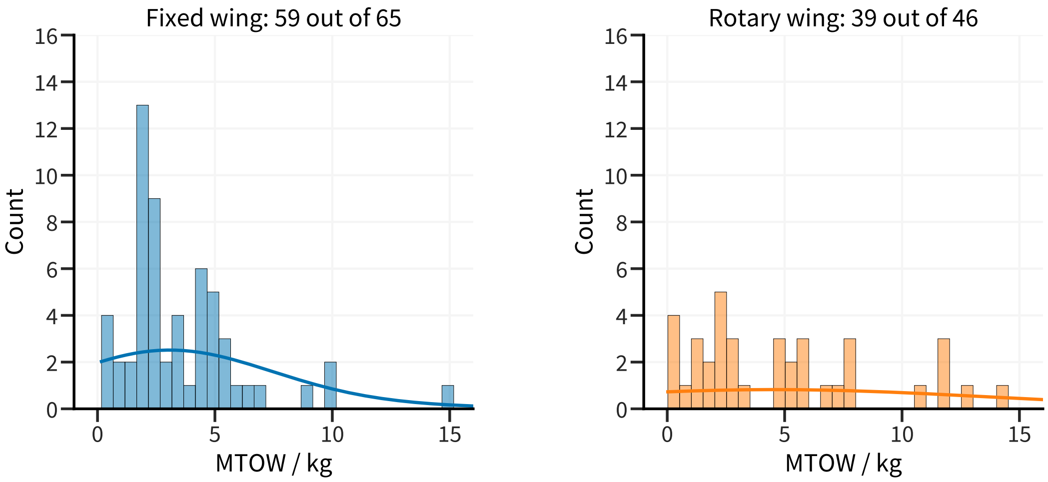
Figure 8.10: Range distribution of fixed- and rotary-wing UAVs. The bin width is 5 km, and curves represent a Gaussian kernel density estimation. Not included: *Futura* (range: 400 km), *Comandor* (range: 200 km).



(a) Fixed-wing UAVs.

(b) Rotary-wing UAVs.

Figure 8.11: Endurance distribution of fixed- and rotary-wing UAVs. The bin width is 10 min, and curves represent a Gaussian kernel density estimation.



(a) Fixed-wing UAVs.

(b) Rotary-wing UAVs.

Figure 8.12: MTOW distribution of fixed- and rotary-wing UAVs. The bin width is 0.5 kg, and curves represent a Gaussian kernel density estimation. Not included: *Futura* (MTOW: 70 kg), *Comandor* (MTOW: 110 kg).

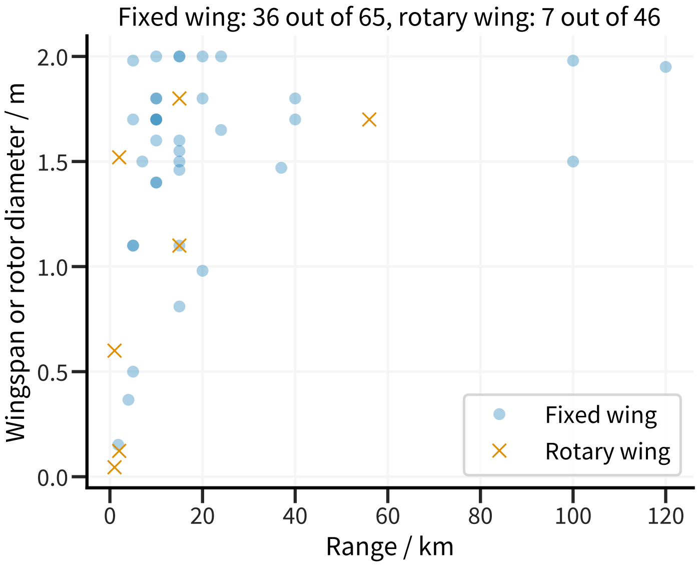


Figure 8.13: Wingspan or rotor diameter versus range of fixed- and rotary-wing UAVs. Deeper shades of colour indicate multiple data points. Not included: *Futura* (range: 400 km, wingspan: 2 m), *Comandor* (range: 200 km, rotor diameter: 1.5 m).

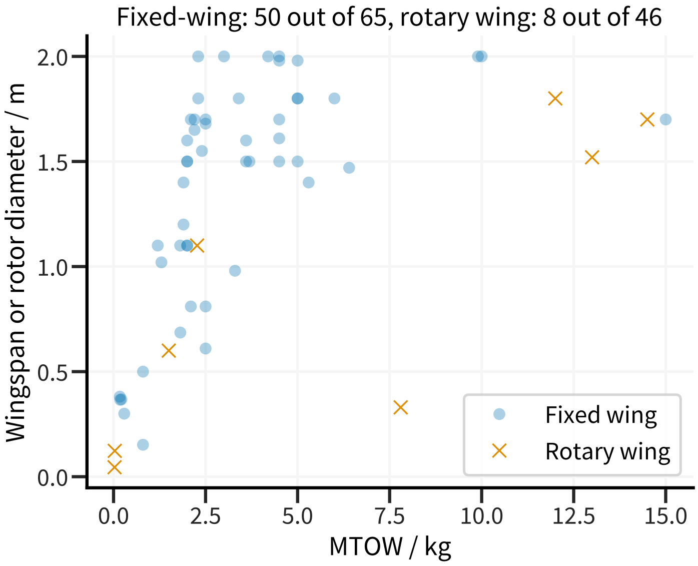


Figure 8.14: Wingspan or rotor diameter versus MTOW of fixed- and rotary-wing UAVs. Deeper shades of colour indicate multiple data points. Not included: *Futura* (MTOW: 70 kg, wingspan: 2 m), *Comandor* (MTOW: 110 kg, rotor diameter: 1.5 m).

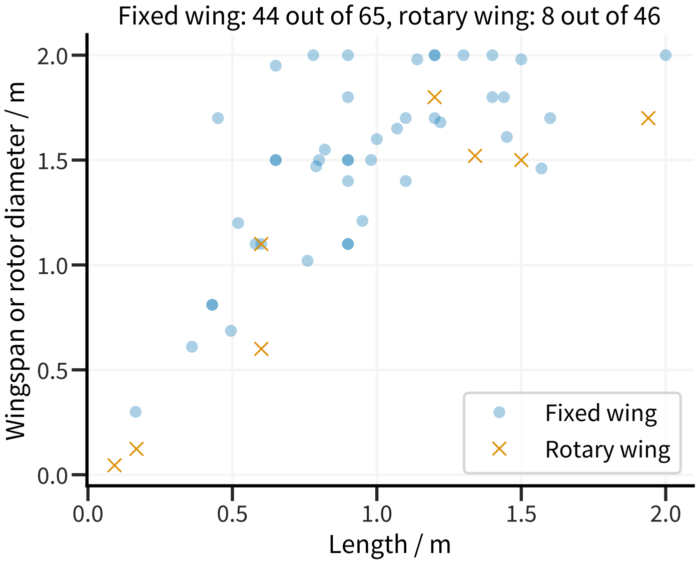


Figure 8.15: Wingspan or rotor diameter versus length of fixed- and rotary-wing UAVs. Deeper shades of colour indicate multiple data points.

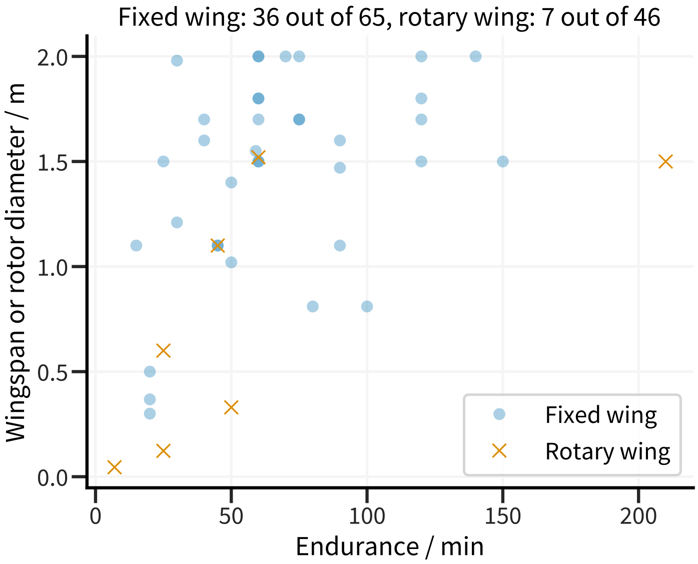


Figure 8.16: Wingspan or rotor diameter versus endurance of fixed- and rotary-wing UAVs. Deeper shades of colour indicate multiple data points.

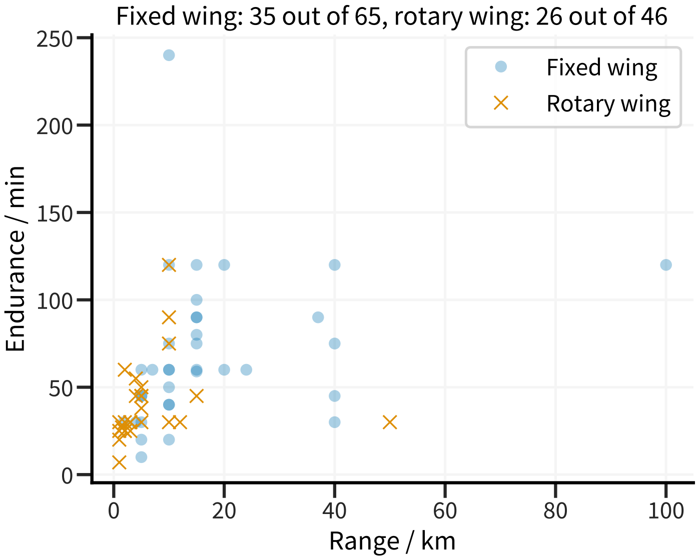


Figure 8.17: Endurance versus range of fixed-wing (blue) and rotary-wing (orange) UAVs. Deeper shades of colour indicate multiple data points. Not included: *Futura* (range: 400 km, endurance: 70 min), *Comandor* (range: 200 km, endurance: 210 min).

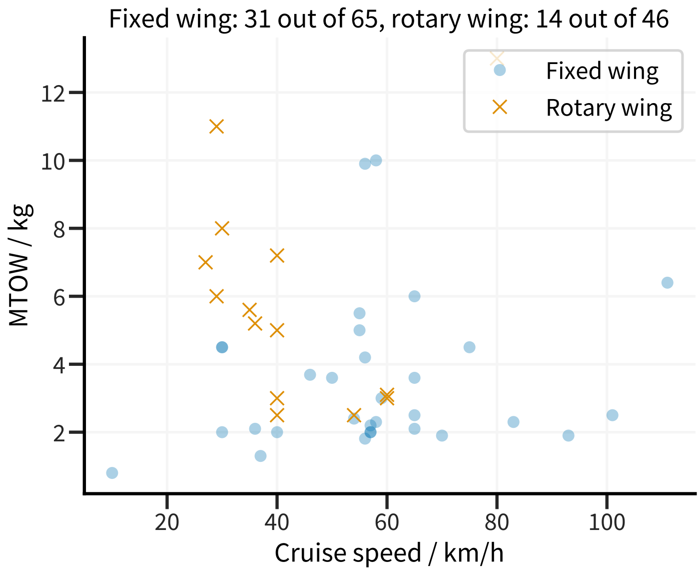


Figure 8.18: MTOW versus cruise speed of fixed-wing (blue) and rotary-wing (orange) UAVs. Deeper shades of colour indicate multiple data points. Not included: *Futura* (cruise speed: 341 km/h).

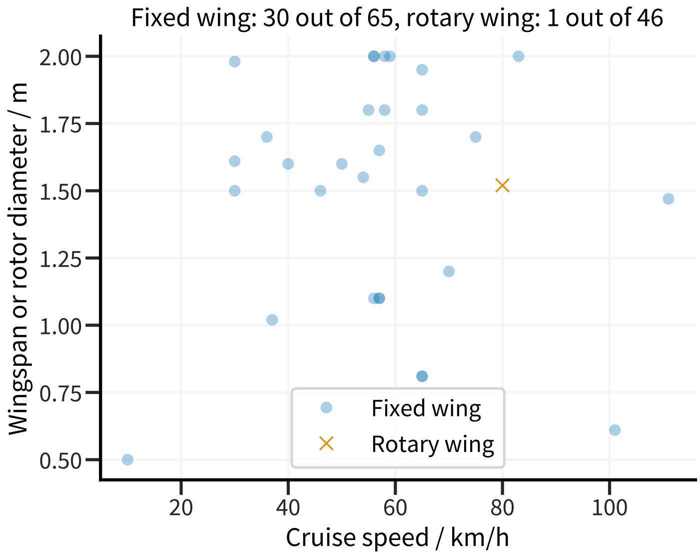
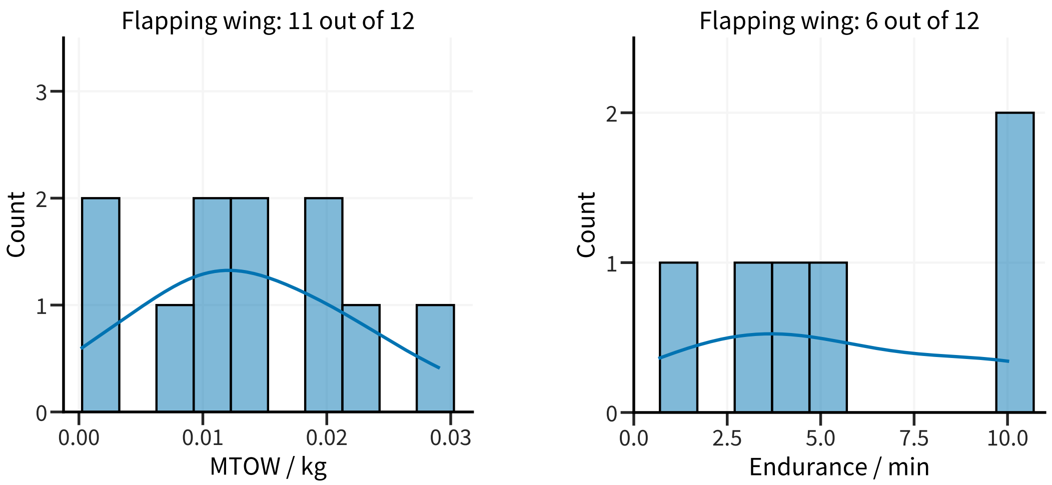


Figure 8.19: Wingspan versus cruise speed of fixed-wing (blue) and rotary-wing (orange) UAVs. Deeper shades of colour indicate multiple data points. Not included: *Futura* (cruise speed: 341 km/h).

8.4.2 Flapping-wing UAVs



(a) MTOW distribution of flapping-wing UAVs. The bin width is 3 g.

(b) Endurance distribution of flapping-wing UAVs. The bin width is 1 min.

Figure 8.20: MTOW and endurance distributions of flapping-wing UAVs. Here we count all flapping-wing configurations, including tethered ones. Curves represent a Gaussian kernel density estimation.

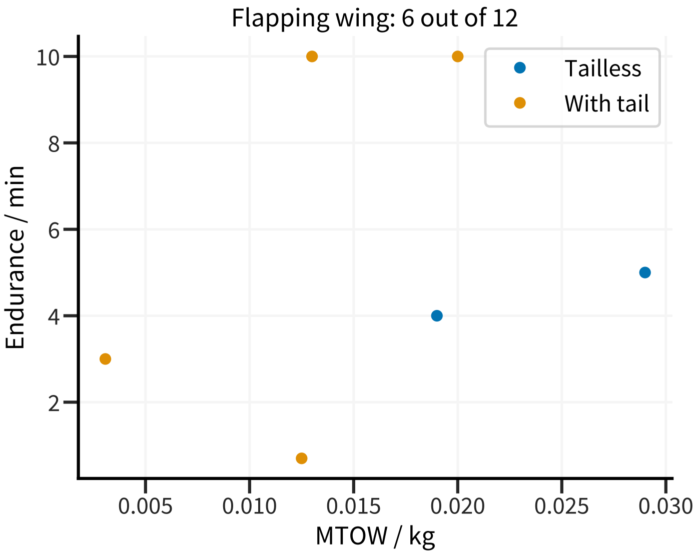


Figure 8.21: Endurance versus MTOW of flapping-wing UAVs. No data pair was available for tethered UAVs.

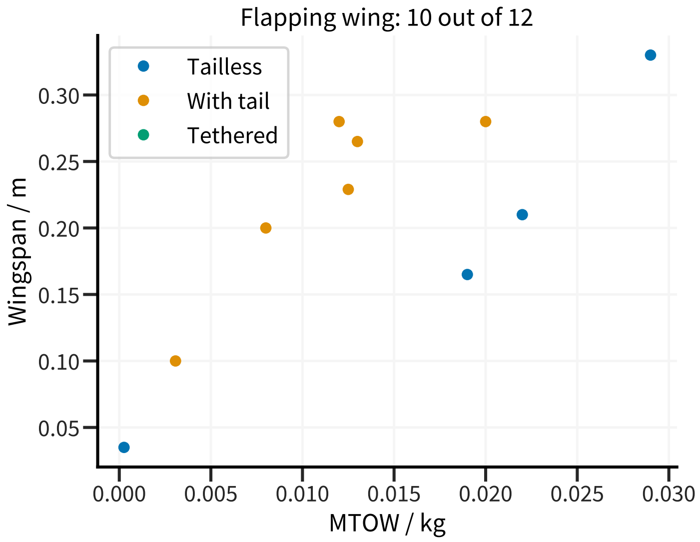


Figure 8.22: Wingspan versus MTOW of flapping-wing UAVs.

9 Conclusion

While hobbyists have built and used model aircraft since many decades, small and very small uninhabited aircraft started to play a role in military research and development about 20 years ago. Since then the number of types has increased greatly; our database – that excludes hobby multicopters – has 129 entries. At the same time the number of countries researching, developing or building small and very small UAs in or for a military context has increased to at least 27, exports went to at least 39 countries.

Various configurations are being used, mostly fixed wings and rotary wings. Most of them have take-off masses of 2 to 10 kg and sizes between 0.5 and 2 m. Propeller power is usually provided by a battery. Typical endurances are tens of minutes and typical ranges 5 to 40 km.

Flapping wings are only used by very small aircraft all of which are at the research stage. Their mass is below 30 g, with a few minutes of endurance at most. Some types are extremely light-weight (below 1 g or even below 0.1 g).

Armed forces use small UAs mainly for intelligence, surveillance and reconnaissance, they carry various types of sensors. But ten countries have built UAs with offensive payloads. In most cases, a warhead is integrated so that the UAs self-destruct in operation. These armed UAs can fly for tens of minutes above a target area and thus can function as loitering munitions. The warhead mass is between 0.2 and 2.5 kg, with 11 to 31 % of the total UA mass.

The degree of autonomous targeting is unclear. Specific missiles or precision-guided munitions for re-usable small armed UAs seem to not have been developed yet.

Very small UAs (i.e. < 0.2 m wingspan or rotor diameter) have not yet been armed. The heaviest in our database has 0.80 kg mass. Assuming a similar percentage, such UAs could carry a warhead of 0.08 to 0.25 kg, in the range of anti-personnel mines. But lethal action against a human is possible with only a few grams of explosive, a chemical or biological agent could function with a much smaller mass.

Whether flapping-wing UAs will be deployed by armed forces remains to be seen; one possible application is inside buildings where wind gusts to not present a problem.

In the near future, small UAs will be made more capable. In particular the number of armed types will likely increase. Research and development will continue to increase autonomy.

Concerning small-UA swarms, first demonstrations of unarmed systems have occurred, with some autonomy. One can expect more efforts in this direction, and towards armament.

The military capabilities of small and very small UAs will remain limited for several reasons: the payload is small, the cruise speed is low, the endurance and range are limited. Thus, the qualitative arms race in (armed) UAs will mostly take place in bigger systems. Nevertheless, relevant countries probably will continue to compete in small armed UAs, with a particular focus on swarms. If the former could be built at low cost, swarms of high numbers could become formidable tools for applying military force.

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A Table of Small and Very Small UAVs

On the following pages, the complete UAV database is presented in table format. We recommend using the interactive online version available at `https://url.tu-dortmund.de/pacsam-db-sa` instead, which allows searching and sorting. Additionally, all data files, including the interactive HTML file, are available under `https://doi.org/10.5281/zenodo.4537704` (Pilch et al., 2021). The printed version here was updated on 5th February 2021.

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Name	Manufacturer	Origin	Intro	Status	In service	Configuration	Armament	MTOW / kg	Wingspan or rotor diameter / m	Length / m	Endurance / min	Range / km
A1-S Furia	SPE Athlon Avia	Ukraine		Unclear		Fixed wing	None		1.95	0.65		120
AL-4	Aeroland	Taiwan	2010	Unclear		Fixed wing	None	4.2	2.00	1.40	60	24
ALADIN	EMT	Germany	2003	Deployed	Germany	Fixed wing	None	<4	1.46	1.57	>60	15
ALUDRA SR-08	UST	Malaysia		On offer		Fixed wing	None	2.1	0.81	0.43	100	15
AR1 Blue Ray	Tekever	Portugal	2013	On offer		Fixed wing	None	5.0	1.80	1.40	120-180	20
AR4 Light Ray Compact	Tekever	Portugal	2012	Deployed	Portugal	Fixed wing	None	2	1.10	0.90	45	5
AR4 Light Ray Evolution	Tekever	Portugal	2014	Deployed	Portugal	Fixed wing	None	2	1.10	0.90	45	5
ATLAS C4EYE / ppx	C-ASTRAL	Slovenia		On offer		Fixed wing	None	2.4	1.55	0.82	59	15
AiD-MC8	AiDrones	Germany		On offer		Rotary wing	None	8		0.90	30	3
Alpagu	STM	Turkey	2017	On offer		Fixed wing	Warhead (mass unknown)	1.9			10	5
Alpagu Block II	STM	Turkey	2017	On offer		Fixed wing	<1.3 kg or <1.5 kg or <5.0 kg warhead				10-20	5-10
Aster-T	SCR & Everis	Spain	2019	On offer		Tethered rotary wing	None	14		0.65		

Name	Speed / km/h	Cruise speed / km/h	Max. speed / km/h	Alt. AGL / m	Alt. AMSL / m	Power	Propulsion	Guidance	Targeting	Payload	Launch	Recovery	References
A1-S Furia		65	100.0	80 (minimum, cruising), 2500 (ceiling)		Electric	Pusher propeller	GPS, autopilot, automatic take-off and landing, manual, semi-automatic and automatic flight modes, GCS		Day/night vision module	Catapult	Parachute	Streetly & Bernadi, 2018, p. 219
AL-4		56	100.0	3000 (ceiling)		Brushless electric motor	Pusher propeller	GPS, IMU, autopilot, truck-mounted GCS		1.0 kg total, 0.4 kg batteries, TV camera	Hand	Belly landing	Streetly & Bernadi, 2018, p. 206; Aeroland UAV, 2019
ALADIN	40-70			30 (minimum), 100-300 (typical), 4500 (ceiling)		Electric	Tractor propeller	Automatic and manual flight mode, autopilot, GCS		4 CCD cameras, IR	Hand or bungee rope		EMT Penzberg, 2019a
ALUDRA SR-08		65	130.0		4000 (ceiling)	Electric	Tractor propeller	GPS, GLONASS, autonomous and semi-autonomous flight modes, GCS		Video, IR	Hand	Parachute	Streetly & Bernadi, 2018, p. 146
AR1 Blue Ray		55				Electric	Pusher propeller	Semi- and fully autonomous, laptop and tablet GCS		1.5 kg payload	Hand, catapult	Parachute	Streetly & Bernadi, 2018, p. 168
AR4 Light Ray Compact		57				Electric	Pusher propeller	GPS, IMU, autopilot, autonomous, laptop and tablet GCS		EO/IR	Hand	Parachute	Streetly & Bernadi, 2018, pp. 169–170
AR4 Light Ray Evolution		57	80.0			Electric	Pusher propeller	GPS, IMU, autopilot, autonomous, GCS		EO/IR	Hand	Parachute	Streetly & Bernadi, 2018, pp. 169–170
ATLAS C4EYE / ppx		54	108.0	5000 (ASL)		Brushless electric	Tractor propeller	GCS		0.3 kg EO/IR	Hand	Parachute	C-Astral, 2019a; C-Astral, 2019b
AiD-MC8			40.0	4000		Electric	6 rotor blades	GPS, autonomous flight, waypoint navigation, GCS		5 kg total, camera, thermal	VTOL	VTOL	Streetly & Bernadi, 2018, pp. 69–70; AiDrones, 2020
Alpagu		93	120.0	122		Electric	Pusher propeller	Autonomous, GCS	Embedded and real-time object tracking, detection and classification	EO/IR	Tube		STM, 2019a
Alpagu Block II				250-400	2000-3500	Electric	Pusher propeller	Autonomous or manually via GCS	Autonomous, real-time object tracking, detection and classification	1.3 or 1.5 or 5.0 kg	Tube, single or multi-launcher		STM, 2019b; Army Recognition, 2019
Aster-T				70-100		Electric ground supply unit and on-board battery	Rotor blades	GCS		4 kg total, EO/IR	VTOL	VTOL	SCR, 2019a; SCR, 2019b

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Name	Manufacturer	Origin	Intro	Status	In service	Configuration	Armament	MTOW / kg	Wingspan or rotor diameter / m	Length / m	Endurance / min	Range / km
Bat Bot (B2)	Coordinated Science Laboratory, Urbana; University of Illinois, California Institute of Technology	USA	2017	Research	None	Flapping wing, tailless	None	0.0093				
Bayraktar Mini	Baykar	Turkey	2005	Deployed	Turkey, Qatar	Fixed wing	None	9.9	2.000	1.200	60-80	15
Black Hornet PRS	FLIR Systems	Norway	2013	Deployed	Australia, France, United Kingdom, Germany, India, Norway, USA, Poland, Spain, Turkey, Netherlands	Rotary wing	None	0.033	0.123	0.168	25	2
Black Widow	AeroVironment	USA	2000	Research finished	None	Flying wing	None	0.80	0.152		30	1.8
Blackstart	Blue Bear Systems Research	United Kingdom	2010	On offer		Fixed wing	None	5	1.500	0.980	60	7
Blackwing	AeroVironment	USA	2013	Deployed	USA	Fixed wing		1.814	0.686	0.495		
CEUAV	UAV Solutions	USA	2018	On offer		Fixed wing	None			0.483	40-60	>10
CH-901	China Aerospace Science and Technology Corporation	China	2016	Unclear		Fixed wing	Warhead (mass unknown)	9		1.200	120	15
COLIBRI	TU Delft	Netherlands	2017	Research	None	Flapping wing, tailless	None	0.022	0.210		0.25-0.3	
CREX-B	Leonardo Airborne & Space Systems	Italy		Unclear		Fixed wing	None	2.1	1.700	0.450	75	10
Cardinal II	NCSIST	Taiwan	2014	Deployed	China	Fixed wing	None	5.5		1.900	60	
Casper 200	Top I Vision	Israel	2004	Unclear		Fixed wing	None	2.3	2.000	1.300	140	

Name	Speed / km/h	Cruise speed / km/h	Max. speed / km/h	Alt. AGL / m	Alt. AMSL / m	Power	Propulsion	Guidance	Targeting	Payload	Launch	Recovery	References
Bat Bot (B2)	20					Electric coreless DC motor	2 morphing wings	Autonomous flight manoeuvers (zero-path flight, banking turn, diving)	None		Hand		Ramezani et al., 2017
Bayraktar Mini		56		1000		Electric	Pusher propeller	Automatic take-off and cruise, return home and landing, GCS		2 axis day/night camera	Hand	Automatic body or parachute landing	Baykar, 2019b; Army Technology, 2019b; Baykar, 2019a
Black Hornet PRS			22.0			Electric	Rotor blades	GCS, GPS and in GPS denied areas, BLOS navigation, auto and manual hover and stare, route and user selectable waypoint actions, automatic return, lost link navigation		EO/IR, video HD snapshot, thermal	VTOL	VTOL	FLIR, 2019b; Army Recognition, 2018; FLIR, 2019a; Army Technology, 2019a; Asia Pacific Defence News, 2019; Military.com, 2016; DroningON, 2017
Black Widow				234 (max.)		Electric 10 W DC motor	Tractor propeller	3 g radio control system, GCS	None	Colour video system and transmitter	Pneumatic		Shkarayev et al., 2007
Blackstart			120.0			Brushless electric	Tractor propeller	Autopilot, fully autonomous flight, point-and-click loiter/waypoint control, GCS		EO/IR	Hand, catapult	Belly landing	Streetly & Bernadi, 2018, pp. 232–233
Blackwing						Electric	Pusher propeller			EO/IR	Underwater-to-Air delivery canister, tube, multipack launcher		Naval Drones, 2019b; AeroVironment, 2017b; LaGrone, 2016
CEUAV						Electric	Pusher propeller			EO/IR	Tube		UAV Solutions, 2019
CH-901	64-113					Electric	Pusher propeller				Tube		IHS Jane's 360, 2017
COLIBRI						Electric EPS8-brushed DC motor, Nanotech LiPo 160 mAh 25 C	2 flapping wings		None		VTOL	VTOL	Roshanbin et al., 2017
CREX-B		36	110.0	30 (operating), 500 (max.)	3100 (ceiling)	Electric	Tractor propeller	Waypoint navigation, automatic landing, autonomous/semi-autonomous flight modes, return home, portable GCS		EO/IR	Hand	Belly landing	Streetly & Bernadi, 2018, p. 130; Leonardo, 2019
Cardinal II		55				Brushless electric motor	Tractor propeller				Hand	Parachute	Air Force Technology, 2019
Casper 200		83		70		Electric	Tractor propeller	GPS, pre-programmed, portable or vehicle-mounted GCS		TV camera, thermal, radiological	Hand	Belly landing	Streetly & Bernadi, 2018, pp. 124–125

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Name	Manufacturer	Origin	Intro	Status	In service	Configuration	Armament	MTOW / kg	Wingspan or rotor diameter / m	Length / m	Endurance / min	Range / km
Cerberus	Skyborne	Australia	2018	Development		Tiltrotor	40 mm grenade launcher or 12-gauge shotgun or micro munitions or net launcher	6.0		0.820	22 (3 x 40mm Grenades), 28-32 (no payload)	5
Comandor	Matrix UAV	Ukraine	2016	Unclear		Rotary wing	Anti-tank missile or free-fall bombs	110	1.500	1.500	210	200
Coyote	Raytheon	USA	2007	Ordered		Fixed wing	<0.9 kg warhead	6.4	1.470	0.790	90	37
Crazyflie 2.1	bitcraze	Sweden	>2014	Commercially available	None	Rotary wing	None	0.027	0.045	0.092	7	1
Cyclone	ISPRA	Israel	2015	Deployed	Israel	Rotary wing	Tear gas	1.5				
Cygnus A10	Asteria	India	2015	On offer		Fixed wing	None	3.6	1.600		90	15
Da-Vinci	Flying Production/ Elbit Systems	Israel	2014	On offer		Rotary wing	None	5.6			90	10
DelFly Explorer	MAVLab TU Delft	Netherlands	2014	Research	None	Flapping wing, with tail	None	0.020	0.280		10	
DelFly Micro	MAVLab TU Delft	Netherlands	2008	Research	None	Flapping wing, with tail	None	0.00307	0.100		3	0.050
DelFly Nimble	MAVLab TU Delft	Netherlands	2018	Research	None	Flapping wing, tailless	None	0.029	0.330		5	>1
Demon	Matrix UAV	Ukraine	2018	Development		Rotary wing	RPG-22/26 or RPG-7 or 5 kg bomb or 7 kg high-explosive fragmentation warhead					10-20
Desert Hawk	Integrated Dynamics	Pakistan		On offer		Fixed wing	None	4.5	1.500	0.900	>60	10-15

Name	Speed / km/h	Cruise speed / km/h	Max. speed / km/h	Alt. AGL / m	Alt. AMSL / m	Power	Propulsion	Guidance	Targeting	Payload	Launch	Recovery	References
Cerberus	60-80			<400		Electric	Trirotor	GCS		1.5 kg total, grenade launchers, micro munitions, shotguns or cameras	VTOL	VTOL	Skyborne Technologies, 2019
Comandor			60.0	5-1500 (operating), 2000 (ceiling)		12 electric or 2 piston engines	12 rotor blades	GPS, autopilot, manual, semi-automatic and automatic flight modes, GCS		50 kg total, civil and military cargo, fire suppressants, anti-tank missiles, free-fall bombs, video, radar, laser scanners, nuclear/explosives detectors	VTOL	VTOL	Streetly & Bernadi, 2018, pp. 216–217
Coyote		111	157.0	150-365 (operating), 6095 (ceiling)		Electric	Pusher propeller	GCS		1.4 kg maximum	Tube, canister	None	Raytheon, 2019; Streetly & Bernadi, 2018, pp. 340–341
Crazyflie 2.1						5 x 7 mm electric DC coreless motor, 240 mAh LiPo battery	4 rotor blades	IMU	None	15 g maximum	VTOL	VTOL	Bitcraze, 2020; Ben-Moshe et al., 2018
Cyclone						Electric	6 rotor blades	GCS			VTOL	VTOL	ISPRA, 2019; Amity Underground, 2018
Cygnus A10		50	85.0	300-1000		2-cylinder, 2-stroke engine	Pusher propeller	Fully autonomous and pre-programmable, 2-person GCS		EO/IR	Hand	Belly landing	Streetly & Bernadi, 2018, pp. 81–82
Da-Vinci		35	45.0	610		Electric	6 rotor blades	Autonomous take-off and landing, programmed flight patterns, waypoint navigation, "click and fly", return home, GCS	GPS assisted point-to-target function, target management modes	EO/IR	VTOL	VTOL	Streetly & Bernadi, 2018, pp. 105–106
DelFly Explorer						Brushless electric motor, 180 mAh LiPo battery	2 pairs of flapping wings	4.0 g stereo vision system, autonomous, barometer, IMU, autopilot, GCS	None	4.0 g stereo vision system	Hand		de Croon et al., 2016
DelFly Micro						Electric, 1 g 20 mAh LiPo battery	2 flapping wings	Radio GCS	None	0.4 g camera and transmitter, 0.2 g receiver	Hand		de Croon et al., 2016; MAVLab TU Delft, 2019b
DelFly Nimble	10.8-25.2 (forward), 14.4 (sideways)	10.8-25.2				Brushless DC motor, battery	2 pairs of flapping wings	Onboard 2.8 g autopilot, GCS	None	4.0 g total	Hand		Karásek et al., 2018; MAVLab TU Delft, 2019a
Demon						Electric	4 rotor blades			5-7 kg total, video, weaponry	VTOL	VTOL	Kasyanov, 2019
Desert Hawk	30-100		100.0			Electric	Tractor propeller	GPS, autonomous, telemetry, laptop GCS		0.5 kg daylight/IR	Hand	Belly-/deep-stall landing	Integrated Dynamics, 2019a

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Desert Hawk IV	Lockheed Martin	USA	2014	On offer		Fixed wing	None	3.69	1.500		150	
Drone-40	DefendTex	Australia	2017	On offer		Rotary wing	Kinetic anti-UAV or high-explosive warhead or anti-armour warhead or smoke grenade					10
DroneCatcher	Delft Dynamics	Netherlands	2015	On offer		Rotary wing	Net launcher	<6		0.75	30	
FanCopter	EMT	Germany	2006	Deployed	Germany, USA, South Africa	Rotary wing	None	1.5	0.600	0.60	25	1
FlyFast	IDS	Italy		On offer		Fixed wing	None	1.2	1.100	0.58	15	
Futura	Alcore	France	2000	Unclear		Fixed wing	Fragmentation warhead (mass unknown)	70.0	2.000	2.00	70	400
Golden Snitch	Tamkang University, Taipei	Taiwan	2012	Research	None	Flapping wing, with tail	None	0.008	0.200			
Green Dragon	Israel Aerospace Industries	Israel	2016	On offer		Fixed wing	2.5 kg warhead: anti-personnel or anti-tank or both combined	15	1.700	1.60	75	40
H2 Bird	Univ. of California, Berkeley; Carnegie Mellon University	USA	2013	Research	None	Flapping wing, with tail	None	0.013	0.265		10	
HERO-20	UVision	Israel	2019	On offer		Fixed wing	0.2 kg anti-personnel warhead	1.8			20	10
HERO-30	UVision	Israel	2015	On offer		Fixed wing	0.5 kg anti-personnel warhead	3			30	5-10-40
HERO-70	UVision	Israel	2015	On offer		Fixed wing	1.2 kg anti-light-vehicle warhead	7			45	40

Name	Speed / km/h	Cruise speed / km/h	Max. speed / km/h	Alt. AGL / m	Alt. AMSL / m	Power	Propulsion	Guidance	Targeting	Payload	Launch	Recovery	References
Desert Hawk IV		46	102.0			Electric	Tractor propeller	GCS		0.9 kg	Hand	Deep-stall landing	Lockheed Martin, 2019a; Jane's 360, 2019
Drone-40		72				Electric	Rotor blades	GCS		Camera	Grenade launcher, VTOL	VTOL	Australian Defence Magazine, 2019; N., 2019; Soldier Systems, 2019
DroneCatcher			72.0			Electric	4 rotor blades			EO	VTOL	VTOL	Delft Dynamics BV, 2015; Delft Dynamics BV, 2016
FanCopter						Electric	2 coaxial rotor blades, 3 steering rotor blades	Portable GCS		EO/IR	VTOL	VTOL	Streetly & Bernadi, 2018; EMT Penzberg, 2019b
FlyFast						Electric	Pusher propeller	GPS, IMU, waypoint navigation, man-portable GCS		0.3 kg modular	Hand	Parachute	IDS, 2019a
Futura	130 (loitering)	341	359.0	200-1000-4000		Turbojet	Turbojet	Automatic flight control, pre-programmed, GCS		EO/IR	Catapult	Skid landing	Streetly & Bernadi, 2018, p. 73
Golden Snitch						Electric motor, battery	2 flapping wings		None	None	Hand		Hsiao et al., 2012
Green Dragon	120-157 (loitering)		370.0	304-912		Electric	Pusher propeller				Canister		IAI, 2019; Army Technology, 2019c
H2 Bird	4					Electric, 90 mAh LiPo battery	2 flapping wings	GCS	None	2.8 g VGA camera	Hand		Julian et al., 2013
HERO-20						Electric	Pusher propeller			EO	Canister		UVision, 2019a
HERO-30						Electric	Pusher propeller			EO/IR	Canister		UVision, 2019b
HERO-70			185.0			Electric	Pusher propeller			EO	Canister		UVision, 2019c

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Name	Manufacturer	Origin	Intro	Status	In service	Configuration	Armament	MTOW / kg	Wingspan or rotor diameter / m	Length / m	Endurance / min	Range / km
HORUS	Leonardo Airborne & Space Systems	Italy	2012	Deployed	Brazil	Fixed wing	None	2.3	1.800	0.900	60	5-10
Heidrun V1	Sky-Watch	Denmark		On offer		Fixed wing	None	2.2	1.650	1.070		24
Hornet	AeroVironment	USA	2003	Research finished	None	Flying wing	None	0.170	0.381		6	
HoverMast 100	Sky Sapience	Israel	2013	Deployed	Israel	Tethered rotary wing	None					
Huginn X1D	Sky-Watch	Denmark	2012	Unclear		Rotary wing	None	1.59		0.630	25	2
I-Bird	Univ. of California, Berkeley	USA	2010	Research	None	Flapping wing, with tail	None	0.012	0.280	0.210		
IA-12 Stark	IDS	Italy	2014	Unclear		Rotary wing	None	12		1.500	120	10
IA-17 Manta	IDS	Italy	2014	On offer		Flying wing	None	5.0	1.800	1.150	240	10
IA-3 Colibri	IDS	Italy	2014	On offer		Rotary wing	None	5-7			50	
IBIS	Leonardo Airborne & Space Systems	Italy	2013	On offer		Rotary wing	None	12		1.700	35	5-10
INTISAR 100	UST	Malaysia		On offer		Rotary wing	None	13	1.520	1.340	60	2
Indago	Lockheed Martin	USA	2015	Deployed	USA	Rotary wing	None	2.3		0.813	50	2-10

Name	Speed / km/h	Cruise speed / km/h	Max. speed / km/h	Alt. AGL / m	Alt. AMSL / m	Power	Propulsion	Guidance	Targeting	Payload	Launch	Recovery	References
HORUS		58	72.0	300 (operating), 3500 (max.)		Electric	Tractor propeller	GPS, autopilot, waypoint navigation, semi-autonomous loitering, autonomous take-off and landing, GCS			Automatic, hand, catapult, pneumatic	Conventional landing, parachute	Streetly & Bernadi, 2018, pp. 136–137; Army Technology, 2019d
Heidrun V1		57	107.0	30-175		Electric	Tractor propeller	Fully autonomous, tracking antenna, compact GCS		EO/IR	Hand	Deep-stall landing	Streetly & Bernadi, 2018, p. 43
Hornet						Hydrogen fuel cell	Tractor propeller	GCS	None				Shkarayev et al., 2007
HoverMast 100				50-150		Electric power supply from ground vehicle	Rotor blades	Autonomous, GCS		11-8 kg (Alt. AGL / m: 50/150 m), CCD/IR, radar, relay, cellular antennas, hyperspectral sensors	VTOL	VTOL	Sky Sapience, 2019; Eshel, 2013
Huginn X1D	22		22.0	0.4-200		Electric	Rotor blades	GCS		EO/IR	VTOL	VTOL	Streetly & Bernadi, 2018, p. 44
I-Bird						Electric, 1.6 g DC motor, 1.6 g 60 mAh LiPo battery	4 flapping wings		None	IR camera, bluetooth module	Hand		Baek & Fearing, 2010
IA-12 Stark			100.0			Petrol engine	Main and tail rotors	Vehicle-mounted or portable GCS, mission planning, real time mission management		EO/IR, thermal	VTOL	VTOL	Streetly & Bernadi, 2018, pp. 128–129
IA-17 Manta			200.0		4500	2-stroke petrol engine	Pusher propeller	Pre-programmed mission, real-time mission management with portable GCS		EO/IR	Catapult	Parachute	Streetly & Bernadi, 2018, p. 129
IA-3 Colibri						Electric	4 rotor blades	GPS/IMU, person-portable GCS, auto-stabilisation, pre-programmed navigation		EO/IR	VTOL	VTOL	Streetly & Bernadi, 2018, p. 128; IDS, 2019b
IBIS			90.0			Electric	Main rotor blades, tail rotor	Fully autonomous mode, autopilot, waypoint navigation, loitering, take-off and landing, GCS		EO/IR	VTOL	VTOL	Streetly & Bernadi, 2018, p. 137
INTISAR 100		80		245		Petrol engine	Main and tail rotor	GPS, GLONASS, automatic take-off and landing, GCS		Digital stills, HD Video	VTOL	VTOL	Streetly & Bernadi, 2018, p. 147
Indago				3-91		Electric	4 rotor blades	GCS		Multiple, hot-swappable, EO/IR	VTOL	VTOL	Lockheed Martin, 2019b; Lockheed Martin, 2017

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Name	Manufacturer	Origin	Intro	Status	In service	Configuration	Armament	MTOW / kg	Wingspan or rotor diameter / m	Length / m	Endurance / min	Range / km
InstantEye Mk-3 GEN4-D1(ISR)	InstantEye Robotics	USA	2019	On offer		Rotary wing	None	1.361		0.309	45	4
InstantEye Mk-3 GEN5-D1/D2	InstantEye Robotics	USA	2018	On offer		Rotary wing	None	<0.255		0.330	27	1.5
Irkut-3	Irkut Engineering	Russia	2011	Unclear		Fixed wing	None	3.0	2.000	0.900	75	15
KX4-Interceptor	Threod	Estonia		On offer		Rotary wing	None	6		0.850	>30	5
KX4-LE Titan	Threod	Estonia		Deployed	Estonia	Rotary wing	None	11		1.180	45	5
KYB-UAV	Zala Aero Group	Russia	2019	On offer		Fixed wing	<3 kg warhead		1.210	0.950	30	
Kargu	STM	Turkey	2017	Deployed	Turkey	Rotary wing	Multiple warhead configurations (mass unknown)					
Koliber	ITWL	Poland		Unclear		Rotary wing	None	3.1		0.870	25	3
Leleka-100	DeViRo	Ukraine		Unclear		Fixed wing	None	5.0	1.980	1.140	120-150	100
MAGNI	Elbit Systems	Israel		On offer		Rotary wing	None	2.5			30	3
MITE 2 (Configuration B)	U.S. Naval Research Laboratory	USA	2001	Research finished	None	Fixed wing	None	0.213	0.368		20	
Malazgirt	Baykar	Turkey	2006	Unclear	Turkey	Rotary wing	None	12	1.800	1.200	35-90	15

Name	Speed / km/h	Cruise speed / km/h	Max. speed / km/h	Alt. AGL / m	Alt. AMSL / m	Power	Propulsion	Guidance	Targeting	Payload	Launch	Recovery	References
InstantEye Mk-3 GEN4-D1(ISR)			56.0	3658 (MSL, ceiling)		Electric	4 rotor blades	Operator-controlled waypoint navigation, GCS		0.454 g total, EO/IR	VTOL	VTOL	InstantEye Robotics, 2019; Air Force Technology, 2018
InstantEye Mk-3 GEN5-D1/D2			32.0	3658 (MSL, ceiling)		Electric	4 rotor blades	Operator-controlled waypoint navigation, GCS		EO/IR	VTOL	VTOL	InstantEye Robotics, 2019; Air Force Technology, 2018
Irkut-3		59	89.0	100-500 (operating), 3000 (ceiling)		Piston engine	Pusher propeller	Radio link, GCS		0.5 kg total, TV/IR, stills camera	Hand	Parachute	Streetly & Bernadi, 2018, p. 172
KX4-Interceptor		29		400		Electric	4 rotor blades	Fully autonomous or fly-by-camera flight mode, remote video terminal, GCS		Dual EO/IR	VTOL	VTOL	Threod, 2019a
KX4-LE Titan		29		400		Electric	4 rotor blades	GCS		Dual EO/IR	VTOL	VTOL	Threod, 2019b; Threod, 2019c
KYB-UAV	80-130					Electric	Pusher propeller	GCS		3 kg max.	Hand		ZALA Aero, 2019a
Kargu							Rotor blades		Autonomous targeting	EO/IR	VTOL	VTOL	STM, 2019c; Jane's 360, 2017
Koliber		60				Electric	4 rotor blades	GPS, autopilot, fully automatic, manual, pre-programmed, imagery exploitation package, GCS		Camera	VTOL	VTOL	Streetly & Bernadi, 2018, p. 164
Leleka-100		60-70	120.0	1500 (max.)		Electric	Pusher propeller	Autopilot, anti-GPS spoofing/jamming, inertial navigation, autonomous functionality, pre-programmed routes, GCS	None	Daylight camera	Hand, catapult	Parachute, belly landing	Streetly & Bernadi, 2018, pp. 214–215
MAGNI		40		13123 (ASL)		Electric	4 rotor blades	GCS	Coordinate tracking capabilities	EO	VTOL	VTOL	Elbit Systems, 2020; Elbit Systems, 2019a
MITE 2 (Configuration B)	32					2 x 7 W coreless, geared electric, 45 g 12 V LiSO2 primary (CR2)	2 tractor propellers	Remote, Range / km-based vision for object recognition and pose estimation, monocular vision for navigation and collision avoidance	None	Colour video system	Hand		Shkarayev et al., 2007; Christopher et al., 2001; Kellogg et al., 2002
Malazgirt				1095 (operating), 3660 (ceiling)		Petrol or electric engine	Main and tail rotor blades	GPS, INS, autonomous cruise, waypoint navigation, automatic take-off, landing and hover, return home, GCS		CCD, thermal	VTOL	VTOL	Streetly & Bernadi, 2018, p. 210

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Name	Manufacturer	Origin	Intro	Status	In service	Configuration	Armament	MTOW / kg	Wingspan or rotor diameter / m	Length / m	Endurance / min	Range / km
Mavic Mini	DJI	China	2019	Commercially available		Rotary wing	None	0.249		0.245	30	
Mavic Pro	DJI	China	2006	Commercially available		Rotary wing	None	0.734		0.200	21-27	13
Maya	Alcore	France	2002	Unclear		Rotary wing	None	2.5		0.320	30	50
MicroB	BlueBird Aero Systems	Israel	2018	On offer		Fixed wing	None	2.2	1.700		120	10
MicroFalcon LP	Innocon	Israel	2011	Deployed	Peru	Fixed wing	None	6	1.800		120	40
Microbat	California Institute of Technology, Pasadena; University of California, Los Angeles; AeroVironment Inc.	USA	2000	Research	None	Flapping wing, with tail	None	0.0125	0.229		0.7	
MultiRotor	Uconsystem	South Korea	2014	On offer		Rotary wing	None	8		1.530	30	1
Multirotor ELIX	ELi	Estonia	2014	On offer		Rotary wing	None	2.5		0.760	30	5
Multirotor ELIX XL	ELi	Estonia	2014	On offer		Rotary wing	None	4.7		1.100	45	5
Multirotor ELIX XXL	ELi	Estonia	2014	On offer		Rotary wing	None	5.5		1.160	50	5
NOX	Elbit Systems	Israel		On offer		Rotary wing	None	5			55	4
NX110m	Novadem	France		Deployed	France	Rotary wing	None	1.7		1.100	20	1

Name	Speed / km/h	Cruise speed / km/h	Max. speed / km/h	Alt. AGL / m	Alt. AMSL / m	Power	Propulsion	Guidance	Targeting	Payload	Launch	Recovery	References
Mavic Mini			47.0	3000 (ASL)		Electric	4 rotor blades	GPS, GLONASS, remote control via smartphone	None	Image/Video	VTOL	VTOL	DJI, 2019b; O'Kane, 2019
Mavic Pro			65.0	5000 (AMS)		Electric	4 rotor blades	GPS, GLONASS, GCS	None	EO	VTOL	VTOL	Streetly & Bernadi, 2018, p. 33; DJI, 2019a
Maya		54	104.0	50-1000		Rotary piston engine	Ducted fan	GPS, autopilot, GCS		CCD/IR	VTOL	VTOL	Streetly & Bernadi, 2018, pp. 57–58
MicroB				1000-4000		Electric	Pusher propeller	GCS		0.3 kg EO/IR	Hand-held launcher		BlueBird Aero Systems, 2020
MicroFalcon LP		65	120.0	4570		Electric	Tractor propeller	Fully autonomous flight control, including launch and recovery, 1-person GCS		EO/IR	Bungee catapult		Streetly & Bernadi, 2018, pp. 119–120
Microbat						Electric, DC motor, 3 g Sanyo Ni-Cad 50 mAh battery	2 flapping wings	Remote control	None		Hand		Pornsin-Sirirak et al., 2001
MultiRotor		30		150 (operating), 500 (max.)		Electric	Rotor blades	Autonomous navigation, 1-person GCS		EO/IR	VTOL	VTOL	Streetly & Bernadi, 2018, p. 143
Multirotor ELIX			58.0	500		Electric	4 rotor blades	GPS, GCS, compass avionics, waypoint navigation, autonomous flight control and mission execution, return home, emergency modes, pre-programmed flight patterns		EO/IR	VTOL	VTOL	Streetly & Bernadi, 2018, pp. 45–46
Multirotor ELIX XL			43.0	500		Electric	4 rotor blades	GPS, GCS, compass avionics, waypoint navigation, autonomous flight control and mission execution, return home, emergency modes, pre-programmed flight patterns		EO/IR	VTOL	VTOL	Streetly & Bernadi, 2018, pp. 45–46
Multirotor ELIX XXL			43.0	500		Electric	4 rotor blades	GPS, GCS, waypoint navigation, autonomous flight control and mission execution, return home, emergency modes, pre-programmed flight patterns, GCS		EO/IR	VTOL	VTOL	Streetly & Bernadi, 2018, pp. 56–57
NOX		40	50.0	3-457		Electric	3 rotor blades	Fully autonomous, GCS		0.7 kg total, EO	VTOL	VTOL	Elbit Systems, 2019b
NX110m			36.0	2200		Electric	4 rotor blades	GPS, waypoint, go-to, return home, emergency mode, autopilot, altimeter, GCS		CCD/IR, gas detection, radiation monitoring, spectrometer	VTOL	VTOL	Streetly & Bernadi, 2018, pp. 59–60

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Name	Manufacturer	Origin	Intro	Status	In service	Configuration	Armament	MTOW / kg	Wingspan or rotor diameter / m	Length / m	Endurance / min	Range / km
NX70	Novadem	France	2016	Deployed	France	Rotary wing, optionally tethered	None	1		0.510	45	1-5
Nano Hummingbird	AeroVironment	USA	2012	Research finished	None	Flapping wing, tailless	None	0.019	0.165		4	
PC-1	Ukrspecsystems	Ukraine		Deployed	Ukraine	Rotary wing	None	5.2		0.560	38	5
Patriot R2	ITEC	Ukraine		Unclear		Fixed wing	None	3.6	1.500	0.650	120	100
Perdix	Strategic Capabilities Office, US DoD	USA	2013	Development		Fixed wing	None	0.290	0.300	0.165	20	
Phoenix 30	UAV Solutions	USA	2014	Deployed	Romania, Bulgaria	Rotary wing	None	4.54		0.500	25-30	3
Pigeon	Sparkle Tech	China	2017	Commercially available		Fixed wing	None	1.9	1.200	0.520	60-90	
Pride	Integrated Dynamics	Pakistan		On offer		Fixed wing	None	4.5	1.610	1.450	30-45	3-5
Pszczoła	ITWL	Poland		Unclear		Fixed wing	None	0.8	0.500		20	5
REMOEYE-002B	UCONSYSTEM	South Korea	2015	Deployed	South Korea	Fixed wing	None	3.4	1.800	1.440	60	10
ROTEM	Israel Aerospace Industries	Israel	2016	On offer		Rotary wing	1.2 kg warhead, <1 m strike precision	5.8			30	10
RQ-11B Raven	AeroVironment	USA	2006	Deployed	USA, Philippines, Thailand, Ukraine, Uzbekistan, Belgium, Bulgaria, Czechia, Estonia, Hungary, Lithuania, Luxembourg, Netherlands, Norway, Portugal, Romania, Spain, Colombia, Iraq, Lebanon, Canada, Kenya, Uganda, Burundi	Fixed wing	None	1.9	1.400	0.900	60-90	10

Name	Speed / km/h	Cruise speed / km/h	Max. speed / km/h	Alt. AGL / m	Alt. AMSL / m	Power	Propulsion	Guidance	Targeting	Payload	Launch	Recovery	References
NX70						Electric	4 rotor blades	GCS		Dual EO/IR	VTOL	VTOL	Novadem, 2019; sUAS News, 2019a
Nano Hummingbird						DC brushed electric motor, LiPo battery pack	2 flapping wings	Remote	None	0.61 g camera and transmitter	VTOL	VTOL	Keennon et al., 2012
PC-1		36		1000 (ceiling)		Electric	4 twin rotors	Automatic take-off and landing, programmable flight route, GCS		EO/IR	VTOL	VTOL	Ukrspecsystems, 2020
Patriot R2		65		100 (operating, minimum), 2000 (ceiling)		Electric	Pusher propeller	Pre-programmed, GPS/GLONNAS, inertial navigation, GCS	Real-time air vehicle location tracking	Video/Photo	Catapult	Parachute	Streetly & Bernadi, 2018, p. 215
Perdix	74-111		111.0			Electric	Pusher propeller, 6.6 cm diameter	Autonomous			Airborne, ground-based or shipboard launchers		US SCO, 2019
Phoenix 30				15 (typical), 150 (max.)		Electric	4 rotor blades	Fully autonomous, laptop GCS		EO/IR	VTOL	VTOL	Streetly & Bernadi, 2018, p. 360
Pigeon		70	100.0	1000		Electric	Pusher propeller	Autopilot, inertia, GPS, GCS		0.5 kg EO	Hand, catapult	Parachute	Streetly & Bernadi, 2018, p. 36
Pride		30	100.0			Brushless electric	Tractor propeller	GPS, GCS		EO/IR	Hand	Deep-stall landing	Streetly & Bernadi, 2018, pp. 156–157
Pszczoła		10	100.0	50-300			Pusher propeller	GCS		Camera	Hand		Streetly & Bernadi, 2018, p. 165
REMOEYE-002B			80.0			Electric	Pusher propeller	Autopilot, pre-programmed flight, automatic return home, GCS		EO/IR	Hand	Automatic air-bag recovery	Uconsystem, 2019a; Air Recognition, 2019
ROTEM		102-157	370.0	1524		Electric	4 rotor blades	Obstacle avoidance, autonomous modes: emergency return home; nav-to-route, observation, attack, abort and ATOL (auto takeoff and landing), GCS	Strike precision <1 m	EO/IR, COMINT, fire detection sensors	VTOL	VTOL	IAI, 2020; Eshel, 2016
RQ-11B Raven	32-81		81.0	30-152		Electric	Pusher propeller	GPS, manually with GCS, programmed for autonomous flight		EO/IR	Hand	Deep-stall landing	AeroVironment, 2019a; Gettinger, 2019

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Name	Manufacturer	Origin	Intro	Status	In service	Configuration	Armament	MTOW / kg	Wingspan or rotor diameter / m	Length / m	Endurance / min	Range / km
RoboBee	Harvard University	USA	2013	Research	None	Tethered flapping wing, tailless	None	0.000080	0.030			
RoboBee X-Wing	Harvard University	USA	2013	Research	None	Flapping wing, tailless	None	0.000259	0.035	0.065		
Rover Mk I	Integrated Dynamics	Pakistan	2007	On offer		Fixed wing	None	2.0	1.500	0.900	20-45	2-4
SIS A-3 Remez	SIS	Ukraine		Deployed	Ukraine	Fixed wing	None	10.0	2.000	0.780	120	20
STORM	Blackbar Engineering	USA		On offer		Fixed wing	None	2.5	1.680	1.220	60-80	6-10
Scout	GIDS	Pakistan		On offer		Fixed wing	None	4.5	2.000	1.200	60	10
Skimmer Mk I	Swallow Systems	India	2011	Unclear		Fixed wing	None	2.5	1.700	1.200	60	5
Sky.Spider	INDELA	Belarus		Legacy		Rotary wing	None	7.2		1.580	20-40	15
SkyRanger R60	FLIR Systems	Norway	2013	Deployed	USA, New Zealand	Rotary wing	None				30-50	3-10
Skycam	Integrated Dynamics	Pakistan		On offer		Fixed wing	None	4.5	1.980	1.500	30	5
Skywalker X6	Skywalker	China	2016	Commercially available	China	Fixed wing	None	1.8-2.0	1.500	0.650	25	

Name	Speed / km/h	Cruise speed / km/h	Max. speed / km/h	Alt. AGL / m	Alt. AMSL / m	Power	Propulsion	Guidance	Targeting	Payload	Launch	Recovery	References
RoboBee						External electric power source wire tether	2 flapping wings	External active flight controller	None	None	VTOL	VTOL	Ma et al., 2013
RoboBee X-Wing		23-28				Electric, six-cell photovoltaic array	4 flapping wings		None	70 mg total	Hand		Jafferis et al., 2019
Rover Mk I		30	100.0	1000		Electric	Pusher propeller	GPS, telemetry with GCS		EO/IR	Hand	Belly or deep-stall landing	Streetly & Bernadi, 2018, p. 157; Integrated Dynamics, 2019b
SIS A-3 Remez		58	105.0			Piston engine	Shrouded pusher propeller	GPS, GCS (laptop)		3.0 kg total, 2 TV cameras	Wheeled take-off, catapult	Parachute	Streetly & Bernadi, 2018, p. 217–218
STORM				610		Electric	Tractor propeller	GCS		EO/IR	Hand	Skid or stall landing	Blackbar Engineering, 2019
Scout				455 (operating)		Brushless electric motor	Pusher propeller	GPS, waypoint navigation, autonomous, semi-autonomous, GCS		EO or IR	Hand	Skid landing	Streetly & Bernadi, 2018, p. 153; Global Industries & Defence Solutions, 2019
Skimmer Mk I			95.0	300		Electric	Pusher propeller	Waypoint navigation, return home, manual override, 2-person GCS		TV camera, low-light TV camera, thermal	Hand	Belly landing	Streetly & Bernadi, 2018, p. 83–84
Sky.Spider		40				Electric	4 rotor blades	2-screen GCS, auto-positioning antenna system		EO/IR	VTOL	VTOL	Streetly & Bernadi, 2018, p. 83–84
SkyRanger R60		50				Electric	4 rotor blades	Automated flight planning, touchscreen-controlled GCS		EO/IR	VTOL	VTOL	FLIR, 2020; Pointon, 2018; sUAS News, 2018
Skycam		30	100.0	305 (operating)		Combustion engine	Pusher propeller	Autopilot, telemetry, laptop GCS		Daylight TV and still camera	Hand	Belly landing, net capture	Streetly & Bernadi, 2018, p. 157
Skywalker X6	40			200		Electric	Pusher propeller		None		Hand, catapult	Glide down, parachute	Skywalker, 2019; HobbyKing, 2019

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Name	Manufacturer	Origin	Intro	Status	In service	Configuration	Armament	MTOW / kg	Wingspan or rotor diameter / m	Length / m	Endurance / min	Range / km
Snipe Nano UAS	AeroVironment	USA	2017	Unclear		Rotary wing	None	0.140			15	>1
Sparrow	Spaitech	Ukraine		On offer		Flying wing	None	3.3	0.98		60	20
Spike Firefly	Rafael	Israel	2018	Ordered	Israel	Rotary wing	<0.35 kg omnidirectional fragmentation warhead	3			15	5-10
Switchblade	AeroVironment	USA	2010	Deployed	USA	Fixed wing	Warhead (mass unknown)	2.5	0.61	0.36	>15	10-45
T-Hawk RQ-16A	Honeywell	USA	2003	Unclear	USA, United Kingdom, Poland	Rotary wing	None	7.8	0.33		50	
T-Rotor	Uconsystem	South Korea	2014	On offer		Tethered rotary wing	None	20		1.80	>1440	
THOR	Flying Production/ Elbit Systems	Israel		Deployed		Rotary wing	None	3			75	10
Tactical UAV	IPCD	Indonesia	2012	Deployed	Indonesia	Fixed wing	None	2	1.60	1.00	40	10
Urban View	Aurora Integrated Systems	India	2011	On offer		Fixed wing	None	2.0	1.50	0.80	60	15
VR1 Colibri	Tekever	Portugal	2015	Unclear		Rotary wing	None	2.8		0.50	30	2
Vapor 35	AeroVironment	USA	2012	On offer		Rotary wing	None	14.5	1.70	1.94	45-60	56

Name	Speed / km/h	Cruise speed / km/h	Max. speed / km/h	Alt. AGL / m	Alt. AMSL / m	Power	Propulsion	Guidance	Targeting	Payload	Launch	Recovery	References
Snipe Nano UAS	35					Electric	4 rotor blades	GPS waypoint navigation, GCS		EO/IR	VTOL	VTOL	AeroVironment, 2017a; Digital Trends, 2017
Sparrow	60-120			300-700-2000		Electric	Tractor propeller	IMU, GNSS, GCS	Automatic tracking of moving targets, target aiming and artillery fire correction	EO/IR or dosimeter or photo camera	Catapult	Parachute	Spaitech, 2019
Spike Firefly	70 (diving)	60	70.0			Electric	Coaxial twin rotor	Electro-optical / man-in-the-loop, autonomous: fly-by waypoints, fly-by video, GCS	Proximity sensors, tracker designed for agile targets	<0.35 kg EO, IR, CMOS, proximity sensor	VTOL	VTOL	Rafael, 2019; IHS Jane's 360, 2019; Ahronheim, 2020
Switchblade		101	161.0			Electric	Pusher propeller	GPS, automated waypoint navigation, GCS	Target selection by operator	EO/IR	Tube launch, air and ground vehicle, water craft	None	AeroVironment, 2019b; Streetly & Bernadi, 2018, pp. 252–253; Bledsoe, 2015
T-Hawk RQ-16A			93.0	0-150	3200 (ceiling)	Piston engine	Ducted fan	GPS, INS, pre-planned waypoints, retasking and manual intervention, GCS		EO or IR, radio relays, data links, radiation sensors	VTOL	VTOL	Streetly & Bernadi, 2018, pp. 278–280
T-Rotor				100 (operating)		Electric	8 rotor blades	Fully autonomous flight, waypoint navigation, real-time flight path modification, GCS		EO/IR	VTOL	VTOL	Streetly & Bernadi, 2018, p. 145; Uconsystem, 2019b
THOR		40	65.0	5-610		Electric	Four rotor blades	Automatic takeoff and landing, autonomous mission flight, GCS		3 kg total, EO/IR	VTOL	VTOL	Elbit Systems, 2019c; Streetly & Bernadi, 2018, p. 106; Frantzman, 2019
Tactical UAV		40	80.0	100-500		Electric	Pusher propeller	GCS		HD camera	Hand	Belly landing	Streetly & Bernadi, 2018, pp. 84–85
Urban View			59.0	90-305		Electric	Pusher propeller	Fully autonomous, pre-set flight patterns, GCS		EO/IR	Hand	Belly landing	Streetly & Bernadi, 2018, pp. 82–83
VR1 Colibri				250 (max.)		Electric	Rotor blades	Fully autonomous take-off and landing, mobile GCS		EO/IR	VTOL	VTOL	Streetly & Bernadi, 2018, p. 128
Vapor 35			54.0		0-12000	Electric	Main and tail rotor	Fully automatic flight operation without operator intervention, post-processed kinematic (PPK) mapping, GCS		2.27 kg total, EO/IR, LiDAR, hyperspectral sensors	VTOL	VTOL	AeroVironment, 2019c

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Name	Manufacturer	Origin	Intro	Status	In service	Configuration	Armament	MTOW / kg	Wingspan or rotor diameter / m	Length / m	Endurance / min	Range / km
Vector Hawk (VTOL)	Lockheed Martin	USA	2014	On offer		Rotary wing	None	2.27	1.100	0.60	45	15
Vector Hawk (fixed wing)	Lockheed Martin	USA	2014	On offer		Fixed wing	None	1.81	1.100	0.60	90	15
Vector Hawk (tiltrotor)	Lockheed Martin	USA	2014	On offer		Tiltrotor	None	2.27	1.100	0.60	80	15
Warmate	WB Electronics	Poland	2017	Deployed	Poland, Ukraine, Peru	Fixed wing	<1.4 kg fragmentation or shaped fragmentation warhead	5.3	1.400	1.10	50	10
Warmate R	WB Electronics	Poland	2019	On offer		Fixed wing	None	5.2			80	15
Warmate TL	WB Electronics	Poland	2019	On offer		Fixed wing	1.4 kg warhead	4.5	1.700	1.10	40	10
Warmate V	WB Electronics	Poland	2019	On offer		Rotary wing	1.6 kg warhead	7			30	12
Wasp	AeroVironment	USA	2002	Research finished	None	Flying wing	None	0.181	0.366		30	4
Wasp AE RQ-12A	AeroVironment	USA	2012	Deployed	Australia, Czechia, Spain, Netherlands, Sweden, USA	Fixed wing	None	1.3	1.020	0.76	50	>5
ZALA 421-08M	Zala Aero Group	Russia	2007	On offer		Fixed wing	None	2.5	0.810	0.43	80	15-25
ZALA LANCET-1	Zala Aero Group	Russia	2019	On offer		Fixed wing	Warhead (mass unknown)	5			30	40

Name	Speed / km/h	Cruise speed / km/h	Max. speed / km/h	Alt. AGL / m	Alt. AMSL / m	Power	Propulsion	Guidance	Targeting	Payload	Launch	Recovery	References
Vector Hawk (VTOL)			130.0		3050 (ceiling)	Electric	4 rotor blades	Autopilot, autonomous GPS, flight and landing, virtual cockpit GCS		EO/IR, laser illuminator	VTOL	VTOL	Streetly & Bernadi, 2018, pp. 302–303
Vector Hawk (fixed wing)		56	130.0		5180 (ceiling)	Electric	Tractor propeller, 2 rotor blades	Autopilot, autonomous GPS, flight and landing, virtual cockpit GCS		EO/IR, laser illuminator	Hand	Inverted skid, deep stall landing	Streetly & Bernadi, 2018, pp. 302–303
Vector Hawk (tiltrotor)		56	93.0		5180 (ceiling)	Electric	Tractor propeller, 2 rotor blades	Autopilot, autonomous GPS, flight and landing, virtual cockpit GCS		EO/IR, laser illuminator	Hand	VTOL	Streetly & Bernadi, 2018, pp. 302–303
Warmate						Electric	Pusher propeller	GCS		1.4 kg total, warhead	Canister	None	WB Group, 2019b; Gettinger, 2019
Warmate R				500 (ceiling)		Electric	Pusher propeller	GCS	Automatic target lock	EO/IR, laser illuminator		Parachute	WB Group, 2019c
Warmate TL		75	120.0	3000 (ASL, ceiling)		Electric	Pusher propeller	Pre-programmed waypoints, automatic loitering mode, fly-to-coordinate, cruise, i. e. flying into the direction the camera is facing, GCS	Automated videotracker even under communication loss	EO/IR	Tube	None	WB Group, 2019a
Warmate V		27		100 (operating), 300 (max.)	2000 (ceiling)	Electric	Trirotor	GCS		Observation (1.6 kg) or warhead payload	VTOL	VTOL	WB Group, 2019d
Wasp	40-48			91 (max.)		10 W DC electric motor	Tractor propeller	Autopilot	None	Colour video camera and transmitter	Hand		Shkarayev et al., 2007
Wasp AE RQ-12A		37	83.0	152		Electric	Tractor propeller	Autonomous, GCS		EO/IR	Hand	Deep-stall landing	AeroVironment, 2019d; Naval Drones, 2019a; Business Wire, 2016; Eshel, 2012; Armadni Noviny, 2017; Stevenson, 2017; ECD Confidencial Digital, 2013; Unmanned Systems Technology, 2016
ZALA 421-08M		65	130.0	3600 (ceiling)		Electric	Tractor propeller	GPS, GLONASS, autopilot, telemetry, magnetometer, GCS	Active target tracking unit	0.3 kg total, EO, thermal, stills and video	Hand or catapult	Parachute or net capture	Streetly & Bernadi, 2018, pp. 180–181
ZALA LANCET-1	80-110					Electric	Pusher propeller	GCS		EO/IR			ZALA Aero, 2019b; sUAS News, 2019b

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