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History and Overview

1.1 Overview

The first portion of the chapter reviews the history of UAV systems from the earliest and crudest “flying objects” through the events of the last decade, which has been a momentous period for UAV systems.

The second portion of the chapter describes the subsystems that comprise a complete UAV system configuration to provide a framework for the subsequent treatment of the various individual technologies that contribute to a complete UAS. The air vehicle itself is a complicated system including structures, aerodynamic elements (wings and control surfaces), propulsion systems, and control systems. The complete system includes, in addition, sensors and other payloads, communication packages, and launch and recovery subsystems.

Finally, a cautionary tale is presented to illustrate why it is important to consider the UAV *system* as a whole rather than to concentrate only on individual components and subsystems. This is the story of a UAS that was developed between about 1975 and 1985 and that may be the most ambitious attempt at completeness, from a system standpoint, that has so far been undertaken in the UAS community.

It included every key UAS element in a totally self-contained form, all designed from scratch to work together as a portable system that required no local infrastructure beyond a relatively small open field in which a catapult launcher and a net recovery system could be located. This system, called the Aquila remotely piloted vehicle (RPV) system, was developed and tested over a period of about a decade at a cost that approached a billion dollars. It eventually could meet most of its operational requirements.

The Aquila UAS turned out to be very expensive and required a large convoy of 5-ton trucks for transportation. Most importantly, it did not fully meet some unrealistic expectations that had been built up over the decade during which it was being developed. It was never put in production or fielded. Nonetheless, it remains the only UAS of which the authors are aware that attempted to be complete unto itself and it is worth understanding what that ambition implied and how it drove costs and complexity in a way that eventually led the system to be abandoned in favor of less complete, self-sufficient, and capable UAV systems that cost less and required less ground support equipment.

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Companion website: www.wiley.com/go/fahlstrom/uavsystems5e

1.2 History

1.2.1 Early History

Throughout their history, UAV systems have tended to be driven by military applications, as is true of many areas of technology, with civilian applications tending to follow once the development and testing had been accomplished in the military arena.

One could say that the first UAV was a stone thrown by a caveman in prehistoric times or perhaps a Chinese rocket launched in the thirteenth century. These "vehicles" had little or no control and essentially followed a ballistic trajectory. If we restrict ourselves to vehicles that generate aerodynamic lift and/or have a modicum of control, the kite would probably fit the definition of the first UAV.

In 1883, an Englishman named Douglas Archibald attached an anemometer to the line of a kite and measured wind velocity at altitudes up to 1,200 ft. Mr. Archibald attached cameras to kites in 1887, providing one of the world's first reconnaissance UAVs. William Eddy took hundreds of photographs from kites during the Spanish–American war, which may have been one of the first uses of UAVs in combat.

It was not until World War I, however, that UAVs became recognized systems. Charles Kettering (of General Motors fame) developed a biplane UAV for the Army Signal Corps. It took about 3 years to develop and was called the Kettering Aerial Torpedo, but is better known as the "Kettering Bug" or just plain "Bug." The Bug could fly nearly 40 mi at 55 mi/h and carry 180 lb of high explosives. The air vehicle was guided to the target by pre-set controls and had detachable wings that were released when over the target, allowing the fuselage to plunge to the ground as a bomb. Also, in 1917, Lawrence Sperry developed a UAV, similar to Kettering's, for the Navy, called the Sperry-Curtis Aerial Torpedo. It made several successful flights out of Sperry's Long Island airfield, but was not used in the war.

We often hear of the UAV pioneers who developed the early aircraft, but other pioneers were instrumental in inventing or developing important parts of the system. One was Archibald Montgomery Low, who developed data links. Professor Low, born in England in 1888, was known as the "Father of Radio Guidance Systems." He developed the first data link and solved interference problems caused by the UAV engine. His first UAVs crashed, but on September 3, 1924, he made the world's first successful radio-controlled flight. He was a prolific writer and inventor and died in 1956.

In 1933, the British flew three refurbished Fairey Queen biplanes by remote control from a ship. Two crashed, but the third flew successfully, making Great Britain the first country to fully appreciate the value of UAVs, especially after they decided to use one as a target and couldn't shoot it down.

In 1937 another Englishman, Reginald Leigh Denny, and two Americans, Walter Righter and Kenneth Case, developed a series of UAVs called RP-1, RP-2, RP-3, and RP-4. They formed a company in 1939 called the Radioplane Company, which later became part of the Northrop-Ventura Division. Radioplane built thousands of target drones during World War II. (One of their early assemblers was Norma Jean Daugherty, later known as Marilyn Monroe.) Of course, the Germans used lethal UAVs (V-1's and V-2's) during the later years of the war, but it was not until the Vietnam War era that UAVs were successfully used for reconnaissance.

1.2.2 The Vietnam War

The first real use of UAVs by the United States in a combat reconnaissance role began during the Vietnam War. UAVs, such as the AQM-34 Firebee developed by Teledyne Ryan, were used for a wide range of missions, such as intelligence gathering, decoys, and leaflet dropping.

During the Vietnam War era, UAVs were used extensively in combat, but for reconnaissance missions only. The air vehicles were usually air launched from C-130's and recovered by parachute. The air vehicles were what might be called deep penetrators and were developed from existing target drones.

The impetus to operations in Southeast Asia came from activities during the Cuban Missile Crisis when UAVs were developed for reconnaissance but not used because the crisis ended before they became available. One of the first contracts was between Ryan and the Air Force, known as 147A, for vehicles based on the Ryan Firebee target drone (stretched versions). This was in 1962 and they were called Fireflys. Although the Fireflys were not operational during the Cuban crisis, they set the stage for Vietnam. Northrop also improved their early designs, which were essentially model airplanes, to jet-propelled deep penetrators, but stuck mostly to target drones. The Ryan Firefly was the primary air vehicle used in Southeast Asia.

A total of 3,435 sorties were flown, and most of these (2,873, or nearly 84%) were recovered. One air vehicle, the TOMCAT, successfully completed 68 missions before it was lost. Another vehicle completed 97.3% of its missions of low-altitude, real-time photography. By the end of the Vietnam War in 1972, air vehicles were experiencing 90% success rates [1].

1.2.3 Resurgence

At the end of the Vietnam War, general interest in UAVs dwindled until the Israelis neutralized the Syrian air defense system in the Bekaa Valley in 1982 using UAVs for reconnaissance, jamming, and decoys. The Israeli Air Force pioneered several UAVs in the early 1980s. In 1982, United States observers noted Israel's use of UAVs in Lebanon and persuaded the Navy to acquire a UAV capability. One of the early UAVs acquired by the Navy was the RQ-2 Pioneer. It was developed jointly by AAI Corporation and Israeli Aircraft Industries and became a very useful air vehicle during Desert Storm for collecting tactical intelligence.

Actually, the Israeli UAVs were not as technically successful as many people believe, with much of their operational success being achieved through the element of surprise rather than technical sophistication. The air vehicle was basically unreliable and couldn't fly at night, and the data-link transmissions interfered with the manned fighter communications. However, they proved that UAVs could perform valuable, real-time combat service in an operational environment.

The United States began to work again on UAVs in August 1971 when the Defense Science Board recommended mini-RPVs for artillery target spotting and laser designation. In February 1974, the Army's Material Command established an RPV weapons system management office and by the end of that year (December) a "Systems Technology Demonstration" contract was awarded to Lockheed Aircraft Company, with the air vehicle subcontracted to Developmental Sciences Incorporated (later DSC, Lear Astronics, Ontario, CA). The launcher was manufactured by All American Engineering (later ESCO-Datron), and the recovery net system by Dornier of the then still-partitioned West Germany. Ten bidders competed for the program. The demonstration was highly successful, proving the concept to be feasible. The system was flown by Army personnel and accumulated more than 300 flight hours.

In September 1978, the so-called Target Acquisition/Designation and Aerial Reconnaissance System (TADARS) required operational capability (ROC) was approved, and approximately 1 year later, in August 1979, a 43-month Full Scale Engineering Development (FSED) contract was awarded to Lockheed as the sole source. The system was given the name "Aquila" and is discussed in more detail at the end of this chapter. For a number of reasons that provide important lessons to

UAV system developers, Aquila development stretched out for many years and the system was never fielded.

In 1984, partly as a result of an urgent need and partly because the Army desired some competition for Aquila, the Army started a program called Gray Wolf, which demonstrated, for the first time for a UAV, hundreds of hours of night operations in what could be called "combat conditions." This program, still partly classified, was discontinued because of inadequate funding.

1.2.4 Joint Operations

The US Navy and Marine Corps entered the UAV arena in 1985 by purchasing the Mazlat/Israeli Aircraft Industries (IAI) and AAI Pioneer system, which suffered considerable growing pains but still remains in service. However, Congress by this time became restless and demanded that a joint project office (JPO) be formed so that commonality and interoperability among the services would be maximized. The JPO was put under the administrative control of the Department of the Navy. This office has developed a master plan that not only defines the missions but also describes the desirable features for each kind of system needed by the services. Some elements of this plan will be discussed in Chapter 2 in the section called "Classes of UAV Systems."

The US Air Force was initially reluctant to embrace UAVs, notwithstanding their wealth of experience with target-drone unmanned aircraft. However, this attitude changed significantly during the 1990s and the Air Force not only has been very active in developing and using UAVs for a variety of purposes but also has been the most active of the four US services in attempting to take control of all UAV programs and assets within the US military.

1.2.5 Desert Storm

The invasion of Iraq to Kuwait in 1990–1991 allowed military planners an opportunity to use UAVs in combat conditions. They found them to be a highly desirable asset even though the performance of the systems then available was less than satisfactory in many ways. Five UAV systems were used in the operation: (1) the Pioneer by US forces, (2) the Ex-Drone by US forces, (3) the Pointer by US forces, (4) the "Mini Avion de Reconnaissance Telepilot" (MART) by French forces, and (5) the CL 89, a helicopter UAV, by British forces.

Although numerous anecdotal stories and descriptions of great accomplishments have been cited, the facts are that the UAVs did not play a decisive or a pivotal role in the war. For example, the Marines did not fire upon a single UAV-acquired target during the ground offensive according to a Naval Proceedings article published in November 1991 [2]. What was accomplished, however, was the awakening in the mind of the military community of a realization of "what could have been." What was learned in Desert Storm was that UAVs were potentially a key weapon system, which assured their continuing development.

1.2.6 Bosnia

The NATO UAV operation in Bosnia was one of surveillance and reconnaissance. Bomb-damage assessment was successfully accomplished after NATO's 1995 air attacks on Bosnian-Serb military facilities. Clearly shown in aerial photographs are Serbian tanks and bomb-damaged buildings. Night reconnaissance was particularly important as it was under the cover of darkness that most clandestine operations took place. The Predator was the primary UAV used in Bosnia, flying from an airbase in Hungary.

1.2.7 Afghanistan and Iraq

The war in Iraq (which lasted from 2003 to 2011) has transformed the status of UAVs from a potential key weapons system searching for proponents and missions to their rightful place as key weapon systems performing many roles that are central to the operations of all four services. At the beginning of the war, UAVs were still under development and somewhat "iffy," but many developmental UAVs were committed to Operation Iraqi Freedom.

The Global Hawk was effectively used during the first year despite being in the early stages of developmental. The Pioneer, the Shadow, the Hunter, and the Pointer were used extensively.

The Marines flew hundreds of missions using Pioneers during the battle for Fallujah in 2004 to locate and mark targets and keep track of insurgent forces. They were especially effective at night and could be considered one of the decisive weapons in that battle.

The armed version of the Predator, mini-UAVs such as the Dragon Eye, and a wide range of other UAV systems have been used on the battlefields of Afghanistan and Iraq and have proven the military value of UAVs.

Predator UAVs have been operational in Bosnia since 1995 and as part of Operation Enduring Freedom in Afghanistan and Operation Iraqi Freedom, flying more than 500,000 flight hours on over 50,000 flights. It is interesting to know that in 2002, an Iraqi MiG-25 intercepted an air-to-air equipped Predator. Both fired missiles at each other, but MiG-25 evaded but Predator was shot down.

During Operation Iraqi Freedom, the Global Hawk flew 15 missions, collecting over 4,800 images from March 18 to April 23, 2003.

1.2.8 Long-Range Long-Endurance Operations

After the 9/11/2001 terrorist attack on the World Trade Center in New York City, and during wars in Iraq and Afghanistan, US military explored the high value of UAVs in wars and even peace-time operations. Afterward, there were multiple UAV applications around the world including the war with ISIS and Al-Qaeda (2013–2017), many of which were long-range long-endurance wars. Three top UAVs that were employed for long-range long-endurance operations around the world are RQ-4 Global Hawk, RQ-1 Predator, and MQ-9 Reaper. The Reaper with its missiles, sensors, and relatively long endurance is a UAV that transformed military combat.

During Operation Enduring Freedom (from November to September 2002 in Afghanistan), the Global Hawk provided more than 17,000 near-real-time, high-resolution intelligence, surveillance, and reconnaissance images, flying more than 60 combat missions and logging more than 1,200 combat hours. By 2015, the Global Hawk surpassed 140,000 flight hours and 100,000 combat flight hours and exceeded operational performance targets. The following summarizes three recent projects for HALE UAVs with a pseudo-satellite mission.

In 2020, in partnership with NASA, the Swift Engineering [3] has developed the Swift HALE UAV to demonstrate how a successful high-altitude, long-endurance flight can expand science research in a cost-efficient and timely manner. This solar-powered UAV has a wingspan of 72 ft and weighs less than 180 lb, flies 10- to 15-lb payloads at a time, and is designed to operate at an altitude of 70,000 ft for 30 days or more.

Furthermore, BAE Systems is developing a solar-powered, stratosphere-flying UAV that can act as a backup option to disabled communications satellites. The Phasa-35 is designed to operate at altitudes of up to 70,000 ft. This HALE UAV with a wing span of 115 ft can remain in the air for up to a year without returning to Earth.

Moreover, the Airbus Zephyr unmanned aerial system has been designed and tested as an ultra-light high-altitude pseudo-satellite. However, in 2020, the UAV broke up in flight after encountering unstable atmospheric conditions, which resulted in a series of uncommanded rolls and an uncontrolled spiral descent.

1.3 Overview of UAV Systems

The primary element of an unmanned aerial system is the air vehicle (AV). A number of titles are employed in the literature for the air vehicle, including: (1) unmanned aerial vehicle, (2) remotely piloted vehicles (RPV), (3) radio-controlled (RC) plane, (4) model airplane, (5) remotely piloted aircraft (RPA), and (6) drones. The term RPV is an older name, and currently not much used. The term “RC plane” and “model airplane” are primarily used by hobbyists, aeromodellers, and Academy of Model Aeronautics (World’s largest model aviation association)[1], and “drone” is mainly employed by the media.

All, of course, are unmanned so the name “unmanned aerial vehicle” or UAV can be thought of as the generic title. To the purist, the “remotely piloted vehicle” is piloted or steered (controlled) from a remotely located position, so an RPV is always a UAV, but a UAV, which may perform autonomous or preprogrammed missions, need not always be an RPV.

In the past, these aircraft were all called drones, that is, a “pilotless airplane controlled by radio signals,” according to *Webster’s Dictionary*. Today the UAV developer and user community do not use the term “drone” except for vehicles that have limited flexibility for accomplishing sophisticated missions and fly in a persistently dull, monotonous, and indifferent manner, such as a target drone. This has not prevented the press and the general public from adopting the word “drone” as a convenient, if technically incorrect, general term for UAVs. Thus, even the most sophisticated air vehicle with extensive semiautonomous functions is likely to be headlined as a “drone” in the morning paper or on the evening news.

Whether the UAV is controlled manually or via a preprogrammed navigation system, it should not necessarily be thought of as having to be “flown,” that is, controlled by someone that has piloting skills. UAVs used by the military usually have autopilots and navigation systems that maintain attitude, altitude, and ground track automatically.

Manual control usually means controlling the position of the UAV by manually adjusting the heading, altitude, speed, etc., through switches, a joystick, or some kind of pointing device (mouse or trackball) located in the ground control station, but allowing the autopilot to stabilize the vehicle and assume control when the desired course is reached. Navigation systems of various types (global positioning system (GPS), radio, inertial) allow for preprogrammed missions, which may or may not be overridden manually.

As a minimum, a typical UAV system is composed of air vehicles, one or more ground control stations (GCS) and/or mission planning and control stations (MPCS), payload, and data link. In addition, many systems include launch and recovery subsystems, air-vehicle carriers, and other ground handling and maintenance equipment. A very simple generic UAV system is shown in Figure 1.1.

1 https://www.modelaircraft.org

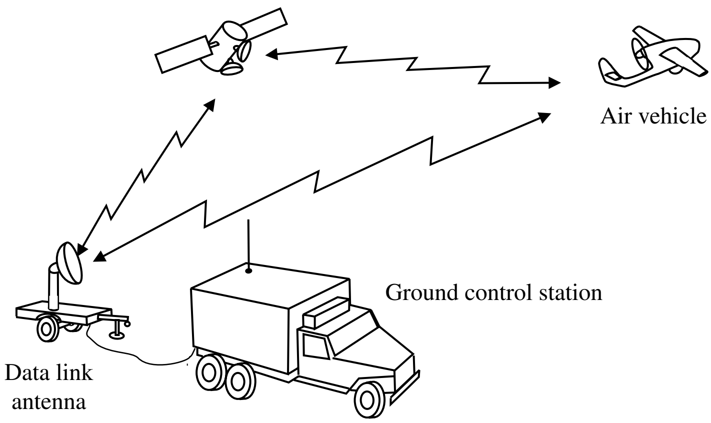

Figure 1.1 Generic UAV system

1.3.1 Air Vehicle

The air vehicle is the airborne part of the unmanned aerial system that includes the airframe, propulsion unit, flight controls, and electric power system. The air data terminal is mounted in the air vehicle, and is the airborne portion of the communications data link. The payload is also onboard the air vehicle, but it is recognized as an independent subsystem that often is easily interchanged with different air vehicles and uniquely designed to accomplish one or more of a variety of missions. The air vehicle can be a fixed-wing airplane, rotary wing (single or multiple), or a ducted fan. Lighter-than-air vehicles are also eligible to be termed UAVs.

1.3.2 Mission Planning and Control Station

The MPCS, also called the GCS, is the operational control center of the UAV system where video, command, and telemetry data from the air vehicle are processed and displayed. These data are usually relayed through a ground terminal, which is the ground portion of the data link. The MPCS shelter incorporates a mission planning facility, control and display consoles, video and telemetry instrumentation, a computer and signal processing group, the ground data terminal, communications equipment, and environmental control and survivability protection equipment.

The MPCS can also serve as the command post for the person who performs mission planning, receives mission assignments from supported headquarters, and reports acquired data and information to the appropriate unit, be it weapon fire direction, intelligence, or command and control, for example, the mission commander. The station usually has positions for both the air vehicle and mission payload operators to perform monitoring and mission execution functions.

In some small UAS, the ground control station is contained in a case that can be carried around in a back-pack and set up on the ground, and consists of little more than a remote control and some sort of display, probably augmented by embedded microprocessors or hosted on a ruggedized laptop computer.

At the other extreme, some ground stations are located in permanent structures thousands of miles away from where the air vehicle is flying, using satellite relays to maintain communications with the air vehicle. In this case, the operator's consoles might be located in an internal room of a large building, connected to satellite dishes on the roof. A cut-away view of a typical field MPCS for a long-range UAV is shown in Figure 1.2.

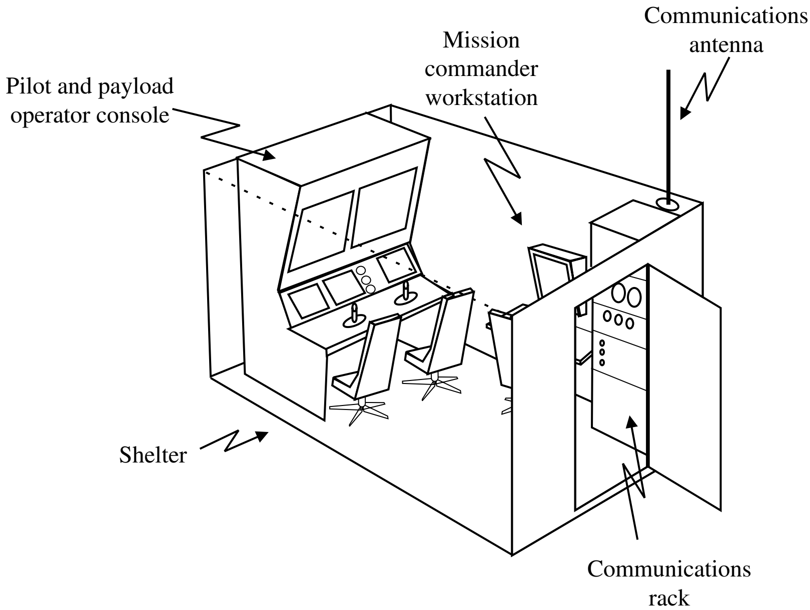

Figure 1.2 Mission planning and control station for a long-range UAV

1.3.3 Launch and Recovery Equipment

Launch and recovery can be accomplished by a number of techniques ranging from conventional takeoff and landing on prepared sites to vertical ascent/descent using rotary wing or fan systems. Catapults using either pyrotechnic (rocket) or a combination of pneumatic/hydraulic arrangements are also popular methods for launching air vehicles. Some small UAVs are launched by hand, essentially thrown into the air like a toy glider.

Nets and arresting gear are used to capture fixed-wing air vehicles in small spaces. Parachutes and parafoils are used for landing in small areas for point recoveries. One advantage of a rotary-wing or fan-powered vehicle is that elaborate launch and recovery equipment usually is not necessary. However, operations from the deck of a pitching ship, even with a rotary-wing vehicle, will require hold-down equipment unless the ship motion is minimal.

1.3.4 Payloads

Carrying a payload is the ultimate reason for having a UAV system, and the payload sometimes is the most expensive subsystem of the UAV. Payloads often include video cameras, either daylight or night (image-intensifiers or thermal infrared), for reconnaissance and surveillance missions. Film cameras were widely used with UAV systems in the past, but are largely replaced today with electronic image collection and storage, as has happened in all areas in which video images are used. Currently, video cameras are the most popular payloads in UAVs.

If target designation is required, a laser is added to the imaging device and the cost increases dramatically. Radar sensors, often using a Moving Target Indicator (MTI) and/or synthetic aperture radar (SAR) technology, are also important payloads for UAVs conducting reconnaissance missions. Another major category of payloads is electronic warfare (EW) systems. They include the full spectrum of signal intelligence (SIGINT) and jammer equipment. Other sensors such as meteorological and chemical sensing devices have been proposed as UAV payloads.

Armed UAVs carry weapons to be fired, dropped, or launched. “Lethal” UAVs carry explosive or other types of warheads and may be deliberately crashed into targets. As discussed elsewhere in this book, there is a significant overlap between UAVs, cruise missiles, and other types of missiles. The design issues for missiles, which are “one-shot” systems intended to destroy themselves at the end of one flight, are different from those of reusable UAVs and this book concentrates of the reusable systems, although much that is said about them applies as well to the expendable systems.

Another use of UAVs is as a platform for data and communications relays to extend the coverage and range of line-of-sight radio-frequency systems, including the data links used to control UAVs and to return data to the UAV users.

1.3.5 Data Links

The data link is a key subsystem for any UAV. The data link for a UAV system provides two-way communication (i.e., uplink and down link), either upon demand or on a continuous basis. An uplink with a data rate of a few kbps provides control of the air-vehicle flight path and commands to its payload. The downlink provides both a low data-rate channel to acknowledge commands and transmit status information about the air vehicle and a high data-rate channel (1–10 Mbps) for sensor data such as a video camera and radar.

The data link may also be called upon to measure the position of the air vehicle by determining its azimuth and range from the ground-station antenna. This information is used to assist in navigation and in accurately determining air-vehicle location (e.g., altitude). Other flight parameters, such as aircraft speed, climb rate, and direction, are often transmitted by a down link to MPCS.

Data links require some kind of anti-jam and anti-deception capability if they are to be sure of effectiveness in combat.

The ground data terminal is usually a microwave electronic system and antenna that provides line-of-sight communications, sometimes via satellite or other relays, between the MPCS and the air vehicle. It can be co-located with the MPCS shelter or remote from it. In the case of the remote location, it is usually connected to the MPCS by hard wire (often fiber-optic cables). The ground terminal transmits guidance and payload commands and receives flight status information (altitude, speed, direction, etc.) and mission payload sensor data (video imagery, target range, lines of bearing, etc.).

The air data terminal is the airborne part of the data link. It includes the transmitter and antenna for transmitting video and air-vehicle data and the receiver for receiving commands from the ground.

1.3.6 Ground Support Equipment

Ground support equipment (GSE) is becoming increasingly important because UAV systems are electronically sophisticated and mechanically complex systems. GSE for a long-range UAV may include: test and maintenance equipment, a supply of spare parts and other expendables, a fuel supply and any refueling equipment required by a particular air vehicle, handling equipment to move air vehicles around on the ground, if they are not man-portable or intended to roll around on landing gear, and generators to power all of the other support equipment.

If the UAS ground systems are to have mobility on the ground, rather than being a fixed ground station located in buildings, the GSE must include transportation for all of the things listed earlier, as well as transportation for spare air vehicles and for the personnel who make up the ground crew, including their living and working shelters and food, clothing, and other personal gear.

As can be seen, a completely self-contained, mobile UAS can require a lot of support equipment and trucks of various types. This can be true even for an air vehicle that is designed to be lifted and carried by three or four men.

1.4 The Aquila

The American UAS called the Aquila was a unique early development of a total integrated system. It was one of the first UAV systems to be planned and designed having unique components for launch, recovery, and tactical operation. The Aquila was an example of a system that contained all of the components of the generic system described previously. It also is a good example of why it is essential to consider how all the parts of a UAS fit together and work together and collectively drive the cost, complexity, and support costs of the system. Its story is briefly discussed here. Throughout this book, we will use lessons learned at great cost during the Aquila program to illustrate issues that still are important for those involved in setting requirements for UAS and in the design and integration of the systems intended to meet those requirements.

In 1971, more than a decade before the Israeli success in the Bekaa Valley, the US Army had successfully launched a demonstration UAV program, and had expanded it to include a high-technology sensor and data link. The sensor and data-link technology broke new ground in detection, communication, and control capability. The program moved to formal development in 1978 with a 43-month schedule to produce a production-ready system. The program was extended to 52 months because the super-sophisticated MICNS (Modular Integrated Communication and Navigation System) data link experienced troubles and was delayed. Then, for reasons unknown to industry, the Army shut the program down altogether. It was subsequently restarted by Congress (about 1982), but at the cost of extending it to a 70-month program. From then on everything went downhill.

In 1985, a Red Team formed to review the system came to the conclusion that not only had the system not demonstrated the necessary maturity to continue to production, but also that the systems engineering did not properly account for deficiencies in the integration of the data link, control system, and payload, and it probably would not work anyway. After two more years of intensive effort by the government and contractor, many of the problems were fixed, but nevertheless it failed to demonstrate all of the by then required capabilities during operational testing (OT) II and was never put into production.

The lessons learned in the Aquila program still are important for anyone involved in specifying operational requirement, designing, or integrating a UAS. This book refers to them in the chapters describing reconnaissance and surveillance payloads, and data links in particular, because the system-level problems of Aquila were largely in the area of understanding those subsystems and how they interacted with each other, with the outside world, and with basic underlying processes such as the control loop that connects the ground controller to the air vehicle and its subsystems.

1.4.1 Aquila Mission and Requirements

The Aquila system was designed to acquire targets and combat information in real time, beyond the line-of-sight of supported ground forces. During any single mission, the Aquila was capable of performing airborne target acquisition and location, laser designation for precision-guided munitions (PGM), target damage assessment, and battlefield reconnaissance (day or night). This is quite an elaborate requirement.

To accomplish this, an Aquila battery needed 95 men, 25 five-ton trucks, 9 smaller trucks, and a number of trailers and other equipment, requiring several C-5 sorties for deployment by air. All of this allowed operation and control of 13 air vehicles. The operational concept utilized a central launch and recovery section (CLRS) where launch, recovery, and maintenance were conducted. The air vehicle was flown toward the Forward Line of Own Troops (FLOT), and handed off to a forward control section (FCS), consisting mainly of a ground control station, from which combat operations were conducted.

It was planned that eventually the ground control station with the FCS would be miniaturized and be transported by a High Mobility Multipurpose Wheeled Vehicle (HMMWV) to provide more mobility and to reduce target size when operating close to the FLOT. The Aquila battery belonged to an Army Corps. The CLRS was attached to Division Artillery because the battery supported a division. The FCS was attached to a maneuver brigade.

1.4.2 Air Vehicle

The Aquila air vehicle was a tail-less flying wing with a rear-mounted 26-horsepower, two-cycle piston engine, and a pusher propeller. Figure 1.3 shows the Aquila air vehicle. The fuselage was about 2 m long and the wingspan was 3.9 m. The airframe was constructed of kevlar-epoxy material but metalized to prevent radar waves from penetrating the skin and reflecting off the square electronic boxes inside. The gross takeoff weight was about 265 lb and it could fly between 90 and 180 km/h up to about 12,000 ft.

1.4.3 Ground Control Station

The Aquila ground control station contained three control and display consoles, video and telemetry instrumentation, a computer and signal processing group, internal/external communications equipment, ground data terminal control equipment, and survivability protection equipment.

The GCS was the command post for the mission commander and had the display and control consoles for the vehicle operator, payload operator, and mission commander. The GCS was powered by a 30-kW generator. A second 30-kW generator was provided as a backup. Attached to the GCS by 750 m of fiber-optic cable was the remote ground terminal (RGT). The RGT consisted of a tracking dish antenna, transmitter, receiver, and other electronics, all trailer-mounted

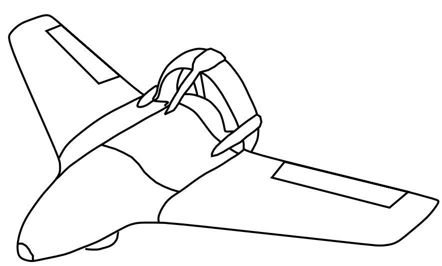

Figure 1.3 Aquila air vehicle

as a single unit. The RGT received downlink data from the air vehicle in the form of flight status information, payload sensor data, and video. The RGT transmitted both guidance commands and mission payload commands to the air vehicle. The RGT had to maintain line-of-sight contact with the air vehicle. It also had to measure the range and azimuth to the air vehicle for navigation purposes, and the overall accuracy of the system depended on the stability of its mounting.

1.4.4 Launch and Recovery

The Aquila launch system contained an initializer that was linked to the RGT and controlled the sequence of the launch procedure including initializing the inertial platform. The catapult was a pneumatic/hydraulic system that launched the air vehicle into the air with the appropriate airspeed.

The air vehicle was recovered in a net barrier mounted on a 5-ton truck. The net was supported by hydraulic-driven, foldout arms, which also contained the guidance equipment to automatically guide the air vehicle into the net.

1.4.5 Payload

The Aquila payload was a day video camera (Electro-Optic) with a bore-sighted laser rangefinder/designator for designating targets. Once locked on to a target, moving or stationary, it would seldom miss. The laser rangefinder/designator was optically aligned and automatically bore-sighted with the video camera. Scene and feature track modes provided line-of-sight stabilization and auto-tracking for accurate location and tracking of moving and stationary targets. An infrared (IR) night payload was also under development for use with Aquila.

1.4.6 Other Equipment

An air-vehicle handling truck was part of the battery ground support equipment and included a lifting crane. The lifting crane was necessary, not because the air vehicle was extremely heavy, but because the box in which it was transported contained lead to resist nuclear radiation. In addition, a maintenance shelter, also on a 5-ton truck, was used for unit-level maintenance and was a part of the battery.

1.4.7 Summary

The Aquila system had everything imaginable in what one could call "The Complete UAV System;" "zero-length" launcher, "zero-length" automatic recovery with a net, anti-jam data link, and day and night payload with designator. This came at a very high cost, however – not only in dollars but also in terms of manpower, trucks, and equipment. The complete system became large and unwieldy, which contributed to its downfall. All of this equipment was necessary to meet the elaborate operational and design requirements placed on the Aquila system by the Army, including a level of nuclear blast and radiation survivability (a significant contributor to the size and weight of shelters and the RGT mount). Eventually, it was determined that many of the components of the system could be made smaller and lighter and mounted on HMMWVs instead of 5-ton trucks, but by that time the whole system had gained a bad reputation for:

- Having been in development for over 10 years;
- Being very expensive;
- Requiring a great deal of manpower, a large convoy of heavy trucks for mobility, and extensive support;
- What was widely perceived to be a poor reliability record (driven by the complexity of the data link, air-vehicle subsystems, and the zero-length recovery system);
- Failure to meet some operational expectations that were unrealistic, but had been allowed to build up during the development program because the system developers did not understand the limitations of the system.

Foremost among the operational “disappointments” was that Aquila turned out to be unable to carry out large-area searches for small groups of infiltrating vehicles, let alone personnel on foot. This failing was due to limitations on the sensor fields of view and resolution and on shortcomings in the system-level implementation of the search capability. It also was partly driven by the failure to understand that searching for things using an imaging sensor on a UAV required personnel with special training in techniques for searching and interpretation of the images provided. The sources of these problems and some ways to reduce this problem by a better system-level implementation of area searches are addressed in the discussions of imaging sensors in Part Four and data links in Part Five.

The Aquila program was terminated as a failure, despite having succeeded in producing many subsystems and components that individually met all of their requirements. The US Army Red Team concluded that there had been a pervasive lack of systems engineering during the definition and design phases of the program. This failure set back US efforts to field a tactical UAS on an Army-wide basis, but opened the door for a series of small-scale “experiments” using less expensive, less-sophisticated air vehicles developed and offered by a growing “cottage industry” of UAV suppliers.

These air vehicles were generally conventionally configured oversized model airplanes or undersized light aircraft that tended to land and take off from runways if based on land, did not have any attempt at reduced radar signatures and little if any reduced infrared or acoustical signatures, and rarely had laser designators or any other way to actively participate in guidance of weapons.

They generally did not explicitly include a large support structure. Although they required most of the same support as an Aquila system, they often got that support from contractor personnel deployed with the systems in an ad hoc manner.

UAV requirements that have followed Aquila have acknowledged the cost of a “complete” standalone system by relaxing some of the requirements for self-sufficiency that helped drive the Aquila design to extremes. In particular, many land-based UAVs now are either small enough to be hand launched and recovered in a soft crash landing or designed to take off and land on runways. All or most use the global positioning system (GPS) for navigation. Many use data transmission via satellites to allow the ground station to be located at fixed installations far from the operational area and eliminate the data link as a subsystem that is counted as part of the UAS.

However, the issues of limited fields-of-view and resolution for imaging sensors, data-rate restrictions on downlinks, and latencies and delays in the ground-to-air control loop that were central to the Aquila problems are still present and can be exacerbated by use of satellite data transmission and control loops that circle the globe. Introducing UAV program managers, designers, system integrators, and users to the basics of these and other similarly universal issues in UAV system design and integration is one of the objectives of this textbook.

1.5 Global Hawk

1.5.1 Mission Requirements and Development

The requirement for a Global Hawk type of system grew out of Operation Desert Storm (in 1991). The Global Hawk was intended to compliment or replace the aging U-2 spy plane fleet. The Global Hawk is an advanced intelligence, surveillance, and reconnaissance air system (i.e., ISR mission). The strategy for this UAV program involved four phases, which were to be completed between 1994 and 1999.

It flew for the first time at Edwards Air Force Base, California, on Saturday, February 28, 1998. The first flight of the Global Hawk became the first UAV to cross the Pacific Ocean in April 2001 when it flew from the United States to Australia. The entire mission, including the takeoff and landing, was performed autonomously by the UAV as planned.

A total of 21 sorties of flight tests were conducted over 16 months using two air vehicles accumulating 158 total flight hours. It entered service in 2001 and reached the serial production stage in 2003. The Global Hawks, monitored by shifts of pilots in a ground control station in California, fly 24-hour missions, and they are cheaper to operate than the manned aircraft Lockheed U-2.

1.5.2 Air Vehicle

The Global Hawk unmanned aerial system consists of the aircraft, payloads, data links, ground stations, and logistics support package. Global Hawk is the largest active current UAV with successful flights, and with a high altitude and long endurance (HALE). A Global Hawk (Figure 1.4) is equipped with a single AE 3007H turbofan engine – mounted on top of the rear fuselage – supplied by Rolls-Royce. The engine is mounted on the top surface of the rear fuselage section with the engine exhaust between the V tail.

The wing and tail are made of graphite composite materials. The wing has structural hard points for external stores. The aluminum fuselage contains pressurized payload and avionics compartments. The V-configuration of the tail provides a reduced radar and infrared signature. Some mass and geometry features as well as the flight performance of Global Hawk are provided in Table 1.1.

Figure 1.4 Global Hawk (Source: Bobbi Zapka / Wikimedia Commons / Public Domain)

Table 1.1 RQ-4B Global Hawk data and performance

No.	Parameter	Value (unit)
1	Wingspan	39.9 m
2	Length	14.5 m
3	Maximum takeoff mass	14,628 kg
4	External payload weight	3,000 lb
5	Internal payload weight	750 lb
6	Turbofan engine thrust	34 kN
7	Maximum speed	340 knots
8	Range	22,779 km
9	Endurance	32+ hours
10	Service ceiling	60,000 ft

The prime navigation and control system consists of two systems, the Inertial Navigation System and the Global Positioning System (INS/GPS). The aircraft is flown by entering specific way points into the mission plan. The GCS consists of two elements, the Launch and Recovery Element (LRE) and the Mission Control Element (MCE). The LRE is located at the air vehicle base. It launches and recovers the air vehicle and verifies the health and status of the various onboard systems. The MCE is employed to conduct the entire flight from after takeoff until before landing.

Many changes have been applied in the design of Northrop Grumman RQ-4B Global Hawk as compared with RQ-4A. For instance, the RQ-4B Global Hawk has a 50% payload increase, larger wingspan (130.9 ft) and longer fuselage (47.6 ft), and a new generator to provide 150% more electrical output. Although RQ-4B carries more fuel than RQ-4A, it has a slightly shorter range and endurance, due to a heavier maximum takeoff weight.

1.5.3 Payloads

Originally RQ-4A had three sensors (as payload): an Electro-Optical/Infrared sensor and two Synthetic Aperture Radar Sensors – which are located under the fuselage belly in the integrated sensor suit – have been enhanced for RQ-4B. The main thrust of the air vehicle changes over time has involved the sensors. The enhancement improves the range of both the SAR and infrared system by approximately 50%.

1.5.4 Communications System

The Global Hawk has a wide-band satellite data link and a line-of-sight data link. Data is transferred by: (1) Ku-band satellite communications, (2) X-band line-of-sight links, and (3) both Satcom and line-of-sight links at the UHF-band. The synthetic aperture radar and ground moving target indicator operates at the X-band with a 600 MHz bandwidth.

The air traffic control (ATC) and command-and-control (C2) of the NASA Global Hawk from the Dryden Flight Research Center is applied in two distinct regions: (1) The line-of-sight (LOS) and (2) The beyond line-of-sight (BLOS). The communications link used for LOS are through UHF/VHF links. The primary communications links used for BLOS are two Iridium Satcom links. However, an Inmarsat Satcom link provides a backup communications capability.

The NASA Global Hawk payload communications architecture is independent of the communications links utilized to control the aircraft. Four dedicated Iridium SatCom communication links are used for continuous narrow band communications between the ground station and the UAV payloads. Moreover, two additional Iridium links are used to monitor power consumption by individual payloads, and to control features such as lasers and dropsonde. The use of the Iridium system provides a complete global coverage, including the Polar regions.

1.5.5 Development Setbacks

During Global Hawk flight tests programs and long operations, there were a number of setbacks [4], where a few resulted in the loss of the air vehicle and one caused damage to the sensor suite of another air vehicle.

The major setback during flight testing was the destruction of air vehicle 2 on March 29, 1999. The aircraft experienced an uneventful liftoff from the runway at Edwards Air Force Base (AFB). As it was climbing, the air vehicle unexpectedly flipped over on its back, shut down its engine, and locked the flight controls into a death spin. The aircraft executed the termination command and crashed. The crash was due to a lack of proper frequency coordination between the Nellis AFB and Edwards AFB flight test ranges.

In December 1999, a software problem caused another Global Hawk to accelerate to an excessive taxi speed after a successful, full stop landing on Edwards' main runway. An error in software code to coordinate between the mission planning system and the aircraft commanded the vehicle to taxi at 155 knots. The nose gear collapsed causing $5.3 million worth of damage to the electro-optical/infra-red (EO/IR) sensors. The primary cause of this mishap was the execution of a commanded ground speed of 155 knots for a taxi on the contingency mission plan.

During the deployment phase, two of the prototype air vehicles were lost and sustained. The first loss occurred on December 30, 2001, when the Global Hawk was returning from a truncated operational mission in support of Operation Enduring Freedom. To help a descent at 54,000 ft, four spoilers were raised to the maximum deflection (45 degrees), which caused a turbulent air-induced flutter. The subsequent energy of the resultant flutter was absorbed by the right V-tail main spar. The right outboard ruddervator actuator control rod failed, allowing the ruddervator to travel unrestrained beyond its normal range. Then, the vehicle departed controlled flight, entered a right spin, and crashed. The loss was attributed to a structural failure of the right ruddervator assembly of the V-tail (massive delamination of the main spar).

The second loss occurred on July 10, 2002, when a Global Hawk was flying an operational mission in Operation Enduring Freedom. The mishap vehicle experienced a catastrophic engine failure and glided for about half an hour. The vehicle impacted the ground during the attempted emergency landing. The mishap was attributed to a fuel nozzle failure in the high flow position that eventually led to the engine internal failure.

Another loss was when on June 20, 2019, Iran shot down a Global Hawk with a surface-to-air missile over the Strait of Hormuz. Iran said that the UAV violated its airspace, while US officials responded that the air vehicle was flying in international airspace.

These real stories provided valuable lessons and presented expensive experiences for young UAV designers. As typical of any development program, the Global Hawk design changed as the result of flight tests.

1.6 Predator Family

1.6.1 Predator Development

RQ-1 Predator is a long-endurance, medium-altitude unmanned aircraft system for surveillance, reconnaissance, and attack missions, designed and manufactured by General Atomics Aeronautical Systems.

The Predator had an unconventional development cycle with origins going back to a project by Abraham E. Karem. He is a pioneer in innovative fixed and rotary-wing unmanned vehicles and is regarded as one of the founding fathers of UAV technology. Initially, by 1983, a small long-endurance tactical reconnaissance UAV prototype was developed called the Albatross for the DARPA. Then, by 1988, further development resulted in a more advanced design, the Amber, which was followed by the GNAT 750. Karem's company (Karem Aircraft, Inc.) and its UAV were soon acquired by General Atomics.

The CIA utilized the GNAT 750 in military operations over Bosnia in 1993 and 1994. The program suffered from a few weaknesses, but it held enough promise that the DOD expressed interest in a larger, more advanced version of the GNAT 750 for medium-altitude reconnaissance, then designated RQ-1 Predator. By 1995, it became operational over Bosnia. In parallel, the Air Force saw the Predator as a new tool in tactical reconnaissance with the added benefit of a live satellite data link.

In the late 1990s, Predator's capability was expanded to include a laser designator to illuminate targets and guide weapons dropped from other aircraft. In 1999, the UAV had its first significant test during Operation Allied Force in Kosovo. By 2000, due to concern over the rising threat of al Qaeda, the Predator was scheduled for arming with the Hellfire laser-guided missile.

After the September 11, 2001 attacks, the armed Predator become fully operational, and by January 2003, flew 164 missions over Afghanistan. The armed Predator – capable of both reconnaissance and attack missions – has continued to have a pivotal role in combat operations. In 2002, the Air Force adapted a Predator to carry Stinger missiles and attempted an air-to-air engagement with an Iraqi MiG-25, but resulted in the loss of the Predator.

Predator UAVs have been operational since 1995 in support of NATO, UN, and US operations, and as part of Operation Enduring Freedom in Afghanistan and Operation Iraqi Freedom, flying more than 500,000 flight hours. The US Air Force Predator production ended in 2011 with 268 air vehicles manufactured. Hundreds of Predators have been sold to a number of countries including Italy, Spain, France, UK, Australia, Netherlands, Canada, and Germany.

This military UAV has been used in the Balkans, Afghanistan, Iraq, and other global locations. By 2011, the US military had nearly 11,000 UAVs on their inventory, including hundreds of Predators. The Predator was retired in 2018. The Predator-series family encompasses MQ-1 Predator, MQ-1C Gray Eagle, MQ-9 Reaper (Predator B), MQ-9B SkyGuardian, and Predator C Avenger.

1.6.2 Reaper

After about 10 years of Predator operations, and when some weaknesses were identified, new challenges arose in employing Predator. DOD decided to have a new version of Predator with enhanced performance features and an advanced design. The operation requirements included such performance items as a faster cruising speed and higher flight altitude, and also heavier and more advanced payloads. The conceptual design and the air vehicle configuration were almost kept. The only major configuration change was to have a V-tail instead of an inverted V-tail.

(a) (b)

Left: A British MQ-9A Reaper operating over Afghanistan in 2009 (Source: Tam McDonald / Wikimedia Commons / OGL v1.0). Right: CBP's Reaper (Source: Gerald L. Nino / Wikimedia Commons / Public Domain)

Figure 1.5 General Atomics MQ-9 Reaper

The US Air Force first deployed the MQ-9 Reaper (developed by General Atomics, then called Predator B) to Afghanistan in October 2007 for precision airstrikes and it slowly began replacing the Predator. The General Atomics MQ-9 Reaper (Figure 1.5) flew its first operational mission in Iraq in July 2008. In the meantime, the Army began development of a refined derivative, the MQ-1C Gray Eagle, which began operations in 2012. The US Air Force retired the Predator in 2018, replacing it with the Reaper.

The first version of Predator (A) had a piston engine, but the upgraded Predator B, or MQ-9 Reaper, is equipped with a turboprop engine (with a greater power). Predator B is larger, much heavier, with an improved flight performance (e.g., faster cruise speed, longer range, and longer endurance) than the earlier MQ-1 Predator.

There are two groups of Payloads: (1) surveillance imagery sensors, which include a synthetic aperture radar, electro-optic video, and forward-looking infrared (FLIR) cameras, (2) weapon payloads, which include four anti-armor missiles AGM-114 Hellfire), two laser-guided bombs (GBU-12), and 500 lb joint direct attack munition. Other payload options include a laser designator and rangefinder, electronic support and countermeasures, a moving target indicator (MTI), and an airborne signals intelligence payload.

1.6.3 Features

Reaper UAV has a single turboprop engine on the rear fuselage, a fixed tricycle landing gear, a high aspect ratio wing, with a V-tail. It has an aileron for roll control and a ruddervator for longitudinal and directional control. The air vehicle is equipped with UHF and VHF radio relay links, a C-band line-of-sight data link, which has a range of 150 nm, and UHF and Ku-band satellite data links.

The ground control station (GCS) is built into a single 30 ft trailer, containing pilot and payload operator consoles, three data exploitation and mission planning consoles, and two synthetic aperture radar workstations together with satellite and line-of-sight ground data terminals. The GCS also includes a data distribution system, which is equipped with a 5.5 m dish antenna or Ku-band ground data terminal and a 2.4 m dish antenna for data dissemination. The flight can be controlled through line-of-site data links or through Ku-band satellite links to produce a continuous video. Some mass and geometry features as well as flight performance of Reaper are provided in Table 1.2.

Predator and Reaper still have two major weaknesses: (1) the inability to operate in contested airspace with effective enemy air defenses and (2) jamming. These highlight the advances required

Table 1.2 Reaper data and performance

No.	Parameter	Value (unit)
1	Wingspan	65 ft 7 in
2	Length	36 ft 1 in
3	Maximum takeoff weight	10,494 lb
4	External payload weight	3,000 lb
5	Internal payload weight	800 lb
6	Turboprop engine power	900 hp
7	Maximum speed	260 knots
8	Range	1,200 mi
9	Endurance – fully loaded	14 hours
10	Service ceiling	50,000 ft

for future Reaper versions to maintain its operational significance. Jamming can pose a significant threat to the Predator's data links and GPS navigation.

1.7 Top UAV Manufacturers

The global unmanned aerial vehicle market is witnessing a strong compounded annual growth, even in 2020 where the COVID-19 emerged as a global pandemic. By January 2019, at least 60 countries were using or developing over 1,300 various UAVs. Top unmanned aerial systems and air vehicles in the market are Northrop Grumman (US), General Atomics (US), AeroVironment (US), Lockheed Martin (US), Elbit Systems (Israel), Israel Aerospace Industries (Israel), BAE Systems (UK), Parrot (France), Microdrones (Germany), SZ DJI Technology (China), Ehang (China), Yuneec International (China), Textron (US), Saab (Sweden), and Raytheon (US). The overall market is expected to reach $21.8 billion by 2027.

A number of European countries (France, Italy, Greece, Spain, Switzerland, and Sweden) are collectively developing the next generation of UCAVs (most notably the nEUROn) and the MALE unmanned aircraft. It is interesting to note that, as of March 2020, DJI accounts for around 70% of the world's consumer UAV market. The dominant US UAV manufacturers include Boeing, Lockheed Martin, Aurora Flight Sciences, General Atomics, Northrop Grumman, and AeroVironment.

1.8 Ethical Concerns of UAVs

All engineering products share some ethical issues, but the ethical concerns in UAVs are new and not yet regulated. Like other engineering products, there are many ways that UAVs are utilized unlawfully or unethically (e.g., drug trafficking). There are basically two ethical issues in employing UAVs: (1) invasion of privacy and (2) killing innocent individuals (lethal use). For instance, between 2004 to 2010, the US drone program in Pakistan [3] has killed several hundred civilians accidentally.

There are many unanswered questions regarding these two major areas. There are much less ethical concerns regarding mechanical robots than UAVs. When a UAV is flying over houses and is collecting data, this is a case for ethical concern. Due to these concerns, when a user of an UAV does not feel accountability, he/she may trespass the privacy of other citizens and cause loss of life of other individuals.

According to the US government accountability office, there are still four areas of concern for UAVs in using airspace: (1) the inability to recognize and avoid other aircraft, (2) lack of operational standards, (3) vulnerability in command and control of UAV, and (4) lack of Government regulations necessary to safely facilitate the accelerated integration of UAVs into the national airspace system. Moreover, the utilization of unmanned aerial systems for military applications is currently a contested and debated issue.

Having a center in ethics-informed interdisciplinary research and the integration of ethical literacy throughout the UAV curriculum is a valuable step toward removing ethical concerns. It is promising that AIAA has developed a code of ethics, and recommends all aeronautical engineers to observe these codes in designing and developing air vehicles.

There are concerns about the risks of flying the military UAVs outside war zones. There are reports that US UAVs have repeatedly crashed at civilian airports overseas throughout the world. Among the problems cited in the reports "are pilot error, mechanical failure, software bugs, and poor coordination with civilian air-traffic controllers. Since an initial report of a crash in January of 2011 at a US base in Djibouti, there have been 'at least six more Predators and Reapers' crashes" in the vicinity of civilian airports overseas.

In 2021, the FAA announced [3] two final rules for unmanned aircraft, which will require Remote Identification (Remote ID) of drones and allow remote operators of small drones to fly over people and at night under certain conditions. This is a major step toward further integrating UAVs into the National Air Space.

A great many arguments challenge the ethical justifiability of remote weapons (UAVs) by US military. One of the questions is: Does it really matter if a human kills an enemy or if a machine (UAV) kills that enemy as long as the enemy is eliminated? The issues at stake in the "UAV ethics" discussions are complex. The authors are not ready to answer these types of questions, but we invite scholars to dive deep into this topic and help law makers to cast laws to resolve these concerns.

Questions

1) What do UAV, RPV, RPA, GPS, UAS, MTI, SAR, MPCS, GCS, PGM, CLRS, HMMWV, EO/IR, LOS, BLOS, FLOT, and SIGINT stand for?
2) Write the titles that are employed in the literature for the unmanned air vehicle.
3) Briefly write what Chapter 1 presents.
4) When was the first real use of UAVs by the United States in a combat reconnaissance role?
5) What UAVs were used in the operation during the Kuwait/Iraq war?
6) What UAVs were used in the Operation Iraqi Freedom?
7) How many bidders were competing in 1971 on the UAV program for a call by US DOD?
8) Name four companies that worked on a UAV in the early 1970s in response to a call by the Defense Science Board.
9) When did the US Navy and Marine Corps enter the UAV arena? What did they purchase in that year?

10) What UAV systems – and by which countries – were used in combat operation during the invasion of Iraq to Kuwait in 1990–1991?
11) What was the mission of NATO UAV operation in Bosnia in 1995?
12) Which UAV was the primary UAV used in Bosnia in 1995? Where was the UAV flying from?
13) What UAVs were used extensively during the war in Iraq (from 2003 to 2011)?
14) What UAV was used during the battle for Fallujah in Iraq in 2004 to locate and mark targets and keep track of insurgent forces?
15) How many missions did the Global Hawk fly during Operation Iraqi Freedom in 2003?
16) What term is adopted by the press and the general public as a general term for UAVs?
17) What does manual control of a UAV usually mean?
18) What is a typical UAV system composed of?
19) Show a very simple generic UAV system in a figure.
20) What does the air vehicle as the airborne part of the unmanned aerial system include?
21) What is the mission planning and control station also called?
22) Briefly describe the function of the mission planning and control station.
23) Write two extreme forms (with brief features) of an MPCS.
24) Write a few popular types of launch and recovery techniques/equipment.
25) Write one advantage of a rotary-wing or fan-powered vehicle over a fixed-wing UAV in launch and recovery.
26) What is the ultimate reason for having a UAV system?
27) Briefly compare the cameras (as the UAV payload) that were used in the past versus current ones.
28) What is the most popular payload in UAVs today?
29) Name a few types of UAV payloads.
30) What does a "Lethal" UAV carry as the payload?
31) Briefly compare a lethal UAV with a missile.
32) What is the function of a UAV when used as a platform for data and communications relays?
33) What does a downlink provide?
34) What is the typical data rate of: (a) uplink and (b) downlink?
35) What typical flight parameters are often transmitted by a downlink to MPCS?
36) What feature is required by a data link, if it is to be sure of effectiveness in combat?
37) Briefly describe the features of the ground data terminal of a data link.
38) What does the air data terminal include as the airborne part of the data link?
39) What does a ground support equipment for a long-range UAV typically include?
40) When must a GSE include transportation?
41) What American UAS was a unique early development of a total integrated system?
42) In what year did the Aquila program move to formal development?
43) What was the initial and final durations of the Aquila program?
44) What were the Aquila mission and requirements?
45) List the number of personnel, trucks, sorties, and other equipment used to allow operation and control of an Aquila battery (i.e., 13 air vehicles).
46) Briefly describe the configuration of the Aquila air vehicle.
47) Write the fuselage length and wingspan of the Aquila air vehicle.
48) Write engine type and engine power of the Aquila air vehicle.
49) What material was the Aquila air vehicle made of?
50) Write the speed range of the Aquila air vehicle.
51) Write the flight altitude of the Aquila air vehicle.

52) Briefly describe the equipment used in the Aquila ground control station.
53) How was the connection made between the ground control station and the remote ground terminal of the Aquila UAS?
54) How much was the power of the generator for the ground control station of the Aquila UAS?
55) Did the remote ground terminal have to maintain line-of-sight contact with the Aquila air vehicle?
56) Briefly describe the launch and recovery systems of the Aquila.
57) What was the Aquila payload?
58) Why was the box – in which Aquila was transported – heavy?
59) Did the data link of Aquila have an anti-jam capability?
60) Did the Aquila system include a level of nuclear blast and radiation survivability?
61) Provide reasons why the whole Aquila system gained a bad reputation.
62) What was the foremost operational “disappointment” of the Aquila? What was this failing due to?
63) Was the Aquila program terminated as a failure or as a success?
64) Some of the UAV requirements – that have followed Aquila – have been relaxed. Provide at least three items.
65) The Global Hawk was intended to compliment or replace a manned aircraft. What was that?
66) When and where was the first flight of the Global Hawk?
67) When did the Global Hawk enter service? When did it reach the serial production stage?
68) Which unmanned aerial vehicle became the first UAV to cross the Pacific Ocean?
69) Which unmanned aerial vehicle is the largest active current UAV?
70) Briefly describe the configuration of the Global Hawk.
71) What propulsion system generates thrust for the Global Hawk?
72) Does the Global Hawk have pressurized compartments?
73) What material is the wing and tail of the Global Hawk made of?
74) What material is the fuselage of the Global Hawk made of?
75) What systems are employed for the navigation of the Global Hawk?
76) Name two elements for the GCS of the Global Hawk.
77) Write: (a) maximum takeoff mass, (b) length, and (c) engine thrust of the RQ-4B Global Hawk.
78) Write: (a) maximum speed, (b) range, (c) endurance, and (d) ceiling of the RQ-4B Global Hawk.
79) Briefly compare the RQ-4A Global Hawk with the RQ-4B Global Hawk.
80) List sensors of the RQ-4A Global Hawk.
81) What frequency bands are employed by the Global Hawk?
82) Briefly describe: (a) line-of-sight (LOS) and (b) beyond line-of-sight (BLOS) communications for the Global Hawk.
83) Briefly describe the major setback during flight testing of the Global Hawk.
84) What was the reason behind the mishap for the Global Hawk in the December 1999 flight?
85) Why were two Global Hawk prototype air vehicles lost during the deployment phase in 2002 and 2003? Explain.
86) Why was a Global Hawk lost on June 20, 2019?
87) Briefly describe the unconventional development cycle of the Predator during the 1980s.
88) An advanced version of what aircraft was designated as RQ-1 Predator in the early 1990s?
89) What UAV attempted an air-to-air engagement with an Iraqi MiG-25 in 2002?
90) When was the Predator UAV retired?
91) Briefly compare the primary differences between the Predator and the Reaper.
92) Compare the main difference between configurations of the Predator and the Reaper.

93) When was the first operational mission of the MQ-9 Reaper?
94) What are the payloads of the MQ-9 Reaper?
95) Briefly describe the characteristics of GCS of the MQ-9 Reaper.
96) What is the type of propulsion system for the MQ-9 Reaper?
97) Write: (a) maximum takeoff mass, (b) wingspan, and (c) engine Power of the MQ-9 Reaper.
98) Write: (a) maximum speed, (b) range, (c) endurance, and (d) ceiling of the MQ-9 Reaper.
99) List the dominant US UAV manufacturers.
100) Briefly discuss the ethical concerns of UAVs.
101) What is the mission of the Swift HALE UAV?
102) Name three recent UAV projects with a pseudo-satellite mission.