LECTURE NOTES

ON

UNMANNED AIR VEHICLES

B.Tech VII Semester

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UNIT – I

INTRODUCTION TO UNMANNED AIRCRAFT SYSTEMS

Course Outcomes	
After successful completion of the course, students will be able to:	
CO1	**Recall** the functions of each major sub-systems of the unmanned air vehicle systems to select the suitable subsystem
CO2	**Demonstrate** the knowledge of basic design phases which will be considered for the design of unmanned air vehicle systems

Program Outcomes	
PO 1	**Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
PO 2	**Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences

1.1 Introduction

The development and entry into service of unmanned air vehicle systems has a long, drawn-out history. Unfortunately, the vision of engineers and scientists is seldom matched by that of administrators, regulators or financiers. The availability of UAV systems has also often depended upon maturation of the requisite technology.

The systematic nature of UAV systems is achieved through the combination of many elements and their supporting disciplines. Although the aircraft element is but one part of the coordinated system, it is almost certainly the element which drives the requirements of the other system elements to the greatest extent. An over-simplistic view of an unmanned aircraft is that it is an aircraft with its aircrew removed and replaced by a computer system and a radio-link. In reality it is more complex than that, and the aircraft must be properly designed, from the beginning, without aircrew and their accommodation, etc. The aircraft is merely part, albeit an important part, of a total system.

The aircraft itself will have much in common with manned aircraft, but also several differences which are explained. These differences often result from the differences in operational requirements compared with manned aircraft, for example the need to take off from remote, short, unprepared airstrips or to fly for long periods at very high altitudes. The performance of the aircraft is often enhanced by not having to carry the weight of equipment and structure required to accommodate aircrew, and having a lower aerodynamic drag for the same reason. The UAV also often benefits from advantageous scale effects associated with a smaller aircraft.

1.1.1 What are UAS?

An unmanned aircraft system is just that – a system. It must always be considered as such. The system comprises a number of sub-systems which include the aircraft (often referred to as a UAV or unmanned air vehicle), its payloads, the control station(s) (and, often, other remote stations), aircraft launch and recovery sub-systems where applicable, support sub-systems, communication sub-systems, transport sub-systems, etc.

It must also be considered as part of a local or global air transport/aviation environment with its rules, regulations and disciplines.

UAS usually have the same elements as systems based upon manned aircraft, but with the airborne element, i.e. the aircraft being designed from its conception to be operated without an aircrew aboard. The aircrew (as a sub-system), with its interfaces with the aircraft controls and its habitation is replaced by an electronic intelligence and control subsystem.

The other elements, i.e. launch, landing, recovery, communication, support, etc. have their equivalents in both manned and unmanned systems.

Unmanned aircraft must not be confused with model aircraft or with 'drones', a radio-controlled model (RC Model) aircraft is used only for sport and must remain within sight of the operator. The operator is usually limited to instructing the aircraft to climb or descend and to turn to the left or to the right.

A drone aircraft will be required to fly out of sight of the operator, but has zero intelligence, merely being launched into a pre-programmed mission on a pre-programmed course and a return to base. It does not communicate and the results of the mission, e.g. photographs, are usually not obtained from it until it is recovered at base.

A UAV, on the other hand, will have some greater or lesser degree of 'automatic intelligence'. It will be able to communicate with its controller and to return payload data such as electro-optic or thermal TV images, together with its primary state information – position, airspeed, heading and altitude. It will also transmit information as to its condition, which is often referred to as 'housekeeping data', covering aspects such as the amount of fuel it has, temperatures of components, e.g. engines or electronics.

If a fault occurs in any of the sub-systems or components, the UAV may be designed automatically to take corrective action and/or alert its operator to the event. In the event, for example, that the radio communication between the operator and the UAV is broken, then the UAV may be programmed to search for the radio beam and re-establish contact or to switch to a different radio frequency band if the radio-link is duplexed.

A more 'intelligent' UAV may have further programmes which enable it to respond in an 'if that happens, do this' manner. For some systems, attempts are being made to implement on-board decision-making capability using artificial intelligence in order to provide it with an autonomy of operation, as distinct from automatic decision making.

1.1.2 Categories of Systems Based upon Air Vehicle Types

Although all UAV systems have many elements other than the air vehicle, they are usually categorized by the capability or size of the air vehicle that is required to carry out the mission.

They are as follows:

(i) HALE – *High altitude long endurance*. Over 15 000 m altitude and 24+ hr endurance.

(ii) MALE– *Medium altitude long endurance.* 5000–15 000 m altitude and 24 hr endurance.

(iii)TUAV – Medium Range or Tactical UAV with range of order between 100 and 300 km.

(iv) Close-Range UAV used by mobile army battle groups, for other military/naval operations and for diverse civilian purposes. They usually operate at ranges of up to about 100 km.

(v) MUAV or Mini UAV– relates to UAV of below a certain mass probably below 20 kg, but not as small as the MAV, capable of being hand-launched and operating at ranges of up to about 30 km.

(vi) Micro UAV or MAV. The MAV was originally defined as a UAV having a wing-span no greater than 150 mm.

(vii) NAV – Nano Air Vehicles. These are proposed to be of the size of sycamore seeds and used in swarms for purposes such as radar confusion or conceivably, if camera, propulsion and control sub-systems can be made small enough, for ultra-short range surveillance.

(viii) RPH, remotely piloted helicopter or VTUAV, vertical take-off UAV. If an air vehicle is capable of vertical take-off it will usually be capable also of a vertical landing, and what can be sometimes of even greater operational importance, hover flight during a mission.

(ix) UCAV and UCAR. Development is also proceeding towards specialist armed fixed-wing UAV which may launch weapons or even take part in air-to-air combat. These are given the initials UCAV for unmanned combat air vehicle. Armed rotorcraft are also in development and these are known as UCAR for Unmanned Combat Rotorcraft.

1.1.3 Why Unmanned Aircraft?

Unmanned aircraft will only exist if they offer advantage compared with manned aircraft. An aircraft system is designed from the outset to perform a particular role or roles. The designer must decide the type of aircraft most suited to perform the role(s) and, in particular, whether the role(s) may be better achieved with a manned or unmanned solution. In other words it is impossible to conclude that UAVs always have an advantage or disadvantage compared with manned aircraft systems. It depends vitally on what the task is. An old military adage (which also applies to civilian use) links the use of UAVs to roles which are dull, dirty or dangerous (DDD). There is much truth in that but it does not go far enough. To DDD add covert, diplomatic, research and environmentally critical roles. In addition, the economics of operation are often to the advantage of the UAV.

(i) Dull Roles

Military and civilian applications such as extended surveillance can be a dulling experience for aircrew, with many hours spent on watch without relief, and can lead to a loss of concentration and therefore loss of mission effectiveness. The UAV, with high resolution colour video, low light level TV, thermal imaging cameras or radar scanning, can be more effective as well as cheaper to operate in such roles. The ground-based operators can be readily relieved in a shift-work pattern.

(ii) Dirty Roles

Monitoring the environment for nuclear or chemical contamination puts aircrew unnecessarily at risk. Subsequent detoxification of the aircraft is easier in the case of the UAV.
Crop-spraying with toxic chemicals is another dirty role which now is conducted very successfully by UAV.

(iii) Dangerous Roles

For military roles, where the reconnaissance of heavily defended areas is necessary, the attrition rate of a manned aircraft is likely to exceed that of a UAV. Due to its smaller size and greater stealth, the UAV is more difficult for an enemy air defense system to detect and more difficult to strike with anti-aircraft fire or missiles. Also, in such operations the concentration of aircrew upon the task may be compromised by the threat of attack. The UAV operators are under no personal threat and can concentrate specifically and therefore more effectively, on the task in hand. The UAV therefore offers a greater probability of mission success without the risk of loss of aircrew resource.

(iv) Covert Roles

In both military and civilian policing operations there are roles where it is imperative not to alert the ‘enemy’ (other armed forces or criminals) to the fact that they have been detected. Again, the lower detectable signatures of the UAV make this type of role more readily achievable.

(v) Research Roles

UAVs are being used in research and development work in the aeronautical field. For test purposes, the use of UAV as small-scale replicas of projected civil or military designs of manned aircraft enables airborne testing to be carried out, under realistic conditions, more cheaply and with less hazard.

(vi) Environmentally Critical Roles

This aspect relates predominantly to civilian roles. A UAV will usually cause less environmental disturbance or pollution than a manned aircraft pursuing the same task. It will usually be smaller, of lower mass and consume less power, so producing lower levels of emission and noise.

(vii) Economic Reasons

Typically, the UAV is smaller than a manned aircraft used in the same role, and is usually considerably cheaper in first cost. Operating costs are less since maintenance costs, fuel costs and hangarage costs are all less. The labour costs of operators are usually lower and insurance may be cheaper, though this is dependent upon individual circumstances.

1.2 The Systemic Basis of UAS

Technically, a UAV system comprises a number of elements, or sub-systems, of which the aircraft is but one. It is always most important to view each sub-system of the UAV system as an integral part of that system. No one sub-system is more important than another, though some, usually the aircraft, have a greater impact upon the design of the other subsystems in the system than do others. The technical functional structure of a typical system is shown in Figure 1.1.

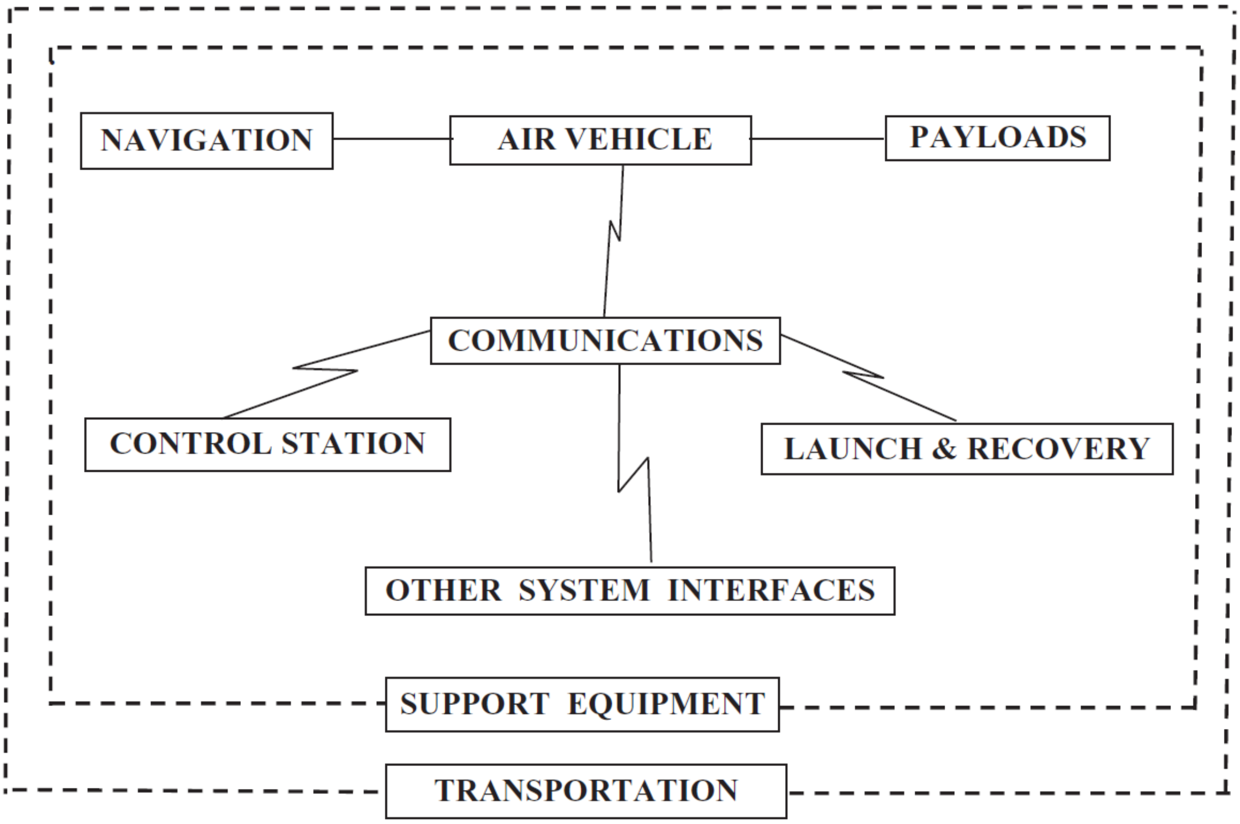

Figure 1.1: UAV system – functional structure

1.3 System Composition

1.3.1 Control Station (CS)

Usually based on the ground (GCS- Ground control station), or aboard ship (SCS- Shipboard control station), though possibly airborne in a ‘parent’ aircraft (ACS- Airborne control station), the control station is the control centre of the operation and the man–machine interface. It is also usually, but not always, the centre in which the UAV mission is pre-planned, in which case it may be known as the mission planning and control station (MPCS).

From the CS, the operators 'speak' to the aircraft via the communications system up-link in order to direct its flight profile and to operate the various types of mission 'payload' that it carries.
Similarly, via the communications down-link, the aircraft returns information and images to the operators. The information may include data from the payloads, status information on the aircraft's sub-systems (housekeeping data), and position information. The launching and recovery of the aircraft may be controlled from the main CS or from a satellite (subsidiary) CS.

The CS will usually also house the systems for communication with other external systems. These may include means of acquiring weather data, transfer of information from and to other systems in the network, tasking from higher authority and the reporting of information back to that or other authorities.

Figure 1.2: Ground based control station

1.3.2 The Payload

The type and performance of the payloads is driven by the needs of the operational task. These can range from:

(a) relatively simple sub-systems consisting of an unstabilised video camera with a fixed lens having a mass
as little as 200 g

(b) a video system with a greater range capability, employing a longer focal length lens with zoom facility, gyro-stabilised and with pan and tilt function with a mass of probably 3–4 kg

(c) a high-power radar having a mass, with its power supplies, of possibly up to 1000 kg. Some, more sophisticated,

UAV carry a combination of different types of sensors, within a payload module or within a series of modules.

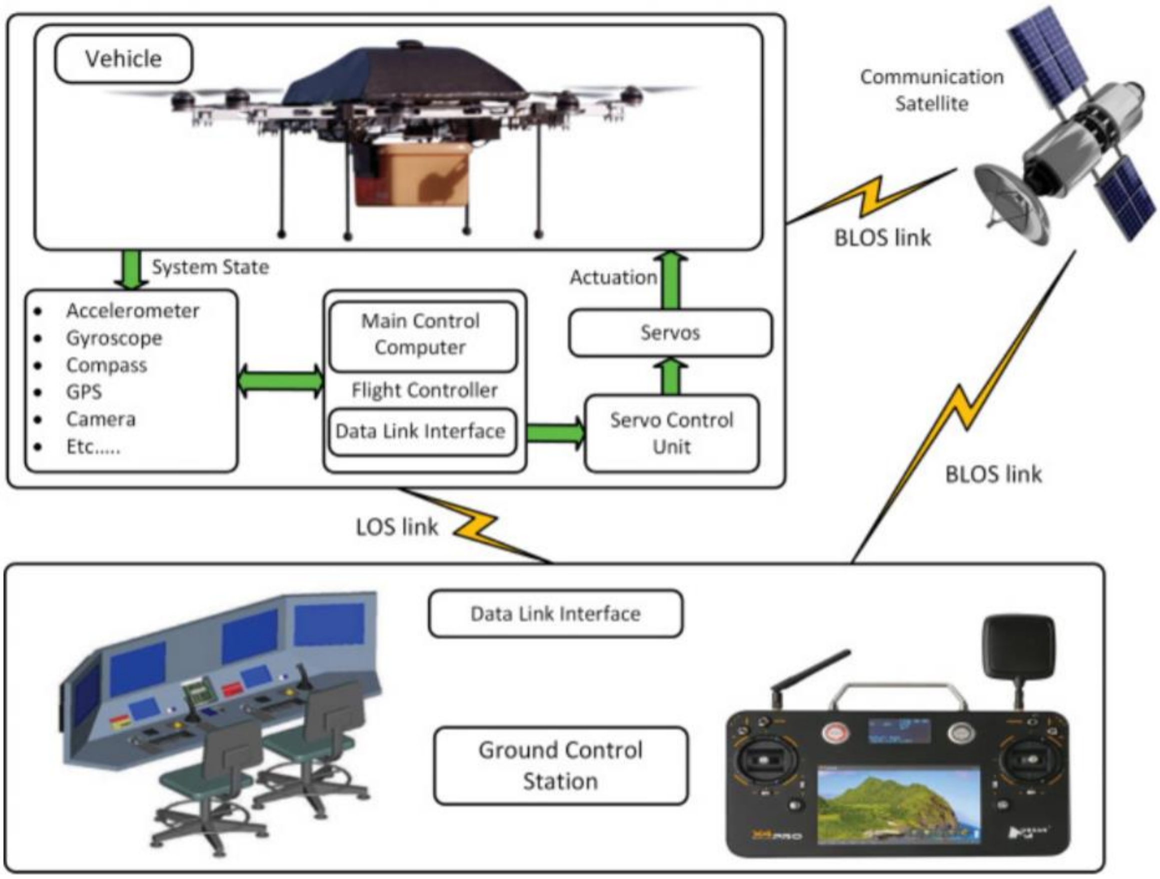

Figure 1.3: High-level architecture of a UAV system

1.3.3 The Air Vehicle

The type and performance of the air vehicle/aircraft is principally determined by the needs of the operational mission. The task of the aircraft is primarily to carry the mission payload to its point of application, but it also has to carry the subsystems necessary for it to operate. These sub-systems include the communications link, stabilization and control equipment, power plant and fuel, electrical power supplies; and basic airframe structure and mechanisms needed for the aircraft to be launched, to carry out its mission, and to be recovered.

Other significant determinants in the design of the aircraft configuration are the operational range, airspeed and endurance demanded of it by the mission requirement. The endurance and range requirement will determine the fuel load to be carried. Achievement of a small fuel load and maximized performance will require an efficient propulsion system and optimum airframe aerodynamics.

The speed requirement will determine more fundamentally whether a lighter-than-air aircraft, or a heavier-than-air fixed-wing, rotary-wing, or convertible aircraft configuration, is used. A long endurance and long range mission for military surveillance will predominately require a high-aspect ratio fixed-wing aircraft operating at high altitude. It will be necessary for it to take off from a long paved runway to achieve the high lift-off speed demanded by the high wing-loading required for low aerodynamic drag.

Figure 1.4: Different air vehicles of UAS

1.3.4 Navigation Systems

It is necessary for the operators to know, on demand, where the aircraft is at any moment in time. It may also be necessary for the *aircraft* to 'know' where it is if autonomous flight is required of it at any time during the flight. For fully autonomous operation, i.e. without any communication between the CS and the air vehicle, sufficient navigation equipment must be carried in the aircraft.

In the past, this meant that the aircraft had to carry a sophisticated, complex, expensive and heavy inertial navigation system (INS), or a less sophisticated INS at lower cost, etc., but which required a frequent positional update from the CS via the communications link.
Nowadays, the availability of a global positioning system (GPS) which accesses positional information from a system of earth-satellites, has eased this problem. The GPSs now available are extremely light in weight, compact and quite cheap, and give continuous positional update so that only a very simple form of INS is now normally needed.

For non-autonomous operation, i.e. where communication between aircraft and CS is virtually continuous, or where there is a risk of the GPS system being blocked, other means of navigation are possible fallback options. These methods include:

(a) Radar tracking. Here the aircraft is fitted with a transponder which responds to a radar scanner emitting
from the CS, so that the aircraft position is seen on the CS radar display in bearing and range.

(b) Radio tracking. Here the radio signal carrying data from the aircraft to the CS is tracked in bearing from the CS, whilst its range is determined from the time taken for a coded signal to travel between the aircraft and the CS.

(c) Direct reckoning. Here, with the computer-integration of velocity vectors and time elapsed, the aircraft position may be calculated. If the mission is over land and the aircraft carries a TV camera surveying the ground, its position can be confirmed by relating visible geographical features with their known position on a map.

1.3.5 Launch, Recovery and Retrieval Equipment

(a) **Launch equipment**: This will be required for those air vehicles which do not have a vertical flight capability, nor have access to a runway of suitable surface and length. This usually takes the form of a ramp along which the aircraft is accelerated on a trolley, propelled by a system of rubber bungees, by compressed air or by rocket, until the aircraft has reached an airspeed at which it can sustain airborne flight.

(b) **Recovery equipment**: This also will usually be required for aircraft without a vertical flight capability, unless they can be brought down onto terrain which will allow a wheeled or skid-borne run-on landing. It usually takes the form of a parachute, installed within the aircraft, and which is deployed at a suitable altitude over the landing zone. In addition, a means of absorbing the impact energy is needed, usually comprising airbags or replaceable frangible material. An alternative form of recovery equipment, sometimes used, is a large net or, alternatively, a carousel apparatus into which the aircraft is flown and caught.

(c) **Retrieval equipment**: Unless the aircraft is lightweight enough to be man-portable, a means is required of transporting the aircraft back to its launcher.

Figure 1.5: Catapult take-off

Figure 1.6: Hydraulic –rail launcher

Figure 1.7: Pneumatic launcher

Figure 1.8: Different recovery methods

1.3.6 Communications

The principal, and probably the most demanding, requirement for the communications system is to provide the data links (up and down) between the CS and the aircraft. The transmission medium is most usually at radio frequency, but possible alternatives may be by light in the form of a laser beam or via optical fibers.

The tasks of the data links are usually as follows:

(a) Uplink (i.e. **from the CS to the aircraft**):

i) Transmit flight path tasking which is then stored in the aircraft automatic flight control system (AFCS).
ii) Transmit real-time flight control commands to the AFCS when man-in-the-loop flight is needed.
iii) Transmit control commands to the aircraft-mounted payloads and ancillaries.
iv) Transmit updated positional information to the aircraft INS/AFCS where relevant.

(b) **Downlink** (i.e. **from the aircraft to the CS**):

i) Transmit aircraft positional data to the CS where relevant.
ii) Transmit payload imagery and/or data to the CS.
iii) Transmit aircraft housekeeping data, e.g. fuel state, engine temperature, etc. to the CS.

The level of electrical power, complexity of the processing and the antennae design and therefore the complexity, weight and cost of the radio communications will be determined by:

i) the range of operation of the air vehicle from the transmitting station;
ii) the sophistication demanded by transmission-down of the payload and housekeeping data;
iii) the need for security.

1.3.7 Interfaces

All these elements, or sub-systems, work together to achieve the performance of the total system. Although some of them may be able to operate as 'stand-alone' systems in other uses, within the type of system described, as sub-systems they must be able to operate together, and so great attention must be paid to the correct functioning of their interfaces.
For example, although the communications radio sub-system itself forms an interface between the CS and the air vehicle, the elements of it installed in both the CS and air vehicle must operate to the same protocols and each interface with their respective parent sub-systems in a compatible manner.

It is likely that the UAV system may be operated by the services (both military and civilian) in different countries which may require different radio frequencies or security coding. Therefore it should be made possible for different front-end modules to be fitted into the same type of CS and air vehicle when the UAV system is acquired by various different operators. This requires the definition of the common interfaces to be made.

1.3.8 Interfacing with Other Systems

A UAV system exists in order to carry out a task. It is unlikely that the task may 'standalone'. That is, it may require tasking from a source external to the system and report back to that or other external source. This network may include information coming from and/or being required by other elements of the military, such as ground-, sea-, or air-based units and space-satellites, or indeed, other UAV systems. The whole then becomes what is known as a 'system of systems' and is known as network centric operation.

A UAV system (UAS) operating alone is usually known as a 'stove-pipe system'. A representative architecture of a 'system of systems' which may include not only other UASs of similar or different types, but also include other operational elements such as naval vessels, mobile ground units or manned aircraft that provide information or mount attack missions is shown in Figure 1.2.Similarly, in civilian operations such as fire patrol, the operators in the CS may be tasked from Fire Brigade Headquarters to move the air vehicle to new locations. It will be necessary therefore to provide, probably within the CS, the equipment required to communicate with the external sources and record/display data received and sent.

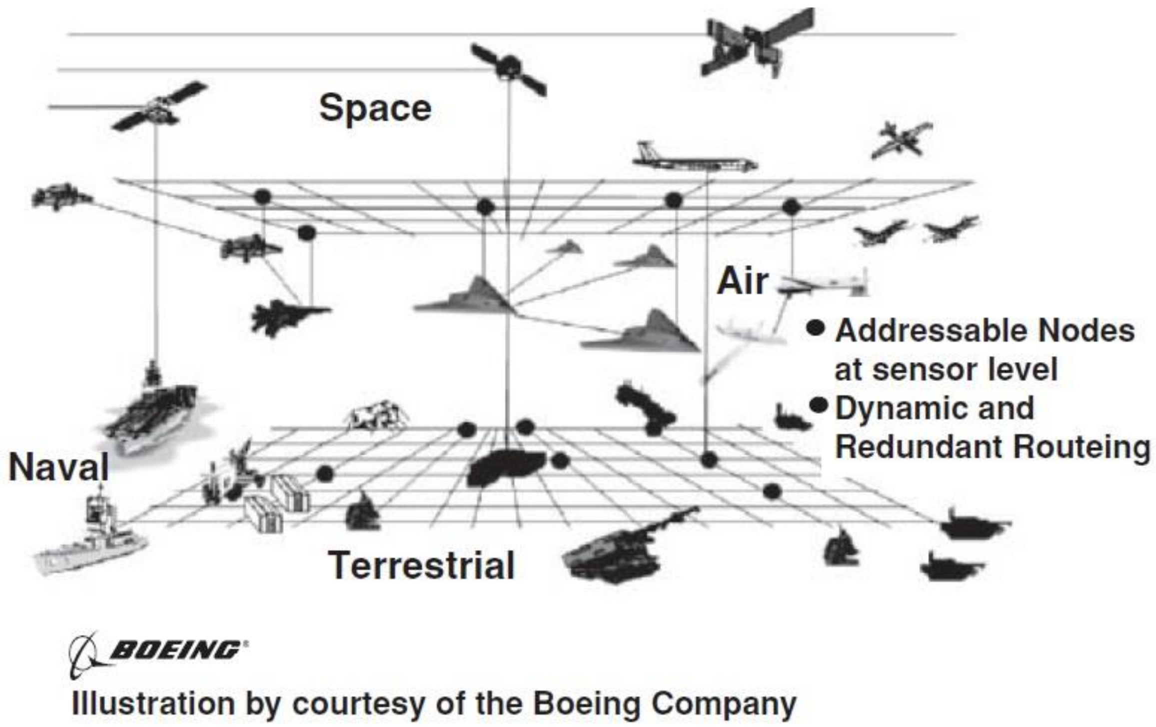

Figure 1.9: Network-centric architecture (Boeing)

1.3.9 Support Equipment

Support equipment is one area which can often be underestimated when a UAV system is specified. It ranges from operating and maintenance manuals, through tools and spares to special test equipment and power supplies.

Figure 1.10: Supporting equipment

1.3.10 Transportation

A UAV system is often required to be mobile. Therefore transport means must be provided for all the sub-systems discussed above. This may vary from one vehicle required to contain and transport a UAV system using a small, lightweight vertical take-off and landing (VTOL) aircraft which needs no launch, recovery or retrieval equipment and is operated by say, two crew, to a system using a large and heavier ramp-launched aircraft which needs all the sub-systems listed, may have to be dismantled and reassembled between flights, and may require, say, ten crew and six large transport vehicles. Even UAV systems operating from fixed bases may have specific transport requirements.

1.3.11 System Environmental Capability

From the initiation of the concept of the system, it is important to recognise the impact that the environment in which it is to operate will have on the design of all elements of the system, including the provision of an acceptable working environment for the operating and support members of the crew. A system which has been designed with only low-altitude, temperate conditions in mind, will fail in more extreme conditions of altitude, temperature, solar radiation, precipitation and humidity.

It is also necessary to recognise the impact that the UAV system may have on the environment. This can be very significant, though with different accent, in both civilian and military roles. It is therefore necessary to consider all of these aspects carefully at the outset of the system design.

1.4 Introduction to Design and Selection of the System

The design of most aircraft-based systems will usually be considered to begin in three phases:

a) the conceptual phase,
b) the preliminary design phase,
c) the detail design phase.

Other phases follow after initial manufacture. These include the design of modifications during development and subsequent modifications or improvements whilst the system is in service.

1.4.1 Conceptual Phase

The most important purpose of manufacturing is fundamentally to make a profit for the company shareholders. This phase will therefore require the persons involved to have an appreciation of the market trends and either find a ‘gap’ in the market or see means of producing a product offering better cost–benefit to the customer. Alternatively the product may be one which is thought to open up an entirely new market. In whichever category the proposed product falls, it is necessary to establish its commercial viability at this early stage. To that end an initial outline design will be made from which the performance and costs of developing, manufacturing and operating the product can be predicted.

a) Is it what the customer needs – (not necessarily what the customer thinks that he wants)?
b)What is the predicted size of the market – i.e. number of units?
c) Will the unit production costs plus mark-up be seen by the customer as value for money?
d) Will the operating costs and system reliability be acceptable to the customer?
e) Will the nonrecurring cost of the programme be recouped in an acceptable time by the return on sales?
f) Are there any forces, political or regulatory, which may prevent sales of the system?

Techniques of operational analysis, cost–benefit and economic studies should be used to answer these questions. Opportunity may be taken during this phase to carry out wind-tunnel testing of an aircraft model to confirm the theoretical aerodynamic calculations or to determine if any modification to the aircraft shape, etc. is needed. This would expedite the design in the next phase.

1.4.2 Preliminary Design

Given the decision to proceed, the original outline design of the total system will be expanded in more detail. Optimization trade-offs within the system will be made to maximize the overall performance of the system over its projected operational roles and atmospheric conditions.

A 'mock-up' of the aircraft and operator areas of the control station may be constructed in wood or other easily worked material, to give a better appreciation in three dimensions as to how components will be mounted relative to one another, ease of accessibility for maintenance and operator ergonomics, etc. It will be determined which elements of the system will be manufactured 'in house' and which will be procured, at what approximate cost, from alternative external suppliers.

The phase concludes with a comprehensive definition of the design of the complete system with its interfaces and a system specification.

The costing of the remaining phases of the programme and the costs of system operation will have been re-examined in greater detail and the decision to proceed further should be revisited.

Careful consideration of options and the addressing of such matters as ease of construction, reliability, maintenance and operation at this stage can save much time and cost in correcting mistakes in the more expensive later phases of the programme.

1.4.3 Detail Design

At this point the work involved expands and a greater number of staff will be employed on the programme. There will follow a more detailed analysis of the aerodynamics, dynamics, structures and ancillary systems of the aircraft and of the layout and the mechanical, electronic and environmental systems of the control station and any other sub-systems such as the launch and recovery systems. The detailed design and drawings of parts for production of each element of the system, including ground support and test equipment unless they are 'bought-out' items, will be made and value analysis applied. Specifications for the 'bought-out' items will be prepared and tenders sought.

The jigs and tools required for manufacture will be specified and will be designed unless 'bought-out'. Test Schedules will be drafted for the test phases and initial thoughts applied to the contents of the operating and maintenance manuals.

1.4.4 Selection of the System

The role requirements, as defined by the customer, place demands upon the system which determine the shape, size, performance and costs principally of the air vehicle, but also of the overall UAV system which operates it. Some of the more important parameters involved, beginning with the air vehicle, are briefly discussed below.

1.4.4.1 Air Vehicle – Payload

The size and mass of the payload and its requirement for electrical power supplies is often the premier determinant of the layout, size and all–up-mass (AUM) of the aircraft. This is perhaps rightly so, as its tasking is the sole reason for the existence of the UAV system. As stated previously, the payload may range in mass from a fraction of a kilogram up to 1000 kg and in volume from a few cubic centimeters to more than a cubic meter, especially in the case of armed air vehicles.

The necessary position of the payload may also be a significant factor in the configuration and layout of the airframe. Imaging payloads for surveillance may require a full hemispheric field of view and others a large surface area for antennae.

Payloads which will be jettisoned must be housed close to the centre of mass of the air vehicle.

1.4.4.2 Air Vehicle – Endurance

The flight endurance demanded of the air vehicle can range from, say 1 hr for a close-range surveillance system to more than 24 hr for a long-range surveillance or airborne early warning (AEW) system. The volume and mass of the fuel load to be carried will be a function of the required endurance and the reciprocal of the efficiency of the aircraft's aerodynamics and its power plant. The mass of the fuel to be carried may be as low as 10% of the aircraft AUM for close-range UAV, but rising to almost 50% for the long-endurance aircraft, thus being a significant driver in determining the AUM of the aircraft.

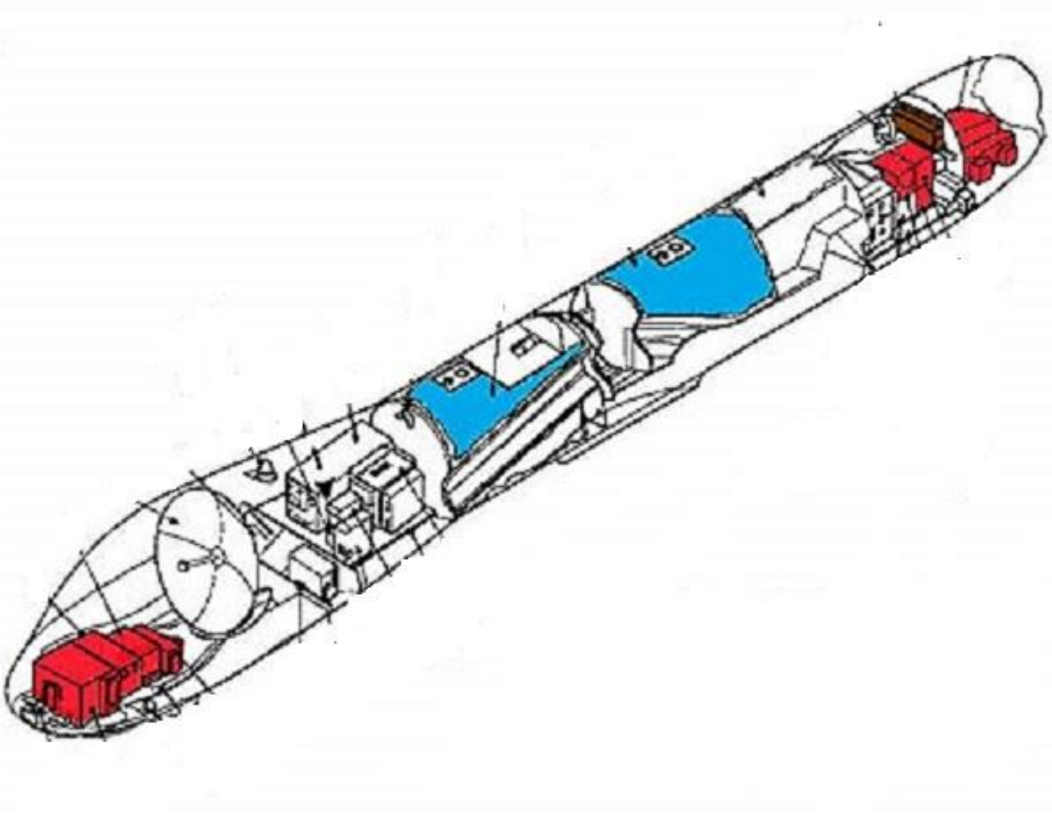

Figure 1.11 Predator UAV payload arrangement view

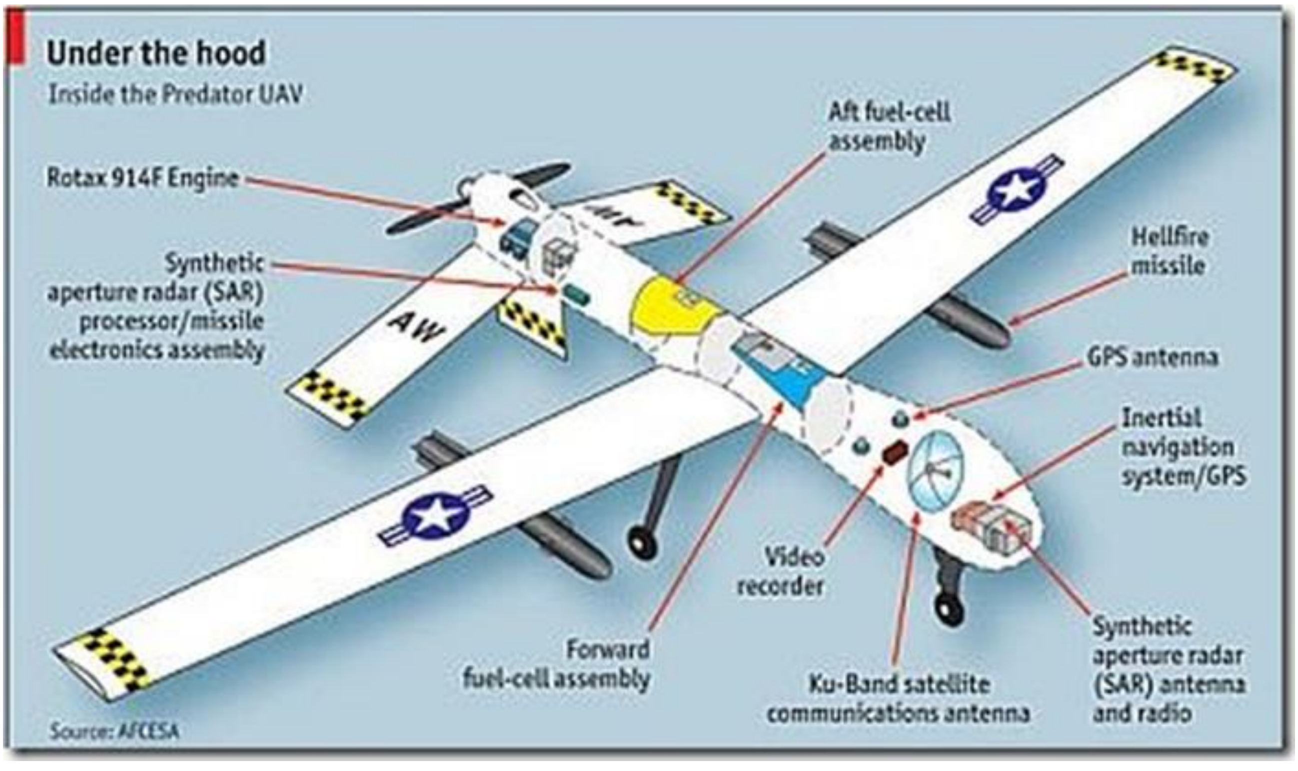

Figure 1.12 Predator UAV payload components

1.4.4.3 Air Vehicle – Radius of Action

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The radius of action of the aircraft may be limited – by the amount of fuel that it can carry, and the efficiency of its use, its speed or by the power, frequency and sophistication of its communication links. The data rate requirements of the payload and other aircraft functions will greatly affect the electrical power and frequency range needed for the radio-links. The design and positioning of the radio antennae will reflect these requirements and could have an effect upon the choice of aircraft configuration. The radius of action will also have a significant impact on the choice of navigation equipment affecting both aircraft and control station.

1.4.4.4 Air Vehicle – Speed Range

Driven particularly by the necessary speed of response, this could range typically as follows:

0–100 kt for a close-range surveillance role;
0–150 kt plus for many off-board naval roles;
80–500 kt for long-range surveillance and AEW roles;
100 kt to mach 1 plus for future interception / interdiction roles.

The required speed range will be a dominant factor in determining the configuration and propulsive power of the aircraft.

Figure 1.13 indicates the aircraft configurations most appropriate to the above speed ranges. However, speed generally comes at a cost in terms of fuel consumption and airframe complexity resulting in reduced efficiency of payload and/or range for size, mass and financial cost. A notional value E for relative efficiency is ventured on the vertical axis of the figure.

1.4.4.5 Air Vehicle – Launch and Recovery

The method for air vehicle launch and recovery, as driven by the operational role, will be significant in determining the aircraft configuration, its structural design and auxiliary equipment.

(i) Launch

The method of launching the aircraft may be considered within three types, each with an appropriate means of recovery:
a) a horizontal take-off and landing (HTOL), on a wheeled undercarriage, where there is a length of prepared surface (runway or strip) available;
b) a catapulted or zero-length rocket-powered launch when the aircraft has no vertical flight capability and where the operating circumstances or terrain preclude availability of a length of runway;
c) a vertical take-off and landing (VTOL).

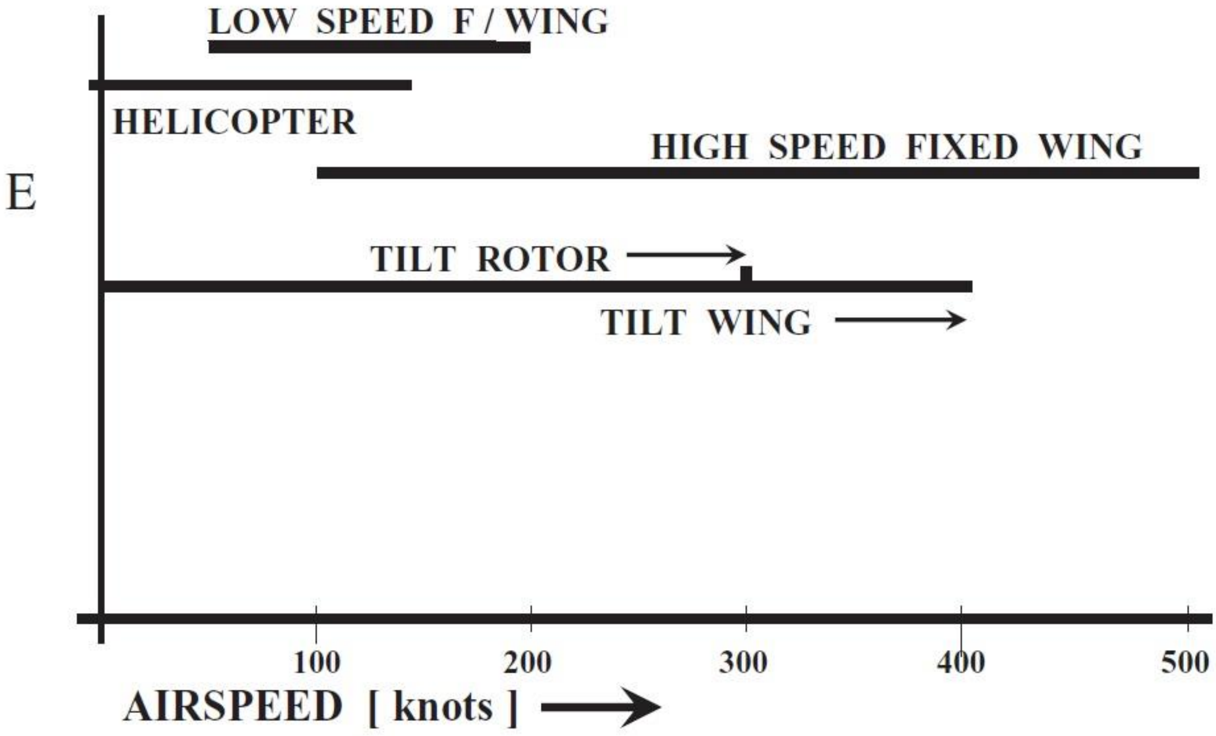


Figure 1.13 Speed ranges of aircraft types

(ii) Recovery

Recovery of the UAV requires not only a safe landing, but the return of the UAV to its base or hangar.

HTOL recovery involves the return of the aircraft to make a controlled touch-down onto its undercarriage at the threshold of runway or airstrip, deceleration along the runway, followed by the aircraft taxiing or being towed back to its base point.

Catapult Launch System Recovery system presents the more complicated provision for recovery. There area number of alternative solutions:

a) a skid or belly landing,
b) guided flight into a catchment net,
c) deployment in flight of a parachute with provision of an energy absorbing system to reduce the severity of ground impact,
d) guided flight onto an arresting pole.

1.4.4.6 Overall System

At this point, discussion of the demands imposed by the role requirements has been limited to those affecting the air vehicle, since the air vehicle is the element of the system which usually has the greatest effect upon the other elements. For example, the launch and recovery of the aircraft may be achieved:
a) using a wheeled-aircraft from and onto a conventional runway;

b) ramp-launching the aircraft with various alternative means of acceleration and subsequent recovery;
c) without any further equipment for a VTOL aircraft

The length of the runway required for (a) will depend upon the aircraft acceleration and lift-off speed. The size, power and sophistication of the launcher for (b) will depend upon the aircraft mass and minimum flight speed. In addition, a transport vehicle to retrieve the aircraft may be required, particularly for cases (a) and (b). The various factors outlined above and other factors will influence the sophistication of the communications equipment and of the control station.

1.4.4.7 Environmental Conditions

It was pointed out that:
(i) it is important to recognise, during the system design, the impact that the environment will have on all elements of that system; and
(ii) it is necessary to recognise the impact that the UAV system may have on the environment.

First, a system which has been designed with only temperate conditions in mind, will fail if operated in more extreme conditions of altitude, temperature, solar radiation, precipitation, humidity and other atmospheric conditions. In cold conditions, batteries tire rapidly; electronics performance may vary; some materials become brittle; air and ground vehicles ice up; engines may fail to start; brakes seize, etc. In conditions of extreme heat, engines and actuators may lose power or seize, electronics components may fail, vapour locks appear in fuel lines, etc.. Even worse are areas where large temperature gradients occur between night and day, resulting in changes in system characteristics and considerable problems with condensation.

Extremes of heat or cold, not only whilst the system is functioning, but also whilst standing idle will determine the level of provision of cooling needed for sub-systems such as sensors, communication equipment, etc. or of anti-icing and de-icing systems and systems for the prevention of condensation.

Atmospheric conditions such as wind strength and turbulence in which operation is required can be an important factor in the design of the structure of the ground control station and support equipment as well as the choice of air vehicle configuration. The suitability of all elements of the system must be addressed if it is to be operated in atmospheric ‘pollution’ such as snow, freezing fog or wind-blown sand particles.

Facilities needed for night operation must be incorporated in the design of both the aircraft and GCS. With particular concern for the aircraft, it is important to design at the outset knowing the atmospheric conditions in which it is to fly. The altitude, whether say 3000 or 20 000 m, will largely determine the wing or rotor blade area, and the amount of atmospheric turbulence present will have an effect on the configuration to be chosen. An aircraft required to maintain an accurate flight path will not be very acceptable if it is blown around like a leaf in turbulent air conditions.

Second, the other important perspective is the impact that the system has on the environment. This can be very significant, though with different accent, in both civilian and military roles:

(a) Too high a level of acoustic noise can cause a nuisance in civil operations, whilst it can result in detection of the system in military operations.
(b) Uncontrolled radio frequency transmission can similarly result in interference or detection.

(c) Visual impact of either aircraft or ground-based equipment can be seen as spoiling the environment from
the civilian point of view and can lead to vulnerability in the military field.
(d) In military operation, too great an infrared or radar signature, particularly of the aircraft, but also of the ground-based equipment, can lead to detection and annihilation.

It is therefore necessary to consider all these aspects carefully at the outset of the system design. Fortunately, because of their smaller size, UAVs naturally have smaller radar, visual, infrared and acoustic signatures than their larger manned brethren. But, even more significantly, because it is not necessary to compromise the UAV to accommodate aircrew, it is far easier to configure them to have very much lower signatures.
The conditions, therefore, in which a UAV system must operate, can have a significant effect upon the design, not only of the air vehicle in determining the power installed, wing area etc., but also upon the other elements of the system.

1.4.4.8 Maintenance

The frequency and length of time during which a UAV system is nonoperable due to its undergoing maintenance are significant factors in the usefulness and costs of the deployment of the system. These are factors which must be addressed during the initial design of the system, involve control of the system liability to damage, system reliability, component lives, costs and supply, and the time taken for component replacement and routine servicing.

The achievement of adequate accessibility to sub-systems in both airborne and control station elements of the system must be carefully considered in the initial design and may have significance in determining the configuration of those elements.

1.4.4.9 System Selection as Categories

It is proposed to consider four categories relating to air vehicle missions. These will be:

a) HALE and MALE systems with the air vehicles operating from runways on established bases away from hostile action, carrying sophisticated payloads over very long distances.
b) Medium-range or tactical systems with air vehicles operating at moderate altitudes, but at moderate to high airspeeds. They may perform reconnaissance, ground attack or air-superiority (UCAV) missions. Typical operating range is of order up to 500 km.
c) Close-range systems in support of land or naval forces operated from the battlefield or from ships. These may also cover most of the civilian roles. They will have an operating range of about 100 km.
d) MAV and NAV which may be hand-launched and of very short range and endurance.

1.5 Some Applications of UAS

Before looking into UAS in more detail, it is appropriate to list some of the uses to which they are, or may be, put. They are very many, the most obvious being the following:

1.5.1 Civilian uses

Aerial photography	Film, video, still, etc.
Agriculture	Crop monitoring and spraying; herd monitoring and driving
Coastguard	Search and rescue, coastline and sea-lane monitoring
Conservation	Pollution and land monitoring
Customs and Excise	Surveillance for illegal imports
Electricity companies	Powerline inspection
Fire Services and Forestry	Fire detection, incident control
Fisheries	Fisheries protection
Gas and oil supply companies	Land survey and pipeline security
Information services	News information and pictures, feature pictures, e.g. wildlife
Lifeboat Institutions	Incident investigation, guidance and control
Local Authorities	Survey, disaster control
Meteorological services	Sampling and analysis of atmosphere for forecasting, etc.
Traffic agencies	Monitoring and control of road traffic
Oil companies	Pipeline security
Ordnance Survey	Aerial photography for mapping
Police Authorities	Search for missing persons, security and incident surveillance
Rivers Authorities	Water course and level monitoring, flood and pollution control
Survey organisations	Geographical, geological and archaeological survey
Water Boards	Reservoir and pipeline monitoring

1.5.2 Military roles

1.5.2.1 Navy

Shadowing enemy fleets

Decoying missiles by the emission of artificial signatures

Electronic intelligence

Relaying radio signals

Protection of ports from offshore attack

Placement and monitoring of sonar buoys and possibly other forms of anti-submarine

Warfare

1.5.2.2 Army

Reconnaissance

Surveillance of enemy activity

Monitoring of nuclear, biological or chemical (NBC) contamination

Electronic intelligence

Target designation and monitoring

Location and destruction of land mines

1.5.2.3 Air Force

Long-range, high-altitude surveillance

Radar system jamming and destruction

Electronic intelligence

Airfield base security

Airfield damage assessment

Elimination of unexploded bombs

UNIT – II

AERODYNAMICS AND AIRFRAME CONFIGURATIONS

CO No	Course Outcomes After successful completion of the course, students will be able to:
CO3	**Recognize** significant role requirement parameters which determine the shape, size, performance, and costs of UAV systems as per role requirement
CO4	**Demonstrate** the knowledge of the different types of drag in fixed, rotary-wing aircraft and UAV response to air turbulence in selecting the suitable airframe configuration
CO5	**Illustrate** the different types of airframe configurations available for unmanned air vehicle systems
CO6	**Outline** the scaling effects, package density, basic aerodynamics, and structures concepts used during the design of UAVs
CO7	**Select** a suitable power-plant based on power generation systems for the given role requirement

Program Outcomes (POs)	
PO1	**Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
PO2	**Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences
PO4	**Conduct Investigations of Complex Problems:** Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions.

2.1 Lift-induced Drag

Fundamentally, an aircraft remains ‘afloat’ simply by accelerating an adequate mass of air downwards and, as Newton discovered, the reaction force in the opposite direction opposes the gravitational force which constantly tries to bring the aircraft back to ground. (A swimmer treading water uses the same principle to keep his head above water). This is illustrated in Figure 2.1 for an aircraft travelling with forward velocity V and deflected air velocity u. A disparity of aerodynamic pressures between the upper and lower surfaces of its wings, whether of the fixed or rotating variety, is caused. The lower pressure on the upper surface and the higher pressure on the lower surface of a wing is merely the ‘transfer mechanism’ for the reaction force.

The horizontal component of the reaction force is a drag, known as the ‘lift-induced drag’, which has to be overcome by the propulsion system of the aircraft if it is to maintain airspeed. Therefore it is necessary to minimize the amount of drag caused in the process of creating lift. Figure 2.1 indicates that the best ratio of lift to drag is obtained for small airstream deflection angles ϕ, where $\tan \phi = u/V$.

The amount of lift produced, however, is equal to the product of the mass-flow of air entrained and the velocity u that is given to it in the downwards direction, i.e. $PAVu$N, where the air density ρ is measured in kg/m^3 and the cross-sectional area of the affected airflow A is in m^2.Hence to create sufficient lift, if u/V is to be smaller for efficiency, the product of the air density ρ and the mass of air being entrained per unit time must be larger.

The amount of air entrained, for a given aircraft velocity, is a function of the frontal area of the wing presented to it but, for efficiency, the incidence of the wing to the air must be kept low in order to retain a small value of ϕ, as discussed. Also, the ability of the air to remain attached to the upper surface of the wing fails at higher wing incidence, resulting in an increase in parasitic drag (see below). Therefore, especially for the low values of air density at high altitudes, the aircraft must fly fast and/or have a

In summary the induced drag Di of an aircraft wing varies as the square of the span loading (lift generated, L N divided by span length [b]), the reciprocal of the air density ρ kg/m^2, and the square ofthe reciprocal of the airspeed V m/s. i.e. from the textbook formula

$$Di = k_i.(L/b)^2/q\pi \text{ or } Di = ki.(L/b)^2/\ 0.5\rho\pi V^2 \qquad (2.1)$$

Where ki is a non-dimensional factor, greater than unity, which increases the drag, depending upon the loss of efficiency of the wing due to poor lift distribution, that is away from the ideal elliptical distribution; k_i is typically in the order of 1.1. L/b is the span loading in N/m and q is the aerodynamic head: $q = 0.5\ \rho V^2$.

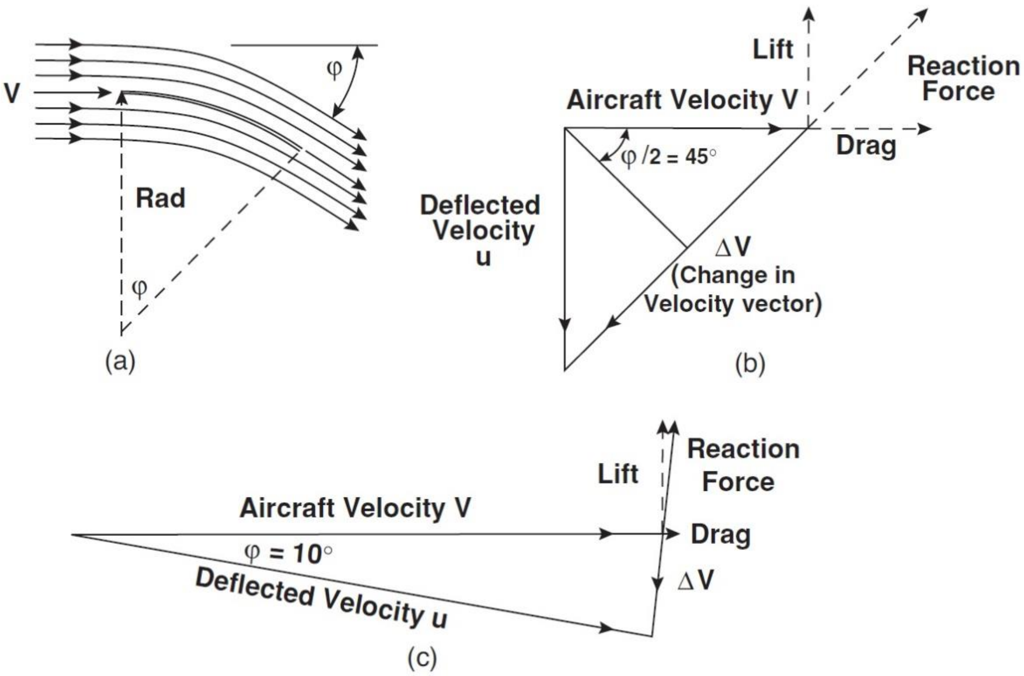


Figure 2.1: Creation of lift (and drag) by air deflection

Hence calculation of the lift-induced drag can be simply summarized as follows: D_i is equal to the square of the span loading divided by πq and multiplied by a form factor ki. The reduction of air density with altitude, shown in Figure 2.2, indicates that at 20000 m the density of the atmosphere is less than one-tenth of its value at sea level, and therefore a greater volume of air must be accelerated downwards to produce lift at high altitudes compared with the volume required at sea-level. This is why it is desirable to have a wing with a greater span on an aircraft required to operate at high altitudes than for aircraft operating at low altitudes.

The air density shown by Figure 2.2 is for the 'standard atmosphere' where the temperature at sea level is 15°C. In cooler conditions, the air density will be greater over the range shown and, conversely, less dense in warmer air.

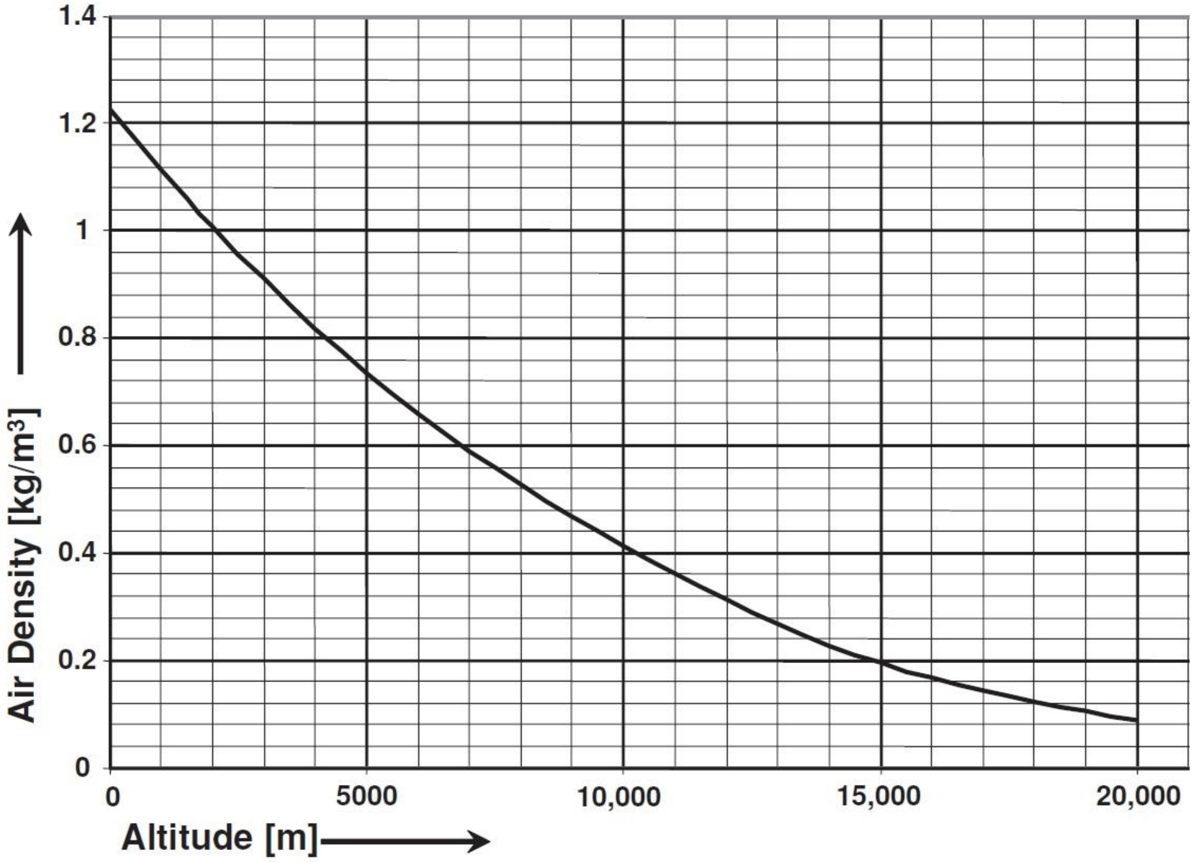


Figure 2.2: The standard atmosphere

2.2 Parasitic Drag

Other factors also create drag on an aircraft. These other origins of drag, which may be collectively grouped as 'parasitic drag', comprise skin friction drag, form drag, interference drag, momentum drag and cooling drag.

Suffice it to say that parasitic drag varies, to first order, on an aircraft of defined configuration, with the air density and with the square of the airspeed. Early in the design of an aircraft, its drag, along with other aerodynamic characteristics, will be measured in a wind tunnel and this will be reduced into a coefficient

form by dividing the measured drag by the airspeed, air density and a reference area *S*, usually the main wing area in fixed-wing aircraft.
That is, the parasitic drag coefficient, $C_{Dp}= D_p/1/2\rho V^2S$, so that the parasitic drag may be estimated for any level flight condition using the expression:

$$D_p= qC_{Dp}.S \qquad (2.2)$$

Where *S* is the wing area and *q* is the aerodynamic head: $q = 1/2\rho V^2$.

There is, however, a further term which represents the increased drag which results from a wing being operated at higher incidence. This term is usually small until the wing approaches a stalled condition, when it becomes extremely large. It is caused by an increased skin friction and form drag as the wing incidence increases either to produce more lift or to fly more slowly. The increase generally trends as a function of the square of the lift coefficient C_L, so that the parasitic drag equation then becomes:

$$Dp= (C_{Dp}+ k_pC_L^2)qS. \qquad (2.3)$$

Combining the induced drag and the parasite drag gives the total drag of the aircraft.
Given that for a fixed configuration, the induced drag reduces as the square of the reciprocal of the airspeed, whilst the parasite drag varies with the square of the airspeed, then to obtain a reduction in induced drag, the aircraft must fly faster but, in doing so, the parasite drag increases. Thus there is an intermediate airspeed, where the induced drag equals the parasitic drag and the total drag is a minimum. The power used by the aircraft is equal to the product of total drag and the airspeed, so there is another airspeed at which the power used is a minimum.

There is yet another airspeed, usually faster than either of the former, at which the aircraft is at its most economic in terms of fuel used per distance travelled. All these values are different at different altitudes and they can be a significant determinant in the design of the aircraft, depending upon its operational roles and conditions.

Two basic criteria for flight at any given airspeed are that the wing produces sufficient lift to oppose the aircraft weight and that the thrust of the propulsor (propeller or jet) is equal to, or greater than, the total drag of the aircraft. For a fixed-wing aircraft, if there is a speed below which either of these criteria is not met, then the aircraft cannot sustain flight. This speed is the absolute minimum flight speed. However, itis not practical for the aircraft to attempt flight at this absolute minimum speed since any air turbulence or aircraft manoeuvre can increase the drag and/or reduce the lift, thus causing the aircraft to stall. A margin of speed above this is necessary to define a practical minimum flight speed V_{min}. This important concept of a minimum flight speed will also determine the speed required for the aircraft to take off or be launched.

The lift produced by a wing is given by the equation

$$L = 1/2\, \rho V^2 SC\mathrm{L} \qquad (2.4)$$

Where C_L is a coefficient that determines the ability of the wing of area *S* to deflect the airstream. This coefficient, itself, is a function of the design of the wing section, the Reynolds number at which it is operating and the wing incidence, increasing in value with incidence and peaking at a value, $C_{L.max.}$, beyond which it sharply reduces.
The value of the absolute minimum flight speed is obtained by rearranging Equation (2.4) as:

$$V = (2\mathrm{L}/\rho SC_{L.\ max\ .})^{1/2}$$

But this provides no margin, as discussed above. A more realistic value of V_{min} can be specified either by allowing a margin in speed or in lift coefficient. The latter approach is adopted by the author. This results in a value of V_{min} given by:

$$V_{min} = (2L/\rho S C_{lo}.)^{1/2} \qquad (2.5)$$

Where C_{Lo} (operating C_L) has been chosen to have a value of about 0.2 less than the $C_{L.max}$ for the selected aerofoil section. Note that this makes but little allowance for turbulent air or for manoeuvres and so refers to an absolute minimum speed at which the aircraft is able to maintain straight and level flight in smooth air. In that sense it is optimistic.

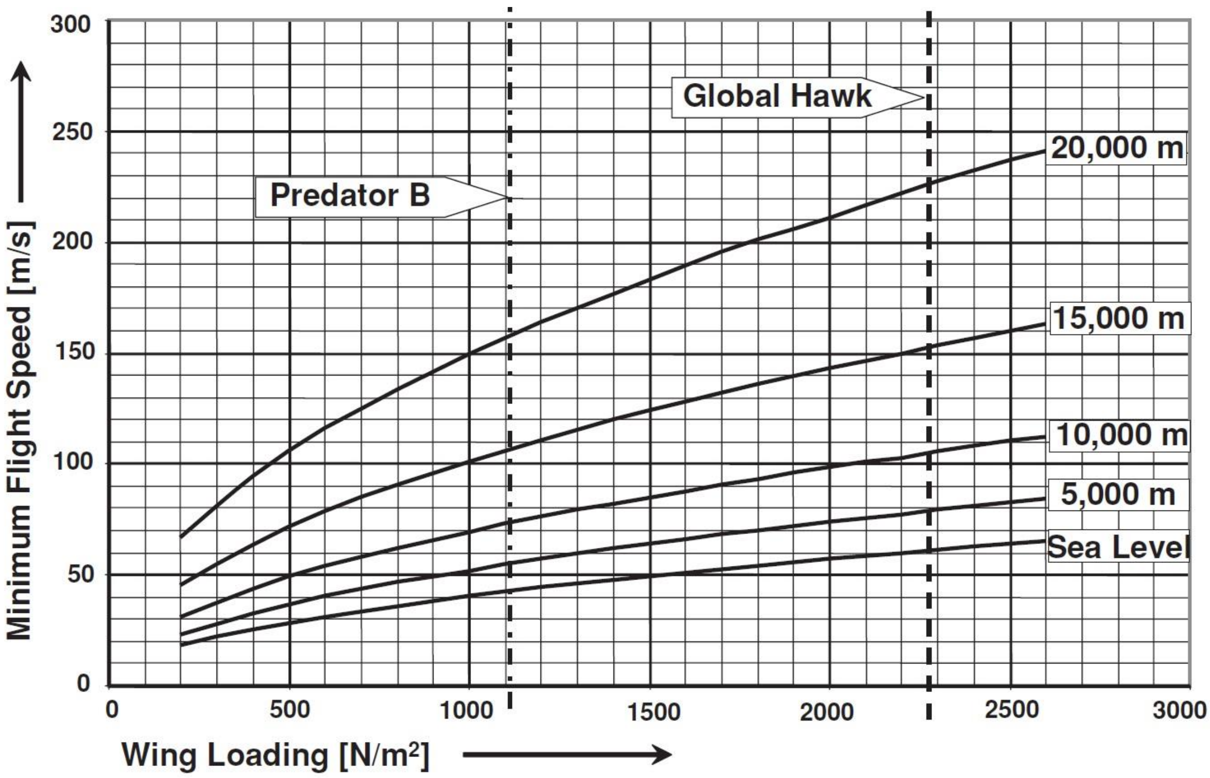
A typical, moderately cambered, section offers a $C_{L.max}$ of about 1.2 when used in practical wing construction and without flaps. Hence a value of 1.0 has been adopted.

Few UAV wings incorporate flaps as they represent complication and extra weight and cost. Although their deployment would produce an increase in lift coefficient, it would also add considerable drag. This would demand extra thrust and an increase in fuel-burn, neither effect desirable for take-off or in cruise flight. Their use is normally limited to the landing mode.

Equation (2.5) can be rewritten as:

$$V_{min} = (2w/\rho C_{Lo})^{1/2} \text{or } (2/\rho_0)^{1/2} (w/\sigma)^{1/2} \qquad (2.6)$$

Where w is the aircraft wing loading in N/m^2, ρ_0 is the air density at sea-level standard conditions and σ is the relative air density at altitude.



Reg Austin, ― Unmanned Aircraft Systems @ 2010 John Wiley and Sons, Ltd.

Figure 2.3 The variation of V_{min} with aircraft wing loading

The variation of V_{min} with aircraft wing loading at several altitudes is shown in Figure 2.3 which covers wing loadings appropriate to the close-range, medium-range and MALE and HALE UAV. Figure 2.4 covers the lower values of V_{min}, resulting from the wing loading relevant to the smaller mini and micro UAV.

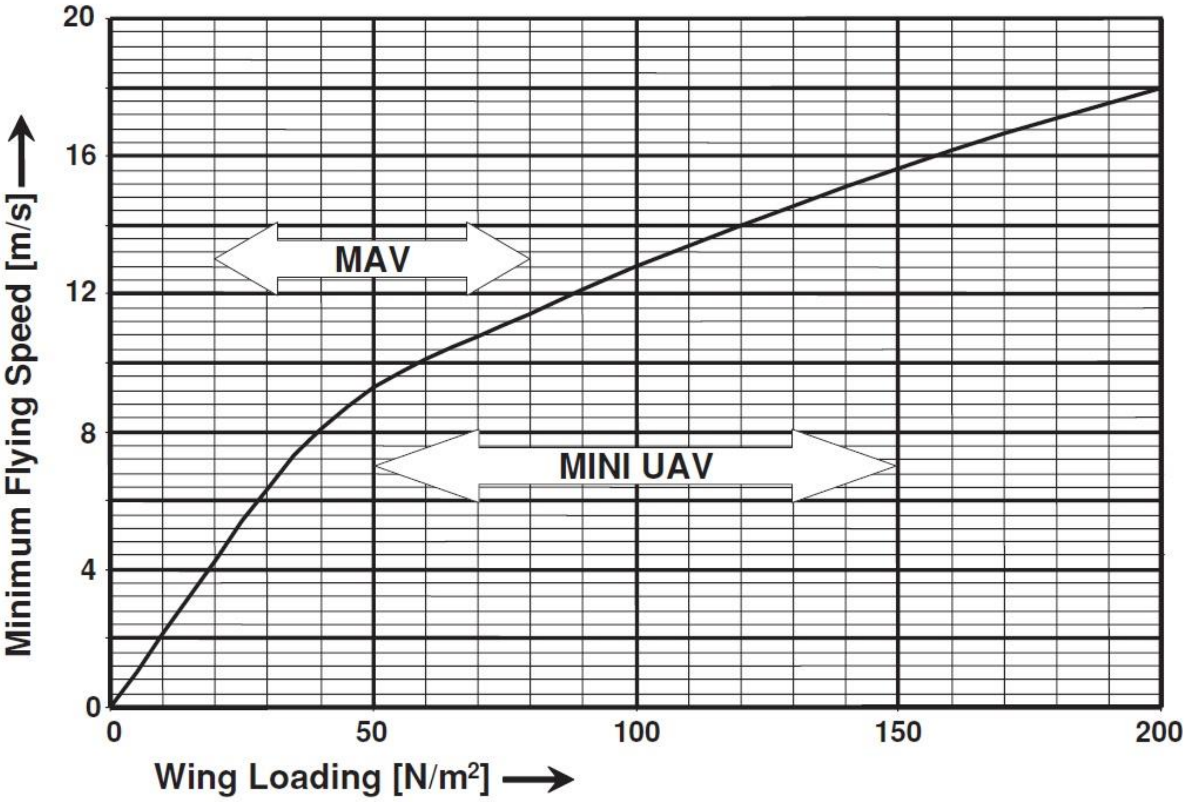


Figure 2.4 The variation of V_{min} with aircraft wing loading (lower values)

2.3 Rotary-wing Aerodynamics

The aerodynamics of rotary-wing aircraft are, by nature, more complex than the aerodynamics of fixed-wing aircraft.

2.3.1 Lift-induced Drag

The same basic mechanism applies for rotary wings as for fixed wings, the difference merely being that the ‘fixed wing’ moves on a sensibly linear path in order to encompass the air, whilst the rotary wing, whilst hovering, moves on a circular path. The latter therefore draws in ‘new’ air from above in order toadd energy to it and accelerate it downwards, compared with the former which receives it horizontally to accelerate it downwards.

At each element of the rotary wing, the aft ward-inclined vector of the lift force produces a drag at the element which translates into a torque demand at the rotor hub. For the same reason as with the fixed wing,

the rotary wing must induce a large mass of air for efficiency. Therefore the larger the diameter of the circle (or disc) traced out by the rotary wing, the more efficient it is.
Thus the disc-loading *p* N/m2, i.e. lift produced divided by the disc area, may be seen as the equivalent of span loading for the fixed wing. The difference, however, is that in the case of the fixed-wing lift, the lift is produced by the air being deflected over a sensibly single linear vortex so that the induced downwash and drag would theoretically increase to infinity at zero speed if the aircraft were able to fly at that condition. For the rotary wing, lift is produced by the air being deflected downwards over a large area covered by a number of rotating vortices so that the induced velocity and drag of the rotor remains at a finite value at zero airspeed.
The velocity induced at the helicopter rotor in the hover is given by:

$$v_i = k_n(p/2\rho)^{1/2} \qquad (2.7)$$

where k_n is a correction factor to account for the efficiency of the lift distribution and the strength of the tip vortices generated at the rotor blade tips. In practice this can vary between about 1.05 to 1.2, with 1.1usually being appropriate to rotors of moderate disc loading p.

The induced power in hover flight is then given by $P_i = k_n.Tv_i$, where T is the thrust produced by the helicopter rotor.

In forward flight the rotor is able to entrain a greater mass of air and so, as with the fixed wing, it becomes more lift-efficient and the induced power rapidly reduces with increasing speed. At a forward speed of about 70 km/hr, the flow pattern through the rotor becomes similar to that passing a fixed wing. Therefore at that speed and above, the same expression may be used to calculate the helicopter-induced power and drag as that used for the fixed-wing i.e. Equation (2.1).For airspeeds between zero and 70 km/hr, the airflow through a rotor is more complex and an empirical solution is normally used. This takes the form of a curve whereby an induced factor *k* is plotted against a function of aircraft forward speed and disc loading ($V \div \sqrt{p}$), The induced power calculated for the hover is multiplied by the factor *k* to obtain the induced power obtaining at the intermediate airspeeds. The ‘Hafner curve’ is shown in Figure 2.5.

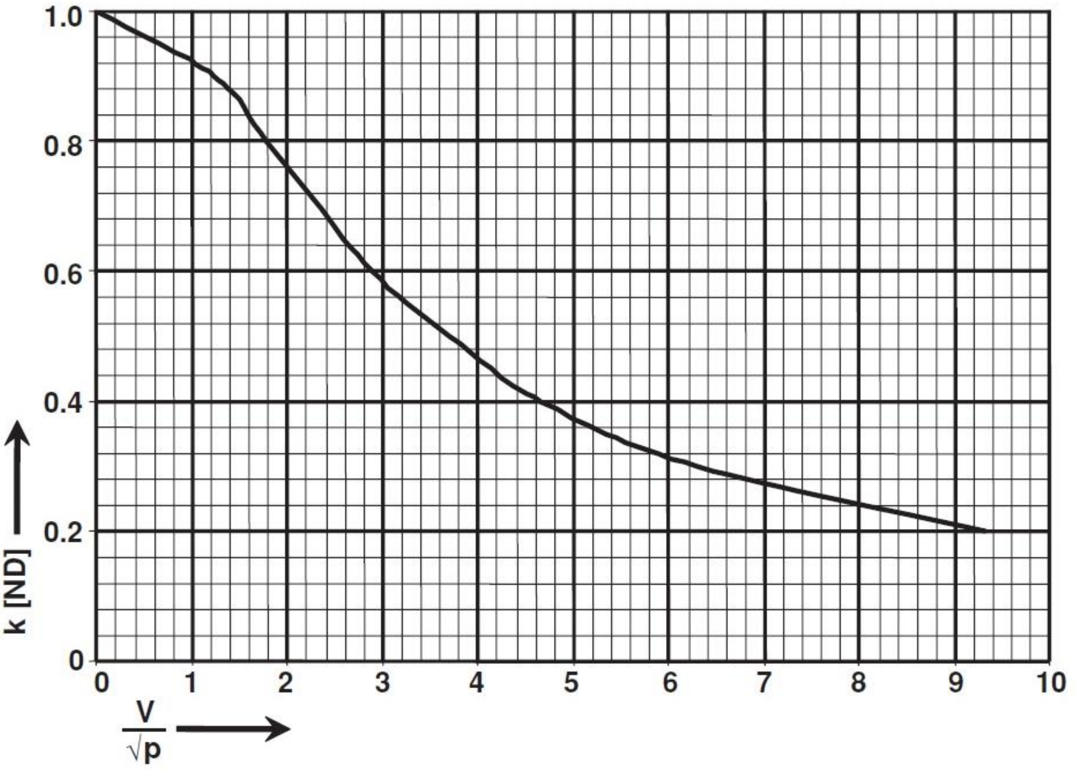


Figure 2.5: The 'Hafner' induced power factor

Figure 2.6: MQ-9 Reaper / Predator B- UAV

Figure 2.7: Global Hawk- UAV

2.3.2 Parasitic Drag

Again, the same elements, form drag, friction drag, momentum drag, etc., as discussed for the estimate of fixed-wing aircraft performance, apply to the rotary-wing aircraft. There is a small difference, however, in the accounting.

Due to the more complex ‘flight path’ of a rotor, its drag is accounted for separately under the heading of‘ profile drag’ or ‘profile power’. The drag of the remaining elements, i.e. fuselage, undercarriage, cooling drag, etc., then comprise the parasitic drag which is calculated in the same way as for a fixed-wing aircraft.

2.3.3 Profile Drag or Power

In hover flight, the profile power required to turn the rotor against the profile drag is computer-calculated by the summation along the length of the rotor blade of the drag of the blade split into elemental sections and multiplied by the local element velocity and radius from the hub. This is referred to as blade element theory. However, for simpler analysis, an average value of drag coefficient δ is used and mathematical integration produces the following expression;

$$\text{Profile power } P_o = \frac{1}{8}\rho\delta A V_T^3 \qquad (2.8)$$

where A is the total blade area and V_T is the speed of the rotor tip.

In forward flight, each blade element no longer describes a circular orbit, but a longer, spiral path which becomes increasingly asymmetric as the forward speed increases. The result is an increase of the profile power compared with that of the hover. Power is expended in translating the rotor as well as rotating it. An exact expression of the multiplier to obtain this power is a power series equation in μ, the 'advance ratio' – i.e. the ratio of the forward speed to the rotor tip speed. This multiplier is usually simplified to the close approximation: $(1 + 4.73\,\mu^2)$, so that the profile power in forward flight is calculable as:

$$P_{o\mu} = P_o\,(1 + 4.73\mu^2) \quad (2.9)$$

2.4 Response to Air Turbulence

It is highly desirable, if not imperative, to reduce the response of a UAV to turbulent air to a practical Minimum. This is primarily in order to more readily maintain payload sensors and beams on to the target. Other equipment, such as navigational sensors, also benefit from a 'smooth ride', but maintaining a course may also be a problem in extreme turbulence.

There are two main causes for an aircraft to have a high response to atmospheric turbulence:

a) if it is designed to have strong aerodynamic stability;
b) if it has large aerodynamic surface areas, coupled with a high aspect ratio of those surfaces, compared with the mass of the aircraft.

If an aircraft is designed to have aerodynamic surfaces whose task is to maintain a steady flight path through a mass of air, by definition, if the air-mass moves relative to spatial coordinates then the aircraft twill move with the air-mass. The aircraft will therefore be very responsive to air turbulence (gusts).To achieve stability with respect to space, it is preferable to design the aircraft to have control surfaces which, together with the aerodynamic shape of the remainder of the airframe, result in overall neutral, or near neutral, aerodynamic stability characteristics. This will ensure minimum disturbance from air turbulence, but the aircraft will then need a system to ensure that it has positive spatial stability to prevent its wandering off course due to other influences such as, for example, payload movement. This will require sensors to measure aircraft attitudes in the three axes of pitch, roll and yaw with speed and altitude and/or height data input. These sensors will be integrated into an automatic flight control and stability system (AFCS) which will control the aircraft in flight as required for the mission.

An aircraft with a large surface area to mass ratio will be disturbed by air gusts far more than an aircraft with a high mass to surface area. Any surface will generate an aerodynamic force though a high aspect ratio lifting surface will generate more than a low aspect ratio wing or fuselage. A high mass, and therefore a high inertia, will reduce the acceleration resulting from an imposed force. The more dense the packaging of an aircraft so will it be less affected by air turbulence. In this respect, UAVs have an advantage compared with manned aircraft as tightly packaged electronics are denser than human aircrew and the room that they require to function. Also, humans come in largely predetermined shapes whereas electronic systems can be tailored to fit.

Unfortunately for fixed-wing (horizontal take-off and landing) aircraft the wing area may be determined by that required to achieve low-speed flight for take-off and/or landing. A compromise may have to be considered between gust reduction and low-speed performance or, if high-lift devices are considered, also with complexity, reliability and cost.

Figure 2.6 shows the results of simple calculations which indicate the degree to which aircraft having different values of wing loading and aspect ratio will respond to a vertical sharp-edged gust of 5 m/s. It has to be pointed out that a sharp-edged gust is a rare phenomenon, gusts usually 'ramping-up', and the acceleration shown is the initial response of the aircraft and the response will be damped somewhat as the aircraft moves and by control applied by the AFCS.

Also, of course, the calculations do not take into account that the aircraft, especially whilst flying at the lower speeds, may have stalled before the full acceleration is felt. However, the results are useful in comparative, if not in absolute, terms. It indicates how vulnerable aircraft of low wing loading can be to turbulent conditions, and also the benefits conferred by a low aspect ratio wing in reducing response. Unfortunately, the latter also confers a penalty in producing high induced drag at lower speeds. As ever, in aviation, compromises have to be effected.

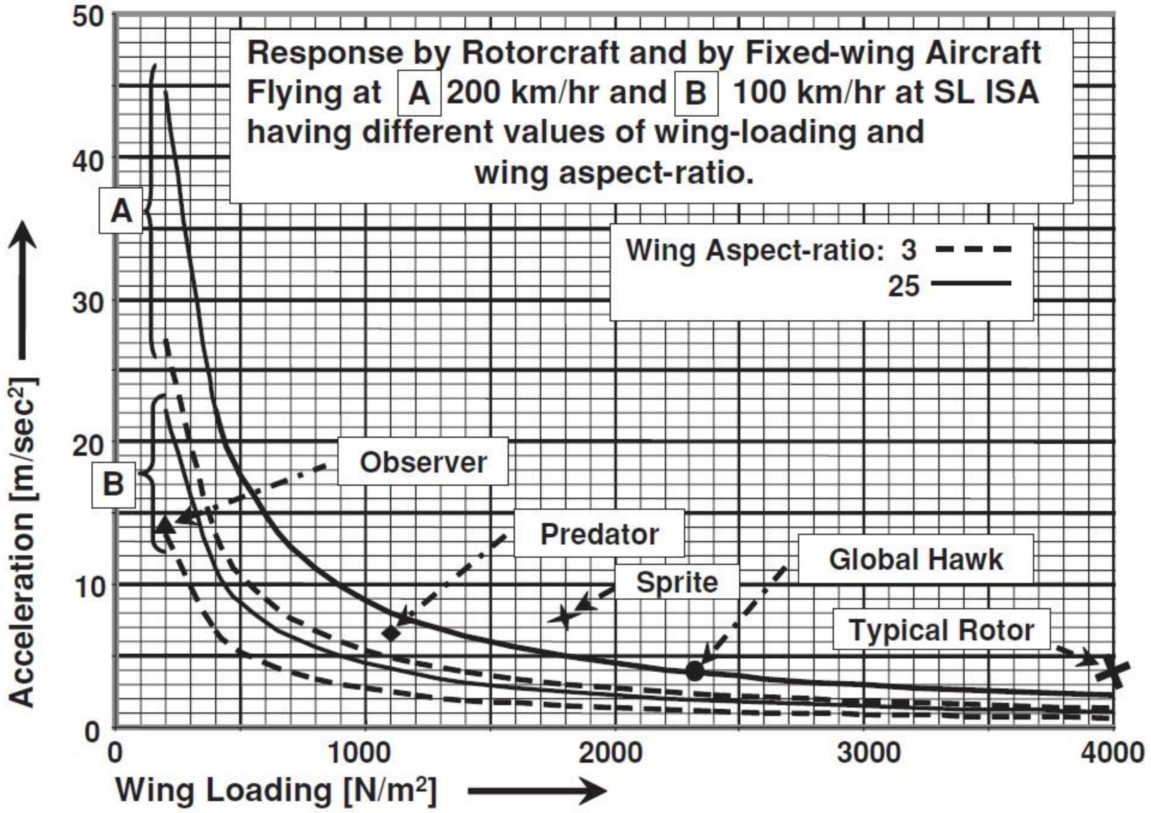


Figure 2.8: Aircraft vertical response to a vertical gust

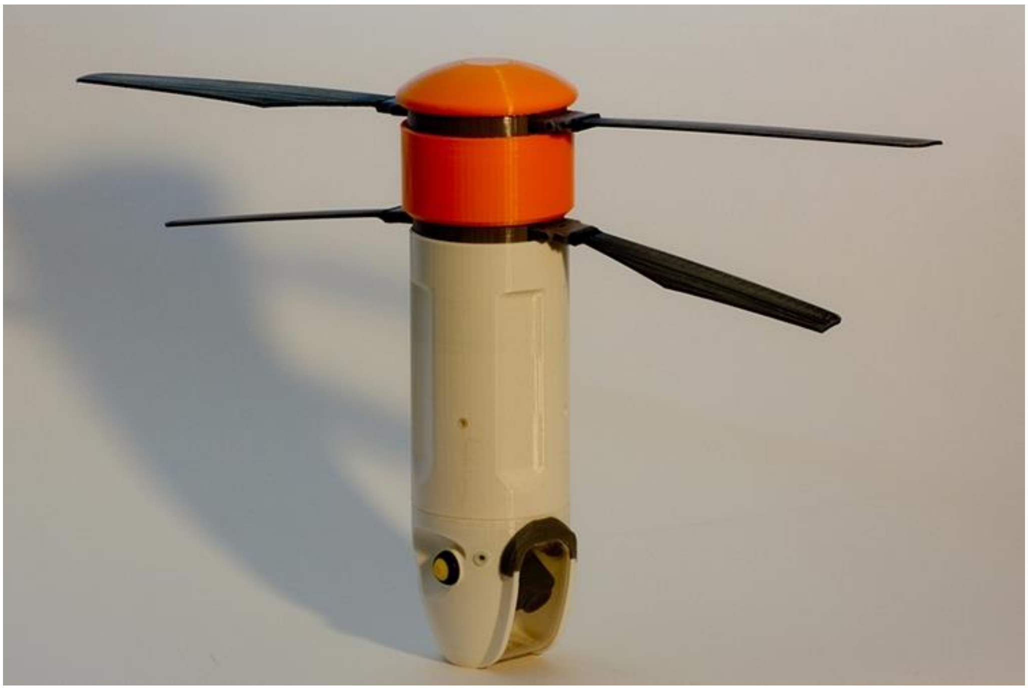


Figure 2.9: Sprite drone

An approximate criterion for comparing the unit initial gust response of an aircraft is as follows. The vertical acceleration in response to a 1 m/s vertical gust is approximately given by the expression :acceleration = $K_1 \times K_2 \times V/w_m$, where K_1 and K_2 are constants: $K_1 = \frac{1}{2}\rho a$ and $K_2 = AR \div (AR + 2.4)$. The former constant is a function of the air density ρ, and the two-dimensional aerofoil lift curve slope (a = 5.73). The latter is a correction for the aspect ratio (AR) of the aeroplane wing. V (m/s) is the forward speed of the aeroplane or 2/3 of the rotor tip speed of the helicopter. w_m (kg/m^2) is the wing loading of the aeroplane or blade loading of the helicopter expressed in mass per unit area, i.e. the wing loading in N/m2 divided by the gravitational acceleration g.

Using this expression, the vertical acceleration in response to a 5 m/s vertical gust by various UAV having different values of wing loading and at two representative forward speeds has been estimated and shown in Figure 2.8.

Medium-range HTOL UAV tend to have wing loadings in the range 300–600N/m^2 and MALE and HALE UAV of the order of 1000 and over 2000 N/m^2 respectively. Helicopter rotor-blades generally operate at tip-speeds in the order of 200 m/s (720 km/hr) and loadings of over 4000 N/m2. This, even whilst the aircraft is hovering, it is in effect equivalent to a HTOL aircraft with a very high wing loading flying at about 500 km/hr (a mean effective speed over the length of a blade) and therefore results in a helicopter rotor having very low response to vertical gusts as shown in Figure 2.8.

A single rotor, however, does have a response to a horizontal gust in the lateral direction, as well as a response, as do all aircraft types, in the vertical and aft directions. Hence ‘single-rotor’ helicopters, due to their asymmetry and cross-coupling of aerodynamic modes, are more difficult to control manually, so do require more complex flight control systems than a typical HTOL aircraft. However, other rotorcraft configurations do not have this problem.

Although rotors in forward flight can produce vibrational forces, the forces occur at predictable frequencies and so can be isolated from the airframe using an appropriately tuned airframe-to rotor suspension. The helicopter, therefore, with its VTOL and hover capability is well suited to operations at low heights to bring sensors to bear accurately onto small targets.

2.5 Airframe Configurations

The range of airframe configurations available for UAV is as diverse as those used for crewed aircraft, and more since the commercial risk in trying unorthodox solutions is less for the UAV manufacturer. This is principally because the UAV airframes are usually much smaller than crewed aircraft and operators are less likely to have a bias against unorthodox solutions. It is convenient to group configurations into three types appropriate to their method of take-off and landing.

The author prefers to use the acronym HTOL for aircraft which are required to accelerate horizontally along a runway or strip in order to achieve flight speed. In his view the acronym CTOL (conventional takeoff and landing) is outdated since VTOL is no longer unconventional. Indeed, many flying organisations and services employ more VTOL aircraft than HTOL aircraft. It also removes the problem in designating fixed-wing aircraft which have a VTOL capability. The following sections will discuss:

a) HTOL or horizontal take-off and landing,
b) VTOL or vertical take-off and landing,
c) hybrids which attempt to combine the attributes of both of these types.

2.5.1 HTOL Configurations

After many years of development in crewed applications, these have reduced to three fundamental types, determined largely by their means of lift/mass balance and by stability and control. They are ‘tail-plane aft’, ‘tail-plane forward’ or ‘tailless’ types, shown in outline form in Figure 2.7.All configurations, with the known exception only of the Phoenix, have the powerplant at the rear of the fuselage. This is to free the front of the aircraft for the installation of the payload to have an unobstructed view forward.

From an aerodynamic viewpoint, if a propeller is used, the induced air velocity ahead 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.

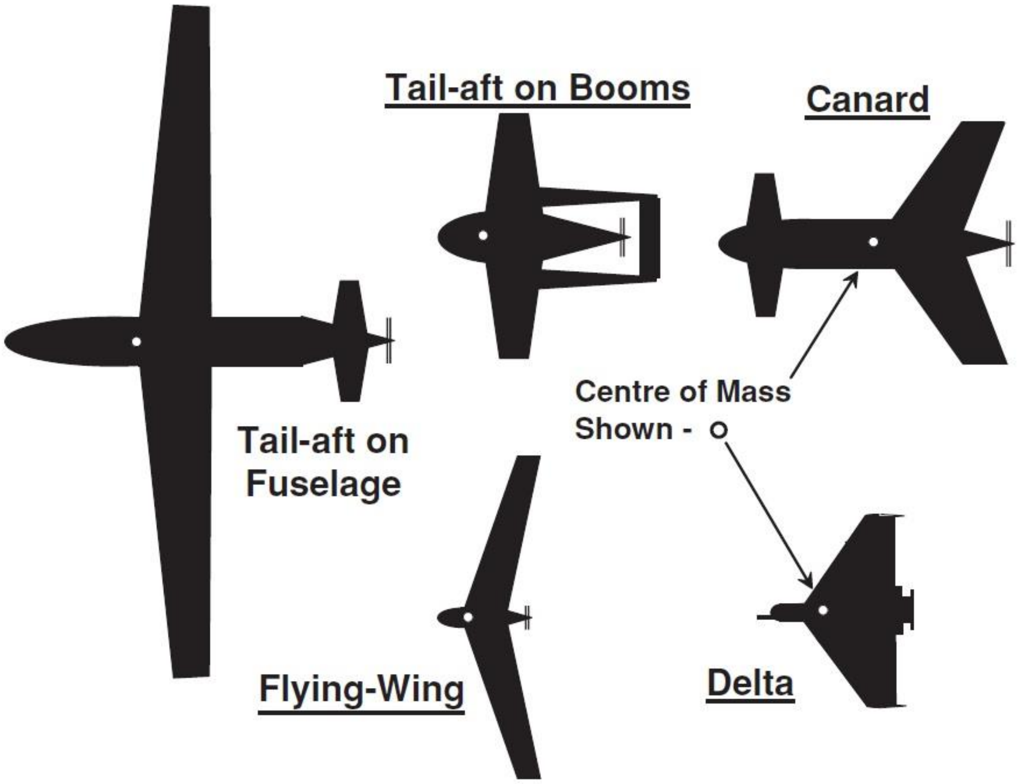


Figure 2.10: HTOL aircraft configurations

(a) Main Wing Forward with Control Surfaces aft

This is accepted as the conventional arrangement and is by far the most ubiquitous. The aircraft centre of mass is forward of the wing center of lift and this is balanced by a down-load on the tailplane, thus providing aerodynamic speed and attitude stability in the horizontal plane. A vertical fin provides weather cock stability in yaw with wing dihedral giving stability in roll. This established configuration is the datum against which other configurations are compared. Differences within the category are to be distinguished from one another only by how the tail surfaces are carried – i.e. Single tail boom or twin tail booms and by the number of engines used.

Current HALE and MALE, i.e. long-range UAV, all have their tail surfaces carried at the rear of the fuselage. This is probably because the volume of a long fuselage is required to carry the large amount of equipment and fuel load needed on their type of operation.

The twin-boom arrangement is popular for the medium- and close-range UAV as this allows the engine to be mounted as a pusher system just aft of the wing, again freeing the front fuselage for payload installation. It also provides a degree of protection for and from the engine and propeller.

There are also some aerodynamic advantages to be gained with this configuration. A pusher propeller and engine closely behind the aircraft centre of mass reduces the inertia of the aircraft in pitch and yaw. The relative proximity of the propeller to the empennage enhances the control power through the slip stream passing over the elevators and rudders and, with the lower inertia, gives an aircraft that is more responsive to pitch and yaw control. These qualities account for the popularity of this configuration. For examples, the Hunter and Seeker UAV.

Figure 2.11: Hunter_RQ-5_UAV

Figure 2.12: Denel Dynamics Seeker drone

(b) Canard Configuration

A canard configuration has the horizontal stabiliser, or fore plane, mounted forward of the wing. The aircraft centre of mass is also forward of the wing and the balance is achieved with the foreplane generating positive lift. Aerodynamic stability in the horizontal plane is a result. An advantage of the canard system is that as both planes are generating positive lift, it is aerodynamically more efficient than the tail-aft configuration. It also has the advantage that, as it is set at higher angles of incidence than the main wing, the foreplane stalls before the main wing. This results only in a small loss of lift and a gentle nose-down pitching motion to a recovery with a small loss of height compared with that following the stall of the tail-aft configuration.

Figure 2.13: E.M.I.T. aviation – "Blue Horizon" UAV

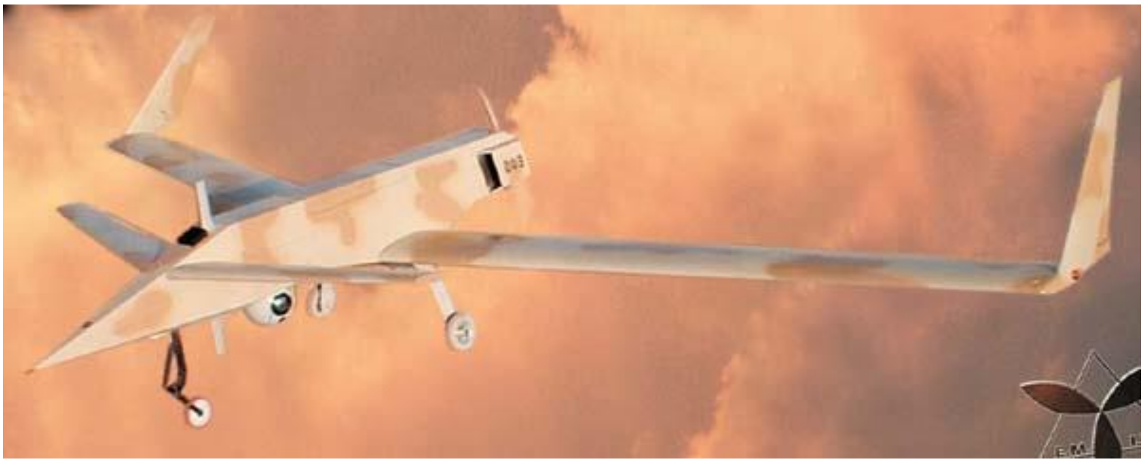


Figure 2.14: E.M.I.T. aviation – “Blue Horizon” UAV

A disadvantage of the canard is that directional stability is less readily achievable since, as the aircraft centre of mass is more rearward, the tail fin (or fins) do not have the leverage that the tail-aft arrangement has. To extend the tail-arm, most canards have the wing swept backwards with fins mounted at the tips. The most usual propulsive system used in the canard is by aft-mounted engine(s) in turbo-jet or propeller form. An example is the Blue Horizon UAV by E.M.I.T. of Israel (Figure 2.8).

(c) Flying Wing or “Tailless” Configurations (Figure 2.10 and 2.15)

This includes delta-wing aircraft which, as with the above, have an effective ‘tail’. The wings have a ‘sweep-back’ and the tip aerofoils have a greatly reduced incidence compared with the aerofoils of the inner wing. This ensures that, as the aircraft nose rises, the centre of lift of the wing moves rearwards, thus returning the aircraft to its original attitude.

These aircraft suffer in similar manner to the canard in having a reduced effective tail-arm in both pitch and yaw axes, though the rearwards sweep of the wing does add to directional stability. The argument generally offered in favour of these configurations is that removing the horizontal stabiliser saves the profile drag of that surface. Opponents will point to the poorer lift distribution of the flying wing which can result in negative lift at the tip sections and result in high induced drag. An example of this configuration is the Boeing-In-situ Scan Eagle. The aircraft, with its unique method of recovery, would probably find a tail system (empennage) to be an embarrassment.

(d) Delta-wing Configuration

The delta-wing configuration, such as in the Observer UAV (see Figure 2.16) gives a rugged airframe for skid or parachute landings, without the lighter and more vulnerable tail. It has a lower gust response, due to its lower aspect ratio, than other HTOL aircraft. However, it shares with the flying-wing the criticism of poor lift distribution, resulting in higher induced drag exacerbated by its higher span loading.

Figure 2.15: Boeing Scan Eagle UAV

All-Up-Mass	36kg
Wing span	2.42m
Wing area	$1.73m^2$
Engine power	5.25kW
Wing loading	$184N/m^2$
Span loading	120N/m
Cruise speed	125km/hr
Loiter speed	110km/hr
Mission radius	25km
Endurance	2 hours

All-Up-Mass	177kg
Wing span	5.5m
Wing Area	$3.48m^2$
Engine power	19kW
Wing loading	$500N/m^2$
Span loading	316N/m
Cruise speed	158km/hr
Loiter speed	126km/hr
Mission Radius	50km
Endurance	4 hours

Figure 2.16: Close-range UAV systems: Observer and Phoenix (Reproduced by permission of Cranfield Aerospace Ltd)

The most usual propulsive system used is, as in the canard and flying wing, by aft-mounted engine(s)in turbo-jet or propeller form.

2.5.2 VTOL Configurations

Crewed helicopters are to be seen in many different configurations, largely driven by the means ofcounter-action of the rotor torque. These are all shown in outline in Figure 2.19.

(a) Single-main-rotor or 'Penny-farthing'

Here the torque of the main rotor, which tends to turn the aircraft body in the opposite rotational direction to the rotor, is counteracted by a smaller, side-thrusting, tail rotor which typically adds about a further10% onto the main rotor power demands. As discussed earlier, a disadvantage is that the aircraft is extremely asymmetric in all planes which adds to the complication of control and complexity of the algorithms of the flight control system. The tail rotor is relatively fragile and vulnerable to striking ground objects, especially in the smaller size of machine.

These are the most ubiquitous of the crewed rotorcraft since the configuration is most suited to aircraft in the range 600–15000 kg which currently covers the majority of rotorcraft requirements. The majority of VTOL UAV manufacturers have opted for this configuration, possibly because some air vehicles are adaptations of crewed machines and others are adaptations of commercial hobby models.

Figure 2.17: NAAVIK UAV (Navigation for Autonomous Aerial Vehicles by IIT Kanpur)

(b) Tandem Rotor

There is a strong scale effect on the size of helicopter rotors such that the ratio of rotor mass to lift increases strongly with the larger rotor sizes required by the heavier aircraft. Therefore, it is more efficient to fit two smaller rotors than one large one to aircraft above a certain AUM. The 'cross-over' point rises as technology, especially in materials, improves. It has increased from a value of about 10 000 kg in the1960s to about 15000 kg today.

Figure 2.18: Tandem Rotor UAV by NGC Aerospace

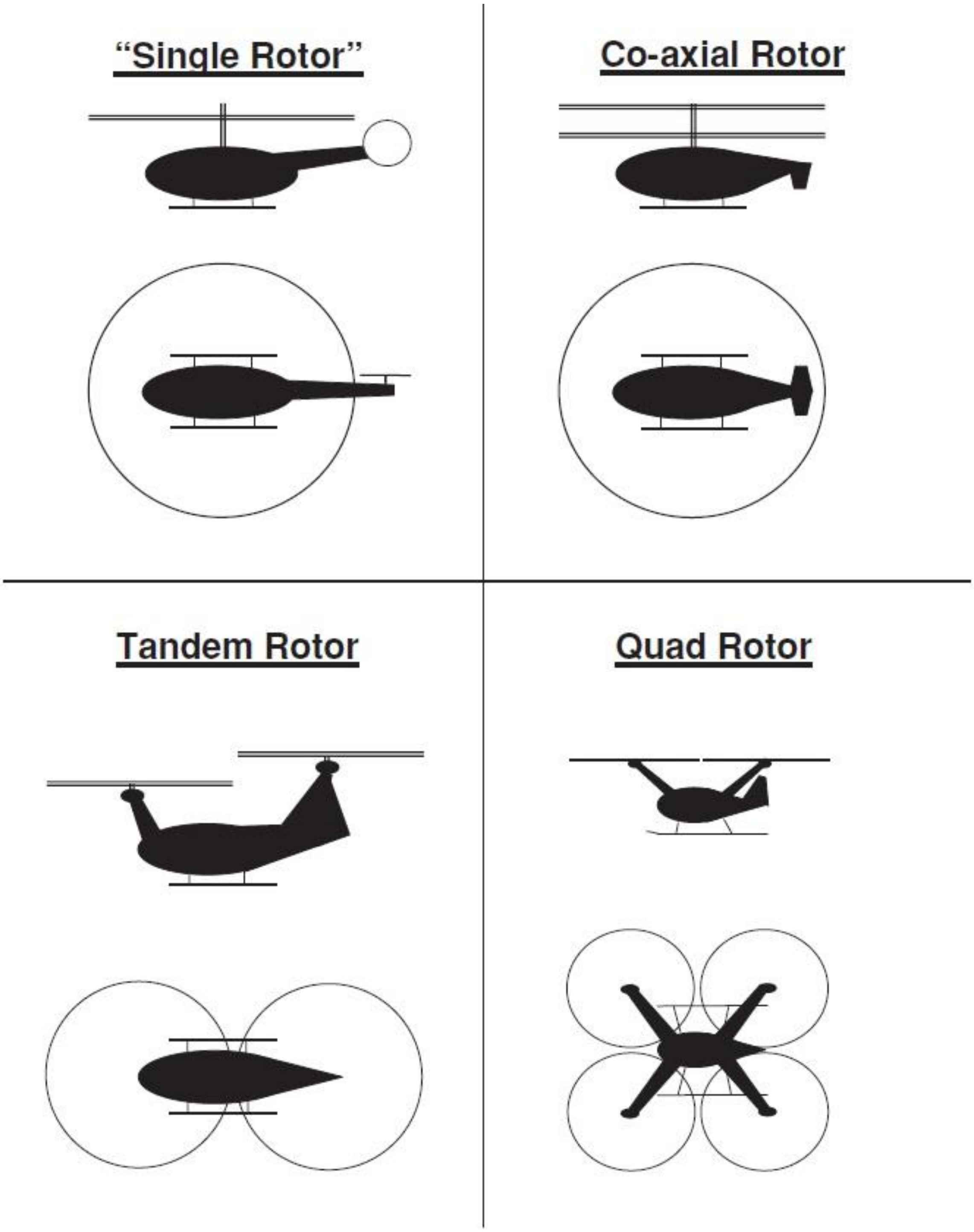


Figure 2.19: Rotorcraft configurations

Until VTOL UAV of this AUM are envisaged the tandem rotor configuration is not appropriate for UAVs, even though the configuration is more symmetric in control than the 'single rotor' and is more power efficient. The small payload volume of a low AUM aircraft does not require a long fuselage so that the rotors have to be mounted on extended pylons. That is not structurally efficient.

(c) Coaxial Rotor

This configuration, principally from the Russian manufacturer Mil., is in limited use for crewed applications. It is not more generally popular due to its greater height compared with that of the other configurations. It can present disadvantages in maintenance and in hangarage. For UAV application, with much lighter and smaller aircraft, these are no longer disadvantages.

The advantages of the configuration include an almost perfect aerodynamic symmetry, compactness with no vulnerable tail-rotor, efficiency of power and the versatility of providing alternative body designs for different uses, but each using the same power unit, transmission, and control sub-systems. Hencethe automatic flight control system (AFCS) algorithms are no more complex than that of a typical HTOL aircraft.

In addition, largely because of its symmetry, its response to air turbulence is the lowest of all of the helicopter configurations, being zero in most modes. Compromises in design may modify this advantage as is the case of the Sprite UAV. For purposes of stealth, in order to reduce the noise emanating from the rotor, a rotor tip speed lower than the norm was chosen. This had the effect of reducing the blade loading to 180 kg/m^2 and subsequently slightly increasing the response to vertical gusts.

Figure 2.20: VR-Technologies-VRT 300- Coaxial Rotor UAV, Russia

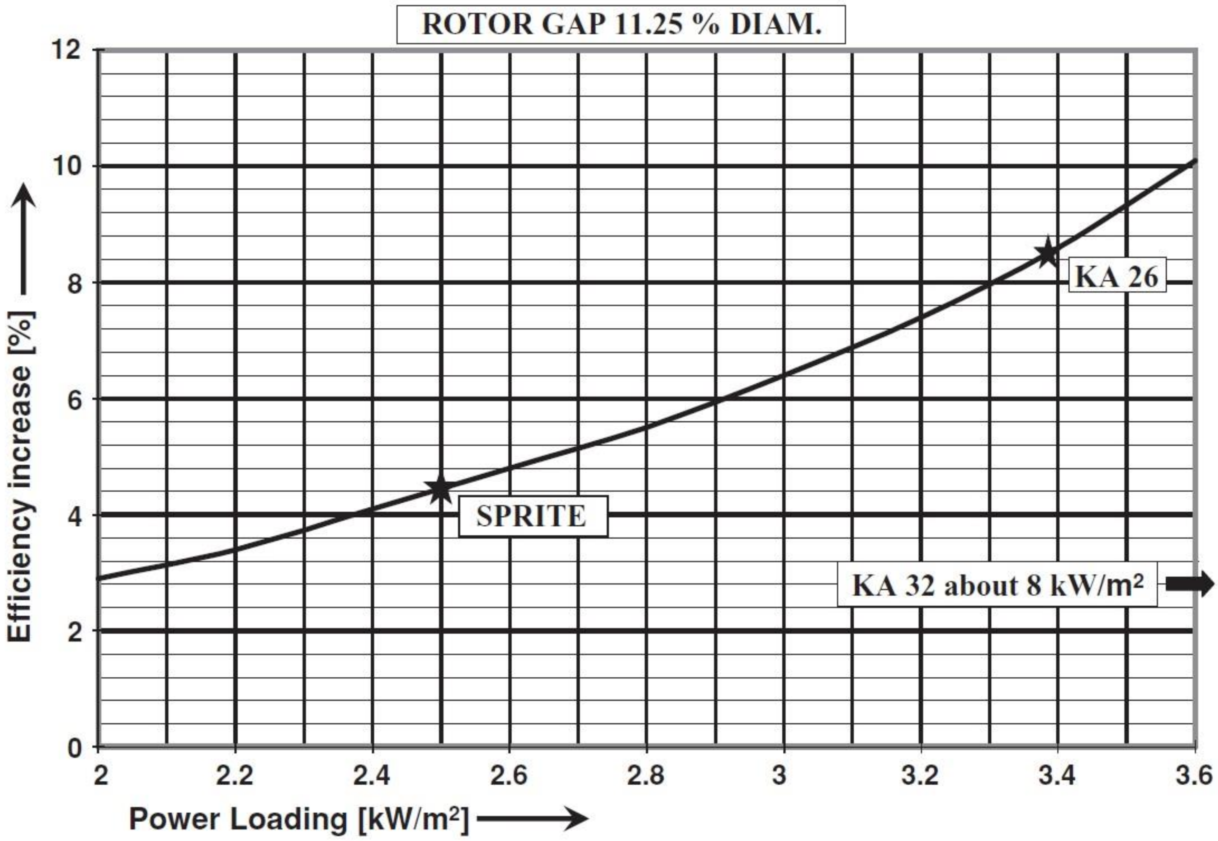


Figure 2.21: Coaxial rotor efficiency

Figure 2.21 shows the incremental percentage improvement in hover efficiency (thrust obtained for the same power) of the contra-rotating coaxial rotor system compared with the equivalent single rotor. The results shown are for a typical coaxial inter-rotor spacing of 11.25% of the rotor diameter. The comparison is more marked for heavier aircraft at higher disc loadings (and therefore higher power loading) for the reason that the induced swirl is greater. However, an advantage within the range of between 3 and 6% is relevant to the power loadings appropriate to helicopter UAV. In forward flight, the shaft between the two rotors will contribute extra drag, but this is offset by the elimination of tail rotor drag.

(d) Tri-rotor

There are no tri-rotor rotorcraft currently in existence or planned. The only known representative of this configuration, the manned 'Cierva Air Horse' was flown as a single prototype in the UK in the late 1940s, but the programme was terminated due to mechanical problems. However, the configuration does have some performance and mechanical advantages compared with the quad-rotor configuration and may yet appear.

(e) Quad-rotor

The only current development of this configuration known to the author is by a number of Universities who are attempting to make a simplified VTOL UAV in mini or micro sizes for urban surveillance. Whilst all of the previously discussed configurations use rotor-head control systems applying both cyclic and collective pitch changes to the rotor blades as the means of aircraft control, the goal of quad-rotor designers is to remove this complication, and also to remove the need for a mechanical transmission system. The idea is to have the rotor blades all fixed in pitch and to achieve thrust changes on each rotor by changing its speed of rotation. Each rotor is individually driven by an electric motor mounted at the rotor head. Thus, for example, for the aircraft to move forward the rotational speed of the two rear rotors would be increased to pitch the aircraft nose-down and direct the resulting thrust vector forwards. At the same time the total thrust must be increased to prevent loss of height and, once established in forward flight, the rotor speeds must again be harmonized.

The control algorithms to achieve this are extremely complicated, taking into account also the changing aerodynamic interference patterns between the rotors. There must be a time-lag in the demanded speed change of each rotor although this becomes less of a problem with the low inertias of a small MAV. The configuration is naturally more gust-sensitive than the other configurations, and its control response must be expected to be slower. Therefore, the achievement of adequate control may be difficult enough in the still air of laboratory conditions and even more problematic in the turbulent air of urban operations. Power failures, either of any one of the individual motors or of the power supply, may be considered unlikely, but such an event would spell an immediate uncontrolled descent to earth.

Figure 2.22: Aeryon Scout UAV Quadcopter

2.5.3 Hybrids

For hover flight, the helicopter has been shown to be the most efficient of the heavier-than-air aircraft. They are limited in cruise speed to the order of 200 kt (370 km/hr) by the stalling of the retreating blade(s). For longer-range missions, it is necessary to have the aircraft cruise at higher speed in order to achieve an acceptable response time to the target or area of patrol. However, the ability to take off and land vertically is a valued asset. From hence comes the wish to have an aircraft which combines the capability of both VTOL and HTOL worlds. Attempts have been made for many years, for crewed aircraft, to achieve this by various devices.

(a) Convertible Rotor Aircraft

One of the most successful methods to date has been to mount a rotor onto each tip of the main wing of a HTOL aircraft. The rotors are horizontal in vertical flight, but tilt forward through 90◦, effectively becoming propellers for cruise flight. There are two main variations on the theme, known generally as 'convertible rotor' aircraft.

One, known as the 'tilt rotor', retains the wing fixed horizontally to the fuselage and the rotors, with their pylons, are tilted relatively to the wing. The alternative is or the wing, power-plants and rotors to be constructed as an assembly and for the assembly to be hinged on the upper fuselage. This is known as a 'tilt wing' aircraft.

Within the tilt rotor configuration, there are two options for installation of the power-plant. One is for an engine to be installed in each of the rotor pylons, thus tilting with the rotors; the other is for the engine(s) to be fixed on the wing or within the fuselage.

Similarly, within the tilt wing configuration, two options are possible. The engines are most usually fixed to, and tilt with, the wing and rotors. Alternatively the engine(s) can be fixed in the fuselage, driving the rotors through a system of gears and shafts which pass coaxially through the wing hinge bearings. Tilting the engines in either tilt rotor or tilt wing requires the engines to be operable over an angular range of at least 90◦ and leads to some complication in the fuel and oil systems. This complication maybe more acceptable, however, than the alternative of the mechanical complexity involved in transferring the drive from a fixed power-plant to a tilting rotor system. Both these configurations have flown successfully as crewed aircraft, the tilt rotor being the more efficient of the two in hover and the tilt wing being the more efficient in cruise flight. However, as both types include the elements required for both regimes of flight, they have a reduced payload fraction compared with the helicopter and are more expensive in both acquisition and operation.

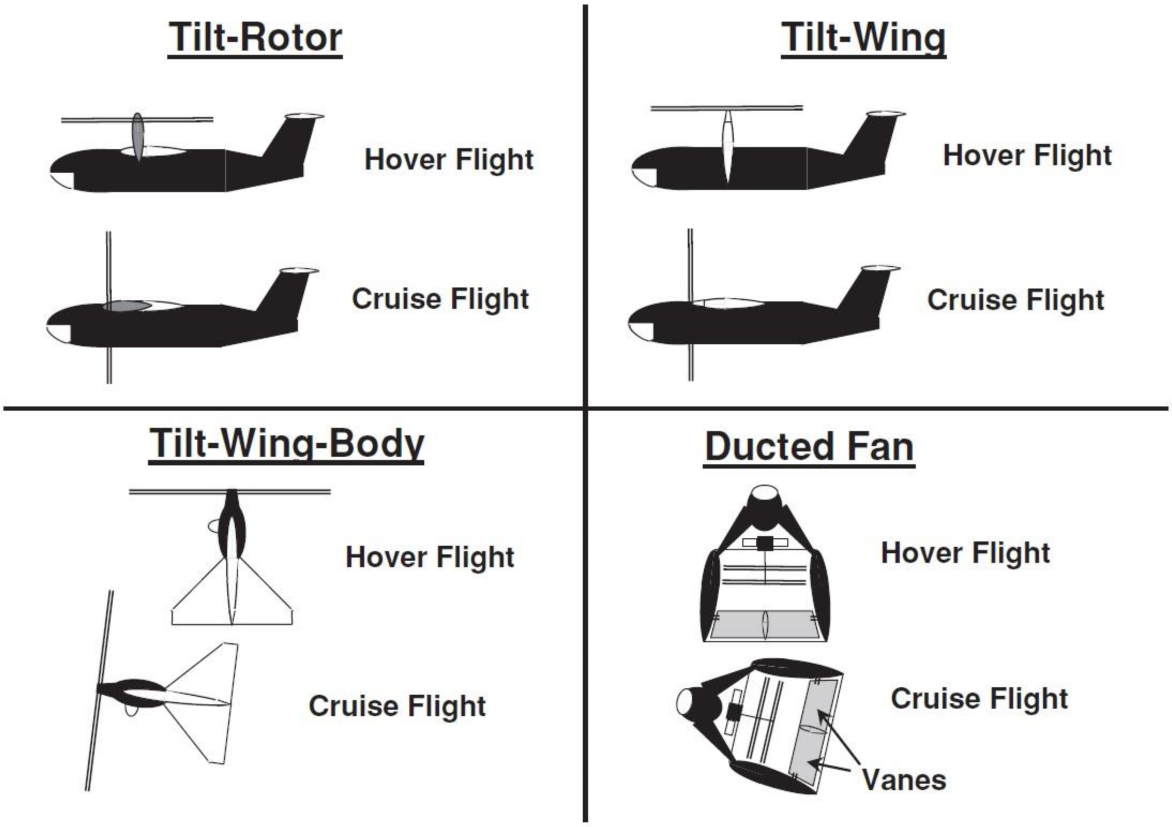


Figure 2.23: Hybrid aircraft configurations

(b) Tilt-wing-body Aircraft

With all convertible rotor aircraft, the critical part of the flight, and which predominantly determines the aerodynamic design of the aircraft, is the transition between full hover flight and full cruise flight. The problems lie in maintaining an attached airflow over the wing and achieving adequate control of the attitude of the aircraft, particularly in the longitudinal pitch angle. The latter is most readily achieved by the use of a helicopter rotor rather than a propeller for propulsion. The use of cyclic pitch can give good pitch and yaw control.

Maintaining flow attachment is a more difficult problem, especially during the conversion from cruise flight back to hover ('transition down') and landing. During 'transition up', the aircraft is accelerating and probably climbing with full thrust on the rotor. In this condition the high air velocity in the slip stream will reduce the otherwise high angle of attack of the wing and reduce the probability of wing stall. Even so, the avoidance of entering a stall will almost certainly require high lift devices, such as Kreuger leading-edge flaps and/or trailing edge flaps on the wing.

In the transition 'down' the velocity of descent will increase the wing angle of attack and will not be mitigated by a high slipstream velocity as the aircraft will be decelerating with low rotor thrust in this manoeuvre. This situation is much worse and may demand a higher disc loading of the rotor to increase the slipstream velocity and a larger wing in order to reduce the wing loading and hence the aerodynamic incidence. The ratio between disc loading of the rotor and wing loading of the wing is known as the 'lift loading ratio'. For a safe transition this may be required to be high, but it also demands more engine power and a larger wing, increasing the mass and cost of the aircraft and reducing its efficiency in both cruise and hover flight modes. A careful design of the wing with a suitable aerofoil section, probably of low aspect ratio, and appropriate flow attachment devices is the more intelligent solution.

(c) Ducted Fan Aircraft

The ducted fan aircraft, as its name implies, encloses its ‘thruster’ within a duct. The thruster is called a ‘fan’ as it will be of constrained diameter and will be of high ‘solidity’ – i.e. the ratio of blade area to disc area. The fan is most likely to be composed of two contra-rotating elements in order to minimize rotation of the body by a resultant torque. It is unlikely to have either collective pitch or cyclic pitch control available on the blades so that changes in thrust will be obtained by changes in fan rotational speed, and angular control of the body will be by tiltable vanes in the slipstream.

This configuration will inevitably result in a high disc loading of the fan and resulting high efflux velocity of the order 30 m/s (100 km/hr). This may ease the transition into, and back from, cruise flight, but flow separation from the duct is still a concern to be addressed. The greater problem here may be the attitude control of the body as the vanes may lack sufficient force or response to ensure a controllable, stable system.
The Northern Ireland Company, Shorts, were attempting to develop such a configuration in the 1970s.The programme was abandoned, it is understood, through the inability to achieve stable control. The technology available for power-plants and control systems now may make this problem surmountable.

(d) Jet-life Aircraft

A further variant of hybrid aircraft, though not shown in Figure 2.12, is the jet-lift configuration, in which the aircraft is suspended in hover flight on one or more high-velocity jets of air. Other, smaller jets, spaced out on wing tips and front and aft fuselage, are needed for roll and pitch attitude control. To transit into forward flight, the jet(s) are rotated backwards to provide an element of forward thrust, but retaining a vertical component until a fixed-wing progressively develops lift enough to sustain the aircraft. At this point the jets are effectively horizontal and provide propulsive force only. This is system has been well proven in the Harrier fighter aircraft, but is very expensive in engine power and fuel consumption. It is not appropriate for an aircraft which is required for other than high-speed missions, yet requiring a vertical take-off and landing.

2.6 Scale Effects

To date, unmanned aircraft in general have been of lower mass than manned aircraft as indicated in Figure 2.13.In terms of their all-up mass (AUM), manned aeroplanes range in size from the smallest single-seater such as the Titan Tornado of about 340 kg through the 590000 kg of the Airbus A380 and the 640 000kgof the AntonovAn 225.

UAV systems aeroplanes are on a lower scale, from about 6 kg for the Raphael Skylight, for example, up to the 12000 kg of the Northrop-Grumman Global Hawk. Hence the smallest fixed-wing UAV are two orders of magnitude smaller, in terms of mass, than their smallest manned counter parts. Similarly for rotorcraft – whilst manned versions range in mass from the 623 kg of the Robinson R22to the 97 000kg of the Mil 12 helicopter, the unmanned versions range only generally from the 20 kg of the EADS Scorpio 6 to the 200 kg of the Schiebel Camcopter.

There are heavier unmanned helicopters as indicated in Figure 2.13 where the original unmanned elicopter, the Gyrodyne DASH naval UAV is shown for reference at 1160 kg, and the more recent Northrop-Grumman Firescout (not shown), at 1430 kg. These latter two, however, are 'unmanned'versions of aircraft originally designed to carry passengers and so carry, to some extent, a penalty of their heritage. In addition they were (are) used to carry light armament. Also not included in the figure is the Bell Aerosystems Eagle Eye at 1364 kg AUM. This is a tilt-rotor configuration which, in terms of mass, carries a penalty of having elements required for both vertical and horizontal flight.

As can be seen, the lightest helicopter UAV design is, as the fixed-wing UAV, two orders of magnitude lighter than its manned counterpart. However, unlike the fixed-wing UAV, the heaviest specifically designed helicopter UAV does not yet enter at all into the domain of the manned machines.

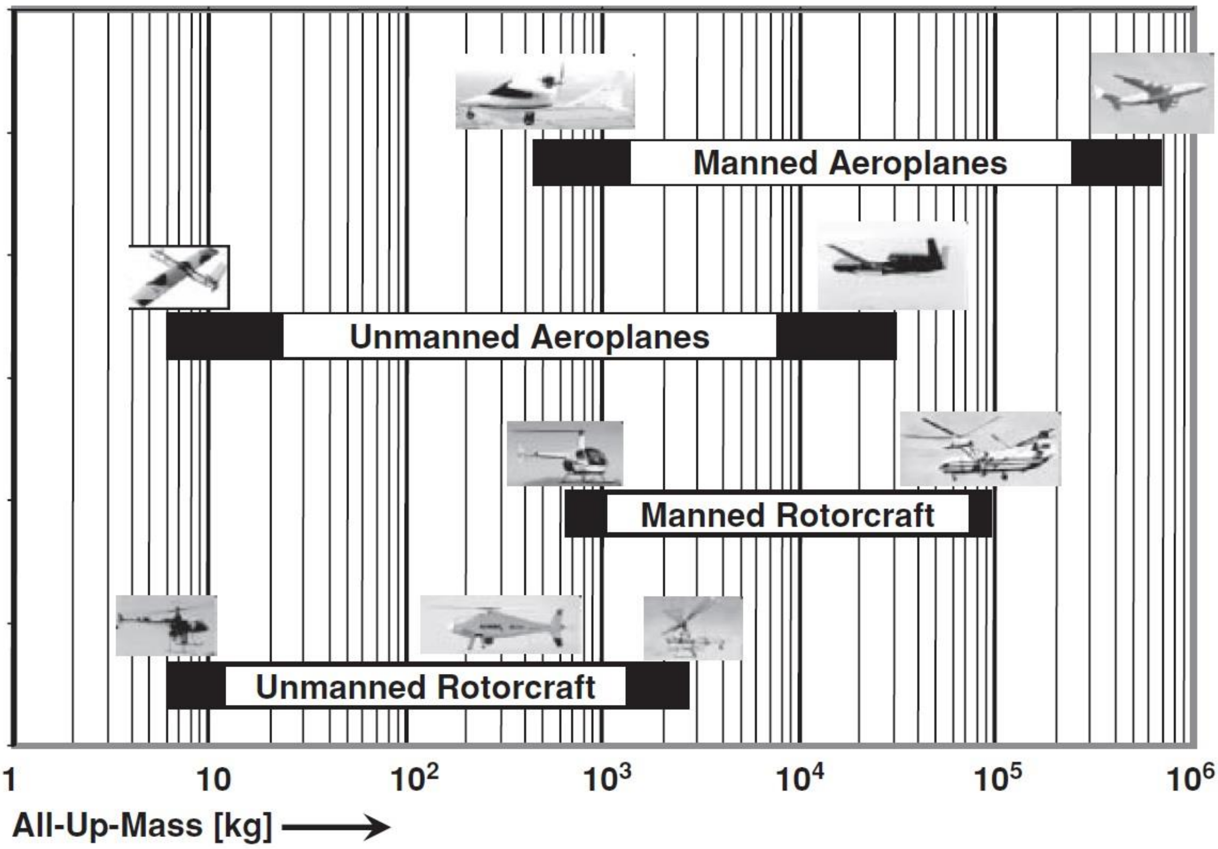


Figure 2.24: Mass domains of manned and unmanned aircraft

There are, of course, even lighter UAV (MAV) in development, down to 0.5 kg or even lighter in both fixed-wing and rotorcraft categories. However, care must be taken when extending the scaling laws to such low masses since they can form a discontinuity in the laws as they may use quite different technologies or configurations from mainstream aircraft. For example, some MAV use flexible membrane wings.

In general it is possible to determine the effect that these differences of scale can have in the design of UAV aircraft. This can be done through the use of the principles of "Froude Scaling".

2.6.1 Froude Scaling

An observer may compare, for example, a mouse with an elephant or a wren with a swan. Within each pecies, both have the same basic structural and locomotion elements, etc., but the frequency of limb or wing movement is vastly higher in the smaller creatures. The bone structure is denser in the larger creatures than in the smaller. These trends may be explained by the following logic using dimensional analysis.

Definitions. Linear dimension ratio is L_a/L_m, = *n* (scale factor) where subscript a indicates ‘actual’, m indicates ‘model’. For a model system where n = 10, an aircraft model represents a full-scale aircraft having linear dimensions 10 times that of the model and areas 100 times those of the model. But the actual size system operates in the same density of air ρ, and gravitation field strength *g* as the model.

Since the dimensions of acceleration are Lt^2; then for a constant value of *g, t* will vary as $L^{1/2}$. From this the following examples of relationships result:

Function	Scale factor	For $n = 10$, model represents system having:
Area $\sim L^2$	n^2	Area × 100
Volume $\sim L^3$	n^3	Volume × 1000
Mass $\sim \rho L^3$	n^3	Mass × 1000
Velocity $\sim L/t \sim L^{1/2}$	$n^{1/2}$	Velocity × 3.16
Dynamic pressure $\sim \rho V^2 \sim L$	n	Dynamic Pressure × 10
Angular inertia $\sim L^4$	n^4	Angular inertia × 10 000
Frequency $\sim 1/t \sim 1/L^{1/2}$	$n^{1/2}$	Frequency × 0.316
etc.		

Thus a small aircraft, built observing these criteria, of the same configuration as one of ten times the size will exhibit similar characteristics when flying at, say, 31.6 m/s to its larger brother flying at100 m/s.

This principle has been used successfully to determine the flight characteristics of full-sized aircraft using fully instrumented small-scale models, usually unmanned, flying at lower speeds. It enables flight experiments, with any subsequent modifications, to be conducted at much lower costs and without the risks sometimes encountered in the initial flight testing of new configurations of aircraft.

2.7 Packaging Density

The size and weight of the UAV can be significantly reduced compared with a manned aircraft designed or the same role by taking advantage of the ability to achieve a high density of packaging (aircraft mass/aircraft aft volume) and the structural and aerodynamic benefits which result.

The specific gravity (SG) of people is a little less than unity, but the effect of providing them with room for access and to operate, reduces the effective SG of the occupied cockpit for most light manned aircraft to an overall value of order 0.1 (i.e. about 100 kg/m^3) or less. In contrast, the electronics and optics for a UAV have densities greater than unity and can be tightly packaged, still allowing room for cooling. The TV camera system or other electro-optic sensor (eyes), AFCS (brain), radio and power supplies, (communication, etc.) and support structure of a UAV will typically have a SG of about 0.7(700 kg/m^3).

Engines, transmissions, actuators and electrical generators, where applicable, though usually of different scale, are common to both manned and unmanned aircraft and have SG of about 5–6 (5000–6000kg/m^3), although still requiring some room for access, cooling, etc. Landing gear varies considerably depending upon type, fixed or retractable, wheeled or skids. Gear for VTOL aircraft is usually much lighter than for HTOL aircraft. Therefore it is not possible to generalize for these components.

Structures such as wings, tail booms and empennage tend to have low values of SG. For example, the packaging density of a light aircraft wing, which typically accounts for about 10% of an aircraft mass, may be as low as about 25 kg/m^3 and these increases only slowly as the aircraft size increases. In contrast, the density of a helicopter rotor system, also accounting for about 10% of the aircraft weight, ranges from about 1200 kg/m^3 for a small helicopter UAV to possibly 4000 kg/m^3 for a large manned helicopter. Fuel is more readily packaged into suitably shaped tanks and a fuel system will have packaging densities, when full, of about 900–1000 kg/m^3. When installed, this will, of course, increase the effective packaging density of the containing wing or fuselage.

The actual overall packaging density of an aircraft depends on configuration and on size. As an example, a light manned surveillance aircraft, such as a two-seat Cessna 152, having an AUM of over700 kg will have an overall packaging density of about 120 kg/m^3. A fixed-wing UAV, such as the Observer with an AUM of only 36 kg, used to carry out a similar surveillance mission with TV camera equipment, has a packaging density of about 200 kg/m^3. A small coaxial rotor helicopter, such as the Sprite, of 36 kg mass can achieve a packaging density of 600 kg/m^3.

2.8 Aerodynamics

An indicative measure of the response to air turbulence of an aircraft, and to some degree its relative aerodynamic efficiency, may be given by the ratio ∧ of its surface area to its mass. The larger the surface area, the more it may be disturbed by aerodynamic forces. The greater its mass, so greater will be its inertia (resistance) to the imposed forces.

Using the scaling laws it may be seen that the area/mass ratio ∧ will vary as n/ρD, the linear dimension ratio n divided by the packaging density ρD. That is to say that ∧ will increase as the aircraft becomes smaller, but will be reduced as the packaging density is increased. Thus UAV, being generally smaller than manned aircraft, will tend to suffer more aerodynamic disturbance in turbulent air than will larger aircraft but this can be offset by the ability of the designer to achieve increased packaging density in the UAV.

The achievement of aerodynamic efficiency is obtained by reducing to an acceptable minimum the profile and friction drag of the wings and body. (This is often quantified by the drag-to-weight ratio of the aircraft – low for efficiency – and usually referred to the drag at 30 m/s airspeed.) Again, this tends to be a higher value for aircraft of low packaged densities.

The smaller aircraft suffers a higher friction and profile drag of both wings and body for the same shape as a larger aircraft as it operates at a lower Reynolds number I_R. The Reynolds number is a non-dimensional parameter which is the ratio between the inertia forces and viscous forces of a fluid flow, and consequently quantifies the relative importance of these two types of forces within a given flow. The inertia forces are greater downstream over longer surfaces at greater flow speeds and therefore are the dominant forces at higher N_R.

The value of NR is given by the expression

$$N_R = vl/v$$

Where v is the flow (air) speed; l is the characteristic length (e.g. wing chord) and υ is the kinematic viscosity of the fluid and has a value of 1.47 × 10−5 m^2/s for air under standard conditions. The aerodynamic drag of surfaces operating at lower values of NR is greater than for those at the higher values. UAV, being generally smaller and generally operating at lower speeds than manned aircraft, operate at lower NR so therefore generally suffer higher levels of drag.

This is shown graphically in Figure 2.14, where the drag coefficient, based on surface area, of a streamlined aerofoil of 15% thickness to chord ratio is shown for a range of values of NR. A number of UAV, ranging from the largest and fastest (Global Hawk) to the smallest UAV (Wasp III) believed to be in current production, are aligned to their respective values of NR based upon their wing chord and approximate minimum-power speed. It can be seen that the drag coefficients appropriate to the smallest, having a mass of only 0.43 kg, are three times that of the largest – the Global Hawk of about 12000 kg mass.

For the small MAV, these high values of drag coefficient apply to the surface area of a wing which is large relative to the aircraft mass. (i.e. a very low wing loading of 5 kg/m^2 necessary to achieve the minimum flight-speed required for hand-launching this aircraft). The other bad news for very small MAV aerodynamics is that the maximum lift coefficients obtainable at low N_R. are considerably lower than are obtainable at the more usual values of N_R.

Designers of MAV therefore have a challenge in making them aerodynamically viable and must alleviate the situation by extracting the maximum benefit through achieving:

a) the highest packaging density possible, and
b) the best aerodynamic shapes of the body.

2.9 Structures and Mechanisms

Although the achievement of an efficient aerodynamic solution for the smaller UAV is a challenge to be met by well-considered design, the good news is that structures and mechanisms usually benefit at smaller scale. Loads in larger aircraft are much higher than their smaller counterparts and so require materials of greater specific strength and stiffness to carry those loads over greater distances without failure through direct loading, bending or buckling.
When the structural design for light manned aircraft moved from fabric-covered tubular framework to monocoque construction in light alloys it was found that the direct loads in the shells (or skins) required the use of only very thin gauge material. To prevent local buckling of the skins between frames (or formers), stringers were added. Even this was insufficient as handling of the bodies and wings caused dents in the surfaces. It became necessary to accept the use of thicker skins to prevent this, but at a weight penalty. The advent of composite materials of lower density helped to alleviate this problem as the skins could be made thicker without an increase in weight. Although, initially, the materials such as glass-fiber epoxy resin matrices had a lower specific stiffness (Young's modulus), the extra thickness of the cross-section more than made up for this and the buckling and handling problem was solved.

This solution is directly applicable to UAV, and composite materials have become de rigueur for UAV construction except in areas where the higher loads must be carried within limited space. Examples of these areas can include undercarriages when reversion to light alloys or steels becomes necessary. However, with the development of materials such as carbon-fibre matrices in more specialised resins, cured in autoclaves (heated and pressure controlled chambers), and plastic–aluminium alloy composites, even these components may undergo material changes. Most UAV benefit through smaller scale in that loads are lighter and are required to be carried over shorter distances. This reduces the probability of buckling though attention must still be paid to ensuring that the structure is robust enough for man-handling.

The reduction of the weight of aircraft components allow for a greater mass of payload and/or fuel to be carried in the same AUM of aircraft. Alternatively, it allows for the task to be carried out with a lighter and smaller aircraft. An indication of the relative mass of the several components within an aircraft is by the use of the ratio.

2.9.1 Mass of Component/AUM of Aircraft

This is known as the 'weight fraction' of the component. The following expressions for weight fraction, derived from the scaling laws, indicate the benefit of small size and higher packaging density available to UAV.

$$
\begin{aligned}
&\text{Body structure (for given package density)} && = \text{Constant } K \\
&\text{Body structure (change in package density)} && = K\left[1/\sigma^2 + 1/\sigma\right] \\
&\text{Wing (change in aircraft AUW)} && = \left[\frac{K_T \mathrm{AR}^{3/2}}{t/c \cdot w^{1/2}} \times \frac{\rho_m}{f_c}\right] W^{1/2} \\
&\text{Rotorcraft gears and shafts} && = K\left[\frac{0.43}{V_T} + \frac{0.0085}{p^{1/2}}\right] W^{1/2} \\
&\text{Rotor blades and hub} && = \left[\frac{22}{\beta_0 V_T^2 p^{1/2}}\right] W^{1/2}
\end{aligned}
$$

where
σ is the package density ratio (dense/less dense);
W is the gross weight of the aircraft (N);
K_T is a constant depending upon the wing geometry, e.g. Taper;
AR is the wing aspect ratio;
ρ_m is the density of the wing material (kg/m^3);
f_c is the allowable direct stress of the wing material (N/m^2);
t/c is the wing thickness to chord ratio;
$w$is the wing loading (N/m^2);
V_T is the tip speed of the rotor (m/s);
p is the disc loading of the rotor (N/m^2);
β_0 is the coning angle of the rotor blades (rad).

These examples give an indication of the benefits that can be gained in structural and mechanical weight fraction for smaller and lighter aircraft and how achieving a high density of packaging, possible in the UAV, reaps rewards. This does depend, of course, on the appropriate selection of materials and good design.

2.9.2 Structure Design

Although the usual structural design methods, detailed in many textbooks, apply equally to UAV as to manned aircraft, their application may be a little different. The design of any UAV structure must take several requirements into account. Not the least of these is ease of initial manufacture, cost, longevity, reliability, accessibility and maintenance.
For manned aircraft, some of the ancillary equipment that must be accessed may be reached from on-board. The remainder has to be accessed through detachable panels in the aircraft external structure though

attempts are made to keep these to a minimum for reasons of structural strength and stiffness and for aerodynamic cleanliness. In UAV, especially the smaller ones, access from on-board is not feasible. Access through external removable covers is limited in scope due to the small size of the structure. For access by human hand, the panels may have to be large in proportion to the surrounding structure and would weaken the structure so that heavy reinforcement would be required. The solution adopted for some manned aircraft is the use of removable stressed-skin panels. The close fitting of these for reliable stress transfer is difficult to achieve at small scale. Therefore, for all but the largest UAV, amore efficient solution is to construct the airframe from detachable modules, using composite materials wherever appropriate. An example of a commonly used construction method for UAV fuselage modules of small or medium sized UAV is shown in Figure 2.14. Glass fibre is used with a suitable resin as the main material, with stiffening elements constructed as shown with a stiff plastic foam core wrapped with carbon fibre tape. Manufacturing the skins from carbon would be very expensive and carbon alone has little inherent damping, thus is prone to shattering if subjected to a sudden blow. Matching it with glass provides the necessary element of damping and has been found to provide a practical solution. Whilst carbon cloth is expensive, carbon tape is reasonably cheap. The whole provides a lightweight, stiff, durable and acceptably cheap structure suitable for mass production.

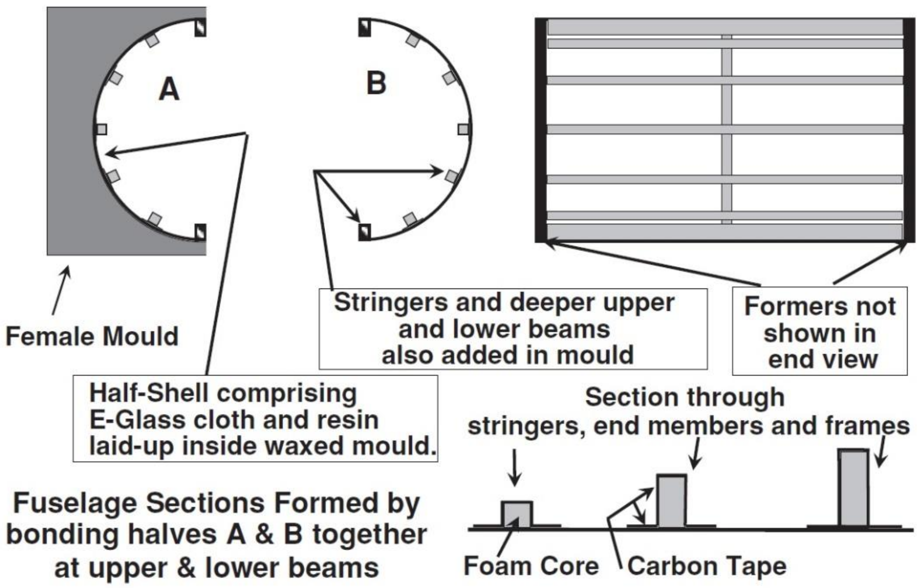


Figure 2.25: Structural techniques using composite materials

An alternative material which has about half the density yet offers similar stiffness to carbon/glass combination is a glass-fibre or carbon-fibre reinforced polycarbonate. It can be thermo-moulded and its forming into structure is less labour intensive than is the case with laid-up materials. Similar construction methods may be applied to the lifting surfaces. Inter-modular structural connections will usually require loads being diffused into connecting lugs or spigots, etc. which may have to be of light-alloy or even steel material depending upon the stress level at the connection.

Much of this can apply to the larger HALE and MALE aircraft, but because of the larger area of structures and greater load densities present in larger aircraft, a greater use is made of stiffer, carbon composites for outer shells of wings and fuselages. To achieve even greater stiffness and robustness as and which construction is another option with a nylon honeycomb layer sandwiched between two layers of carbon-fibre or carbon-fibre and glass-fibre mix. The continuing development of new materials offers several advantages for UAV design and manufacture and suitable material selection should be a prerequisite of any new UAV design.

2.9.3 Mechanical Design

Although the effect of small scale is generally advantageous in terms of stiffness requirements, a downside is that the holding of accurate tolerances in machining operations is more difficult. The approach to fatigue therefore has to be more cautious as stress-raising joints and bearing mountings can be more critical because of the scaled-down radii in corners. It is advisable to use larger reserve factors on joints and larger radii than pure dimensional scaling would indicate.

For example, as shown in the upper diagram in Figure 2.15, the edge radii on a standard small rollerbearing mounting would require a 0.5mm internal radius on the shaft. This would result in a greaterincrease in local stress than the equivalent at a larger scale. A proven solution, shown in the lowerdiagram, is to use a larger radius on the shaft with an abutment washer between the shaft collar and thebearing. The alternative of using a specially designed and produced bearing with larger edge radii wouldresult in a heavier and more expensive assembly.

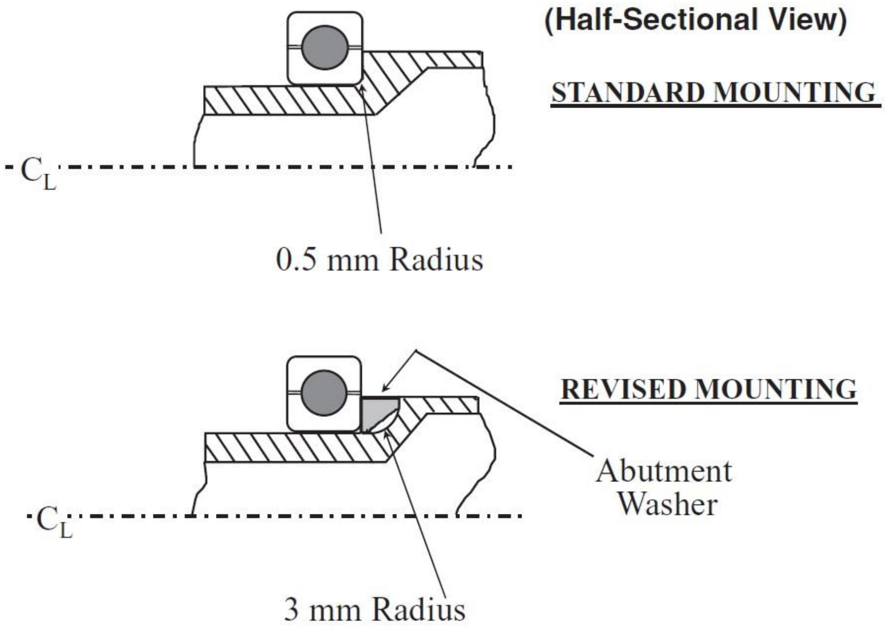


Figure 2.26: Revision of bearing mount design

2.9.4 Wear and Fatigue

Whether the mechanical system in design is a structure or a mechanism, the prerequisite is that it not only adequately and efficiently performs its required function, but that it continues to do so, reliably, fora specified time. Such time values, stemming from the operational requirements, will be specified at the concept of the design.

Components in design will be subjected to calculations aimed at ensuring that the specified lives will be achieved. The lifetime before the replacement of a component becomes necessary will be measured in operating hours for both wear and fatigue.
The wear rate on bearing surfaces is usually estimated from load–velocity charts. Subsequently these components will be tested in the development phase to confirm their operational lives. The number of oscillatory cycles to be applied to a component, before it fails in fatigue, will be calculated and an appropriate reserve factor added to estimate the component life. One effect of scale, as listed above, is that the natural frequencies of the UAV and components increase as size reduces. Therefore fatigue life as determined by the number of cycles before failure will be reached earlier in terms of hours of life in a smaller UAV. This trend may, however, be reversed by the same scale effect if the loads and stresses in the materials are lower.

The careful selection of the type of material to be used can be an important factor in reducing the occurrence of fatigue failure. Composite materials tend to have high resistance to fatigue and so their use instead of light alloys can be of advantage in extending the fatigue lives of airframes. Areas where a complete change from metallic components may be delayed for some time are in engines, rotorcraft hubs and transmission systems where, apart from high load densities occurring, other factors such as high temperatures and wear apply.

With the greater number of stress cycles per hour occurring in the smaller aircraft, if it is required to achieve a fatigue life comparable with a larger aircraft, it may be worthwhile considering the use of steels rather than light alloys in some applications. This may be especially true for rotorcraft. Most steels have a stress level at or below which the component will have an infinite fatigue life. This is not true of light alloys and to obtain a long (though still not infinite) life with a light alloy may require that it be operated at such a low stress level that the component is heavier than if designed in steel. As with components subjected to wear, those subject to fatigue will undergo rigorous testing in the development phases to establish their operational lives.

2.9.5 Undercarriage Design

The functions of the undercarriage are broadly the same for both manned and unmanned aircraft, the main purpose of the undercarriage being to absorb and dissipate the energy of impact on landing and to provide a stable base for the aircraft on the ground. For HTOL aircraft it will provide support whilst accelerating to flight speed on launch and decelerating after landing.

Whilst the design techniques are the same for manned and unmanned aircraft, the structural scale effect alone would favour the weight fraction of the UAV undercarriage. However, other effects more than negate that potential advantage.

Impact velocities tend to be greater for UAV due to the following causes.

a) Smaller HTOL UAV tend to have lower wing loading than manned aircraft and so they can be affected more by air turbulence on landing,

b) Unless the UAV landing is automatically controlled by accurate sensors, the judgment of a remote human pilot in assessing the UAV height above ground can be poor compared with an on-board pilot who has more positional and acceleration cues available.

If the undercarriage has wheels, they are likely to be smaller than the wheels of a manned aircraft. Imperfections of the taxi-way surface, such as drainage channels, present relatively large discontinuities compared with the wheel diameter and entry into them can impose very large drag loads onto the undercarriage and its supporting structure.
Undercarriage configurations range from the very simple to the relatively complex. The simplest will be those employed in land-based VTOL aircraft. These may be a fixed tubular skid type with flexible plates to absorb the initial energy of impact, and use friction between metal plates or the hysteresis in composites to provide a limited amount of damping.

Ship-based VTOL aircraft may require a greater length of undercarriage deflection to cater for higher impact velocities and almost certainly a greater amount of damping to prevent bouncing on deck. This latter may be achieved in various different ways. A composite material of very high natural damping may be employed or discrete pneumatic or hydraulic dampers may be incorporated. An alternative is to design the undercarriage to 'splay' its feet or wheels on impact to provide damping through friction with the deck.

HTOL aircraft will require a wheeled undercarriage which may have similar forms of energy absorption and damping to those outlined above. The wheels will have to be capable of carrying the aircraft to high speeds on take-off and landing and absorb greater shocks than the smaller wheels which may be used on VTOL aircraft merely to assist in maneuvering the aircraft on the ground or deck. Both HTOL and VTOL aircraft may require the undercarriage to be retracted into the aircraft wings, body or nacelles, as appropriate, in order to reduce its aerodynamic drag and/or destabilizing effect in high-speed flight.

Consideration will be given as to the direction of retraction. It is usually preferable for the undercarriage to be retracted forwards or sideways rather than aft. A forward retraction in a HTOL aircraft will move the aircraft centre of mass forwards and so improve its stability in flight. Also the airflow will aid its subsequent extension, particularly pertinent if any power failure has occurred during the flight. The requirement that an undercarriage provide a stable base for the aircraft when on the ground or ship-deck can have a large impact upon the undercarriage design. The first aspect that must be determined is the likely degree of destabilising force. This may arise from wind forces imposed upon the airframe or rotor system or unevenness or movement of the ground or ship's deck.

Naval operations from off-board impose the most adverse conditions for both HTOL and VTOL aircraft due to high wind turbulence, tilt of the ship's deck and movement of the deck. The calculation and addition of these effects will derive the effective displacement of the aircraft centre of mass (CoM) which must be contained by the undercarriage to prevent the aircraft toppling. The stability cone of the undercarriage is defined as the cone whose vertex is at the aircraft CoM and its circular base is the circle contained within the undercarriage footprint. The larger the vertex angle, so is the stability increased. A large vertex angle is obtained by having a low aircraft CoM, i.e. the CoM being as close to the ground as possible, and a large base to the stability cone.

2.9.6 Helicopter Rotor Design

The discussion above has indicated areas where the design of UAV components may differ in detail from those of manned aircraft, and especially effects of scale when the UAV is smaller than the manned counterpart. The difference in scale can bring about significant differences in the design parameters of the aircraft.
Regarding the effects of scale on the parameters of a helicopter rotor can provide a good example. The weight fraction equations, shown above, indicate that the weight fraction of elements in a helicopter rotor

and transmission system vary as the square root of the aircraft design gross mass (DGM). This knowledge is used in the optimisation of the complete aircraft where the mass of one system can be traded against another. The mass (or weight) fraction of a helicopter rotor increases severely with its diameter, principally because much of the mechanical elements are designed to withstand the torque applied to them. The speed at the rotor tip is limited by aerodynamic factors and so tends to be similar for all sizes of rotor. Hence the torque per unit power applied increases with rotor size and so therefore does the rotor mass fraction. As the aircraft DGM is increased, the designer may elect to limit the increase in the rotor diameter in order to save weight. However that will increase the disc loading p of the rotor and require more power and thus a larger and heavier engine. The weight increase with size of a rotor is at a generally greater rate than an engine weight increases with power. Therefore there is a trade-off of power-plant weight with rotor weight. The result is that the designer will choose a disc loading which produces the lowest combined rotor and power-plant weight for the endurance required of the aircraft.

2.10 Selection of Power-Plants

The design and development of a new engine and its integration into a viable power-plant often takes longer than the development of an airframe. The resulting attempted development of a new aircraft and new engine in parallel can result in the engine being late in arrival – it may not meet its promised performance and reliability or, in order for the engine developers to get it to work, may have been changed in form and/or have different output characteristics from those for which the aircraft was designed. The new engine may have become incompatible with installation in the aircraft.

Although it is very appealing to have the latest technology engine in a new aircraft, the aircraft designer must exercise judgement as to the probability of a new engine arriving in time and to specification. It is probably unwise to consider any new power-plant until it has been run satisfactorily on a test-rig for at least 100 hours.

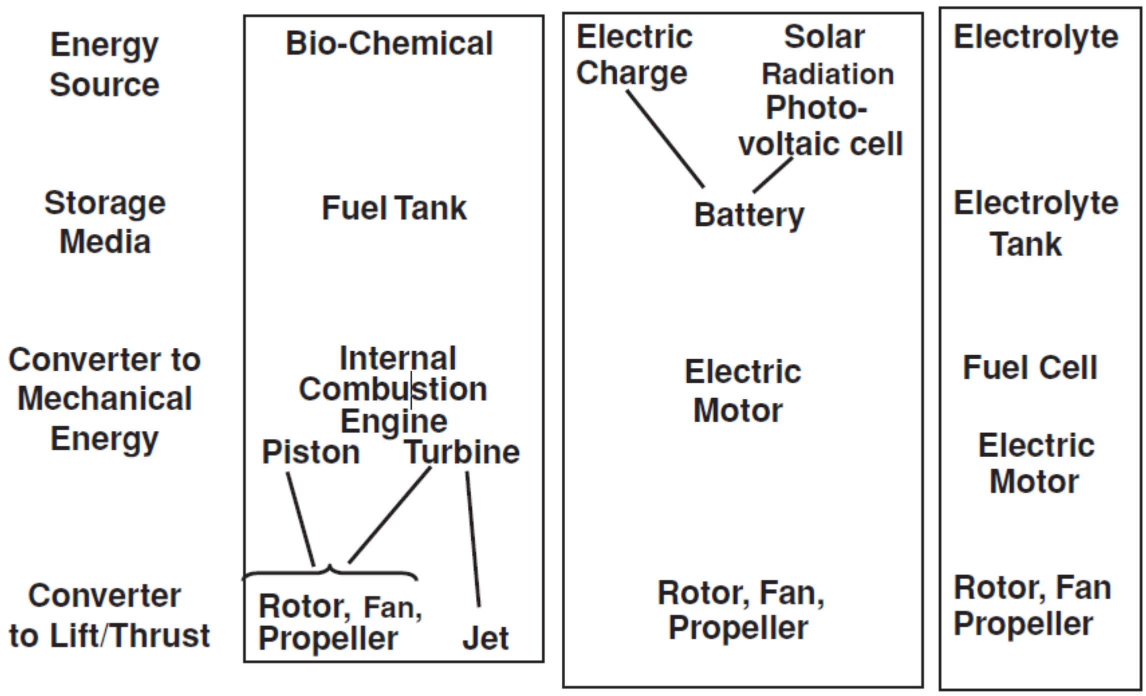


Figure 2.27: Power-generation systems

The power system for a UAV, as for any aircraft, includes an energy source, a means of converting that energy into mechanical energy and a means of converting that into a lift or thrust force, as shown in Figure 2.27. A power-plant will include means of engine speed and/or power output control, engine temperature control and, usually for fixed-wing aircraft, a means of electrical power generation.(Rotorcraft will have electrical generators driven instead from the rotor system, thus ensuring that electrical power remains available, even in the event of engine failure.)The great majority of UAV in operation are powered by internal combustion engines and most of those have piston engines.

2.10.1 Piston Engines

These may be considered to exist in four main types although there are sub-types of each.

a) Two-stroke (two-cycle) engines
b) Four-stroke engines
c) Stepped piston engines
d) Rotary engines.

2.10.1.1 Two-stroke and Four-stroke Engines

There is probably a greater range of sub-types of two-stroke engines than there is for four-stroke units. For simplicity, for example, some two-stroke units achieve lubrication by mixing lubricating oil with the fuel. Others have a separate oil system, as do four-stroke units. Some two-stroke units use valves for controlling the airflow, others do not. Both types can be designed to use petroleum fuels and, with higher compression, to use diesel or other ‘heavy’ fuels. Both types can be equipped, if necessary, with turbo-charging. Both types may be air-cooled or water-cooled.

The only basic difference between the two types is that the two-stroke engine has a power-stroke on each revolution of the crank-shaft whereas the four-stroke has a power-stroke every other revolution. Thus the two-stroke, in theory at least, tends to produce twice the power in unit time at the same rotational speed compared with the four-stroke unit. The two-stroke tends to have greater specific fuel consumption than the four-stroke since the intake gases can be contaminated by the outgoing exhaust gases. Typically a four-stroke engine will consume between 0.3 and 0.4 kg of fuel per kW hr (specific fuel consumption). The two-stroke engine typically will have a sfc between 0.4 and 0.6 kg/kW hr.

However, much depends upon the detailed design of the engine and its carburettor or fuel injection system and also how it is operated. Running a piston engine at full power and speed will tend to increase the specific consumption compared with lower powers and speeds.

As Figure 2.28 shows, at least for those units for which mass/power data is more readily available, there is considerable scatter of data, the more so for the two-stroke engines. This also applies to any attempt to show any trend in fuel consumption and therefore only generalised comments may be made. The reasons for this scatter of results is that not only are there many variants of the configuration ,e.g. one, two, or more cylinders, lubrication from a sump or oil mixed with the fuel especially for the two-stroke units and carburetion etc., but the background ancestry of the units is different.

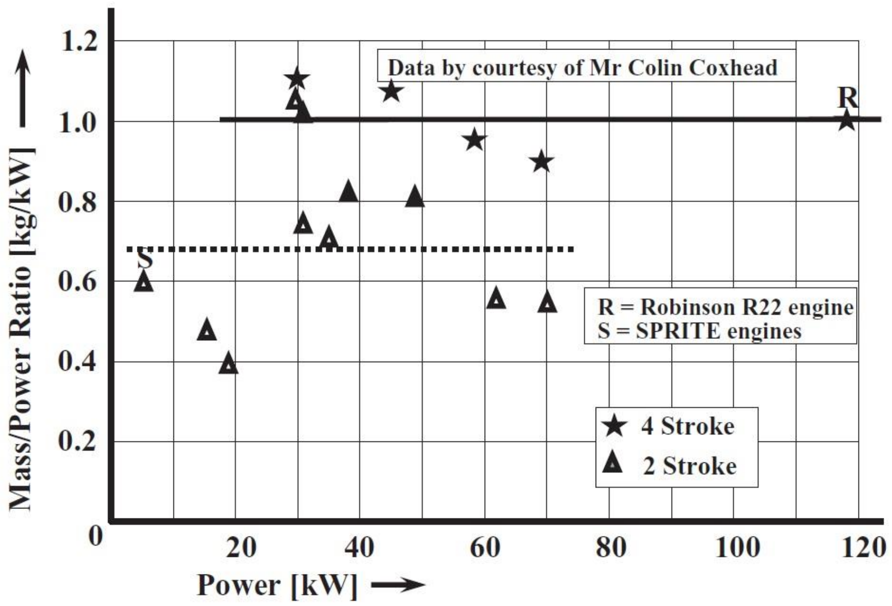


Figure 2.28: Air-cooled piston engines: mass/power ratios

The smaller units have been mostly the products of companies selling to the model market and have little or no aviation heritage. They are not designed to meet any defined manufacturing or reliability standards and, often, the manufacturers have not measured the performance data of their products. With the more recent increase in funding for UAV systems, there are signs of new manufacturers entering the market place with better products. However, it behoves the UAV designer to exercise caution when selecting an engine. Engines for the larger aircraft may be available from approved sources of light aircraft engines, well designed to aeronautical standards and present fewer problems.

The two-stroke unit tends to run hotter than the four-stroke and may require more cooling facilities than the four-stroke. The four-stroke unit tends to be heavier than the two-stroke (see Figure 2.17).Both types will pay for higher performance and higher fuel-efficiency with greater complexity, weight and cost. It is up to the designer to decide the priority. It may be that a two-stroke installation is more suited to the smaller, shorter-range aircraft whilst the four-stroke is more appropriate to the larger, longer-range aircraft.

There is an important advantage that the two-stroke unit offers compared with a four-stroke engine. Neither type produces power with smooth torque (as does a turbine engine), but the torque of both varies during each revolution. However, the torque peaks of the two-stroke unit are much smaller than those of the comparable four-stroke unit. This is of particular concern for a rotorcraft transmission and rotor system which must be the more robust if driven by a four-stroke engine. To a lesser extent this will affect the design of propeller or fan propulsors. Linear vibration has also to be considered and will be largely a function of the number of cylinders of the engine. Although the oscillating mass of a single cylinder may be balanced to some extent by a mass on the other side of the crank-shaft, it is far from perfect. On the other hand, two horizontally opposed twin cylinders will give almost complete balance.

2.10.1.2 Stepped Piston, Two-stroke, Engines

These are a relatively new development where each cylinder has two bores of different diameter, the larger at the base. Each cylinder has a piston with an upper and lower section and rings to fit the two bores. Each cylinder has a double purpose where the lower section of each cylinder supplies compressed air to the upper section of an adjacent cylinder where the air is further compressed and burnt. It is claimed that this arrangement achieves the better features of two-stroke and four-stroke engines, i.e. with the lighter mass/power ratio and torque smoothness of the two-stroke and the better fuel efficiency of the four-stroke. Although prototype units have been built and tested, no such unit has yet been fitted to a UAV.

2.10.1.3 Rotary Engines

Rotary engines have suffered a chequered history but are now becoming more reliable and accepted. Initially, and for a long period, there were problems with seals between the rotor(s) and the casing breaking down. ‘Chattering’ of the rotor lobes in the casing caused early wear, and engine life was short. Although lateral vibration emanating from the engine was low, torsional vibration was high. However, most of these problems seem now to have been overcome.

In the 1980s, a Canadair UAV used a rotary engine, but it was soon replaced with a turbo-shaft engine. Today the Israeli Hermes 180 and Hermes 450 UAV use rotary engines, in 28 and 38 kW form respectively, and they are reported to offer a long life and low specific fuel consumption (0.35 kg/kW hr).Although the basic engines are of low mass/power ratio, because the engines operate at a high rotational speed, a reduction gearbox is usually necessary this, together with high levels of cooling equipment required, increases the mass towards that of a conventional four-stroke engine.

Other reports speak of high fuel consumption, noise and high cost of operation of other engines of the rotary type. It is necessary, therefore, for the designer who is considering such installation to be aware of the possible advantages and down-side of the generic type and to assess the situation with care. Currently the type seems to be available only within a very limited power range. There appear to be norotary engines below a power rating of about 28 kW or above 60 kW available for aircraft.

2.10.2 Gas-turbine Engines

Gas-turbine engines are fundamentally quieter than piston engines and produce smooth power at low mass/power ratios. They may be considered as two generic types:

(i) turbo-jet units which are designed to produce thrust (kN) from a high-velocity jet for direct propulsion;
(ii) Turbo-shaft units which produce power (kW) in an output shaft which may drive a propeller or helicopter
rotor to provide thrust.

In their simplest form they employ a compressor set and turbine set on a single output shaft. Their disadvantage is that any increased load on the output which will slow the turbine also slows the compressor set, thus reducing the power available to accelerate the engine back to operating speed until an increase in fuel injection can take effect. The result is a lag in response which is bad for a propeller-driven aircraft, but can be disastrous for a helicopter.

Most turbo-shaft engines of today therefore are of the free-power-turbine (FPT) configuration. Here the output shaft is a second, separate, shaft from that mounting the power-generating compressor/turbine sets.

Thus when the output demand is increased, the compressor is not slowed and an increase in injected fuel accelerates the ‘compressor spool’ more rapidly, giving a speedy response to extra power demand.

A *turbo-fan unit*, possibly to be regarded as a third type, is in effect a mixture of the turbo-jet and turbo-shaft engines in so far as some of the combustion energy is extracted as a jet whilst some energy is converted to mechanical power to drive a fan which produces a slower-flowing, but larger volume, jet of air.

A thrust-producing jet is at its most efficient when the minimum amount of jet velocity is left in the ambient air mass after the aircraft has passed. Therefore the turbo-jet engine is most appropriate for the higher speed aircraft, the turbo-fan engine for intermediate speed aircraft and the turbo-shaft engine, driving a propeller with its much lower efflux velocity, for the slower aircraft.

Hence the Global Hawk HALE UAV uses a turbo-fan engine, and the Predator B MALE UAV uses a turbo-shaft engine driving a propeller. The choice of a turbo-fan and turbo-prop engine for the HALE and MALE aircraft respectively is appropriate since both aircraft, being at the upper range of size for UAV, require more powerful engines than do the smaller, medium-range aircraft. Gas turbine units are available in the higher power ranges, but due to scale effects are not economic for lower power requirements.

Smaller, medium- and close-range aircraft are invariably powered by piston engines, but they would benefit from the low mass/power ratio of the turbine engine. Unfortunately, there are no small turbo-shaft engines available below the approximately 500 kW power of the Predator or Fire scout engines. Of the current medium- and short-range aircraft, a few would require installed power levels of about 120 kW, several in the 30–40 kW range and a number as low as 5–10 kW. A turbine engine is at its most fuel efficient when operating near maximum power, and its specific fuel consumption deteriorates sharply if operated at part-power. Therefore attempting to use an over-size engine for the smaller aircraft would impose not only a mass and bulk penalty, but an unacceptable level of fuel consumption.

It is perhaps ironic that a number of adaptable turbo-shaft engines were available during the1950s–1970s in powers down to 60 kW, having been developed as auxiliary power units (APU) for manned aircraft. These fell out of use when the increase in size of aircraft required more powerful APUs or their engine-starting and other on-board services were obtained by other means.

2.10.3 Electric Motors

Electric motors, of course, convert electrical energy into mechanical energy to drive a propeller, fan or rotor. The electrical power may be supplied by battery, a solar-powered photovoltaic cell or a fuel cell. They have the particular advantage of being the quietest of all the engines and with the smallest thermal signature.

2.10.3 .1 Battery Power

Currently only micro- and mini-UAV are powered by batteries and electric motors. Typical examples being the Desert Hawk and Skylight.

Although considerable improvements are continuously being made in battery design and production, the demand on the battery is made not only by the motor, but also by the payload and communication system. Therefore the flight endurance and speed of such UAV systems and the capability of their payload and communication systems are limited. The systems are small and light enough to be back-packed so they have a place in very short range operations under relatively benign conditions. Back-up batteries must be carried and regularly charged to ensure an electrical supply. Other means of obtaining a continuous electrical supply are being sought in order to extend the range and capability of electrically powered systems and to this end research is underway to develop solar-powered photovoltaic cells and fuel cells compatible with UAV systems requirements. Both systems have been flown in a UAV, but it is early days for the technology.

2.10.4 Power-plant Integration

The engine is only a part of a power-plant. It must be suitably mounted, possibly on flexible tuned mounts; provided with means of starting; fed with fuel; controlled; cooled; and provision made for fire detection and suppression, an exhaust system and silencing system if required. The characteristics of the engine will inevitably determine the complexity or otherwise of these sub-systems and this will influence the choice of engine.

In addition the UAV services such as electrical power alternators or air blowers may be engine-driven and mounted within the powerplant. Larger engines, for larger UAV, and qualified for aircraft use will most probably come with much of that equipment, but smaller engines, for the smaller UAV, may not. In the latter case that equipment must be separately sourced. Unfortunately starter motors, alternators, carburettors, etc. are not generally available in the small sizes required by small UAV. In the 1980s M L Aviation were forced to design and manufacture their own alternators and cooling fans for their UAV, but the situation has improved and specialist companies are now appearing to provide appropriate items.

2.10.5 Modular Construction

In addition to ready access to components, the modular construction concept allows for the separate manufacture and bench proving of the several modules. This saves factory space and readily allows for the manufacture and testing, to agreed standards, of complete modules by different suppliers, and in different countries. Final assembly will then be carried out at the system's main contractor. Here the total UAV system will be integrated, ground and flight tested before delivery to the customer.

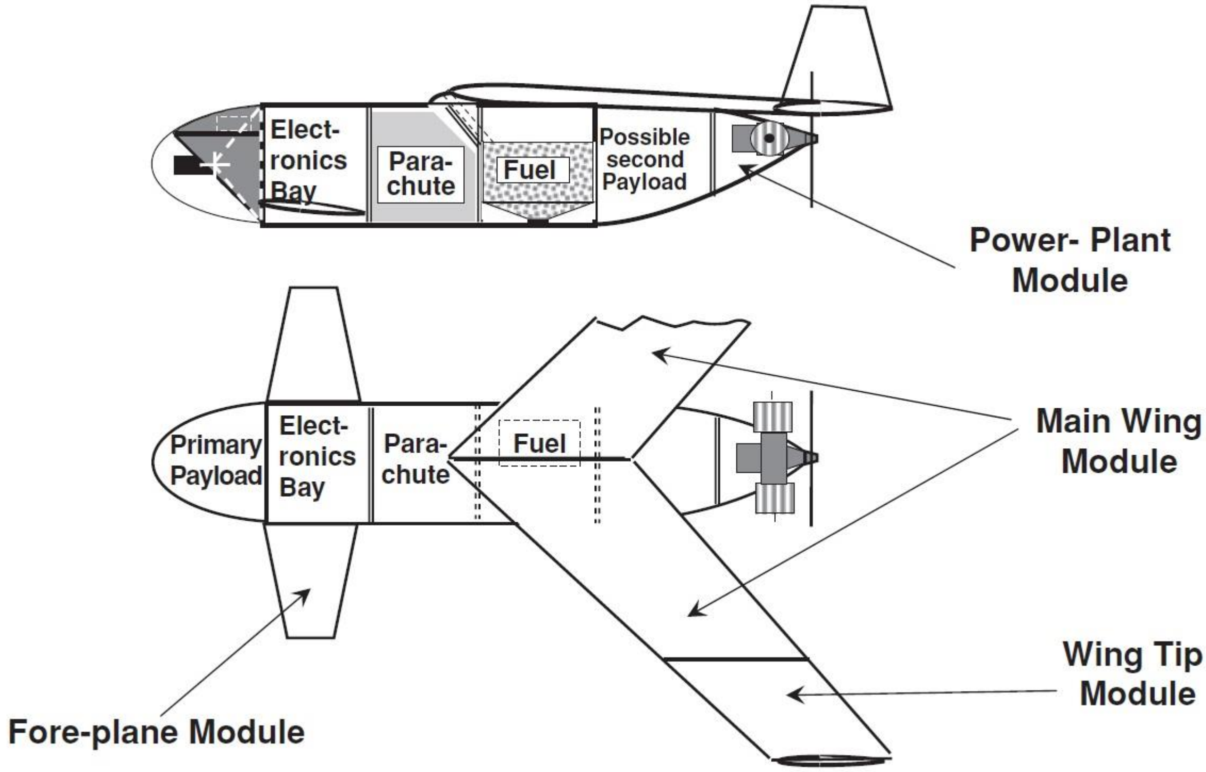


Figure 2.29: Modular construction of HTOL aircraft

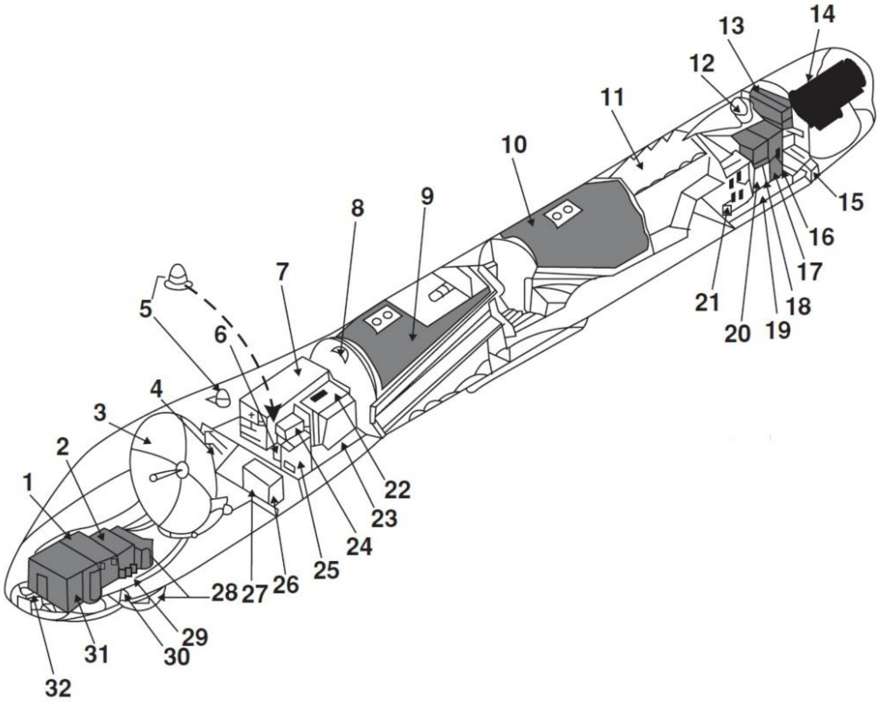
Figure 2.29 shows a possible modular configuration of a medium- or close-range fixed-wing (HTOL) UAV. The advantages of employing modular construction have already been listed and an indication of how this might be realized in such an aircraft is illustrated.

Viewing the layout of the aircraft, access to the main payload in the aircraft nose might be via a removable cover. Replacement of it in its entirety in favour of a different type of payload, or replacement if faulty, would be by removing it at fixing(s) at its rear. The structural connection may involve, say, quick-acting pip-pin(s), and electrical connection by suitable connectors. Built-in test equipment would register on the housekeeping display in the control station whether or not a satisfactory mechanical and electrical connection had been effected. Each exchangeable payload would have to be balanced to be of the same mass moment about the aircraft centre of mass. Thus a change of payload can be effected in minutes.

Removing or hinging forward the payload gives access to the electronics module which could then be slid out in its entirety for bench testing if required. Similarly, the power-plant module could be removed, if required by separating suitable structural, fuel supply and control connections. The lifting-surface modules would also be removable, by disconnecting suitable structural and control connections.

It may be considered advisable to have separate outer-wing modules as the wing-tips are often vulnerable to damage on landing or even take-off (launch). Electric cabling, as required, would be part of each module with suitable inter-module connections.

In the case of a larger, for example, MALE type UAV, which is required to carry far more equipment, modular construction is less easy to achieve. The internal view of a typical MALE UAV is shown in Figure 2.30 with numbers being allocated to the several components.



1. Synthetic Aperture Radar (SAR) Antenna
2. Inertial Navigation System/GPS
3. Ku-Band Satellite Communications Antenna
4. Video Cassette Recorder
5. GPS Antennas (Left and Right)
6. Identification Friend or Foe Transponder
7. Ku-Band Satellite Communications Sensor Processor Modem Assembly
8. C-Band Upper Omni-directional Antenna Bracket
9. Forward Fuel Cell Assembly
10. Aft Fuel Cell Assembly
11. Ancillaries Bay
12. Ancillaries Cooling Fan
13. Oil Cooler/Radiator
14. Engine
15. Tail Servo (Left and Right)
16. Battery Assembly
17. Power Supply
18. Battery Assembly
19. Aft Equipment Bay Tray
20. Secondary Control Module
21. Synthetic Aperture Radar Processor / Electronics Assembly
22. Primary Control Module
23. Front Bay Avionics Tray
24. Receiver/Transmitter
25. Flight Sensor Unit
26. Video Encoder
27. De-ice Controller
28. Electro-Optical/Infrared Sensor Turret / Electronics Assembly
29. Front Bay Payload Tray
30. Ice Detector
31. Synthetic Aperture Radar
32. Nose Camera Assembly

Figure 2.30: Internal view of MALE UAV and listing of components

The considerable mass of fuel required for long-range operation must be carried near the aircraft centre of mass, i.e. near the wing centre of pressure. The forward-looking cameras must be mounted in the nose and the engine and accessories in the rear. Other electronic equipment will be positioned with regard to longitudinal balance and the closeness or otherwise to other components to reduce cable lengths and possible EMC problems. The installation and removal of these several modules poses an access problem. Too many removable panels or hatches will require considerable local reinforcement of the monocoque airframe structure, and recourse may have to be made to stress-carrying removable panels in order to limit the weight penalty incurred by the maintenance needs of ready access.

2.10.6 Ancillary Equipment

UAV need a similar range of ancillary equipment as manned aircraft except for those items relevant to aircrew accommodation and functioning. For the largest UAV this is seldom a problem as they are in a similar mass domain as the lighter manned aircraft. For the smaller UAV problems may arise in sourcing appropriately sized electrical alternators, actuators, air-data systems, attitude and altitude sensors, batteries, fasteners, external lighting, antennae, etc. Existing aircraft-approved and certified equipments, available for even the lightest manned aircraft, are too large and heavy to appropriately meet the requirements of the smaller UAV. Some of these equipments may be available to a limited extent from model aircraft suppliers, but they seldom meet the airworthiness standards required for UAV.

This has certainly been a problem in the past and UAV manufacturers have often had to resort to developing the equipment, and achieving its certification, themselves. Fortunately, following the demand from a burgeoning UAV industry, specialist equipment suppliers have appeared on the scene and, even if they do not have suitable equipment available off-the-shelf for a specific requirement, they are usually able to develop suitable equipment under a sub-contract arrangement.

UNIT – III

CHARACTERISTICS OF AIRCRAFT TYPES

CO No	Course Outcomes
	After successful completion of the course, students will be able to:
CO8	**Analyze** the attributes, performance, design issues and compromises of different types of aircrafts for UAV systems

Program Outcomes (POs)	
PO1	**Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.

The airborne element of a UAV system is often referred to as the 'platform' for carrying the payload. Although the aircraft is but one element of the system, of all the elements it can have the greatest impact upon the design of the rest of the system.

3.1 Long-endurance, Long-range Role Aircraft

These are typified by the Northrop-Grumman Global Hawk, high-altitude, long-endurance UAV and the General Atomics Predator, medium-altitude, long-endurance UAV as shown in Figure 3.1. Both aircraft types employ a conventional airframe configuration with rear-mounted propulsion units, a turbo-fan for the Global Hawk and a propeller turbine in the case of the Predator B. Each has horizontal and vertical tail surfaces at the rear to provide aerodynamic stability in pitch and yaw respectively.

The task of these UAV types is long-range reconnaissance and they are required to carry a sophisticated (and therefore usually heavy) payload into position over long distances (say 5000 km) and to remain on station for a considerable time, probably 24 hr. They therefore rely upon their communications to be relayed via satellites.

The types of payload to the Global Hawk (Block 20) systems:

Sensors:
Synthetic Aperture Radar: 1.0/0.3 m resolution (WAS/Spot)
Electro-optical: NIIRS 6.0/6.5 (WAS/Spot)
Infrared: NIIRS 5.0/5.5 (WAS/Spot)

Communications:
Ku SATCOM Data link: 1.5, 8.67, 20, 30, 40, 47.9 Mbps
CDL LOS: 137, 274 Mbps

UHF SATCOM/LOS: command and control
INMARSAT: command and control
ATC Voice; secure voice

In addition to the heavy payload, a large amount of fuel must be carried to power the aircraft for its long-endurance missions. This mass of fuel with its containing tank(s) plus fuel pumps, filters, etc., in total principally determines the all-up-mass of the aircraft – more so than the mass of the payload. It is an escalating effect, however, since the greater the mass of the aircraft, so it will require larger and heavier wings to support it. This, in itself, will require further mass increase and the greater drag caused will require a greater propulsive thrust, more powerful and thus heavier engine(s) which will use more fuel and further increase the aircraft mass – and so on.

It is therefore imperative that the mass of fuel required must be minimised, both by flying the aircraft en route at its most economical speed, i.e. to achieve the maximum distance for the fuel burnt, and by flying on station at the speed for minimum fuel burn. The most economical speed, however, must be high or the transit time to station will be long and the aircraft may be too late to perform a critical surveillance, or other type of, mission.

The design of all aircraft involves a compromise between many factors in order to achieve an optimum result for the mission or missions envisaged. This is no more true than for the design of long-endurance aircraft where a significant task of the designer is to reduce the fuel-burn. Other than to apply pressure to reduce the mass of the payload whilst retaining its mission capability, three main concerns of the airframe designer must be to:

a) keep the aerodynamic drag of the aircraft as low as possible commensurate with the practical installation and operation of the aircraft systems such as the payload, power-plant, radio antennae, etc.;

b) use the latest practical structural technology to obtain the highest possible ratio of disposable load to aircraft gross mass – this is also known as the 'disposable load fraction'.

c) install a reliable power-plant which provides an adequate level of power, yet is light in weight and is fuel efficient, particularly under the conditions at which the aircraft will spend the majority of its time operating.

3.1.1 Low Aerodynamic Drag

In addition to paying fundamental care in the airframe design to achieve low drag by careful shaping using established and innovative technology, parasitic drag can be kept low by limiting the aircraft to fly at low speeds. However, this is unacceptable if a short transit time is necessary. Also, of course, the induced drag becomes high in low-speed flight.

At high altitude the parasitic drag will be reduced as the air density is low. However the induced drag becomes high in low density air unless the aircraft has a low value of span loading, i.e. a longer wing span than is usual for its gross mass.

To obtain long range, therefore, the designer is driven to design an aircraft which will cruise at high altitude and have a long wing in order to reduce the induced drag at high altitude. The wing area must not be greater than that necessary for take-off at a reasonable speed and length of run, and an acceptable minimum flight speed at altitude; otherwise the parasitic drag will be increased.

This results in a very slender wing of aspect ratio perhaps in the range 20–25 which then gives a structural design challenge to achieve it without incurring excess weight. (The aspect ratio of a wing is the ratio of the wing span to the mean chord of the wing. This is often better derived by dividing the square of the wing span by the wing area, i.e. b^2/S).

Long-endurance UAV, and particularly HALE UAV therefore, are characterised by high aspect ratio wings. This is shown graphically in Figure 4.2 where the silhouette of a Global Hawk (A) HALE UAV, with wing aspect ratio (AR) of 25, is compared in plan view with a Boeing 747-200 airliner, with a wing aspect ratio of merely 7.

Of even greater significance, for high-altitude–long-range operation, is the comparison of their span loadings of 3.23 kN/m and 28.29 kN/m respectively. (Span loading is the weight of the aircraft divided by its wing span).

Both Global Hawk UAV and Boeing 747 wings are optimised for their respective tasks. The latter typically cruises at half the altitude of the UAV and has an endurance of little more than one-quarter of that of the UAV.

3.1.2 High Disposable Load Fraction

This type of aircraft is not required to be particularly manoeuvrable and may be designed to sustain lower levels of acceleration than, for example, combat aircraft. It must, however, be capable of sustaining loads imposed by high-altitude air turbulence and from landing. In addition to careful structural design, advantage may be taken of advanced materials in both metallic and plastic composite form commensurate.

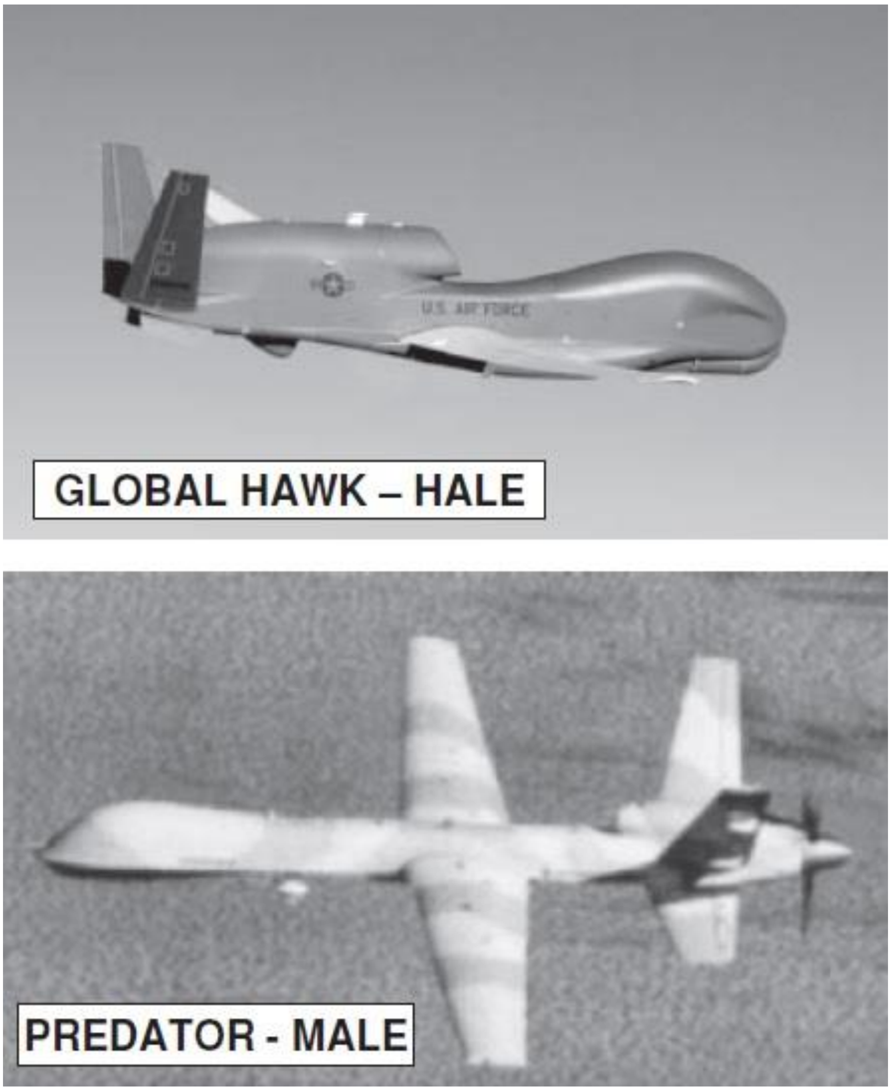


Figure 3.1: Long-endurance, long-range, HALE and MALE air vehicles (Reproduced by permission of General Aeronautical Systems Inc. and Northrop Grumman)

Table 3.1: Technical details of Global Hawk Block 20 and Predator B

Global Hawk Block 20	**Predator B**
by Northrop-Grumman.	by General Atomics Inc.
Wing-span 39.9m	Wing-span 20m
Length 14.5m	Length 10.6m
MTOM 14,628kg	MTOM 4,536kg
Max. Endurance 35hr	Max. Endurance 32hr
Max Altitude 19,800m	Ceiling 12,000m
Payload - mass 1,360kg	Payload :- mass 230kg
Stabilised, high-magnification	Stabilised, High-mag.
Optical and I.R. TV.	Optical and I.R. TV.
Synthetic Aperture Radar	S.A.R.

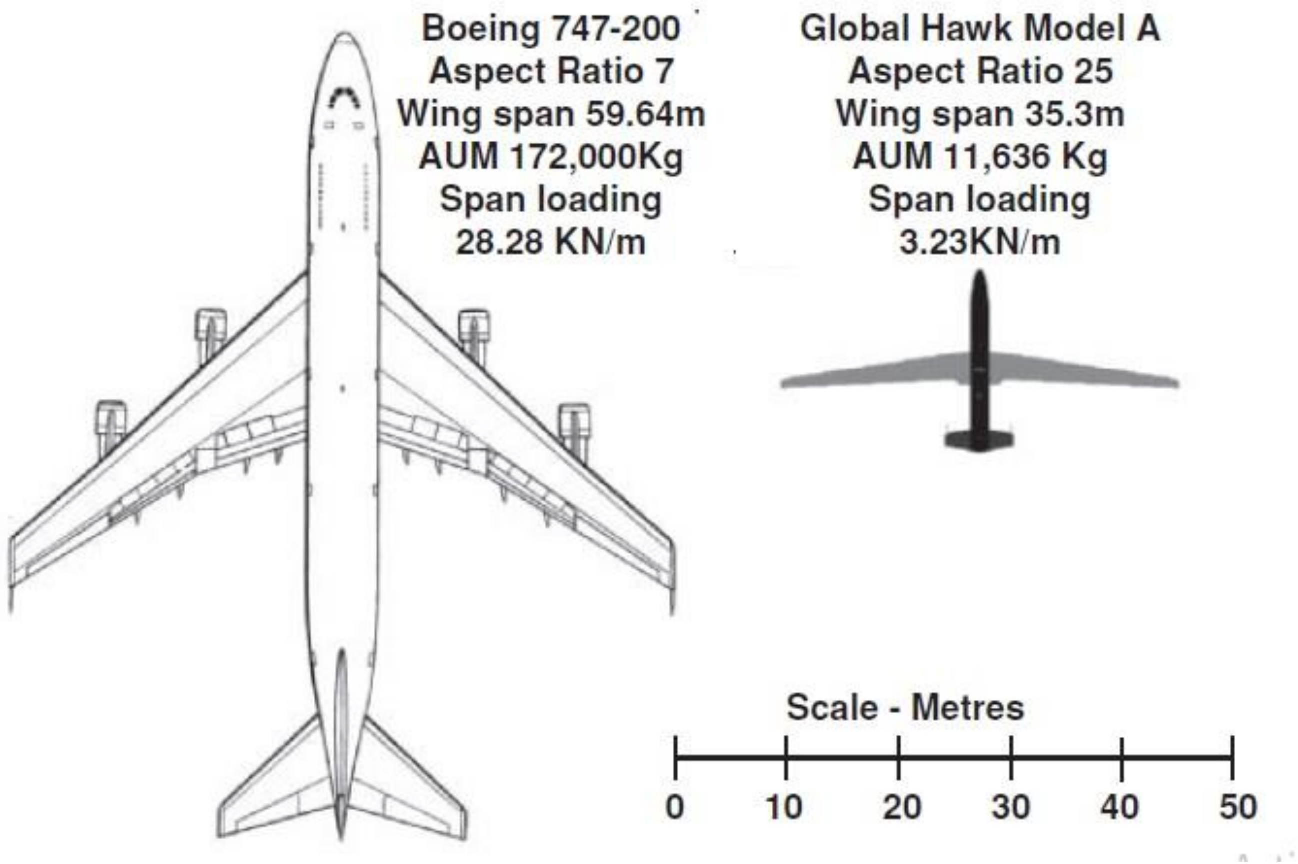


Figure 3.2: Comparison of wing aspect ratios

A further advantage of a UAV is that general fuselage pressurisation is not necessary, thus reducing both steady and flight-cycle fatigue loads compared with a passenger airliner. Protection of certain payloads against low pressure and temperature may still be necessary. The typical disposable load fraction for this type can be in excess of 60%. This disposable load has then to be shared between the payload and the fuel to be carried.

3.1.3 Aspects of Power-plant Selection

Aspects relating particularly to the HALE and MALE UAV are:

a) The achievement of a beneficial trade-off between engine mass and fuel consumption to obtain the lowest
mass of combined power-plant installation and the fuel required for the long-endurance mission. The lightest engine may not result in the lightest overall package if the light engine uses more fuel.

b) To ensure that the power-plant gives a satisfactory performance at altitude. The power or thrust available from the engine will be reduced and it is necessary to ensure that this remains adequate to achieve the required aircraft performance. The specific fuel consumption (sfc) can be expected to remain sensibly constant up to about 11000 m as the effect of the reduced air density on combustion efficiency is compensated by the reduced air temperature. Above that altitude, however, the air temperature remains constant whilst the air density continues to reduce and the sfc will progressively worsen. It is necessary to ensure that, in operating at greater altitudes, the increase in sfc does not negate the reduction of required power achieved through reduced airframe drag.

c) Other issues to be addressed, of course, include the need to prevent icing of the air intake(s) and the effect on fuel metering of the increase in fuel viscosity at the lower temperatures. The latter is ofparticular importance if 'heavy' fuels are to be used.

3.1.4 Representative Performance of a HALE UAV

The following figures are merely indicative of the performance characteristics of the generic type and its power-plant using published geometric and mass data pertaining to the Global Hawk A model rather than the more developed Block 20 system aircraft shown in Figure 31.

The airframe particulars of the A model used in the analysis are as follows:

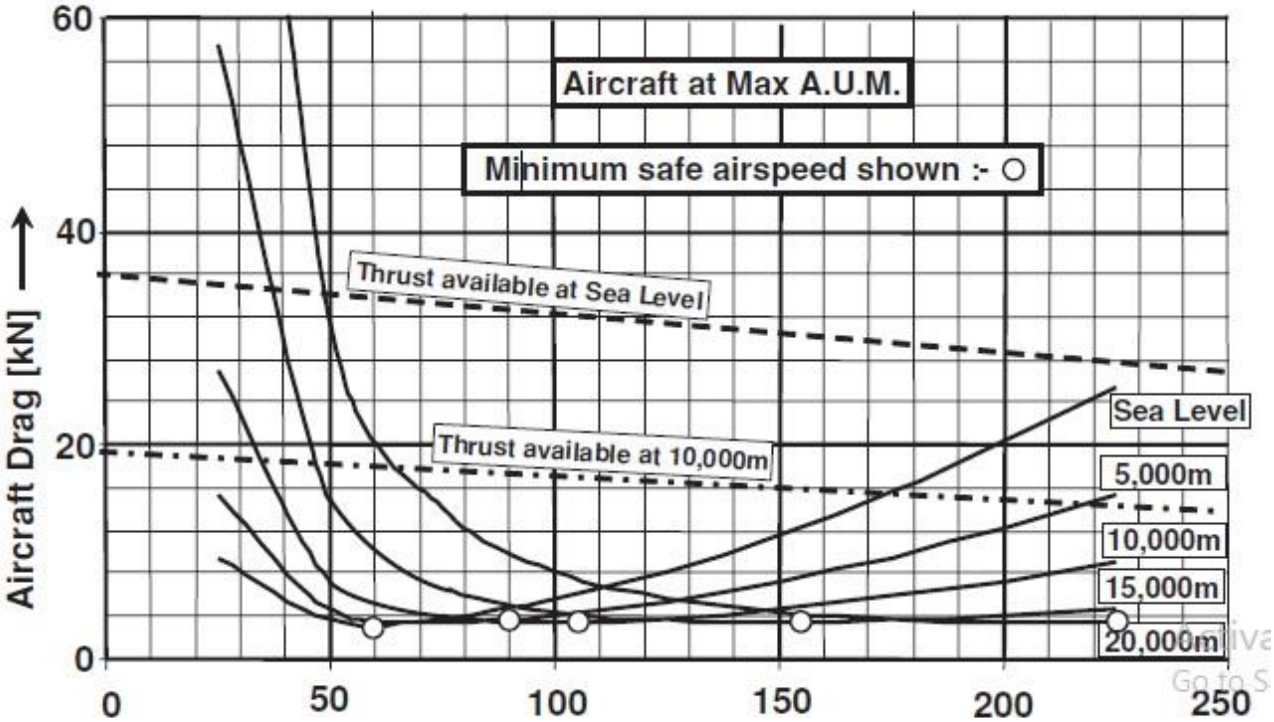
Wing-span 35.3 m
Length 13.5 m
MTOM 11 636 kg
Payload – mass 608 kg

The calculations are based upon the International Standard Atmosphere (ISA) where the temperature and pressure at sea level are 15˚C and 1.013 mb (14.7 psi) respectively. An estimate of the aircraft drag when operating at its maximum weight (114 kN) at various airspeeds and altitudes is shown in Figure 3.3., together with the expected thrust available from the Rolls-Royce, North America AE 3007 turbofan engine. The speed for minimum drag occurs at about the respective minimum safe airspeed at each altitude level, and both increase with increasing altitude.

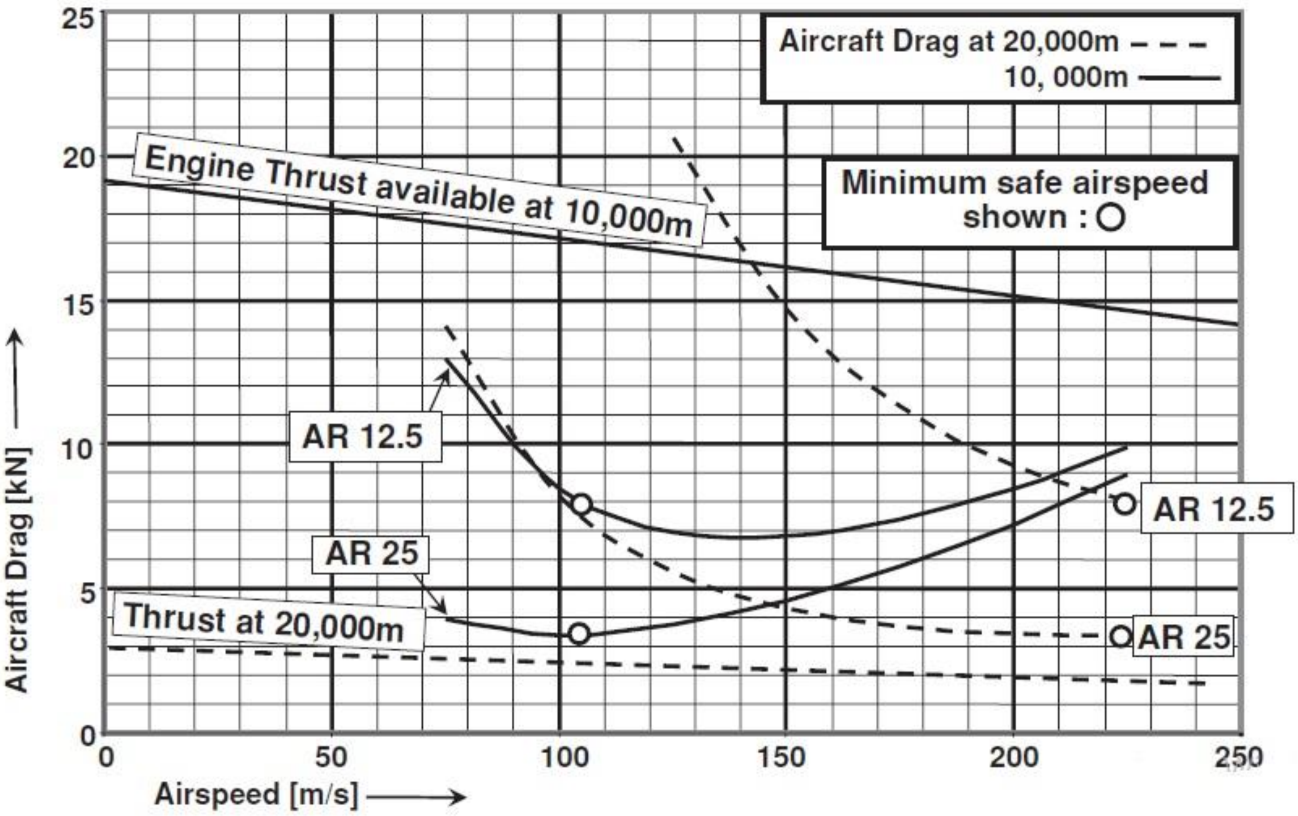
Figure 3.3: HALE UAV variation of aircraft drag with airspeed and altitude (ISA)

If the wing area was to be increased to allow the aircraft to fly more slowly, the rise in drag at the lower speed (added to which would be the extra drag of the enlarged wing area) would deter operation at those lower speeds.

The necessity to have a low value of wing-span loading for operation at high altitude is indicated more expressively in Figures 3.4 and 3.5. Looking first at Figure 3.4, the estimated drag of the aircraft is shown at 10 000 m by the full curve and at 20000 m by the dashed curve. The estimated drag is shown for the actual aircraft with a wing aspect ratio (AR) of 25, but also for a hypothetical aircraft configured with the same wing area but an AR of only half, i.e. 12.5. (Note that this is still quite a high AR compared with the



majority of aircraft). The 'estimated' thrust of the AE 3007 engine is also shown for the same two altitudes.



Reg Austin, ― Unmanned Aircraft Systems @ 2010 John Wiley and Sons, Ltd.

Figure 3.4: HALE UAV: effect of wing aspect ratio on aircraft drag at high altitudes (aircraft at gross mass)

Even at the altitude of 10 000 m, an altitude at which most modern long-haul airliners operate, the reduction in aircraft drag due to the higher AR is immediately obvious. At the respective speeds for minimum drag, the aircraft with the longer wing has half the drag of the other. The difference is even greater at the higher altitude, although even the AR25 aircraft may not achieve that altitude through having inadequate thrust. This analysis is repeated in Figure 3.5 for the aircraft operating at a point at which it will have consumed about one-half of its fuel, resulting in a reduced weight of about 82 kN. The drag of both configurations is seen to be reduced, but the AR25 aircraft can now achieve the altitude level on the thrust available, whilst the AR12.5 aircraft would require a larger engine producing twice the thrust and, presumably, being about twice the weight and having about twice the fuel consumption at that altitude.

Although the larger engine would be throttled back at lower altitudes, it would still use considerably more fuel than the smaller engine as turbine engines are inefficient at reduced power. The extra mass of engine and fuel plus system could amount to 800 and 6000 kg respectively. Although the shorter wing would have less mass, this might amount to a saving of only about 300 kg.

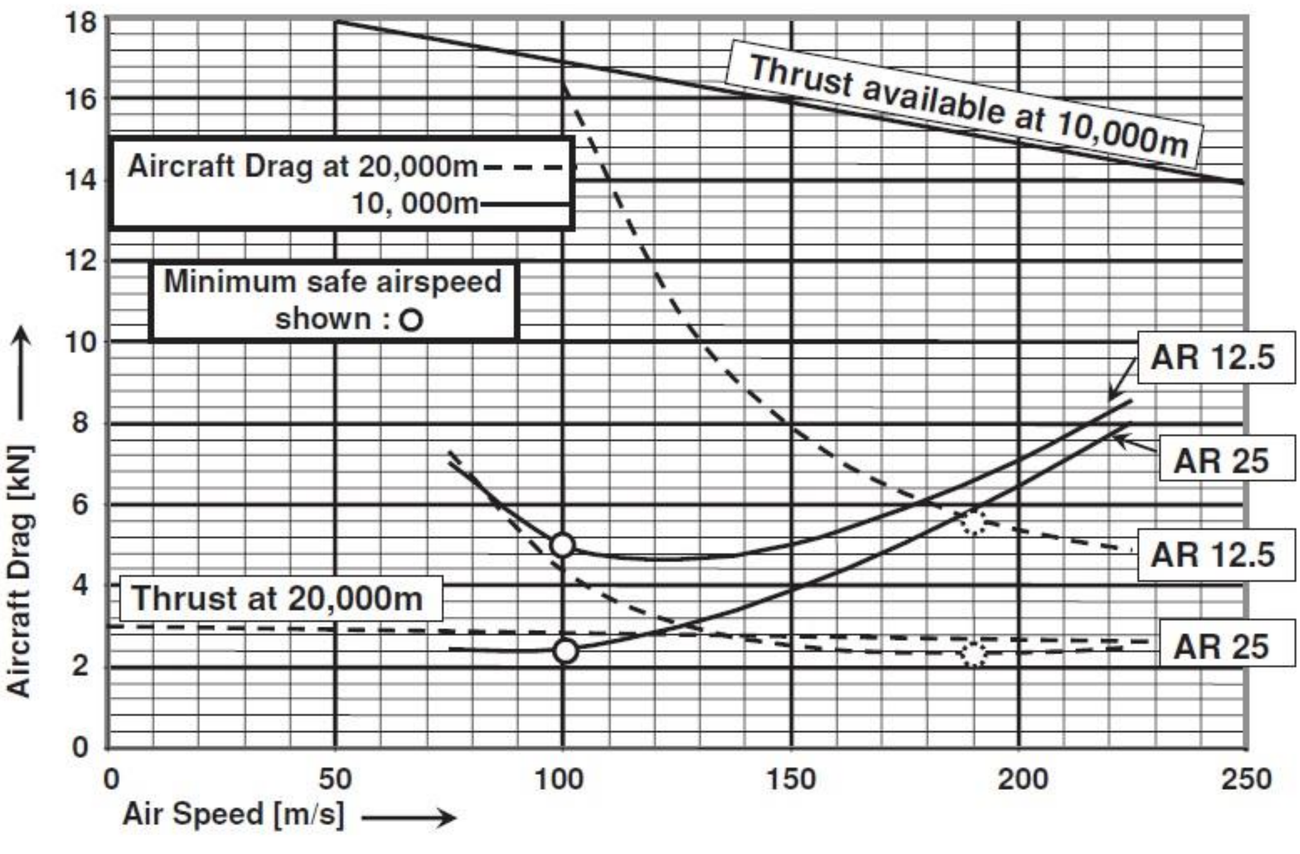


Figure 3.5: HALE UAV: effect of wing aspect ratio on aircraft drag at high altitudes (aircraft mass with half fuel)

To carry this extra mass would require a larger airframe requiring more power, using more fuel and so entering a vicious circle of spiraling size, mass and cost. This indicates most vividly the reason for the HALE UAV needing wings of ultra-high aspect ratio.

Assessment of the power usage at different altitudes and at different speeds for the representative HALE UAV gives the results shown graphically in Figure 3.6 for the aircraft at its maximum weight and in Figure 3.7 for its weight with half of its fuel used.

The speed for minimum power usage occurs when the induced power and the parasitic power are equal. The figures show that the airspeed at which minimum power is required by the aircraft, at both values of AUM, is at its lowest level at low altitude, and is the speed at which the aircraft uses, approximately, the minimum amount of fuel per hour. (This may be varied very slightly by the trend of engine specific fuel consumption with power.) It is, therefore, the speed at which the aircraft can remain airborne for the longest time and is known as the ‘loiter speed’.

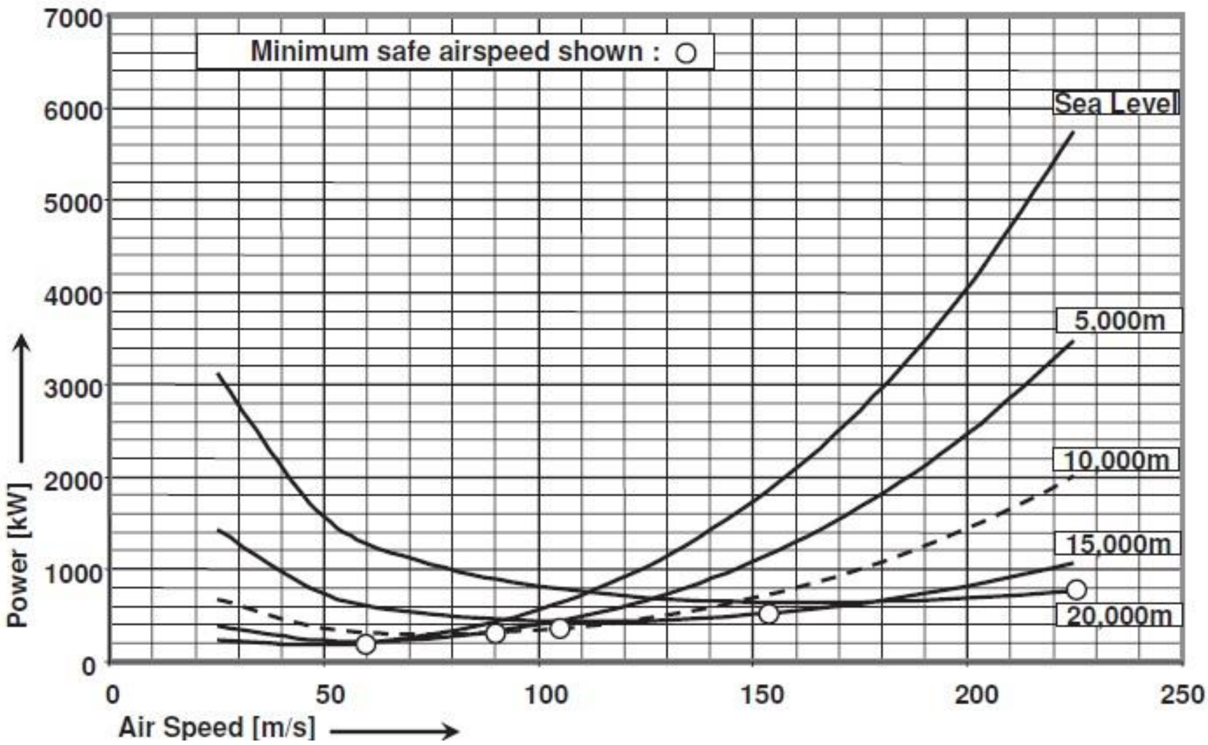


Figure 3.6: HALE UAV: power required to maintain height. Variation with airspeed and altitude – 114 kN AUW, ISA conditions

Figure 3.7: HALE UAV: power required to maintain height. Variation with airspeed and altitude – 81.8 kN AUW, ISA conditions

Other considerations may require the aircraft to loiter at a somewhat higher speed. These include a margin well above the stalling speed, especially in gusty conditions and for reasons of aircraft stability and response. An aircraft usually is more stable when operating on the rising sector of the power–speed curve. The speed for minimum power occurs at very low airspeeds, so that the aircraft is not moving very far for the amount of fuel used. The airspeed for maximum distance travelled for the mass of fuel burned, the 'maximum-range speed' or 'most economical cruise speed' (Vmec), is obtained by taking the tangent from the origin to the curve on a graph showing the rate of fuel burned against airspeed. To close order, this is true of a graph showing the variation with airspeed of aircraft power required to maintain height, i.e. as in Figures 3.6 and 3.7.

If the aircraft is flying into a headwind, then the tangent will be taken, not from the graph origin, but from the airspeed, on the baseline, equal to the headwind. Therefore, when an aircraft is flying into a headwind, its Vmec airspeed is always faster than when it is flying in still air. Note that not only is Vmec obtained at higher speeds at the greater altitudes, but the level of power (and rate of fuel burn) is less. Thus flying at altitude offers a higher transit speed and longer range, so best satisfying the requirements of the typical HALE UAV.

3.1.5 Long-range Strike UAS

The original Predator A was designed purely to perform a reconnaissance mission at long range. However, it soon became obvious that, when it identified priority mobile targets, by the time that strike facilities had been brought to the area, the targets had long since disappeared. An immediate strike action was necessary to take advantage of the long-range target detection. Predator B was therefore developed from the original design to carry a limited weapon load of two Hellfire missiles, as seen in Figure 3.8.

3.2 Medium-range, Tactical Aircraft

There is a plethora of different types in operation and under development in both fixed-wing and rotary wing configurations, and these are part of systems principally conducting reconnaissance and artillery fire control duties. The fixed-wing aircraft in this category generally have wheeled undercarriages to take off from, and land onto, runways or airstrips, sometimes with rocket assistance for take-off and with arrester-wires to reduce landing run distance. Exceptionally the Ranger has the option of a ramp-assisted take-off. VTOL aircraft in this category are often designed for off-board ship operation and this includes operations such as fleet shadowing and mine detection and destruction. The distinction between medium-range tactical systems and MALE systems, however, is becoming increasingly blurred.

It is a known fact in the aeronautical world that an aircraft does not achieve its ultimate efficiency until it has been in service for a while and been ‘stretched’. Even in the day of computer aided design, a new type of aircraft will contain components which are found to be ‘over-strong’ (i.e. have over-large reserve factors) when measured by tests. By strengthening those parts which are found to have realised just the designed factors, the aircraft can be extended in weight to carry more payload and/or more fuel. The power or thrust of the engines may also need to be increased to maintain or enhance performance

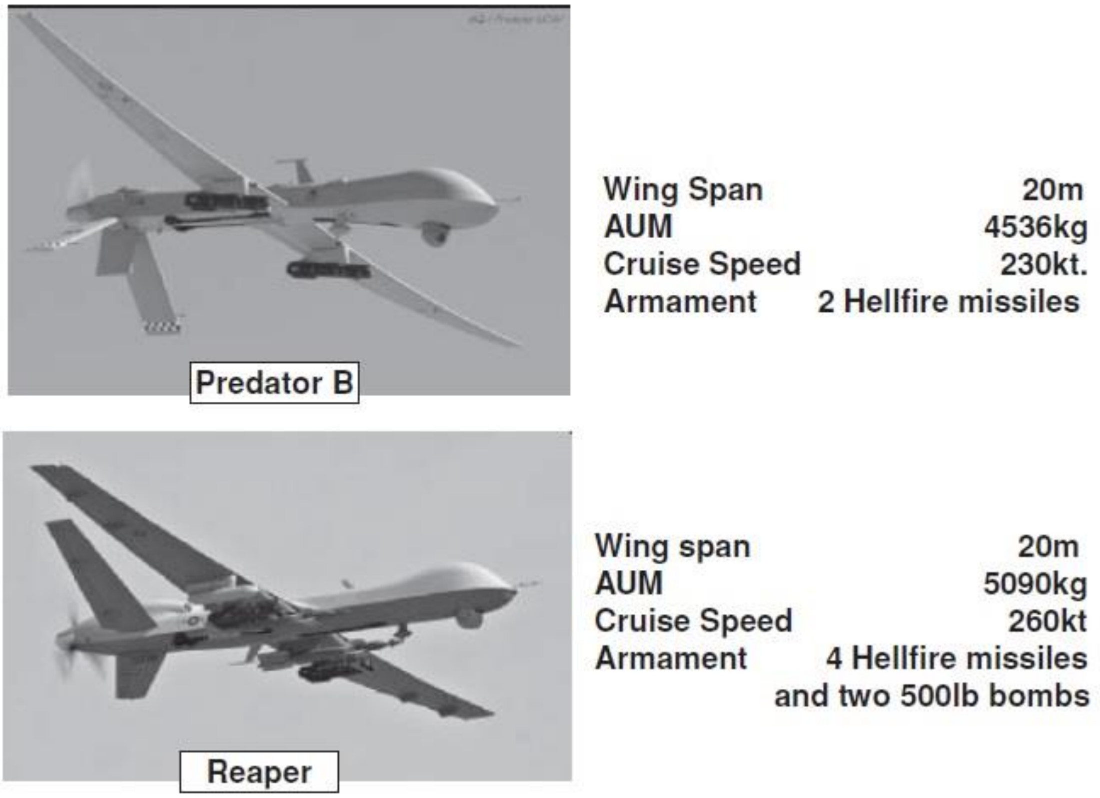


Figure 3.8: Armed MALE UAV (Reproduced by permission of General Aeronautical Systems Inc)

Thus the aircraft, which began life with a medium-range capability, may soon become extended in service ceiling and in endurance, assisted by improved communications, to move towards MALE performance. An example is the Hunter series of UAV described below.

3.2.1 Fixed-wing Aircraft

Typical of these are:
a) the Hunter RQ-5A UAV by IAI, Malat and Northrop Grumman, USA;
b) the Seeker II UAV by Denel Aerospace Systems, South Africa;
c) the Ranger UAV by RUAG Aerospace, Switzerland;
d) the Shadow 600 UAV by AAI Corp., USA.

They are illustrated in Figures 3.9 and 3.10, with further technical data shown in Figure 4.15. The majority of medium-range aircraft, as in the representative types discussed here, use an airframe configuration with the surveillance payload in the nose of the fuselage, or in a 'ball-turret' beneath the forward fuselage, balanced by a power-plant with a pusher propeller at the rear. The fuel tank is mounted, near the centre of mass, between the two. The tail surfaces, for aerodynamic stabilisation and control, are mounted on twin tail-booms.

The Hunter, in course of development, has acquired a second engine in the nose which precludes a nose-mounted camera. IR and optical TV systems are mounted in the under-belly rotatable turret. Although Hunter A models are still widely used in the medium-range role, development through the B and E models has extended the aircraft endurance and altitude capability. This development is illustrated in the following table:

Hunter model	AUM (kg)	Wing-span (m)	Span loading (N/m)	Endurance (hr)	Cruise speed (km/hr)	Service ceiling (m)
RQ5A	727	8.84	807	12	202	4,600
MQ5B	816	10.44	767	15	222	6,100
MQ5C	998	16.6	590	30	222	7,620

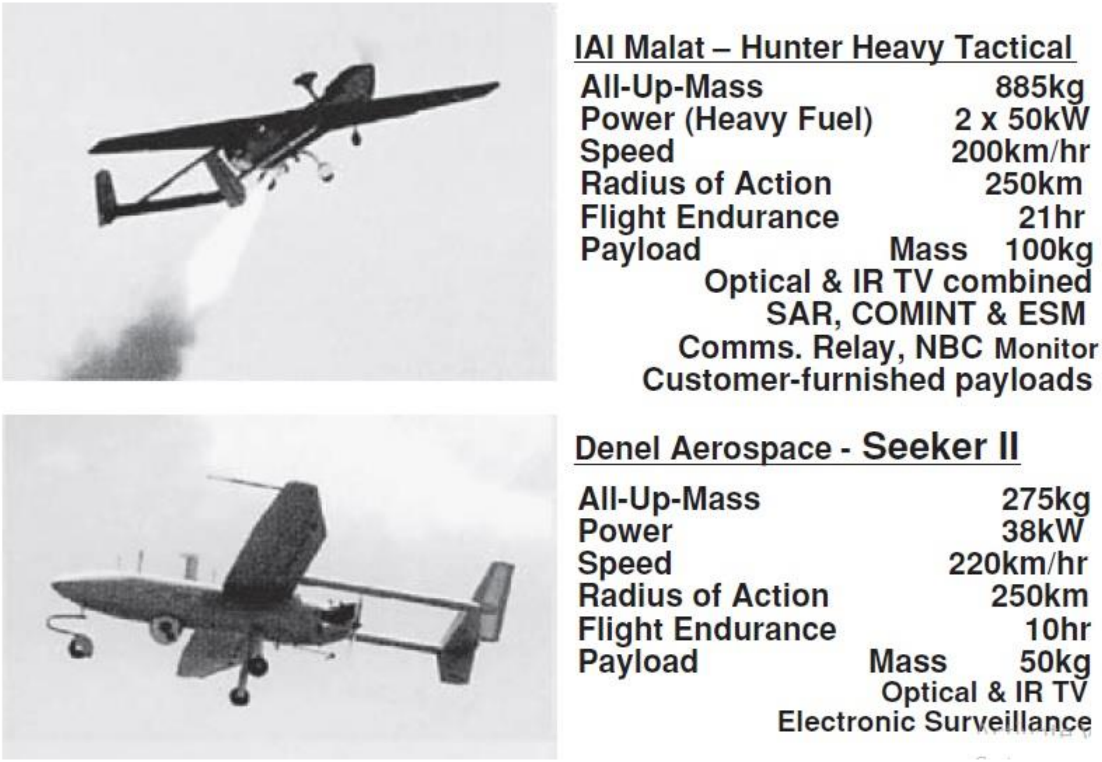


Figure 3.9: Medium-range UAV: Hunter and Seeker (Reproduced by permission of Denel Aerospace). Source: Israeli Aircraft Industries

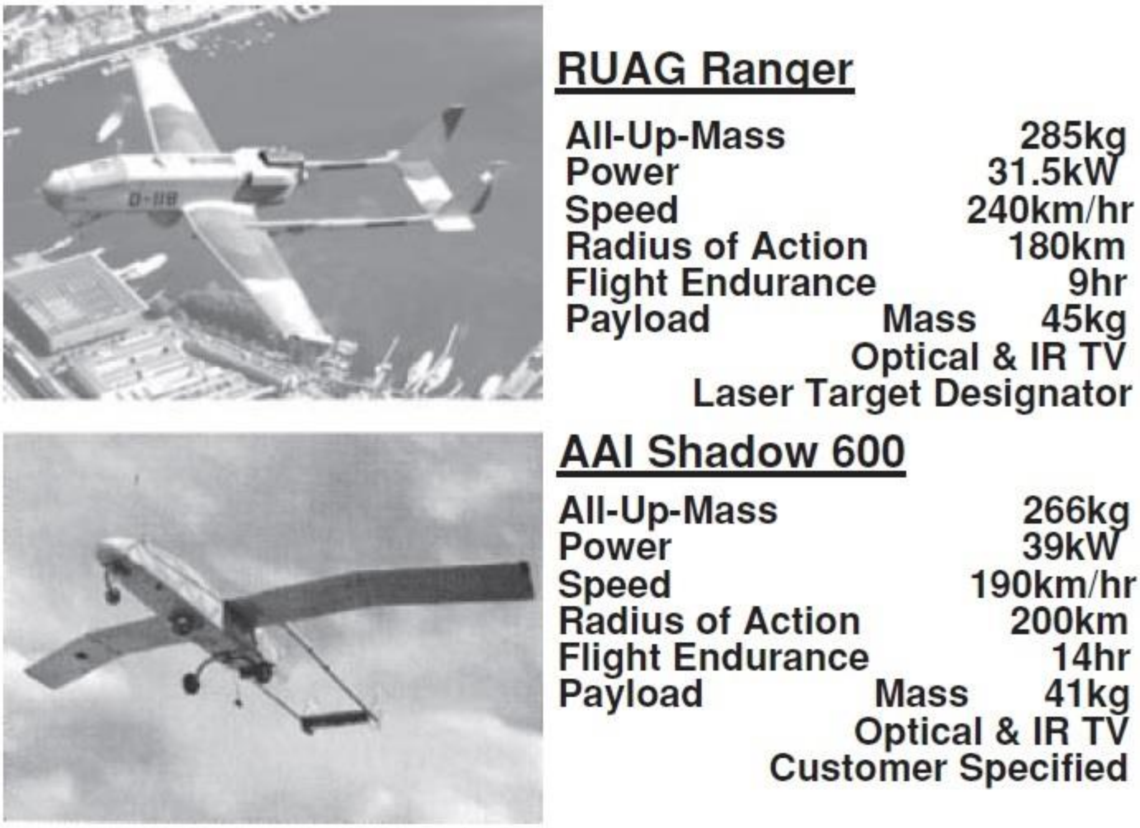


Figure 3.10: Medium-range UAV: Ranger and Shadow (Reproduced by permission of RUAG Aerospace, HQ and All American Industries Inc.)

The operating range of the aircraft, however, has not been extended, limited by its relatively slow cruise speed and its communication system range. The latter is still 125 or 200 km using a second aircraft to act as radio relay. The use of satellites for radio relay is probably not worthwhile with the speed-limited range. A strike capability has, however, been added to the C model with its ability to carry missiles beneath the wings.

3.2.2 VTOL (Rotary-winged) Aircraft

Until the current millennium, relatively little development of VTOL UAV systems took place. This may be thought surprising in view of the advantages that VTOL systems bring to the medium-range and, especially, close-range operations. Perhaps this was because there are far fewer organisations having experience of rotorcraft technology than those with fixed-wing experience, especially within the smaller organisations from where most UAV systems originated. However, their worth is now being realised and a few examples are now to be seen.

In the medium-range category these are represented by:

a) The Northrop-Grumman Firescout, which utilises the dynamic components from a four-seat passenger helicopter within a new airframe.

b) The Schiebel Camcopter, which is an aircraft specifically designed as a UAV.

c) The Textron-Bell Sea Eagle, tilt-rotor aircraft, which uses the technology from military and civilian passenger aircraft in the design of a smaller UAV aircraft. Although this aircraft has been operated invarious trials, further development is currently on hold.

d) The Beijing Seagull – a coaxial rotor helicopter a little larger than the Camcopter.

They are illustrated in Figures 3.11 and 3.12. A summary of technical data for all the medium-range UAV considered here is shown in Table 3.1, and affords some interesting comparisons

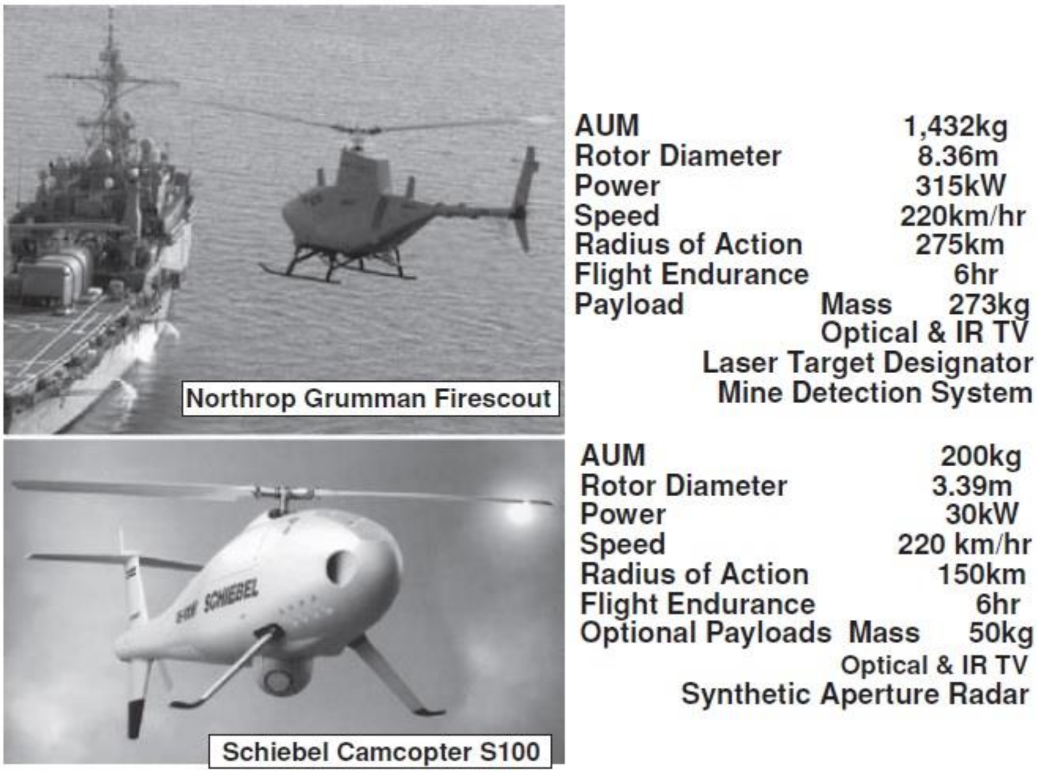


Figure 3.11 Medium-range VTOL UAV systems: Firescout (Reproduced by permission of Northrop Grumman) and Camcopter (Reproduced by permission of Schiebel)

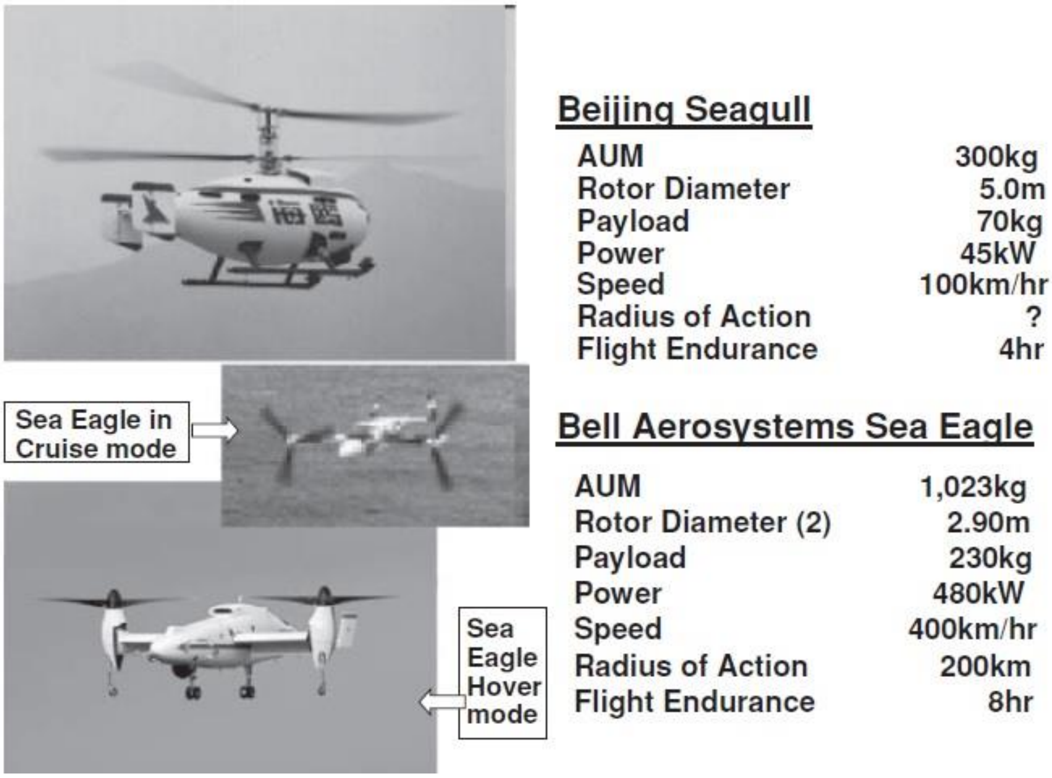


Figure 3.12 Medium-range VTOL UAV systems: Seagull (Reproduced by permission of Beijing UAA) and Sea Eagle (Reproduced by permission of Bell Helicopter Textron Inc.)

Table 3.2: Medium-range UAV technical data. (Reproduced by permission of All American Industries Inc.)

Data \ UAV Type	Hunter RQ-5A	Seeker II	Ranger	Shadow	Firescout	Sea-gull	Cam-copter	Sea Eagle
AUM [kg]	885	275	285	266	1,432	300	200	1,023
Wing Span [m] Rotor Diam. [m]	10.5	7.0	5.71	6.83	8.36	5.0	3.39	3.1 2x2.9
Wing Aspect Ratio	7.7	6.35	8.5	10.29				
Wing Area [m^2] Disc Area [m^2]	14.28	7.7	8.5	4.5	54.89	19.6	9.03	13.21
Span Loading [N/m] Disc Loading [N/m^2]	827	385	472	382	256	150	217	3,240 760
Wing Loading [N/m^2] Blade Loading [N/m^2]	608	350	317	580	?	?	?	?
Installed Power [kW]	2 x 50	38	31.5	39	315	45	30	480
Power Loading [N/kW]	87	71	85.6	66.9	44.6	65.4	65.4	20.9
Cruise Speed [km/hr]	202	220	240	190	220	100?	220	400
Loiter Speed [km/hr]	140#	115#	128	140	140#	60#	100#	140
Flight Endurance [hr]	21	10	9	14	6	4	6	8
Radius of Action [km]	250	?	180	200	275	?	150	200

Estimated at S.L. ISA

The amount of engine power installed per unit of aircraft mass is similar for all the aircraft with piston engines, irrespective of their being HTOL or VTOL aircraft. The gas-turbine-powered aircraft, i.e. Firescout and Sea Eagle have more power installed, partly because both use a higher disc loading (especially in the case of the Sea Eagle) but also because the turbine engines deliver more power fortheir mass.

With the exception of the tilt-rotor Sea Eagle and the Seagull, all types have a similar cruise speed ofabout 200 km/hr. The Sea Eagle has twice the cruise speed of the others, as is expected and has power to match. The actual speed of the Seagull is not confirmed, but it may well be slower than the other aircraft since it is the only one which is configured to accommodate an optional single pilot, making it less compact and having greater aerodynamic drag than the more dedicated UAV. With the exception of the Ranger, all the HTOL aircraft offer longer flight endurance than the VTOL aircraft. This may be due as much to the difference in their operating roles as to their fuel efficiencies. The radii of action of all aircraft are not dissimilar and may be determined more by similar communications limitations as for any other reason.

3.3 Close-range/Battlefield Aircraft

This type of system with its multitude of rˆoles, military, paramilitary and civilian, many of which are carried out at low altitude and require a rapid response time, probably poses the greatest challenge to the designer.

The low-altitude military operation, usually’ over enemy territory, requires that the system, particularly the aircraft, remain invulnerable to enemy countermeasures in order, not only to survive, but to press home the mission upon which so much depends. Flying at low altitudes most frequently means that the flight is in turbulent air, yet a stable platform is necessary to maintain sensors accurately aligned with the ground targets.
Added to those problems is the fact that, unlike the previous two categories of UAV systems, both for civilian roles and military roles, these systems are required to be fully mobile. This mobility includes theGCS and the facility of aircraft launch and recovery. The systems operate
within a very restricted area and often from wild terrain, so frequently no metalled runway or airstrip is available to them. Other means of launch and recovery therefore must be devised.

Unlike the aircraft within the system categories of MAV and NAV, they are too heavy to be hand-launched. It is convenient to sub-divide this category into two sub-types.

a) those systems which use aircraft that depend upon additional equipment to enable their launch and/or recovery, i.e. non-VTOL;

b) those systems which use aircraft that have a VTOL capability.

3.3.1 Non-VTOL Aircraft Systems

The design characteristics of aircraft are often, if not usually, driven by the compromise between take-off and flight performance.
If a long runway is available along which the aircraft can be accelerated at a moderate rate of acceleration to flight speed, then the thrust/power installed in the aircraft need be little more than that required, in any case, for flight manoeuvres. Also, the wing area may be merely that dictated by normal flight manoeuvres. Hence no great premium of thrust/power or wing area has to be added to the aircraft purely for take-off.

No such facility is available for the battlefield aircraft. Its ‘runway’ has to be carried as part of the UAV system and usually takes the form of a ramp, mounted atop of a transport vehicle, along which the aircraft is accelerated to flight speed.

Too long a ramp is ungainly and difficult to transport, but too short a ramp length requires a high value of acceleration be imposed, not only upon the aircraft, but upon its often delicate and expensive payloads and sensor systems. The ruggedisation of airframe and payloads can add considerably to their mass and cost. This compromise can be ameliorated to some extent by reducing the aircraft minimum flight speed needed to reliably sustain flight as the aircraft leaves the end of the ramp. This requires either an increase of wing area or wing flaps, both of these not only adding to aircraft weight and cost, but increasing the aircraft aerodynamic drag, power required and fuel consumption in cruise flight.

The problem, of course, does not end with the design problems of the launch. The aircraft, now airborne, must be recovered at the completion of its mission. But there is no convenient runway awaiting its return, nor is it feasible to align it to decelerate back along the ramp. Two alternative recovery methods are generally employed.

The most ubiquitous is the deployment of a parachute from the aircraft and, to cushion its impact on landing, an airbag is deployed. Both of these sub-systems, together with their operating mechanisms, must be carried within the airframe, further adding to its mass, cost and volume. Non-VTOL systems are represented here by the IAI Pioneer, BAE Systems Phoenix, the smaller Qinetiq/Cranfield Observer and Boeing/In-situ Scan Eagle UAV systems. The IAI Pioneer continues with the ubiquitous pusher-propeller, twin-boom configuration which is the most popular for the medium and close-range UAV systems.

A three-view drawing of the Pioneer UAV is shown in Figure 3.13 as representative of this configuration. The configuration offers a compact fuselage with the option of alternative payloads and electronics in the nose, aft-mounted engine and pusher propeller which distances the power-plant and its ignition system from the electronics and provides an uninterrupted view forwards for the payload. The two booms provide some protection for personnel from the propeller. For recovery, a parachute can be mounted above the fuel tank and aircraft centre of mass. The main challenge in the structure of the configuration is to achieve sufficient stiffness in the twin booms to prevent torsional and vertical oscillation of the empennage.

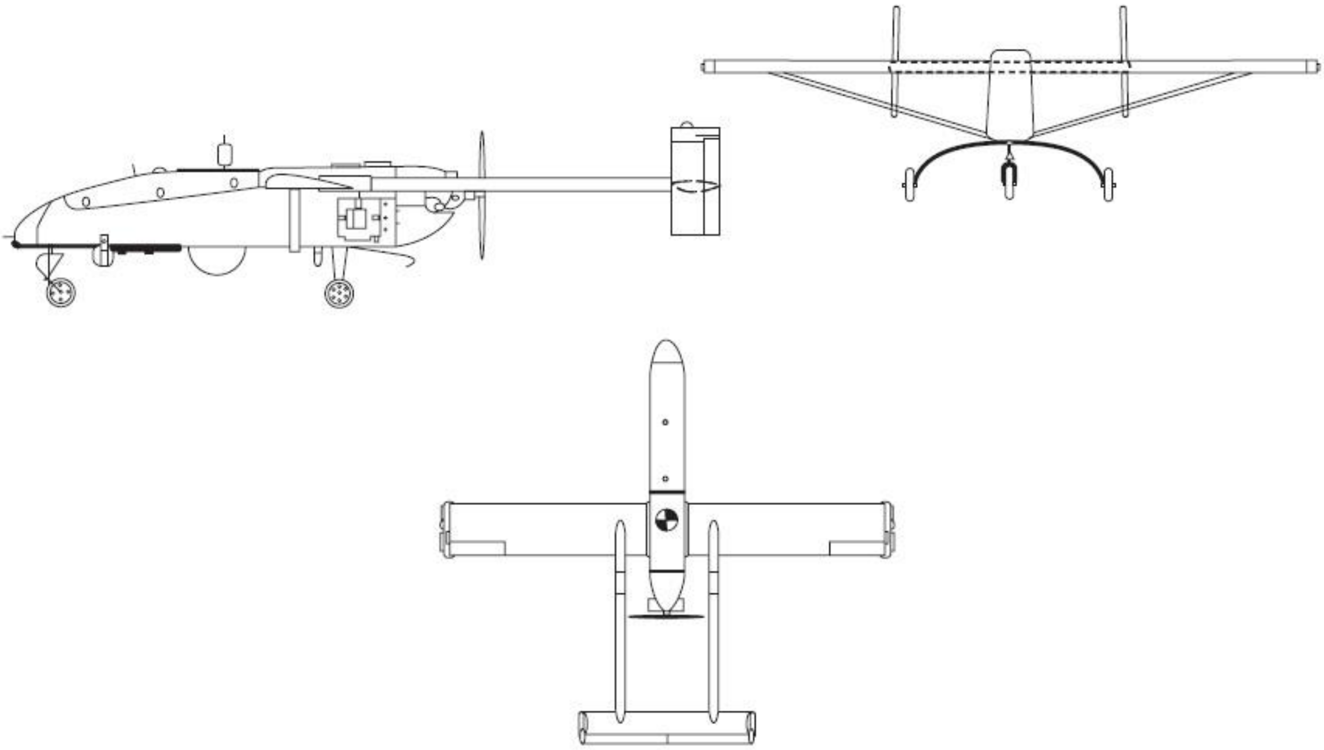


Figure 3.13: Pioneer three-view drawing

All-Up-Mass	36kg
Wing span	2.42m
Wing area	1.73m^2
Engine power	5.25kW
Wing loading	184N/m^2
Span loading	120N/m
Cruise speed	125km/hr
Loiter speed	110km/hr
Mission radius	25km
Endurance	2 hours

All-Up-Mass	177kg
Wing span	5.5m
Wing Area	3.48m^2
Engine power	19kW
Wing loading	500N/m^2
Span loading	316N/m
Cruise speed	158km/hr
Loiter speed	126km/hr
Mission Radius	50km
Endurance	4 hours

Figure 3.14: Close-range UAV systems: Observer and Phoenix (Reproduced by permission of Cranfield Aerospace Ltd)

Close-range systems adopting other airframe configurations are shown in Figures 3.14 and 3.15. The Phoenix system started operation with the British Army about 1990 after an extended development phase. The prime contractor of the system was GEC Avionics who put the emphasis on the aircraft carrying a separate payload and avionics pod slung beneath the fuselage under the aircraft centre of mass. This presumably was the reason for installing the power-plant, unusually, at the front of the aircraft in order to achieve a longitudinal balance. The system saw extensive service in the Balkans and Gulf, but is no longer in service.

Figure 3.15: Boeing/Insitu Scan Eagle. Source: Boeing-Insitu Inc; Cloud Cap Technologies;

The Observer offers a simpler and more rugged airframe, tailored to improve its spatial stability in air turbulence by designing it, as far as is possible, to have neutral aerodynamic stability and stabilising it electronically in space coordinates. It is fitted with an ingenious surveillance payload which uses three miniature TV cameras which look at increasing elevations along the major axis of the aircraft to provide contiguous coverage. This achieves a large image footprint with high resolution and is claimed to reduce operator workload to a minimum.

The Scan Eagle system uses an innovative sky-hook recovery method, but this adds a further vehicle and equipment to the system. However, the system has been successfully introduced into service with several military and naval operators, including the US Army, US Navy, Australian, Canadian and Singaporean Forces. The system has amassed more than 200000 operating hours within its first five years of deployment.

3.3.2 VTOL Aircraft Systems

Little development of VTOL UAV systems took place until relatively recently, following the demise of the 1960s' Gyrodyne Dash system. The close-range systems were particularly neglected.

There are two exceptions: the M L Aviation Sprite system (Figure 3.16) which began life in 1980 and the Yamaha R Max developed from about 1997. These are taken as the main examples of the class since both have seen extensive operation, though in quite different applications. The EADS Scorpio 30 is one of a number of VTOL systems now in development and, although information on it is scant, it is shown, together with the R Max, in Figure 4.20.

3.3.2.1 M L Aviation Sprite

The Sprite system was designed from the outset to meet both civilian and military design and airworthiness requirements. To this end critical systems in both GCS and aircraft have back-up systems and include, in the aircraft, two independent power-plants with their fuel supply. The aircraft can hover on one engine. Communication between the GCS and aircraft is obtained via two parallel radio systems of widely separated frequency bands.

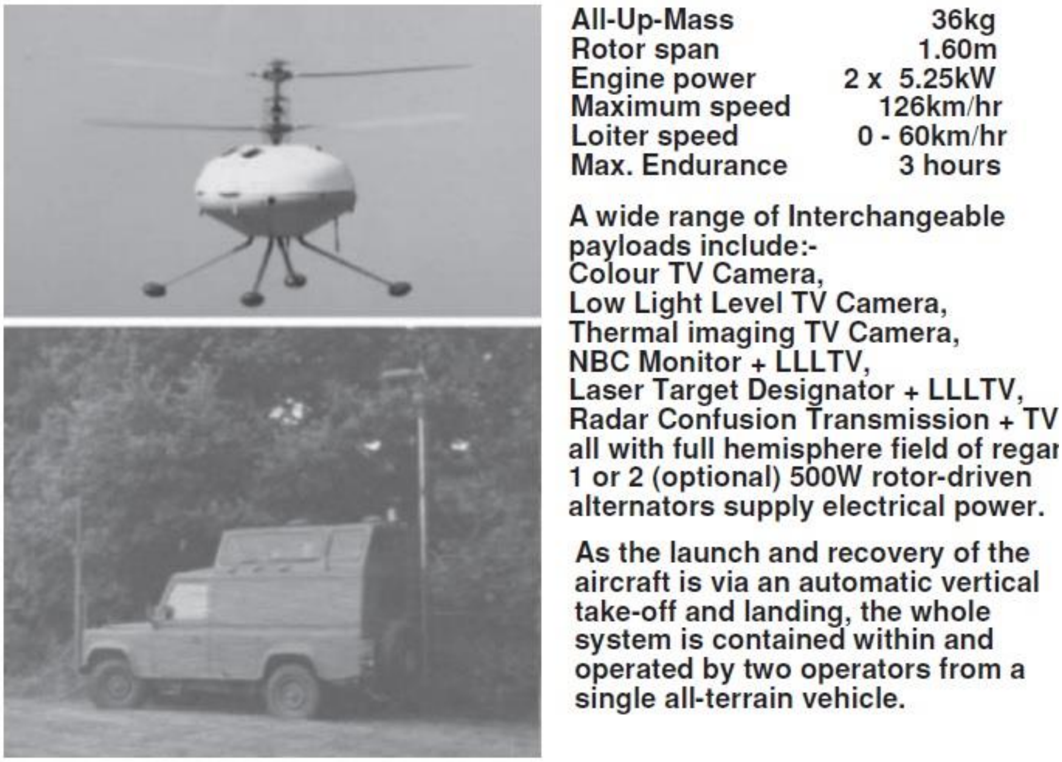
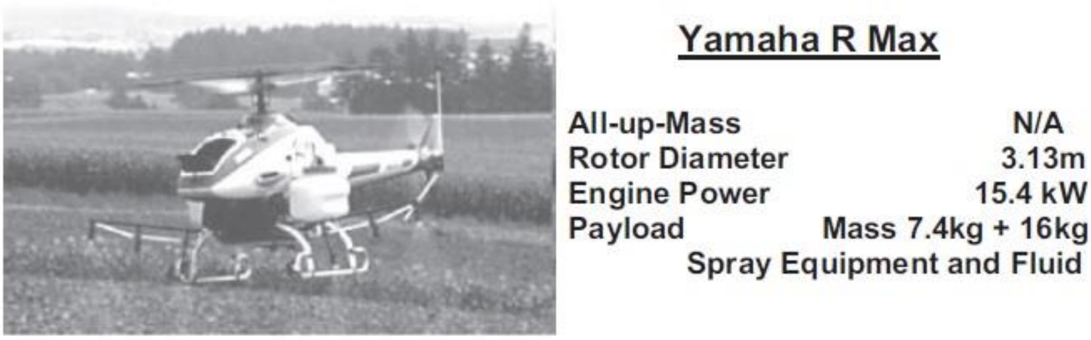


Figure 3.16 ML Aviation Sprite close-range VTOL UAV



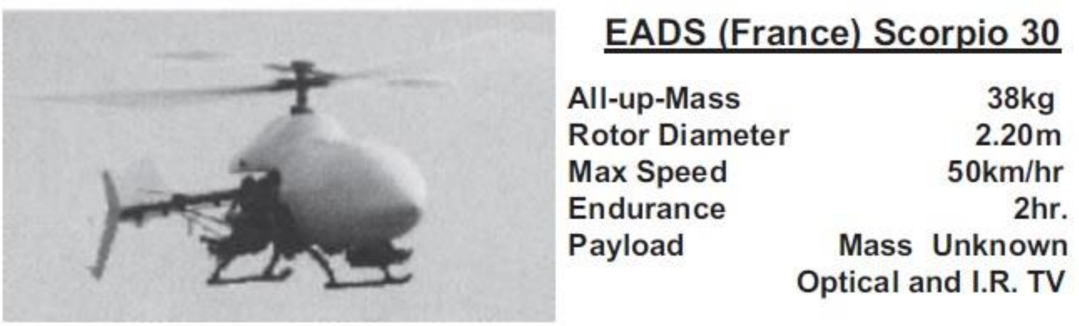


Figure 3.17 Yamaha R Max and EADS Scorpio 30 VTOL UAV. (Reproduced by permission of Schiebel Elektronische and Yamaha Motor Company, Japan). Source: EADS – France

A logic system aboard the aircraft selects the frequency with the better signal-to-noise ratio. Both GCS installation and aircraft are of modular construction which enables ease of build and maintenance and, particularly with the aircraft, gives a very compact solution. It also enables the aircraft to be transported within the one GCS vehicle. The Sprite aircraft is designed to have neutral aerodynamic stability and relies upon the AFCS to provide positive spatial stability. It has demonstrated extreme steadiness when operating in turbulent air.

3.3.2.3 Yamaha R Max

Unlike the Sprite, which is not designed to transport a dispensable load, other than minor ordnance, the R Max was expressly designed for spraying crops with fluid. It can carry 30 kg of fluid and spray gear and is over 2.5 times the gross mass of Sprite. It is not designed to be covert or to fly out to distances, but to fly efficiently at low speeds over local fields. Therefore it uses a large-diameter rotor with a lower disc loading than Sprite. The R Max has found a very profitable niche market, over 1500 aircraft being in operation.

3.3.3 Comparison of Close-range Systems

As discussed in Chapter 3, the HTOL aircraft is usually more efficient than the helicopter in cruising flight since the helicopter carries a penalty for its VTOL and hover capability. However, ramp-launched aircraft also carry a penalty for their launch and recovery method. It is instructive to see how these aircraft compare, with each type carrying a penalty for their different methods of launch and recovery. The available technical data is shown in Table 3.2 for a small number of close-range UAV, both HTOL and VTOL.

Table 3.3: Close-range UAV technical data

UAV Type / Data	Pioneer	Phoenix	Obser-ver	Scan Eagle	Sprite A	Sprite B	R Max
AUM [kg]	203	209	36	18	36	36	?
Span / Diameter [m]	5.11	5.5	2.42	3.10	1.60	1.60	3.11
Wing area [m^2] Blade area [m^2]	3.05	3.48	1.73	0.62	0.2	0.2	?
Wing Loading [N/m^2] Blade Loading [N/m^2]	653	589	204	285	1766	1766	?
Span Loading {N/m] Disc Loading [N/m^2]	390	373	146	57	176	176	121
Installed Power [kW]	20	19	5.25	1.1	5.25x2	5.25x2	15.4
Power Loading [N/kW]	100	108	67.3	160	67.3**	67.3**	59.9
Take-off speed [km/hr]	127*	110*	65*	80*	(Blade 324)	(Blade 324)	?
Take-off C_L	1.0	1.0	1.0	1.0	0.5	0.5	?
Max. Speed [km/hr]	158	158	130	120	126	216*	?
Max Endurance Speed Max Range Speed [km/hr]	130* 150*	? ?	72* 85*	? ?	72 108	100* 153*	? ?

* Estimated ** Power restricted to one engine only

3.3.3.1 Wing Loading

In order to keep the length of the launch ramp to a manageable length and the acceleration imposed upon the aircraft (in particular on sensitive equipment) to an acceptable level, the ramp-launched (RL) aircraft must be able to leave the ramp top and sustain flight at an airspeed which is considerably lower than that of aircraft
which have the advantage of using a runway or airstrip. This means that the RL aircraft must have a large wing area for its weight, i.e. a low wing loading. A RL aircraft has a wing loading typically one-tenth of a HALE aircraft, and half that of a medium-range aircraft, and therefore it carries the penalty of a very high level of friction drag at cruise speeds.

These trends are reflected in the data of Table 3.2 where a comparison shows the take-off speed varying with the wing-loading for the four fixed-wing aircraft. The Phoenix has the highest wing loading of the three ramp-launched aircraft and requires the longest launch ramp. It does therefore offer the highest cruise speed. The Scan Eagle would then offer the next highest speed, but it is power-limited.

3.3.3.2 Propeller Efficiency

As the RL aircraft leaves the ramp it is at its most vulnerable to air turbulence when its airspeed is at a small margin above its stalling speed. Any side-gust may cause a lateral roll, side-slip and ground impact. An up-gust may cause a nose-up attitude, an increase in lift and drag and, if not an immediate stall, a reduction in airspeed into a regime where the aircraft drag increases as the airspeed reduces, resulting in an inevitable stall.
To combat this the propeller must be designed to give its maximum thrust to rapidly accelerate the aircraft from a low airspeed. Therefore unless the extra complexity of a variable-pitch propeller is accepted, the usual fixed-pitch propeller, optimised for acceleration away from the ramp top, will suffer poor efficiency in cruise flight, thus increasing the power required and the cruise fuel consumption. In addition, the propeller diameter of the RL aircraft is likely to be restricted for ramp clearance, thus exacerbating the problem.

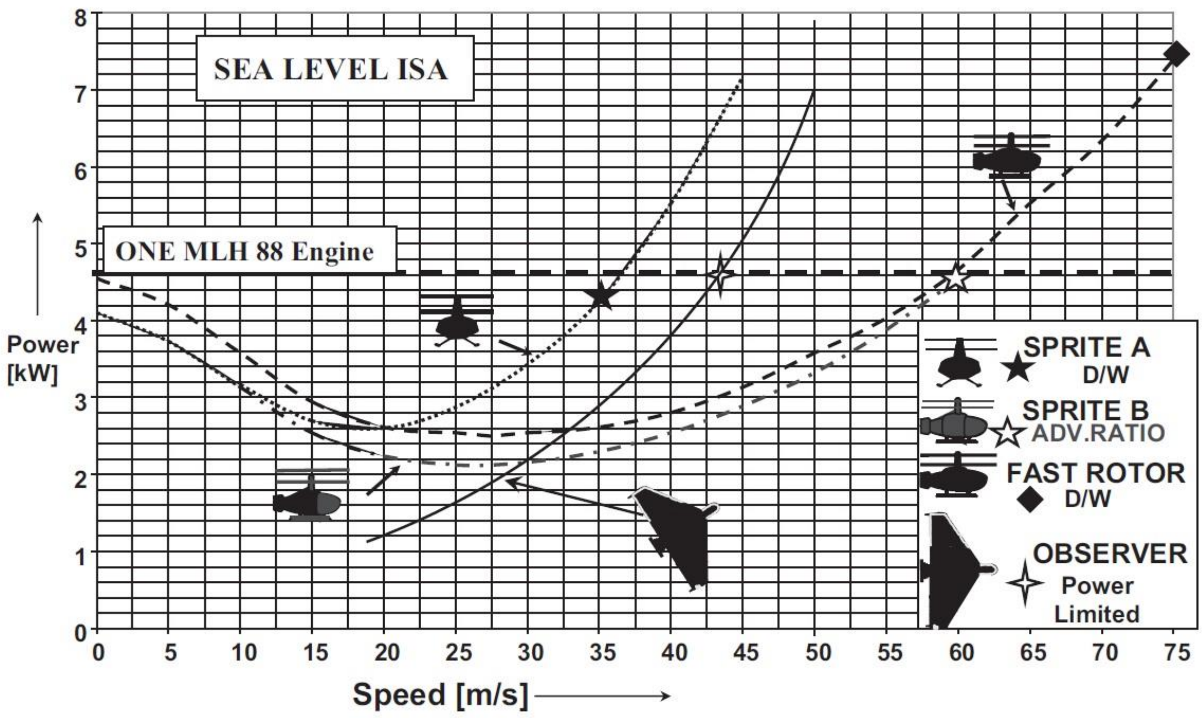


Figure 3.18: Close range UAVL: power/speed comparison

3.3.3.3 Landing Equipment

Both Phoenix and Observer, typifying such systems, are forced to carry a parachute and airbag to reduce the impact loads on touch-down. These and their means of deployment add to the mass, volume and cost of the aircraft. The Scan Eagle aircraft largely avoids these penalties by being arrested onto a vertical cable, but the system has to bear the extra cost and operation of a further mast-deploying vehicle.

3.3.3.4 Comparison of Ramp-launched and VTOL Aircraft

The performances of Observer and Sprite A and Sprite B in terms of power/speed are shown in Figure 3.18 and compared. The choice of these aircraft for representative comparison of RL and VTOL aircraft is particularly relevant since they are of the same all-up mass, have the same mass of payload and use the same engines. (The MLH 88 twin-cylinder, two-cycle units were developed specifically byML Aviation for Sprite and were later made available for projects sponsored by the UK Royal Aircraft Establishment). The figure shows that Sprite A, with the higher drag, axisymmetric, fuselage has a maximum speed limited to 35 m/s (126 km/hr) by its drag-to-weight ratio.

Calculations show that Observer should offer a maximum speed of about 43 m/s (155 km/hr). However, the manufacturers rate it at only 125 km/hr – similar to Sprite A. The alternative Sprite configuration, the B model with the more streamlined, but less stealthy fuselage, has an estimated maximum speed of 60 m/s (216 km/hr) limited by its advance ratio, i.e. stalling of the retreating blades. However, if the rotor speed were to be increased and some of the power from the second engine used, 75 m/s (270 km/hr) could readily be achieved but at a penalty of a small increase in rotor noise. It is also of interest to note that comparing the masses of the two airframes with their equipment, the 'extras' required in both aircraft for launch and recovery are essentially equal. The combined mass of the parachute and inflatable bag installed in Observer for its recovery is equal to the combined mass of the Sprite transmission system plus its bonus of the second power-plant installation which gives it its one-engine-failed hover capability. The latter is an excellent safety feature for hovering over urban areas. If the costs of the two systems are compared subjectively, an assessment can be made using the established method of costing sub-systems as a function of mass and complexity. On the basis that the cost of the more extensive airframe of the RL aircraft equates to the cost of the rotors plus simple airframe of the VTOL aircraft, this cost is used as a 'cost unit'. The remaining sub-systems may then be assessed as follows:

Table 3.4: Sub-systems comparison of RL and VTOL aircrafts

Sub-system	RL aircraft	VTOL aircraft
Airframe plus rotors	1	1
Parachute and airbag	1	0
Undercarriage	0	$^1/_2$
AFCS and actuators	1	1
Communications	1	1
Power-plant(s) and electrics	$^1/_2$	1
Transmission	0	1
Payload	1–3	1–3
Launch ramp on vehicle	2	0
Control Station	5	5
System cost with 1 UAV	$12^1/_2$–$14^1/_2$	$11^1/_2$–$13^1/_2$
System cost with 2 UAV	$17^1/_2$–$19^1/_2$	$17^1/_2$–$19^1/_2$

VTOL rotorcraft system is better suited to the close-range/battlefield scenario than is a ramp-launched HTOL aircraft system:

(a) it is less vulnerable to enemy attack in the air (see Chapter 7) and less vulnerable on the ground as it is more mobile with far less ground equipment and personnel deployed (see also Chapter 26);

(b) VTOL will cost no more as a system to procure and will cost less in operation through lower cost of personnel;

(c) it has the advantage of lower response to air turbulence and the versatility of hover and low-speed flight.

3.4 MUAV Types

The concept of the mini unmanned air vehicle system was that the system could be back-packed, assembled and deployed by no more than two persons. MUAV are prolific largely because they are seen by many people as simple adaptations of model aircraft. Provided that the aircraft has a mass less than 10 kg (originally 5 kg), in some circumstances they can be flown at will under the very restricted rules for model aircraft.

It is often thought that with the addition of a simple video camera system to a model aircraft airframe, controlled via model aircraft radio equipment, a cheap MUAV system can be produced. Little can be further from the truth, but the idea has generated a large number of poor, unreliable 'systems' from entrepreneurs where no consideration is given to proper system integration. Some of them have learned the hard way but, in the process, have often given the MUAV a bad reputation. Few, if any, model aircraft equipments undergo the rigorous design and testing regime necessary to achieve the reliability required by realistic UAV operation. For this reason, the two examples selected for discussion in this volume are from established manufacturers with aeronautical experience and are shown, with their data, in Figure 3.19.

Lockheed Martin Desert Hawk III

All-up-Mass	3.86kg
Mass empty	2.95kg
Wing Span	1.32m
Wing Area	0.323m^2
Wing loading	120N/m^2
Power- Electric motor	?kW
Cruise speed	92km/hr
Endurance	90min
Operating Range	up to 15km
Payload Mass/Vol.	0.91kg/4720cc
Payload	Optical, LLL or IR TV

Bluebird Skylite

All-up-Mass	6.0kg
Wing Span	2.4m
Wing Area*	0.8m^2
Wing loading	74N/m^2
Power- Electric motor	?kW
Cruise speed	75km/hr
Endurance	1.5 hr
Operating Range	10km
Payload Mass	1.2kg
Payload	Optical or IR TV

* estimated

Figure 3.19: Mini-UAV systems. (Reproduced by permission of Lockheed Martin Corp). Source: Rafael Defense

MUAV were originally expected to be hand-launched and controlled via a laptop computer with display showing video images and navigation and housekeeping data. To this end, the aircraft could not, realistically, have an AUM exceeding about 6 kg (for hand-launching) with the total system grossing about 30 kg distributed between two packs. Initially, the aircraft were powered by small petrol- or diesel-powered engines and this required the fuel supply to be included in the backpack(s).
More recently, with the development of improved battery technology and lightweight electric motors, this power source makes back-packing more realistically possible. On grounds of safety, the carriage of a supply of rechargeable batteries is preferable, to inflammable fuels. Battery performance in low temperatures might, however, be a cause for concern. Referring to Figure 3.19 both the Desert Hawk and Skylite are in use with military forces.

It is a tribute to recent development in electronic technologies that a thermal imaging surveillance payload, aircraft stability sensors, flight control computation, GPS navigation equipment, and radio communication equipment can be battery-powered and yet leave sufficient battery power to provide propulsion to maintain the aircraft airborne for an hour within a total platform mass of little more than 3 kg in the case of the Desert Hawk.

The design of any aircraft is a compromise between several aims, and for one which has to be disassembled to be carried by back-pack, this is especially so. Just one compromise here is between the wing size which is practical to be carried, the wing area and span. A larger wing area is necessary for low-speed flight for ease of launch and surveillance at low altitudes, yet will increase the aircraft vulnerability to air turbulence. A larger span is desirable to achieve low propulsive power requirements at low speed yet is limited by practical packaging.

The author calculates that the minimum flying airspeed for the Hawk and Skylite is 50 and 40 km/hr respectively. This is not readily achievable, without herculean effort, by a hand-launch; hence both systems employ other means of boosting the aircraft to above the minimum airspeed.

The Hawk operators hitch a 100-metre-long bungee to the aircraft and tension it between them before the aircraft is released. This would appear to be somewhat hazardous for the second operator (not shown in the illustration), but seems to work in practice. The Skylite system employs a mechanically tensioned, bungee-powered, foldable catapult to launch the heavier aircraft. Both systems are reportedly achieving operational success though the Hawk operators report that the aircraft, with its low wing loading, is limited to operation in moderate wind conditions. The Skylite, surprisingly with its even lower wing loading, is claimed to be 'weather-proof''.

No VTOL aircraft seem to have been successfully developed in this category and certainly none have entered service.

3.5 MAV and NAV Types

Both of these, until recently, largely remained the province of academia. Now commercial companies such as Aerovironment and Prox Dynamics are developing systems, but as yet, neither are believed to have achieved full operational status.

3.5.1 MAV

The concept of the micro Air Vehicle system is that it is a personal system capable of immediate deployment by one person and operated via an iPod or similar device. The original definition of an MAV was that the air vehicle should be of no more than 150 mm (6 inches) span/diameter, but this has been relaxed somewhat of late. Although small, it is required to carry a surveillance camera, means of control and of image transmission. Its use is seen primarily as urban and indoor surveillance.

The development of MAV systems may adopt one of four forms of airframe:

a) fixed-wing
b) rotary-wing
c) flapping wing (ornithopter)
d) ducted lift-fan

3.5.1.1 Fixed-wing

The majority of MAV are, understandably, of fixed-wing configuration since it is seen that these are easier to construct and Figure 3.20 shows two types from well-known aircraft companies. Note that although both are denoted by their manufacturers as MAV, they considerably exceed the size definition of MAV. This is not surprising as the development of an aircraft to carry a useful electro-optical payload with its communications, control, power source and propulsion sub-systems, and yet achieve meaningful flight endurance, within such a small size, is still a formidable task.

The trend with reducing size is generally to the advantage of structural and mechanical elements, but to the disadvantage of aerodynamic performance. With the very small MAV, the better understanding of the aerodynamics involved at the very low Reynolds numbers is becoming critical, and new technical approaches may be necessary to achieve further miniaturization.

Also pictured in the figure are four fixed-wing MAV typical of projects being carried out in universities around the world. The small mass and low wing loading of fixed-wing MAV makes them very vulnerable to air turbulence and heavy precipitation. Without a brief hover capability the fixed-wing MAV is likely to have but a limited use.

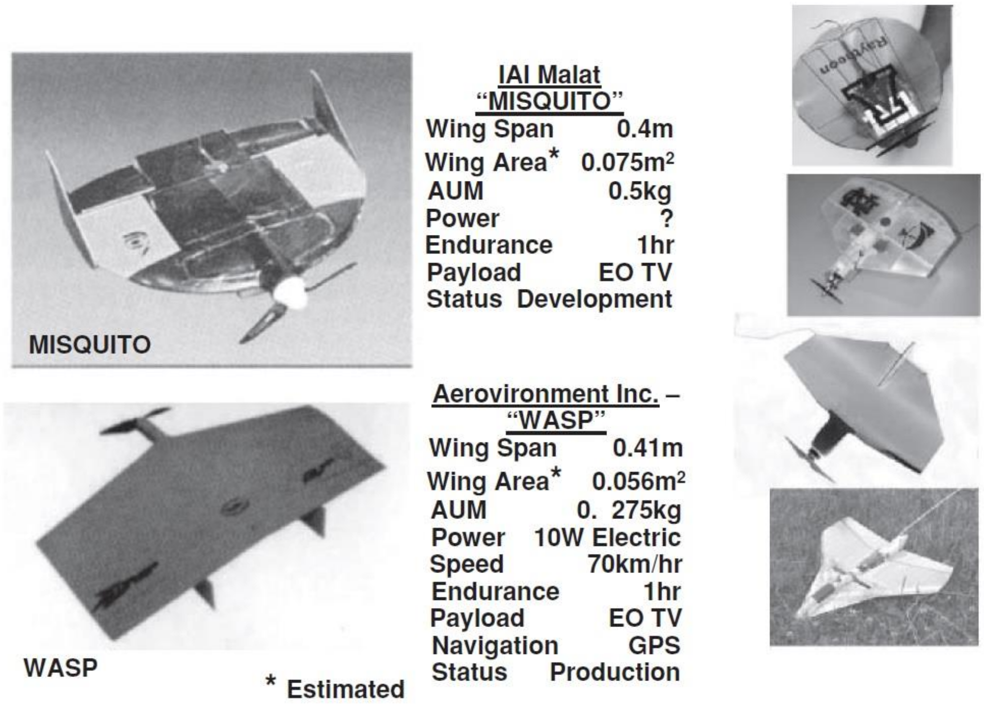


Figure 3.20: Micro air vehicle systems (Reproduced by permission of AeroVironment Inc)

3.5.1.2 Rotary-wing, Ornithopter and Ducted Lift-fan

If the declared aim of indoor flying and to 'perch and stare' is to be achieved, however, this category of UAV must be addressed more actively. Although this work is known to be pursued by a few individuals, little tangible success had been reported until recently. As earlier suggested, the scale effect of size should benefit the mechanisms of these types and the oscillatory aerodynamics of the former two types should give better lift generation (Warren effect) than fixed aerofoils. The higher wing loadings of all types promise a reduced vulnerability to air turbulence and heavy precipitation compared with their fixed-wing equivalents.

The development of micro-sized rotors and mechanisms for the rotary-wing and ducted lift-fan MAV should present no great problems, but the oscillatory mechanism to provide wing flapping frequencies in the ornithopter of 20 Hz or faster may be more of a challenge. The efficiency of the duct of the fan may be questioned at the very small scale due to the difficulty in maintaining ultra-small fan-to-duct clearance and the greater friction drag of the duct at very low Reynolds numbers. The duct surface area may also make the aircraft vulnerable to urban turbulence.

It also may be that the successful outcome of all types has been awaiting the development of miniature attitude sensors and control systems. That these are now appearing is demonstrated by the successful appearance of the rotary-wing NAV by Prox Dynamics, as reported below.

3.5.2 NAV

Nano air vehicles originally sponsored by DARPA, and now by other organisations, are predicted to achieve an aircraft with dimensions of less than 5 cm in any direction, have an AUM of less than 10 g, including a payload of 2 g. These dimensions, themselves, do not imply nano-scale which relates to matter of a few millionths of a millimetre. The use of 'nano' in the UAV context is that these small aircraft will require the embodiment of nanotechnology within the subsystems such as computers, sensors, communications, structures, electric motors and batteries, etc. which, with their precise integration, will be small and powerful enough to provide an aircraft capable of a realistic mission within the defined size and mass constraints.

Their future use is yet to be fully determined, but may include flying into and around the interior of buildings and natural structures, such as caves, to provide information as to the position of the structure's contents and condition. We are looking significantly into the future for their operation but research and development of the possibilities has begun. However, the same concern regarding their operation in wind conditions and precipitation applies as for micro air vehicles, but even more critically. Two examples of NAVs are shown in Figure 3.20.

One is the Prox Dynamics Picoflyer which is the smallest of an existing range by the Company. The range includes the Nanoflyer having a rotor diameter of 85 mm with a 10 min. endurance and the largest, the Microflyer, having an AUM of 7.8 g, a rotor diameter of 128 mm and an endurance of 12 min. These have been more recently complemented by Prox Dynamics' Hornet range of NAV demonstrated at the 24th Bristol UAV Systems Conference, and in particular the Hornet 3 having an AUM of 15 g, a rotor diameter of 100 mm and achieving a flight of 25 min in benign conditions out of doors. The other example shown in Figure 4.25 is being developed by Lockheed-Martin and DARPA. It is not believed yet to have flown, but represents objectives in a programme of technology development.

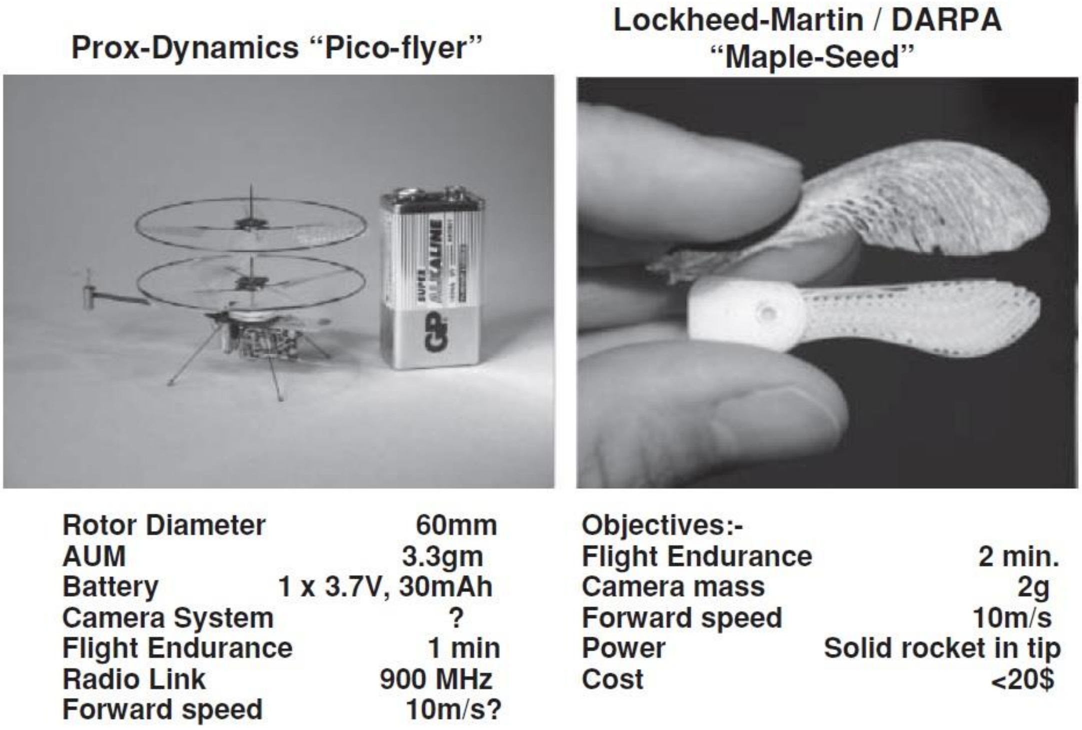


Figure 3.20: Nano air vehicles. (Reproduced by permission of Proxdynamics)

3.6 UCAV

Examples of these, shown in Figure 3.21, are the Northrop-Grumman X-47B in development under the auspices of DARPA and the US Navy, and the BAE Systems Taranis being developed with the support of the UK MoD.

UCAV systems will be deployed in advanced strike missions with the aim of destroying enemy air-defence systems in advance of attacks by manned aircraft. The aircraft, therefore, must achieve a compromise between performance and stealth.

The airframe will be of high wing loading and high thrust-to-weight ratio to achieve high penetrating speed without excess power demand and of dart-shaped, low aspect ratio flying wing with internal weapon carriage to minimise its radar signature on the approach to the target.

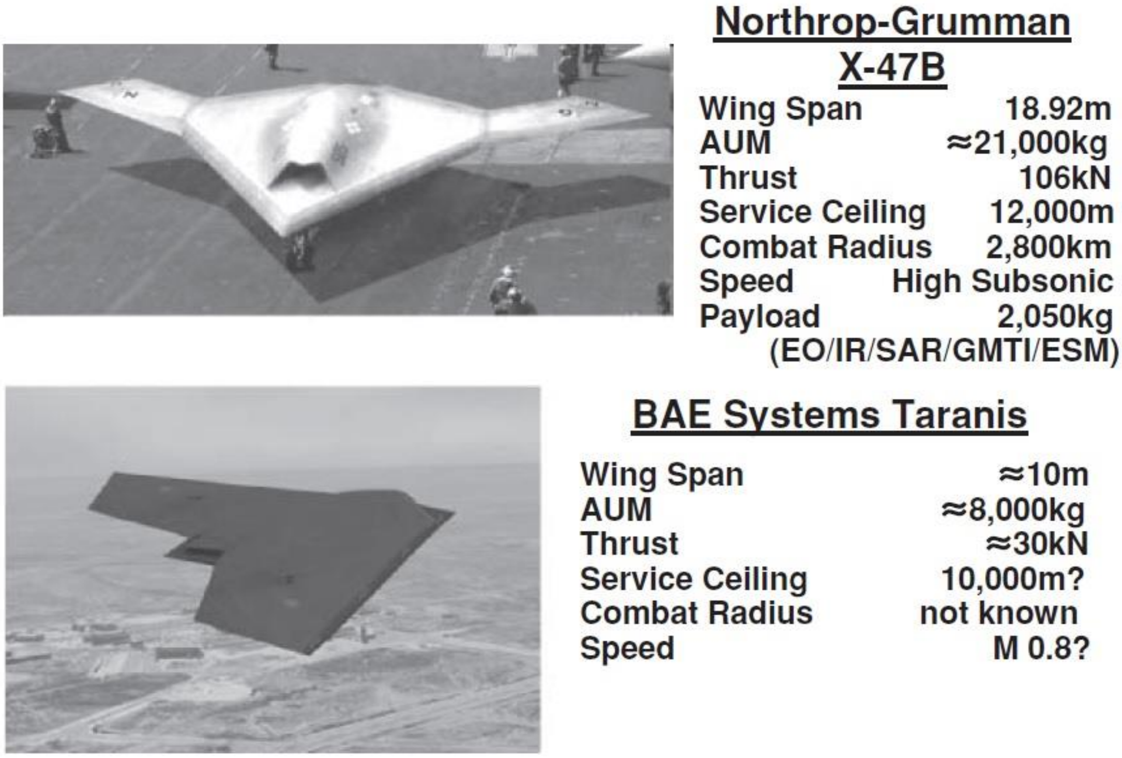


Figure 3.21: Unmanned combat air vehicles (Reproduced by permission of BAE Systems)

3.7 Novel Hybrid Aircraft Configurations

As remarked in the previous chapter, for operational reasons, the ideal aircraft is one which can take off and land vertically, yet fly at high speeds. This benefits the whole system in that less infrastructure is required compared with systems in which the aircraft is launched from a runway or ramp. Helicopter types of rotary wing aircraft are the most efficient in hover flight but, as already explained, have limits to their forward flight ability.

For many years, attempts have been made to produce aircraft which can perform well in both flight regimes. Inevitably the results are compromises where the aircraft are less efficient in both regimes compared with the 'specialist' hover (helicopter) or cruise flight (high wing-loaded fixed-wing) aircraft. Hence the emergence of tilt-rotor and tilt-wing aircraft types. The search for the ideal aircraft continues and is made easier to achieve if no provision has to be made for aircrew to be accommodated or to function. Three different approaches which are aimed at achieving this 'El Dorado' are shown in Figures 3.22 and 3.23.

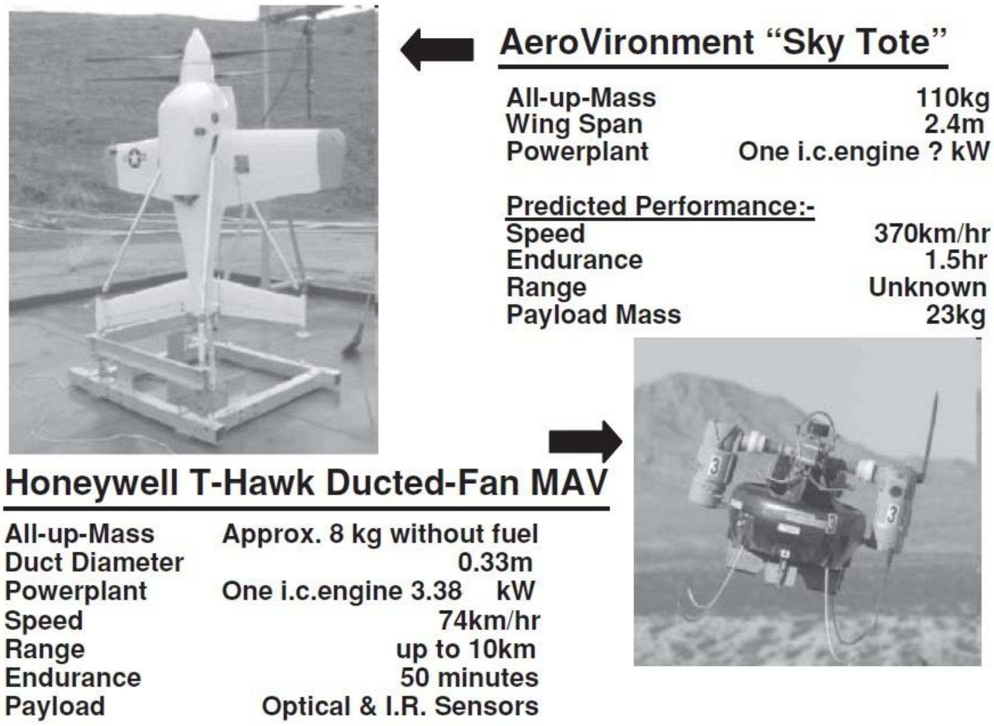


Figure 3.22: Novel UAV systems 1 (Reproduced by permission of AeroVironment Inc and Honeywell)

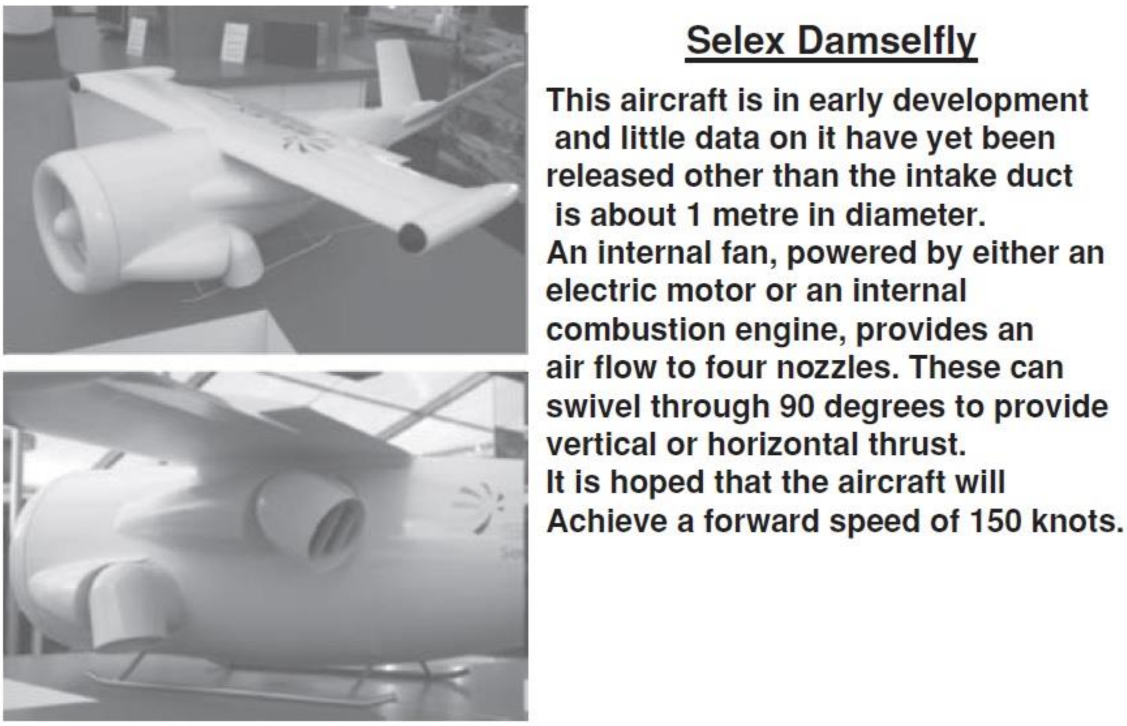


Figure 3.23: Novel UAV systems 2. Source: Selex

3.7.1 The Sky Tote

This is essentially a tilt-wing-body aircraft. A configuration similar to this was built, in prototype form, for VTOL fighter aircraft in the 1960s by Convair and Lockheed of the USA. However, both projects were abandoned when it was found how difficult it was for a pilot to land the aircraft whilst lying on his back with his feet in the air.

AeroVironment Inc. of the USA has a prototype Sky Tote UAV under development. Unlike the Convair and ockheed prototypes which used a delta wing of low aspect ratio, it uses a main wing of relatively high aspect ratio and tail surfaces. At the time of writing the aircraft is undergoing hover tests and very little specification data have yet been released. It will be of interest to see how it fares during the transition mode. One problem which may be presented by the configuration could be interference by the rotors of any forward-looking imaging sensors.

3.7.2 Honeywell Ducted-fan MAV

Although designated a micro-AV, one would have thought that it more appropriately comes within the mini-UAV category by nature of the aircraft mass which is likely to be increased before it is qualified for service. It is creditable that the back-packed system was exposed to a military environment in Iraq so early in its development.
Lessons have been learned already to indicate that it was underpowered, the flight endurance was inadequate and that vibration was causing a sensor problem. These short-comings are not unusual and are to be expected in a relatively novel design, and their discovery is better addressed earlier than later in the programme.

The new engine in development is stated to produce 3.38 kW. A simple estimate indicates that the power required to hover out of ground effect in SL ISA conditions must be of order 2.6 kW. The margin of 0.78 kW may be barely adequate to allow for engine power reduction with increases in ambient temperature and altitude and engine wear with usage in addition to the extra power required in manoeuvres. Those unused to VTOL aircraft operation, for example, seem often to be unaware of the margin of power to be instantly applied in the pull-up from a vertical descent. This is even more critical for small aircraft and ducted systems in particular since they gain little benefit from ground effect.

The designers/developers task in this brave programme will inevitably be centred on mass reduction. Fortunately technological development is on their side.

3.7.3 Jet-lift Aircraft

Amodel of the Selex S&AS Company’s Damselfly is shown in Figure 3.23. This uses the jet-lift principle, in this case employing four separately directable nozzles which, presumably, achieve both lift and control functions. The Company’s claims for the product of having ‘the hover capability of a helicopter’ and ‘outstanding wind-gust resistance’ remain non-validated at the time of publication, with little supporting evidence available in the public domain.

The ultra high jet velocity of the configuration and long ducting must surely result in a large demand for power in a size regime where engines are not known for their frugality. Flight at low speeds must be very expensive in fuel consumption and, with a large wing, vulnerable to gusts, making it a challenge to perform effectively at low speeds in the urban canyons.

The author looks forward to being proven wrong, in which event Selex will have achieved a winner. However, the claim of 150 kt cruise speed hardly justifies the expense of the ambitious new development since a hover-efficient helicopter, let alone a tilt-rotor machine, can achieve that speed.

3.8 Research UAV

As previously noted, another increasing use of UAV is for research purposes. Using dynamically scaled models of proposed full-size aircraft, the flight characteristics of the new aircraft can be assessed more cheaply, quickly and with less risk and waiting until a full-size prototype is built. Should modifications of a new configuration be found necessary, then those modifications can be made far more quickly and cheaply than if made to a full-size prototype. An example of this use is shown in Figure 3.24 with the proposed blended wing-body airliner of the Boeing Company of the USA. The fully-instrumented scaled model was designed and built by Cranfield Aerospace Ltd, UK, for flight testing at NASA Langley, USA.

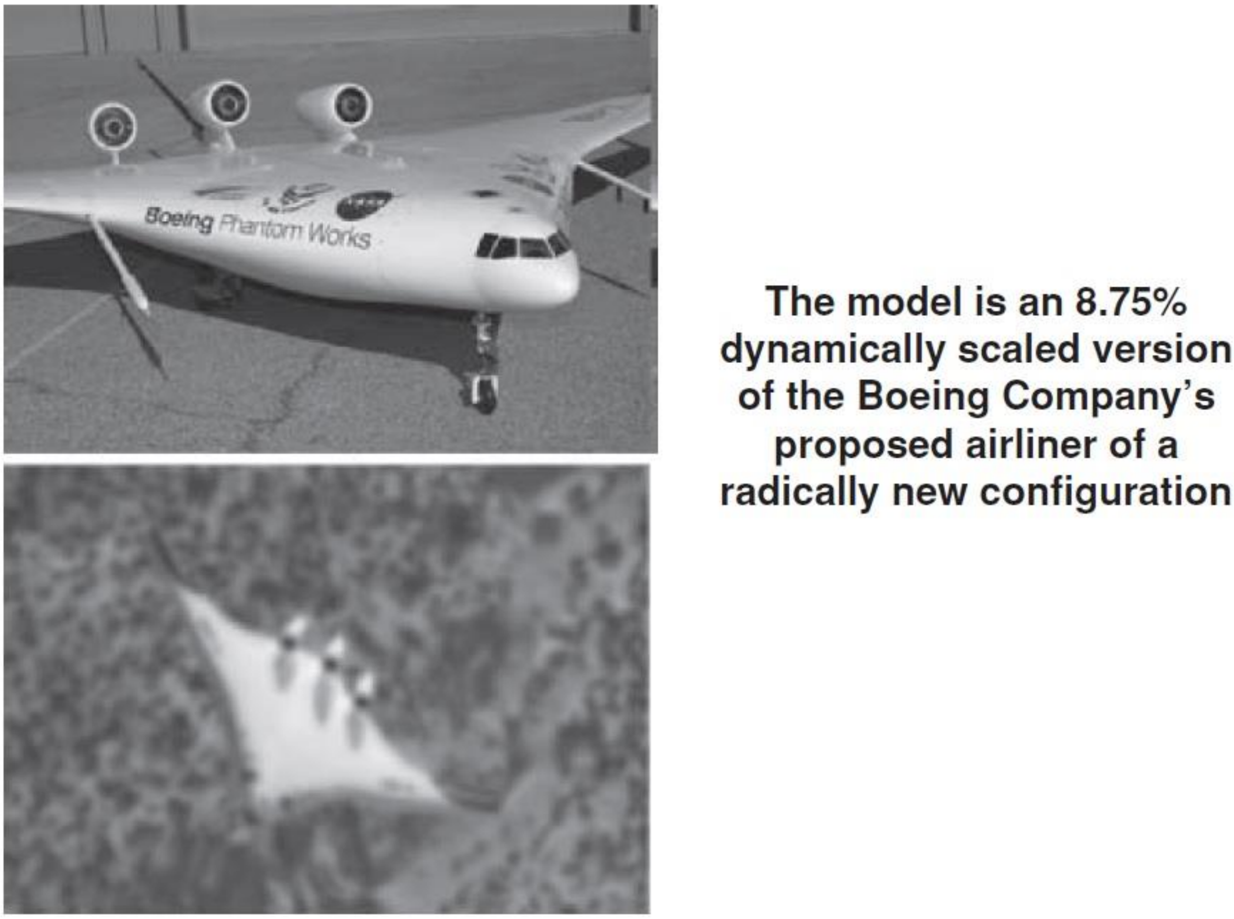


Figure 3.24: Blended wing-body model

UNIT – IV

COMMUNICATIONS NAVIGATION

CO No	Course Outcomes **After successful completion of the course, students will be able to:**
CO9	**Identify** the appropriate communication and navigation systems for the UAVs as per the role requirements

	Program Outcomes (POs)
PO1	**Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
PO2	**Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences

As introduced in previous chapters, the communications between the UAS control station (CS) and the UAV consist primarily of an 'up-link' transmitting command and control from the operators to the UAV (or UAVs in multiple operations) and a 'down-link' which returns data showing UAV, including payload, status and images from the UAV to the CS and to any other 'satellite' receiving stations. The UAV status data is also known as 'housekeeping' data.

The maintenance of the communications is of paramount importance in UAS operations. Without the ability to communicate, the UAS is reduced merely to a drone system and loses the versatility and wide capability of the UAS. Loss of communication during operations may result from:

a) failure of all or part of the system due to lack of reliability,
b) loss of line-of-sight (LOS) due to geographic features blocking the signals,
c) weakening of received power due to the distance from the UAV to the control station becoming too great,
d) intentional or inadvertent jamming of the signals.

These aspects will be addressed later. The specifications for communications performance will include two fundamental parameters:

(a) 'data rate' which is the amount of data transferred per second by a communications channel and is measured in bytes per second (Bps), and

(b) 'bandwidth' which is the difference between the highest and lowest frequencies of a communications channel, i.e. the width of its allocated band of frequencies and is measured in MHz or GHz as appropriate.

4.1 Communication Media

The communication between the GCS and aircraft and between the aircraft and GCS may be achieved by three different media: by radio, by fibre optics or by laser beam. All are required to transmit data at an adequate rate, reliably and securely. All have been attempted.

4.1.1 By Laser

The laser method seems currently to have been abandoned, principally because of atmospheric absorption limiting the range and reducing reliability.

4.1.2 By Fibre-optics

Data transmission by fibre-optics remains a possibility for special roles which require flight at low altitude, high data rate transmission and high security from detection and data interception. Such a role might be detection and measurement of nuclear, biological or chemical (NBC) contamination on a battlefield ahead of an infantry attack.

The fibre would be expected to be housed in a spool mounted in the UAV – not in the ground control station (GCS). This is because it must be laid down onto the ground rather than being dragged over it, when it might

be caught on obstacles and severed. The method is probably better suited to VTOL UAV operation, and necessarily limited in range to a few kilometres. Data would be transmitted securely back to the GCS and at the completion of the mission the fibre would be severed from the UAV which would climb and return automatically to the GCS. Such a system was simulated, designed and partly constructed in 1990, under US Army contract, for the Sprite UAV system.

4.1.3 By Radio

Currently, the only system known to be operative is communication by radio between the UAV and its controller, directly or via satellites or other means of radio relay.

4.2 Radio Communication

The regulation of UAS, including radio communication, is effected in the USA by the FAA which is advised by the Radio Technical Commission for Aeronautics (RTCA). In Europe EASA is the overall regulating authority, and it delegates various aspects of regulation in the UK to CAA which again is advised by OFCOM, the authority within the UK for the allocation of radio frequency.

4.2.1 Radio Frequencies

Electromagnetic waves generally considered usable as radio carriers lie below the infrared spectrum in the range of 300 GHz down to about 3 Hz (Table 4.1 and see Figure 4.4). Frequencies in the range 3 Hz (extremely low frequency, ELF) to 3 GHz (ultra-high frequency, UHF) are generally considered to be the true radio frequencies as they are refracted in the lower atmosphere to curve to some degree around the earth’s circumference, increasing the effective earth radius (EER) by up to 4/3. Frequencies above this range, 3–300 GHz (super-high frequency, SHF and extremely high frequency, EHF) are known as microwave frequencies and, though they may be used to carry radio and radar signals, they are not refracted and therefore operate only line-of-sight.

It is necessary to transmit high rates of data, especially from imaging-sensor payloads, from the aircraft to its control station or other receiving station. Only the higher radio frequencies are capable of doing that and, unfortunately, these depend progressively towards requiring a direct and uninterrupted line-of-sight (LOS) between the transmitting and receiving antennas. There is therefore a compromise to be made when selecting an operating frequency – a lower frequency, offering better and more reliable propagation, but having reduced data-rate ability and the higher frequencies capable of carrying high data rates, but requiring increasingly direct LOS and generally higher power to propagate the signal. UHF frequencies in the range 1–3 GHz are, in most circumstances, a desirable compromise, but due to increasing demand by domestic services, such as television broadcasting, for the use of frequencies in the VHF, UHF ranges, the frequency allocation agencies are requiring that communication systems use increasingly higher frequencies into the SHF microwave band of 5 GHz or above.

Table 4.1 Radio frequency spectra

Band Name (Frequency)	Abbr.	ITU Band	Frequency	Wave Length	Typical Uses
Extremely Low	ELF	1	3-30Hz	100,000km-10,000km	Submarine Communications
Super Low	SLF	2	30-300Hz	10000 - 1000km	Submarine Communications
Ultra Low	ULF	3	300-3000Hz	1000 -100km	Comm. in mines
Very Low	VLF	4	3-30kHz	100-10km	Heart Monitors
Low	LF	5	30-300kHz	10km-1km	AM Broadcast
Medium	MF	6	300-3000kHz	1km-100m	AM Broadcast
High	HF	7	3-30MHz	100m -10m	Amateur Radio
Very High	VHF	8	30-300MHz	10m-1m	TV Broadcast
Ultra High	UHF	9	300-3000MHz	1m-100mm	TV, phones, air to air comm. 2-way radios
Super High	SHF	10	3-30GHz *	100-10mm	Radars, LAN *
Extremely High	EHF	11	30-300GHz *	10mm-1mm	Astronomy *

* Note that these are microwave frequencies and are also used in domestic devices

The radio range in terms of effective LOS available between the air vehicle and the GCS can be calculated by simple geometry which is derived in Figure 4.1, and results in the following expression:

$$\text{LOS Range} = \sqrt{(2 \times (\text{EER}) \times H_1) + H_1^2} + \sqrt{(2 \times (\text{EER}) \times H_2) + H_2^2}$$

where H_1 and H_2 represent the heights of the radio antenna and air vehicle respectively. For the higher, microwave, frequencies the EER is the true earth radius of about 6400 km, while for the lower, radio, frequencies a value EER of 8500 km is appropriate.

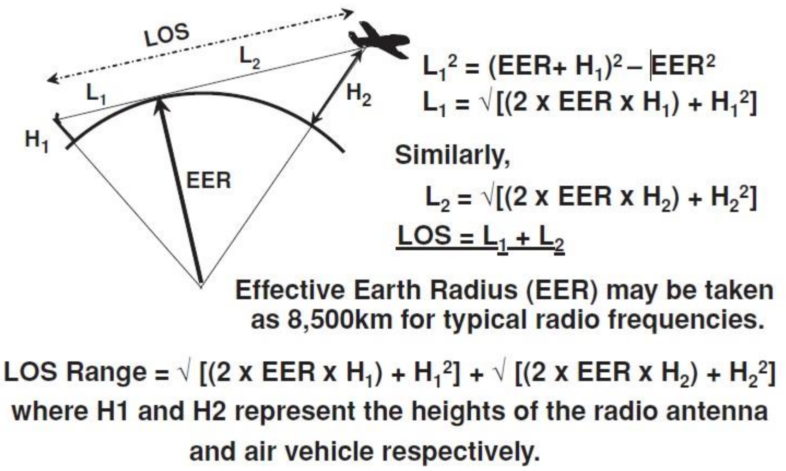


Figure 4.1: Radio LOS derivation

The results are shown in Figure 4.2 for a UAV operating at relatively low altitudes (up to 1000 m) and using radio frequencies. It may be seen, for example, that using a ground-vehicle-mounted transmitting antenna of

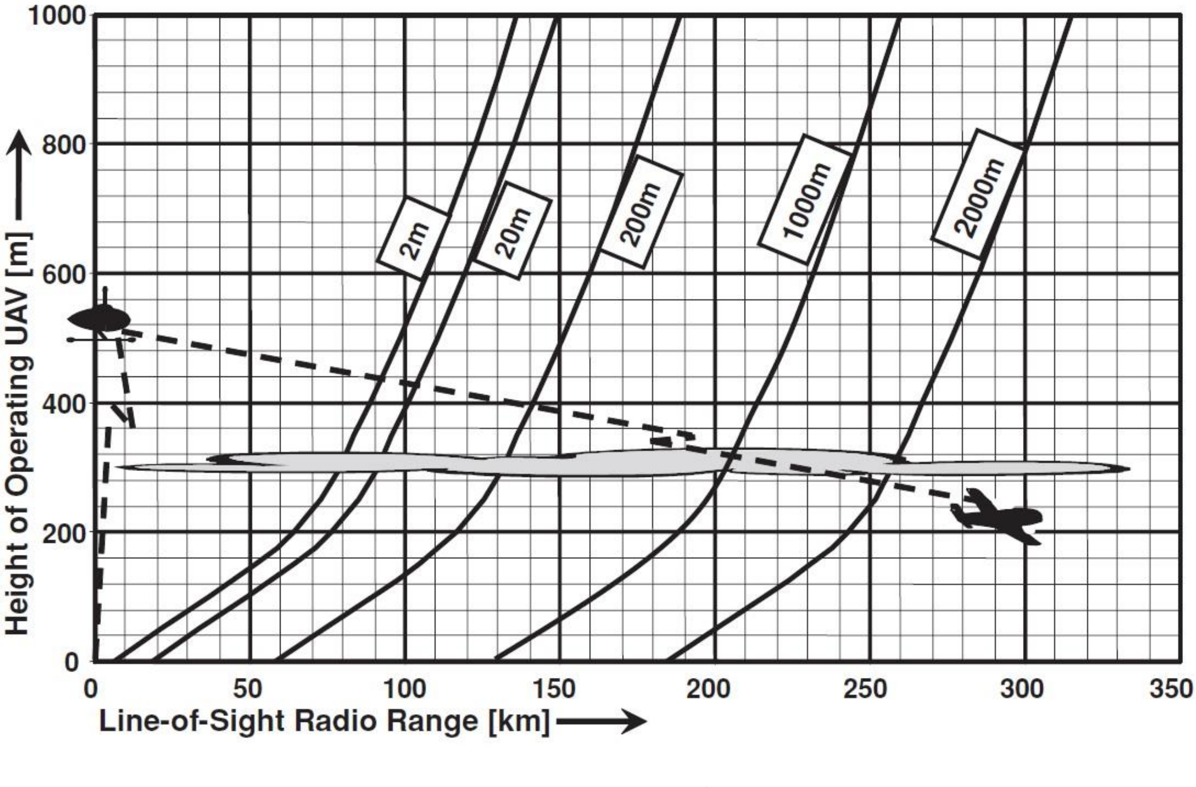


Figure 4.2: Radio line-of-sight

typical height (say 2–4 m) and even with the UAV at 1000 m, the communication range will be little more than 130 km. To achieve a greater range (say 600 km), calculation will show that the aircraft would have to fly at a height greater than 20000 m. For longer ranges, therefore, it is necessary to use an earth satellite or another UAV to act as a relay station. There may often be clouds at, say, 300 m height and, in order to operate electro-optical cameras the air vehicle must remain below the cloud. In that case, the effective radio range will be little more than 50 km, even over level terrain. So for even short/medium range operations a means of relay may have to be employed.

4.2.2 Radio Frequency Band Designations

There are at least three systems in use to designate frequency bands (Table 4.1 and see Table 4.2):

a) The International Telecommunication Union (ITU) designations, shown in Table 4.1, cover the wide spectrum from extremely low frequencies from 3Hz up to the microwave bands.

b) The Institute of Electrical and Electronics Engineering (IEEE) designations were the original band ranges developed in World War 2, but do not cover the lower radio ranges below HF.

c) The NATO and EU Designations are the more recent series, but do not cover the VHF and HF radio frequencies; (b) and (c) are shown in Figure 4.3.

Reference to bands is made when it is not necessary to refer to a specific frequency or it is inadvisable for security reasons.

4.2.3 Radio/Microwave Frequency Allocation

The international forum for worldwide agreement on the use of the radio spectrum and satellite orbits is the World Radio communication Conference (WRC). It is organised every two or three years by the International Telecommunication Union (ITU) of the United Nations Organization. The conference seeks to make the most efficient use of the radio spectrum and to regulate access to it internationally, taking account of emerging radio communication needs arising from technological, economic, industrial and other developments.

Figure 4.2 Radio frequency band designation

IEEE		EU, NATO, US ECM.	
BAND	FREQUENCY RANGE	BAND	FREQUENCY RANGE
HF	3 to 30MHz	A	0 to 0.25GHz
VHF	30 to 3MHz	B	0.25 to 0.5GHZ
UHF	0.3 to 1.0GHz	C	0.5 to 1.0GHz
L	1 to 2GHz	D	1 to 2GHz
S	2 to 4GHz	E	2 to 3GHz
C	4 to 8GHz	F	3 to 4GHz
X	8 to 12GHz	G	4 to 6GHz
K_U	12 to 18GHz	H	6 to 8GHz
K	18 to 26GHz	I	8 to 10GHz
K_A	26 to 40GHz	J	10 to 20GHz
V	40 to 75GHz	K	20 to 40GHz
W	75 to 111GHz	L	40 to 60GHz
		M	60 to 100GHz

With increasing demand for access to the radio spectrum for commercial, scientific development and other purposes, the conference is attended by telecommunication providers, TV and radio broadcasting and equipment industries. It is equally attended by the military, as defence capabilities are largely dependent on the provision of sufficient frequencies. Well in advance of each conference, consultations in the Frequency Management Sub-committee allow NATO member states to adopt common positions on each agenda item affecting the military, in order to protect Alliance interests in the use of the radio spectrum for military purposes.

NATO contributed to drafting the European Union’s Radio Spectrum Policy with a view to maintaining a balance between commercial frequency demands and military spectrum requirements. Regional coordination of the radio spectrum in Europe is carried out by the European Conference of Postal and Telecommunications Administrations (CEPT). The coordinating body covering the United States and Canada is the Inter-American Telecommunications Commission.

Frequency managers based at NATO headquarters are actively involved in the work of the European Radio communications Committee (ERC) of the CEPT and provide advice on NATO’s interests in the military use of radio frequencies. Since the Communications Act of 2003, the coordinating body within the UK is the Office of Communications (OFCOM). Although the allocation of the use of frequencies for civilian or military communication purposes is made by the appropriate authority (or authorities) in different countries and attempts are being made to coordinate the allocation worldwide, the allocation for the same specific purpose may yet be different in different countries. This can pose a problem for exporters of UAV systems and it is a wise design initiative to configure the communications system in the aircraft and control station to be modular so that frequency changes for export are facilitated.

The testing of an export system in the field in the manufacturer’s homeland, using the export frequencies, may not be possible. Hence early consultation with the local regulator, e.g OFCOM in the UK, is advised.

4.2.4. Radio Range Limited by Power

Having established the radio range, as limited by LOS, and available frequencies for the UAV system, the successful operation of the UAV communication system will depend upon the integration of the various components of the system to supply adequate RF energy to achieve the required range. For this, the system designer will take into account the following factors:

1) Transmitter power output and receiver sensitivity.
Line losses – a loss of power will result from the escape of energy through imperfect shielding of the coaxial cables and imperfect line-couplers as the RF energy is sent to and from the antennae. Minimising the distance between the antenna and transmitter and receiver is advisable.

2) Antenna gain – antennae can be constructed to focus the RF energy in a specific plane or pattern to produce an effective gain in a particular direction, thus maximising the range obtained with a given power output. Depending upon the application, an omnidirectional or a unidirectional, antenna, such as a Yagi or a narrow beam parabolic dish antenna may be appropriate. Antenna design is a very specialist technology, and antennae are best acquired from
specialist companies following detailed discussion of the system requirements and options.

3) Path loss – this is the loss of power that occurs to the signal as it propagates through free space from the transmitter to the receiver. The calculation of the path loss must take into account: the distance that the radio wave travels; the operating frequency since the higher frequencies suffer a greater loss than the lower frequencies; and the height of the transmitting and receiving antennae if either is close to the ground.

4.2.5 Multi-path Propagation

Another problem that may occur is known as 'multi-path propagation' whereby two signals displaced in time by microseconds are received at the image display, causing blurring of the image. This may occur, for example, if the transmission is reflected off nearby obstacles. Either very narrow beam transmission or very sophisticated processing is needed to overcome this problem.

4.2.6 Radio Tracking

One of several means of navigating a UAV is by tracking it by radio. This requires the UAV to be fitted with a transponder which will receive, amplify and return a signal from the control or tracking station or to have the UAV down-link transmit a suitable pulsed signal.
The control station transmit/receive antennae would, in fact, consist of two parallel-mounted off-set directional antennae. A signal processing system then detects whether the signals received by the two antennae are in or out of phase, and command the rotation of the antenna system to bring their signals into phase.

At that point, the antenna system would be pointing directly to the UAV and the UAV azimuth bearing relative to the Control Station (CS) would be known. Depending upon the transmitted beam width in elevation, it may be necessary to have a similar arrangement to ensure continuation of contact in elevation also, though there are other means of maintaining direction in elevation if, for example, the altitude of the UAV is known. The inclined distance of the UAV from the CS is obtained by timing the pulse travelling between the two.

4.2.7 Loss of Communication Link between Control Station and UAV

The antenna systems of both the CS and the UAV may be capable of scanning in azimuth and/or elevation as appropriate. Thus, following loss of link, and depending upon the transmitted beam-width of each, one would scan for the other, both knowing the last recorded position of the other. In the event that contact was not resumed after a given programmed time, the UAV may be programmed to return to base and, if necessary, recovered using a stand-by short-distance omnidirectional VHF link, especially if the loss was due to failure of the CS primary transmission. This aspect is again a specialist area where appropriate organisations would be involved.

4.2.8 Vulnerability

There are two ways in which a UAV system may be vulnerable. One is that an enemy detection of the signal from either UAV or CS will warn that enemy of the presence of the system. At the least this will eliminate the element of surprise and alert the enemy to the possibility of an impending attack. It may also lead to countermeasures and the destruction of the UAV and/or the CS. The other is that radio transmission between the CS and the UAV may be subject to inadvertent or intentional jamming of the signal.

The risk of the former may be reduced by the use of very narrow beam transmissions and/or the use of automatic or autonomous systems whereby the transmission is only used in occasional short bursts of radio communication.

Signals beamed downwards are at more risk than those beamed upwards unless a sophisticated airborne detection system patrols over the area. This is unlikely unless the confrontation is with a very sophisticated enemy and then the airborne patrol would be extremely vulnerable to countermeasures. Signals beamed down from relay aircraft or from satellites would be more open to detection. The latter risk may be reduced by three types of anti-jam (AJ) measures:

a) high transmitter power,
b) antenna gain/narrow beam-width,
c) processor gain.

(a) Using high power transmission to out-power a dedicated jammer system in a contest is not very practical, especially for the UAV down-link which will be limited by weight, size and electrical power available.

(b) For higher frequency, LOS links, the available transmitter power can be concentrated into a narrow beam using a suitable antenna. This requires the antennae on both CS and UAV to be steerable for the beam to be maintained directed at the receiver. A high gain obtained through use of very narrow beams will require the CS and UAV to know the position of each other very accurately in three dimensions. It will also need the beams to be held in position with great stability. This can be assisted by the receivers of both UAV and control station seeking the maximum RF power to be found on the centre-line of the received beam by appropriately steering the antennae. However, a compromise must usually be accepted with beams having a width within which connectivity can be assured. The beam width from the UAV will usually be wider than that from the CS as the size of antenna which may, in practice, be carried on the UAV will be smaller than that available at the CS.

Lower-frequency, omnidirectional and long-range non-LOS links are at a much greater risk of jamming since there are ample paths for the jammer power to be inserted. Such links must rely on the third type of AJ measures. These measures include frequency hopping of the communication links so that the transmission frequency is randomly changed at short intervals, thus making signals difficult to intercept or to jam.

An alternative is to adopt ‘band jumping’, where the transmission moves from one band to another, say UHF to S band, at short intervals or when interception or jamming is detected. This, however, requires two parallel radio systems with individual antennae. Such a system was used with great advantage by the Sprite UAV system which enabled the UAV to fly through transmissions such as ship’s radars and missile guidance systems without inadvertent interference.

A further technique is the use of a so-called spread-spectrum system, where the signal is spread over a small range of frequencies with ‘noise’ signals interposed. The receiver is aware of the distribution codes of the noise and is able to extract the genuine signal from it. Not knowing the codes, an intercepting enemy would not be able to decipher the signal.

4.2.9 Multi-agent Communication and Interoperability

So far we have considered only one-to-one communication, i.e. that between one CS and one UAV, which is sometimes known as ‘stove-pipe’ operation. Whilst this situation may often occur, other agents are likely to be involved, with information being sent to and received by one another to mutual advantage. This arrangement will often be the case for military operation and also may be the situation for some civilian applications. This latter may apply, for example, to policing where a larger area has to be covered than is possible with one UAV and with the information needed at different positions. Such operations may employ a number of interoperable systems, as illustrated in Figure 4.3, and give rise to the term ‘system of systems’ (SoS).

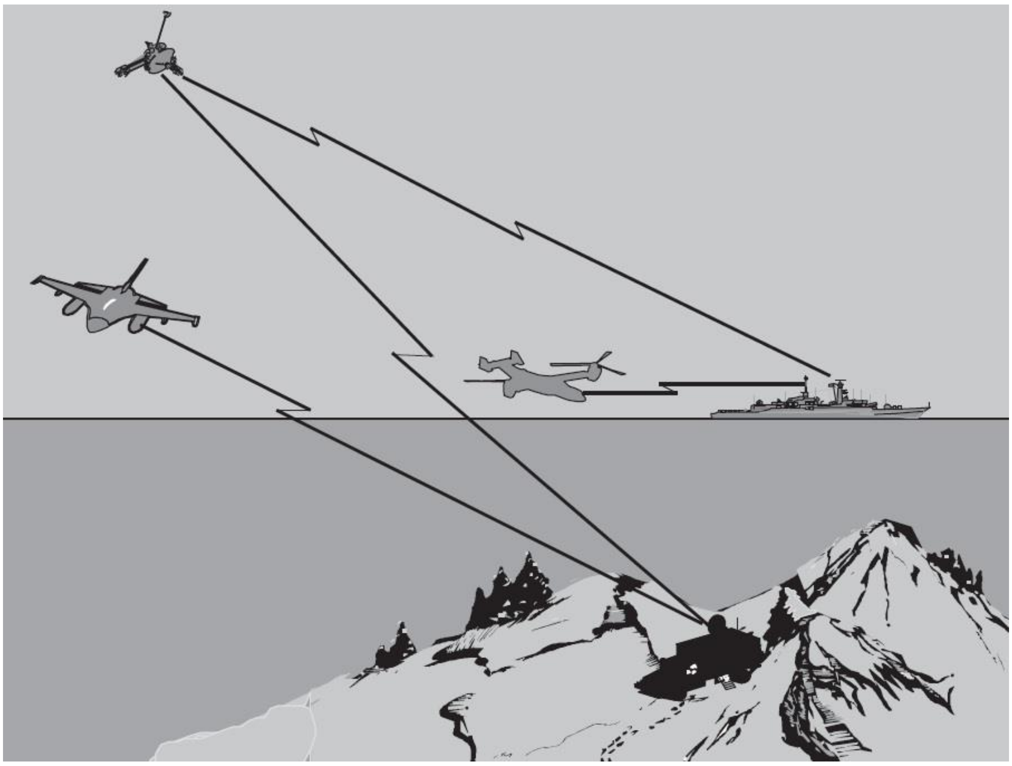


Figure 4.4: Interoperable systems

For such SoS and even more so with network-centric systems, it is vital that the several diverse systems are interoperable. Previously systems' integrators have relied upon adopting proprietary telemetry and sensor data streams which resulted in the inability of systems to interoperate with each other.

NATO recognised the need to ensure interoperability between the forces of its member nations and recommended that a UAV control station Standardisation Agreement (STANAG) be set up to achieve this. The outcome was NATO STANAG 4586, 'UAS Control System Architecture', which document was developed as an interface control definition (ICD). This defines a number of common data elements for two primary system interfaces.

These are the command and control interface (CCI) between the UAS control station (UCS) and the other systems within the network, and the data-link interface (DLI) between the UCS and the UAV(s). STANAG 4586 defines five levels of interoperability between UAS of different origins within NATO. These vary from 100% interoperability whereby one nation's UCS can fully control another's UAV including its payload, down to being limited merely to the receipt of another's payload data. STANAG 4586 also refers to other STANAG such as 4545 covering imagery formats, 4575 – data storage, etc. STANAG 4586 is now substantially accepted in the UAS industry and is often called up as a requirement for UAS defence contracts. It is also available for commercial contracts.

4.3 Mid-air Collision (MAC) Avoidance

Another issue which is, in effect, a communications issue is the avoidance of mid-air collisions between UAV and other aircraft in the event that UAV are allowed to operate in unrestricted airspace. Manned aircraft currently operating are required to carry an avionic system known as the Traffic Alert and Collision Avoidance System (TCAS) if the gross mass of the aircraft exceeds 5700 kg or it is authorized to carry more than 19 passengers.

4.4 Communications Data Rate and Bandwidth Usage

As also noted in Chapters 5 and 8, there is concern that military UAS are currently consuming large amounts of communication bandwidth. If the hopes of introducing more civilian systems into operation are to be realised, then the situation may be exacerbated.

There is a need for the technology, such as bandwidth compression techniques, urgently to be developed to reduce the bandwidth required by UAS communication systems. Much of the work on autonomy for UAV is also driven by the need to reduce the time-critical dependency of communications and the bandwidth needed.

A high-resolution TV camera or infrared imager will produce a data rate of order 75 megabytes per second. It is believed that with its several sensor systems, including the high-definition imaging sensors required to view potential targets from very high altitudes, a Global Hawk HALE UAS uses up to 500 megabytes per second. The bandwidth required to accommodate this with, for example, anti-jam methods such as spread-spectrum techniques added, will be excessive.

Although shorter-range UAV operating at lower altitudes do not use such a huge amount of bandwidth, there is growing danger that radio interference between systems will limit the number of UAS operable in one theatre. It is therefore desirable that as much data processing as possible is carried out within the UAV and, with bandwidth compression, UAS bandwidth usage can be reduced to an acceptable level.

Fortunately, developments in electronic technologies make this possible. For further background to the regulation of radio communication. To ensure safety from inadvertent interference, there is an urgent need for a dedicated communications band for civilian UAS. Most UAS communications currently operate mostly within the L to C bands along with other users, but UAS air traffic integration working groups such as the EUROCAE WG-73 and the RTCA SC-203 are cooperating in preparing a case for a dedicated bandwidth allocation for civilian UAS.

4.5 Antenna Types

Antennae of the same configuration are used both to transmit and to receive RF signals. Unless an omnidirectional antenna is used at the UAV, it will be necessary to mount the antenna(e) in a rotatable turret in order for LOS to be maintained between CS and UAV for all manoeuvres of the UAV. In some cases it may be necessary to install the antenna(e) in more than one position on the UAV.

The most usual types of antennae to be adopted for UAS are:

a) the quarter-wave vertical antenna,
b) the Yagi (or to give it the correct name,Yagi-Uda) antenna,
c) the parabolic dish antenna,
d) and less commonly, the lens antenna and the phased array rectangular microstrip or patch antenna.

These are illustrated in Figure 4.4. However, as previously noted, antenna design is a highly specialised, complex technology and the following must be seen by the reader as an over-simplified elementary introduction.

(a) The quarter-wavelength antenna erected vertically is vertically polarised and requires a receiving antenna to be similarly polarised or a significant loss of signal strength will result. This type of antenna is omnidirectional; that is it radiates at equal strength in all directions. Because of this, the received power rapidly reduces with distance. This type of antenna is used in RC model aircraft systems where the aircraft is always within sight of the operator. Their use in UAS will generally be limited to local launch and recovery operations where there is little risk of enemy jamming, and they have the advantage of not requiring the CS and UAV antennae to be rapidly steered to maintain contact in close-proximity manoeuvres. The down-side is that additional equipment, though small and light, must be added to both UAV and CS.

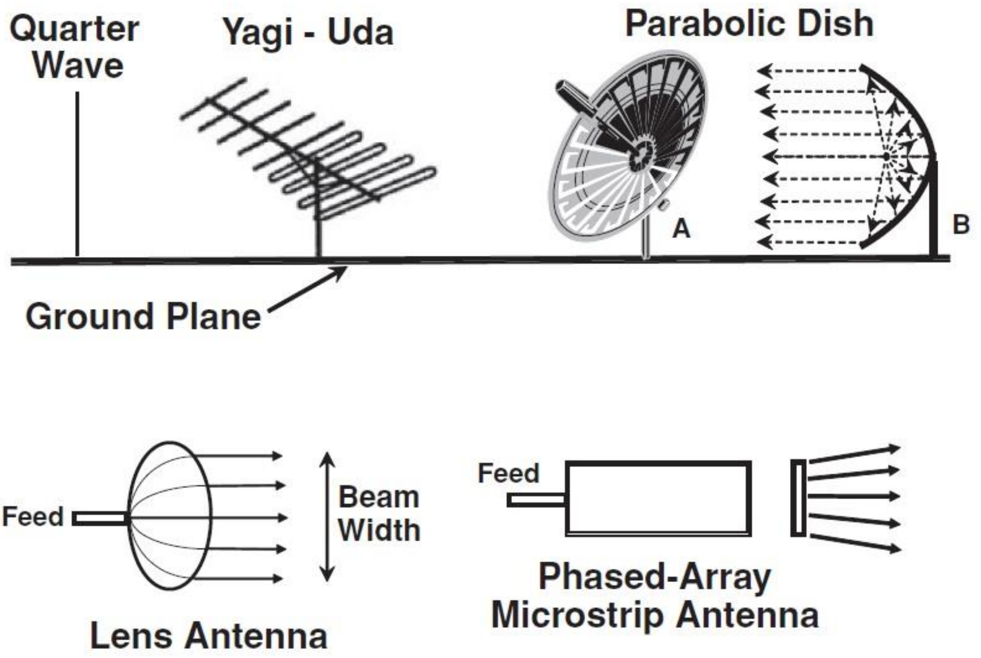
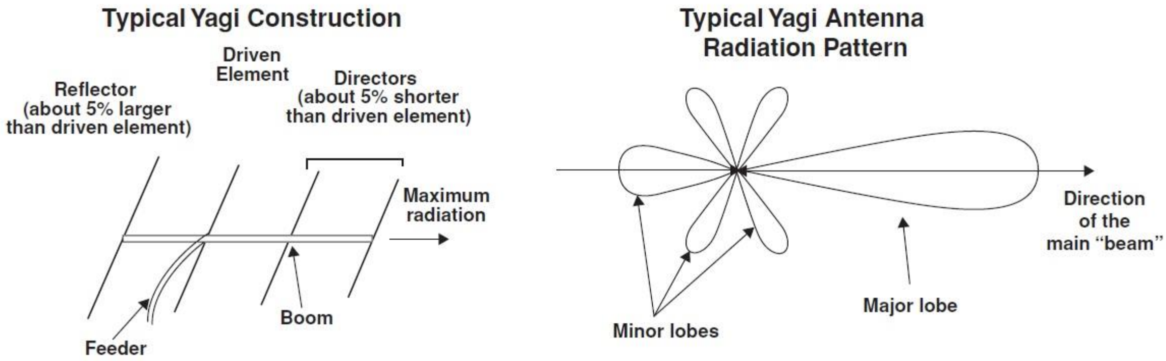


Figure 4.4: Applicable antenna types

(b) The Yagi-Uda antenna contains only one active dipole element backed up by a number of passive, reflector elements which modify the basic radiation pattern to a predominantly directional beam with, however, small side-lobe radiations. The side-lobes of antennae are the easiest route for jamming RF to enter the system. Therefore, for UAS use, particularly, the antenna designer must apply his knowledge of arranging antenna elements to minimise the size of the side-lobes. The Yagi type of antenna is the type usually seen on rooftops for receiving TV signals as it is operable generally in the frequency range of from about 500 MHz to 2 Ghz. A typical Yagi antenna construction and its radiation pattern are shown in Figure 4.5.



Variation of Parabolic Antenna Beamwidth with Radio Frequency and Antenna Diameter.

Diameter

Frequency	0.3 m	0.6 m	1.2 m	1.8 m	2.4 m	3 m	3.7 m	4.5 m
2 GHz	35	17.5	8.75	5.83	4.38	3.5	2.84	2.33
6 GHz	11.67	5.83	2.92	1.94	1.46	1.17	0.95	0.78
8 GHz	8.75	4.38	2.19	1.46	1	0.88	0.71	0.58
11 GHz	6.36	3.18	1.59	1	0.8	0.64	0.52	0.42
14 GHz	5	2.5	1.25	0.83	0.63	0.5	0.41	0.33
18 GHz	3.89	1.94	0.97	0.65	0.49	0.39	0.32	0.26
23 GHz	3	1.52	0.76	0.51	0.38	0.3	0.25	0.2
38 GHz	1.84	0.92	0.46	0.31	0.23	0.18	0.15	0.12

Figure 4.5: Antenna characteristics

(c) Parabolic dish antennae, as the name implies, are so formed, and as a pure parabola, would reflect power from a point source emitter out as a beam, as shown in diagram B in Figure 4.5. By changing the disc diameter, for a given radio frequency, beams of various widths may be generated as listed in Figure 9.7. This type of antenna is practical only for microwave frequencies in UAS usage. For lower frequencies, the dish diameter becomes unacceptably large, especially for mounting in a UAV turret.

(d) The lens antenna works similarly to an optical lens in focusing RF waves instead of light waves. It uses dielectric material instead of glass and is appropriate for use with microwave frequencies. Beam shaping is achieved by asymmetric forming of the lens. The dielectric material is expensive and/or heavy and developments are continuing to reduce both of these factors for UAV application. Patch antennae use a patch (or patches) which are a little less than a half-wavelength long, mounted over a ground plane with a constant separation of order 1 cm, depending upon the frequency and bandwidth required. The patch is generally formed upon a dielectric substrate using lithographic printing methods similar to that used for printed circuit boards. With these techniques it is easy to create complex arrays of patch antennae producing high gain and customised beams at light weight and low cost. A square patch will produce an antenna with equal beam width in vertical and horizontal directions whilst beams of different width in the two planes will result from rectangular patches.

4.6 NAVSTAR Global Positioning System (GPS)

GPS was developed by the United States’ Department of Defence and officially named NAVSTAR GPS. It was initially limited to use by US military forces until 1982 when it was made available for general use. A receiver calculates its position using the signals transmitted from four or more GPS satellites selected from a constellation of 24 (nominal) satellites. The satellites orbit the Earth at an altitude of approximately 20 000 km and the satellites used for the measurements are selected by the GPS receiver on the basis of signal quality and good fix geometry.

Each satellite has an atomic clock and continually transmits its radio signals. The signals which contain the time at the start of the signal, travel at a known speed (that of light). The receiver uses the arrival time to calculate its range from each satellite and so its position on Earth. Radio frequencies used by the GPS lie within the L Band, from about 1.1 GHz to about 1.6G Hz.

GPS is available as two services, the Standard Positioning System (SPS) for civilian users and the Precise Positioning Service (PPS) for military users. Both signals are transmitted from all satellites. The SPS uses signals at GPS L1 frequency with an unencrypted coarse acquisition (C/A) code. It is understood that this will in future be supplemented by an additional L2 service. SPS gives a horizontal position accuracy in the order of 10 m.

The PPS (also known as P code) uses both GPS L1 and L2 frequencies in order to establish a position fix. These signals are modulated using encrypted codes (into Y code). The Y code will be supplemented by a new military (M) code currently in development. The military receivers are able to decript the Y code and generate ranges and hence position. The PPS horizontal position accuracy is of the order of 3 m. The accuracy of GPS position fixes varies with the receiver’s position and the satellite geometry.
Height is available from GPS, but to a lower accuracy.

The accuracy of both GPS services may be improved by use of Differential GPS (DGPS). This provides an enhancement to GPS using a network of fixed, ground-based, reference stations that broadcast the difference between the positions indicated by the satellites and their known fixed positions. These differences are then used by each receiver to correct the errors manifest in the raw satellite data.

The accuracy of DGPS reduces with the distance of the receiver from the reference station and some measurements of this indicate a degradation of about 0.2 m per 100 km. A UAV system may use the available network of reference stations or use its own ground control station as a reference station. This latter may be less appropriate for air- or ship-based control stations.

Although the US-provided GPS is the most extensive system currently operating, other systems are emerging. Such other similar systems include the European Galileo system and the Russian GLONASS with the proposed Chinese COMPASS and Indian IRNSS systems.

The availability of GPS has permitted UAV operation to be vastly extended in range compared with their capability of 25 years ago, enabling MALE and HALE systems, in particular, to be operated. There is continuing concern, however, that in the event of hostilities, GPS signals may be jammed. GPS signals at the receivers tend to be rather weak and therefore relatively easy to jam by natural emissions such as geomagnetic storms and by unintentional or intended radio emissions. It is therefore possible for unsophisticated enemies to jam GPS signals with a closer, stronger signal. In the, hopefully unlikely, event of hostilities with a sophisticated opponent, the satellites, themselves, could be destroyed, but it is more likely that they would wish to maintain the benefits of being able to use the system themselves.

GPS is basically a ‘fixing’ system, in that the measurements provide a sequence of discrete positions or ‘fixes’. It is normal to integrate the GPS with a dead reckoning (DR) system. DR systems work on the basis you know where you are at the start of the mission and you then use time, speed and direction

measurements to calculate your current position. The process of dead reckoning is probably the oldest form of air navigation (clock, airspeed and compass) but it has the disadvantage that position errors will grow with time due to inaccuracies in the measurement of the basic parameters.
GPS on the other hand provides a series of largely independent position measurements with some position error (noise) however it is not continuous and in some circumstances can have local errors. For example in urban areas the satellite signals can be subject to obscuration or reflection from structures which give GPS ‘multipath errors’ (erroneous range measurement). Also, as stated above, GPS can be subject to local radio frequency interference or deliberate jamming. Prudent GPS integration therefore combines GPS with a dead reckoning system to provide an element of smoothing to the raw GPS and a means of providing a continuing navigation capability in the event of GPS signal loss. This combination is normally undertaken in a mathematical filter such as a Kalman filter which not only mixes the signals, but provides an element of modelling of the individual sensor errors. The modelling enables the filter to give improved navigation during periods of GPS signal loss/degradation.

Numerous techniques continue to be proposed to reduce dependence on GPS, and users should consider a fall-back plan in the event of GPS loss. It is believed that some military operators currently retain, as a fall-back, systems which were in use before they were replaced by GPS. These systems are principally TACAN, LORAN C or inertial navigation. Each has disadvantages compared with GPS.

4.6.1 TACAN

Like LORAN C and GPS, TACAN relies upon timed radio signals from fixed ground-based transmitters to enable position fixing. The fix is based on range measurement from multiple transmitters or range and bearing from the same transmitter. The signals, being terrestrially based, are stronger than GPS signals and can still be jammed, although not as easily. For military operations, a major disadvantage of TACAN was that emissions could not be controlled to achieve stealth, and an enemy could track an aircraft equipped with the system.

4.6.2 LORAN C

This long-range radio system based on ground transmitters uses even stronger signals than TACAN and is less easy to jam though it does suffer serious interference from magnetic storms. Although funding is limited, enhanced development of LORAN, known as E-LORAN, is continuing as it is seen as a fall-back to the perceived vulnerability of GPS. It is principally used in marine service. For military UAV application, its major drawback is its very limited availability. It is available principally in the populated areas of Europe and in North America and not in the areas of likely world trouble-spots. It is virtually nonexistent in the southern hemisphere.

4.7 Inertial Navigation

An inertial navigation system (INS) does not rely on external inputs. It is a sophisticated dead reckoning system comprising motion sensing devices such as gyroscopes and accelerometers and a computer which interrogates the data from them and performs appropriate integration to determine the movements of the aircraft from a starting set of coordinates to calculate the aircraft position at any subsequent time. Past systems have been based on platforms gimballed within the aircraft to remain horizontal as determined by pendulums and attitude gyroscopes. The main disadvantage with them has been their need for many expensive precision-made mechanical moving parts which wear and create friction. The friction causes lag in the system and loss of accuracy. The current trend is to use what are termed ‘strapped down’ systems.

The term refers to the fact that the sensors (accelerometers and rate gyros) operating along and around the three orthogonal aircraft body axes, are fixed in the body of the aircraft.

Lightweight digital computers are able to interrogate these instruments thousands of times per second to determine the displacement and rates of displacement of the aircraft at each millisecond during the flight and to compute the attitude, velocity and position changes. The sensors are usually solid-state and the accuracy of the overall system depends upon the accuracy of the individual sensors. Greater accuracy is obtained at greater cost but, inevitably, 'drift' away from the actual spatial position occurs with time.

Problems of accuracy therefore are more critical for long-endurance operations with HALE and MALE systems unless some form of update is possible during the flight. As stated above it is increasingly common for long-range/endurance systems to integrate the INS with GPS.

Heading updating is possible, of course, using magnetometers which point to magnetic north. Height or altitude can be sensed. Developments in Doppler radar sensors provide good prospects for geo-speed measurement, although their use would have to be limited if the aircraft was to remain covert. A problem remains in sensing pitch and roll angles adequate for accurate navigation in the absence of IN and GPS, however pitch and roll accuracy sufficient for flight control is available. Developments which sense the horizon may come to fruition for operations at high altitudes where a horizon is distinct.

4.8 Radio Tracking

This is a well-established and ready solution for aircraft operating at shorter ranges, of the order of 80–100 km. It is particularly applicable to over-the-hill battlefield surveillance and ground attack operations or shorter-range naval operations such as over-the-beach surveillance missions where a line-of-sight radio contact can be maintained between the ground/sea control station and the aircraft.

The narrow-beam up and down data-links carry timed signals which are interpreted by both control station and aircraft computers giving their distance apart. Parallel receiving antennae at the control station (CS) enable it to lock onto the aircraft in azimuth and transmit that information to the aircraft. In the event of loss of radio link, the aircraft and CS will be programmed to scan for the signal in order to re-engage. The aircraft will also carry a simplified INS in order for it to be able to return to the neighbourhood of the CS should there be a failure to re-engage. At the estimated arrival time, two options for recovery are available. Either an automatic landing program is brought into operation or a low-frequency omnidirectional radio system activated to re-establish contact and control the aircraft to a safe landing.

4.9 Way-point Navigation

Using any of the above technologies to ascertain its position, the UAV controller may direct the UAV to any point within its range by one or more of three methods.

a) Direct control, manually operating panel mounted controls to send instructions in real time to the UAV FCS to operate the aircraft controls to direct its flight speed, altitude and direction whilst viewing its progress from an image obtained from the UAV electro-optic payload and relating that as necessary to a geographical map.

b) Input instructions to the UAVFCS to command the UAVto fly on a selected bearing at a selected speed and altitude until fresh instructions are sent. The position of the UAV will be displayed automatically on a plan position indicator (PPI).

c) Input the coordinates of way-points to be visited. The way-points can be provided either before or after take-off.

Methods (b) and (c) allow for periods of radio silence and reduce the concentration necessary of the controller. It is possible that, depending upon the mission, the controller may have to revert to method (a) to carry out a local task. However, with modern advanced navigation capability and the introduction of 'autonomous' technology within the systems the trend is strongly towards pre-planning missions or in-flight updating of flight plans so that the operators are more focused on capturing and interpreting the information being gathered by the UAV than managing its flight path. Future systems with increased use of autonomy are likely to be based on the operators 'tasking' the UAV to achieve aspects of a mission with the UAV system generating the routes and search patterns.

UNIT – V

CONTROL AND STABILITY

CO No	Course Outcomes After successful completion of the course, students will be able to:
CO10	**Categorize** the different techniques used to achieve the control and stability of UAV systems.

Program Outcomes (POs)	
PO1	**Engineering knowledge**: Apply the knowledge of mathematics, science, engineering fundamentals, and an engineering specialization to the solution of complex engineering problems.
PO2	**Problem analysis**: Identify, formulate, review research literature, and analyze complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences, and engineering sciences

The functions of the control and stability of a UAV will depend in nature on the different aircraft configurations and the characteristics required of them. 'Control' may be defined for our purposes as the means of directing the aircraft into the required position, orientation and velocity, whilst 'stability' is the ability of the system to maintain the aircraft in those states. Control and stability are inexorably linked within the system, but it is necessary to understand the difference.

The overall system may be considered for convenience in two parts:

i) The thinking part of the system which accepts the commands from the operator (in short-term or long-term), compares the orientation, etc. of the aircraft with what is commanded, and instructs the other part of the system to make appropriate correction. This is often referred to as the automatic flight control system (AFCS) or FCS logic, and contains the memory to store mission and localized flight programs

ii) The 'muscles' of the system which accept the instructions of (i) and apply input to the engine(s) controls and / or aerodynamic control surfaces.

Another distinction which must be made is whether the aircraft orientation, etc. is to be maintained relative to the air mass in which the aircraft is flying or relative to space coordinates.

5.1 HTOL Aircraft

For a HTOL aircraft the flight variables are basically:

a) direction,

b) horizontal speed,

c) altitude,

d) rate of climb.

The direction of flight (or heading) will be controlled by a combination of deflection of the rudder(s) and ailerons. The horizontal speed will be controlled by adjustment to the propulsor thrust and elevator deflection, the rate of climb to a given altitude is achieved by the application of a combination of elevator deflection and propulsor thrust.

The arrangement of the aerodynamic control surfaces is shown in Figure 5.1 for a typical, aerodynamically stable, HTOL aircraft configuration. Other HTOL configurations will utilize specific arrangements. For example, a ‘flying wing’ configuration will use ‘elevons’ which deflect in the same direction for pitch control and differentially for roll control.

It is somewhat simpler to maintain orientation relative to the air mass, i.e. to configure the aircraft to be ‘aerodynamically stable’. This generally requires tailplane and vertical fin areas to provide ‘weathercock’ stability in both pitch and yaw and requires wing dihedral in fixed-wing aircraft to provide coupling between side-slip and roll motion to give stability in the roll sense. The downside of this is that the aircraft will move with the air mass, i.e. respond to gusts (air turbulence). This movement usually includes linear translations and angular rotations relative to the earth. This will make for greater difficulty in maintaining, for example, a camera sight-line on a ground fixed target.

The alternative is to design the aircraft to be aerodynamically neutrally stable with, in particular, little or no rotation generated by the fixed aerodynamic surfaces in response to gusts. The response now becomes one mainly of translation, so reducing the angular stabilization requirements for the sensors.

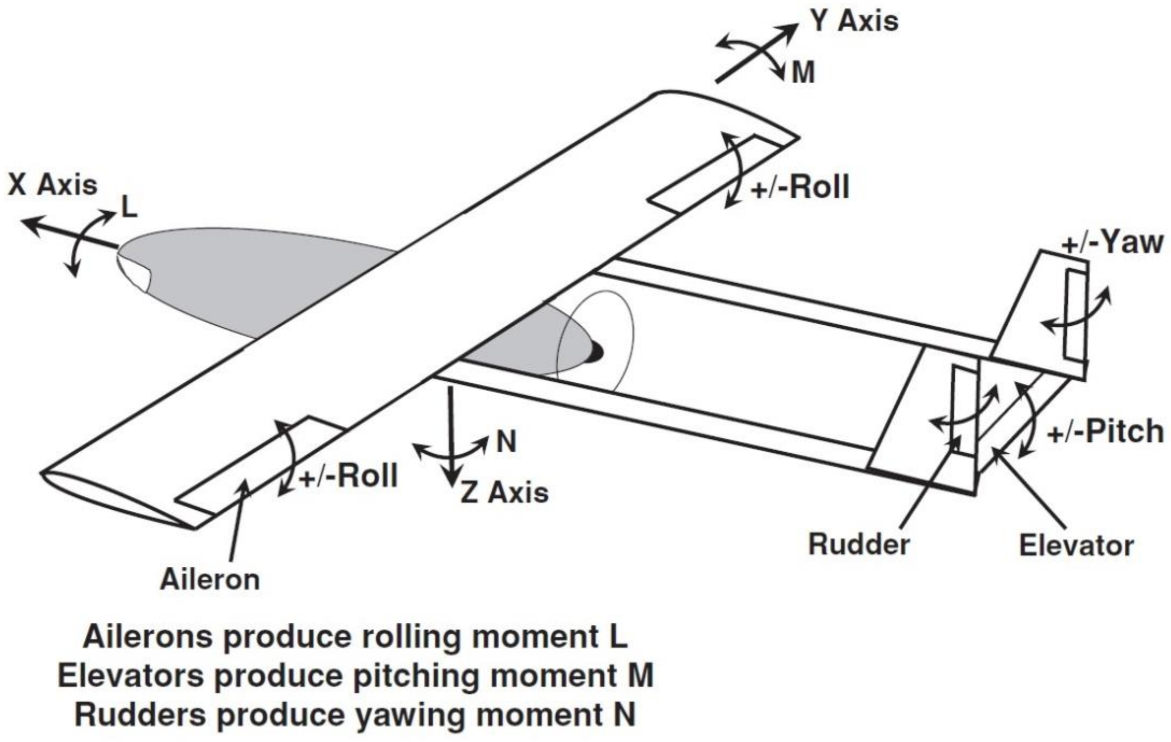


Figure 5.1: HTOL aircraft aerodynamic control surfaces

The movable control surfaces are used to steer and stabilise the aircraft in the normal manner relative to spatial coordinates. Thus the latter configuration has the advantage of providing a steadier platform for payload functions. In reality, however, it is virtually impossible to make an aircraft aerodynamically unresponsive to gusts in all modes, but it may be possible to make it unresponsive in some modes and have only little response in others.

Another advantage of the neutrally aero-stable design is that the aerodynamic tail-plane and fin surfaces, for example, when replaced by much smaller movable surfaces for control, will save the drag of the larger areas and make the aircraft more efficient in cruise flight. Passenger aircraft manufacturers are moving this way now to provide more comfort for passengers and to reduce fuel-burn and improve economy of operation.

The downside of this approach is that more sophisticated sensors and computing power is necessary in the 'brain' of the control system in order to determine the orientation of the UAV in flight and apply the correct amount of the appropriate control or combination of controls. This may increase the system first cost compared with the aerodynamically stable system, but should pay dividends in greater operational effectiveness and reduced operating costs. The control and stability systems will now be addressed according to the chosen coordinate reference (air mass or spatial).

5.1.1 HTOL Aero-stable Configuration

A typical basic flight control system (FCS) is shown in block diagram form in Figure 5.2. Before flight the mission program may be copied into the FCS computer memory. A very basic program may consist of a series of 'way-points' which the aircraft is to over-fly before returning to base, and the transit speeds between those points. It may be more complex in that a flight pattern about those points may be scheduled along with operation of the payload.

If the operators are in radio communication with the aircraft (directly or via a relay) the program commands may be overridden, for example, to carry out a more detailed 'manual' surveillance of a target. Provision also may be made to update the mission program during the aircraft flight.

For take-off and landing the aircraft may be controlled by an initial and terminal part of the program or 'manually' by using the overrides. Currently most systems employ the latter approach since making automatic allowance for the effect of cross-winds in those modes is difficult. As shown in the figure, the aircraft is maintained on condition usually by use of a nulled-error method. By this means the FCS enables the commands of the controller to be accepted and executed and the aircraft to be stabilized onto that commanded condition of speed, direction and altitude. A damping term can be added to any or all modes, for example $\delta\psi/\delta t$ in yaw, to ensure that, following a disturbance, the return to condition is rapid and without undue oscillation. Consider the three control 'channels' of Figure 5.2 as described.

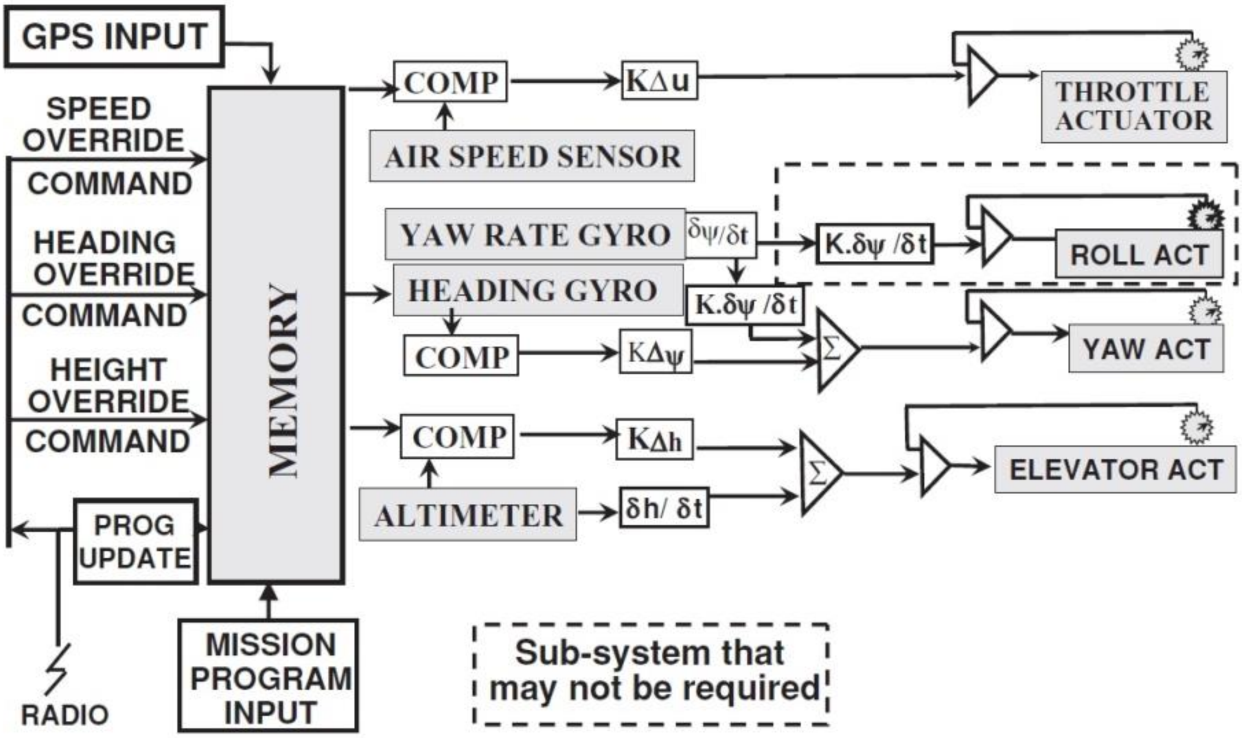


Figure 5.2: HTOL aircraft basic AFCS

5.1.1.1 The Speed Channel

The aircraft airspeed command from the memory is compared with the actual airspeed as sensed and any error between the two is obtained. A multiplier K is applied to the error signal which is passed to the throttle actuator system with its feedback loop. This makes a throttle adjustment proportional to the instantaneous error until equilibrium is achieved. Provided that the power unit response is progressive, and that the correction takes place at an airspeed above the minimum power speed of the aircraft, the motion is stable and normally will need no damping term.

5.1.1.2 The Heading Channel

A similar principle applies. The actual heading of the aircraft can be measured by a magnetometer-monitored attitude gyro and compared with the commanded heading. Any error is processed as before to operate the aircraft rudder via a yaw actuator. In this case, however, damping may be required to prevent the aircraft oscillating in yaw and, in an extreme case, diverging in that mode. The probability of oscillation occurring depends upon the actuation system and aircraft aerodynamic damping characteristics. This phenomenon is covered fully in the specialist textbooks. Should extra damping be required, it may be incorporated by the differentiation respect to time of the gyro position signal or, possibly more readily, through the inclusion of a yaw-rate gyro.

In a turn, if using rudder alone, an aircraft will tend to slip outwards unless its wing dihedral rolls it back into the turn. Most aircraft will be so designed that a coordinated turn occurs naturally. In less conventional configurations, this may not be possible and application of ailerons is required proportional to the rate of turn. A method of achieving this, if required, is also shown in Figure 5.2.

5.1.1.3 The Height or Altitude Channel

The height of an aircraft is recognised as its vertical distance above ground as measured, for example, by a radio ‘altimeter’ and is often referred to as ‘tape height’. Its altitude, also known as the ‘pressure height’ is its height above mean sea level and this is obtained by measuring the ambient air pressure outside the aircraft and comparing that with the ambient air pressure at mean sea level. Either can be used, depending upon the mission needs.

Pressure altitude is more appropriate for use when traversing long distances at greater altitudes but is relatively inaccurate for low altitude operation. It cannot respond to the presence of hilly or mountainous terrain.

Operating using tape height measurement is more appropriate for low-altitude, shorter-range operations when the aircraft will follow the contours of the landscape. It gives a far more accurate measure of height than does a pressure altimeter. Both can be employed in a FCS with the most appropriate sensor being selected for a given phase of the mission.

The same nulled-error method may be used for the height channel with a climb to commanded height being achieved by actuation of an upward deflection of the elevator(s). Entry into a climb will demand more thrust from the propulsor and the aircraft will rapidly lose speed unless the engine throttle is quickly opened. If the response of the engine to the demand of the speed control channel is not adequate then a link from the error signal of the height channel must be taken to the throttle actuator. This will increase the engine power in a timely manner to prevent undue airspeed loss. The reverse, of course, will be ensured when a demand for a descent is made.

In addition to the above, control of the rate of climb will be necessary. The rate of climb (or descent) can be obtained by differentiating the change in measured height with respect to time. A cap must be placed on the allowed rate of climb (and descent) to prevent excessive or unavailable power being demanded from the engine(s) and to prevent the aircraft exceeding its design speed limit in descent. The cap value that is necessary for protection will vary, depending upon the aircraft weight and speed at the time. For best performance it would be necessary for the cap value to be changed with those parameters. An input of speed to the equation is fairly simple, but determination of the aircraft weight at any time during a mission may be possible, but is not as easy. Therefore a compromise may have to be reached in setting the cap value.

The aircraft speed, rate of climb and engine power needed are inextricably linked. A demand for increased speed will increase the lift on the wing and may initiate a climb. The height channel may react to that and demand a deflection downwards of the elevator to prevent it. However, in similar manner to the advance link to the engine throttle from the height channel, it may be necessary to link the elevator to the error signal from the speed channel to prevent the development of any large height excursion.

Thus, the development of even a relatively simple FCS is no mean task and will require careful study and simulation before commitment to prototype build. The logic within the system will, today, be digital and software based. Until recently, the aircraft developers had to develop their own FCS systems but, with the expansion of the industry, companies specializing in FCS design and development have arisen. These organisations are now available to work with the aircraft developers in the creation of applicable FCS.

The several stability derivatives in the computation will be obtained from calculations and, depending upon the degree of novelty of the aircraft configuration, may also be obtained from testing a model in a wind tunnel. Many UAV are of a size that the model used may be of full scale which has the advantage of avoiding the necessity to correct for scale-effect inaccuracies which may obtain in manned aircraft testing.

5.1.2 HTOL Spatially Stabilised Configuration

For this configuration, the aircraft will be designed to have a minimal response to air gusts. For example, the fin aerodynamic surfaces will be reduced in size so that they merely offset the directional instability of the forward fuselage to provide effectively neutral directional stability overall. Preferably the smaller fins will be fully pivoting (all-flying) to retain adequate yaw control. Horizontal tail surfaces will be similarly treated to provide neutral pitch stability but adequate pitch control.

Wing dihedral will be sensibly zero to prevent a roll response to side-gusts. In many respects, this could move the configuration towards an all-wing or delta wing. However, as described, the aircraft is completely unstable and could, of its own volition, pitch or roll fully over and continue to ‘wander’ in those modes. It is necessary to provide a spatial datum in those modes by including such means in the FCS. This is usually done by adding a vertical attitude gyroscope to the pitch and roll channels of the FCS, as shown in Figure 5.3.

5.2 Helicopters

5.2.1 Single-main-rotor Helicopter

The majority of manned helicopters are in this category, principally because, there is a greater number of small to medium-sized machines required than large machines. The single-main-rotor (SMR) configuration is best suited to the former whilst tandem-rotor machines are best suited to the latter, larger category. The aerodynamic control arrangement for a SMR is shown diagrammatically in Figure 5.4. and a typical FCS block diagram in Figure 5.5.

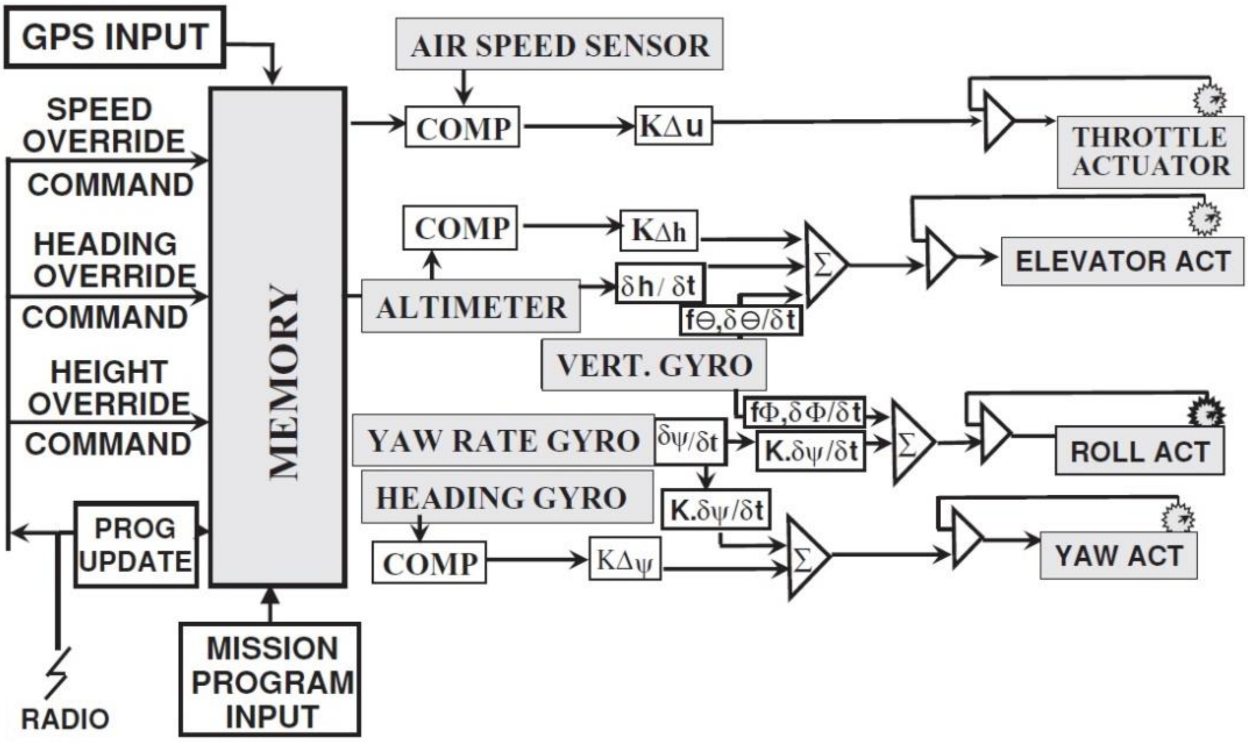


Figure 5.3: Spatially stabilised HTOL aircraft AFCS

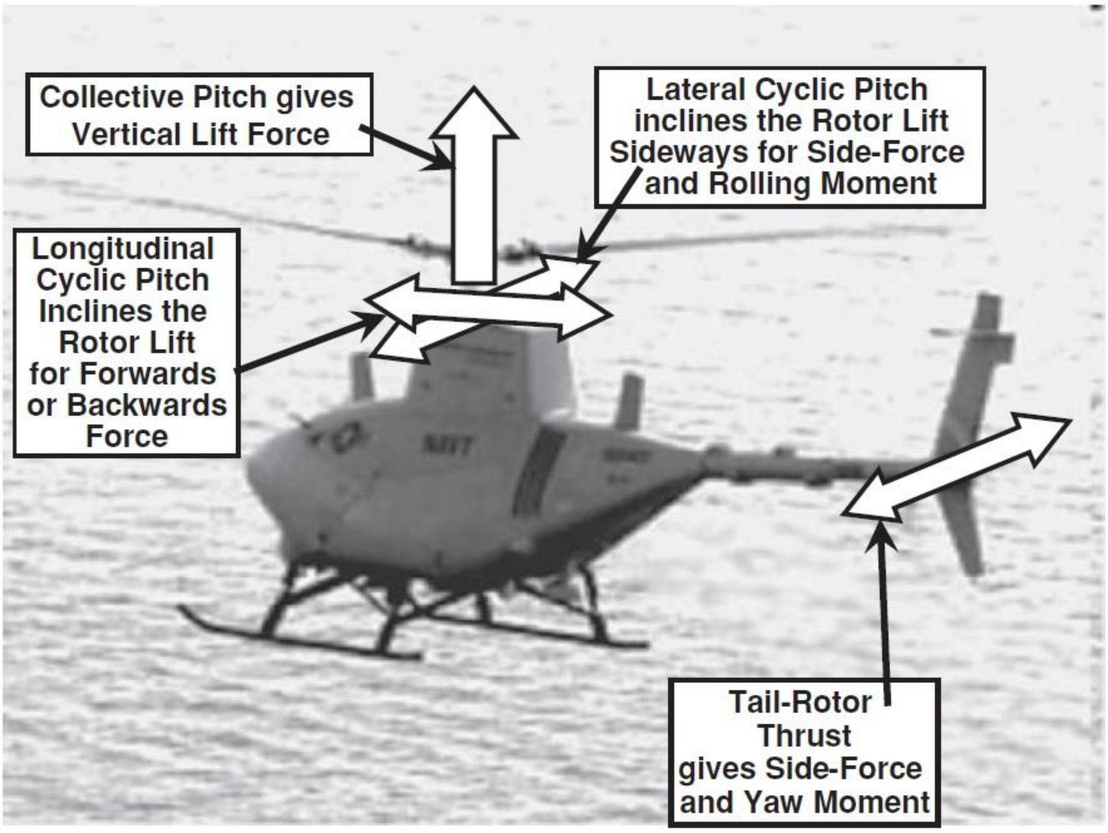


Figure 5.4: SMR helicopter controls

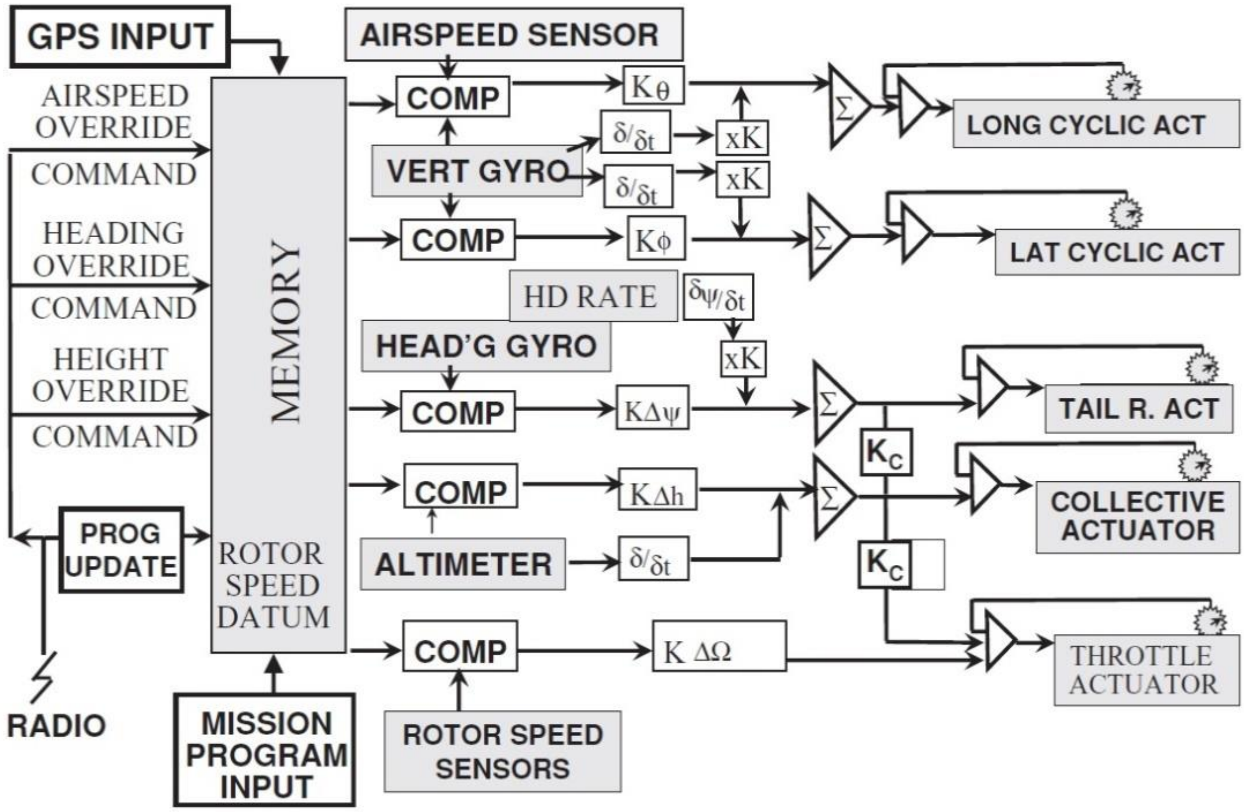


Figure 5.5: AFCS diagram for SMR helicopter

It appears that, at least until recently, most manufacturers of unmanned helicopters have opted for the SMR probably because it is seen as the most understandable technology. In a few cases, existing small passenger-carrying machines have been converted to a UAV by replacement of the crew and their support equipment with an automatic FCS. This latter approach removes much of the development costs and risk of a totally new airframe and systems. The SMR configuration, however, has its shortcomings as a candidate for 'unmanning'.
These are principally as follows:

In the smaller sizes, especially, the tail rotor is relatively fragile and vulnerable, particularly during landings on uneven terrain and scrub land. Means of ensuring the adequate control and stability of the configuration are complicated and caused by its inherent asymmetry compared with the above fixed-wing aircraft which are essentially symmetric.

For example:

a) Execution of a climb requires an increase to be made in the collective pitch of the rotor blades which, in turn, requires more engine power to be applied. In its own right, that constitutes no problem. However, more power implies more torque at the rotor which, if uncorrected, will rotate the aircraft rapidly in the direction opposite to that of the main rotor's rotation.

Therefore the thrust of the tail rotor must be increased to counteract this. Unfortunately, this increase in lateral force will move the aircraft sideways and probably also cause it to begin to roll. To prevent this happening, the main rotor must be tilted to oppose the new increment in lateral force. In a piloted aircraft, the pilot learns to make these corrections, after much training, instinctively. For the UAV FCS, suitable algorithms must be added to achieve accurate and steady flight.

b) In forward flight, the rotor will flap sideways rising on the ‘down-wind’ side. This will produce a lateral force which must be corrected by application of opposing lateral cyclic pitch. The value of this correction will be different at each level of forward speed and aircraft weight. Similarly, a suitable corrective algorithm has to be added to the basic FCS.

c) To effect sideways flight from the hover, lateral cyclic pitch must be applied. The tail rotor will exert a very strong ‘weathercock’ effect which has to be precisely corrected by an adjustment in tail rotor pitch, requiring yet another addition to the FCS.

Although a SMR helicopter has a lower response to gusts in most modes compared with an equivalent sized
HTOL aircraft, its response to side-gusts is high, due to the very large fin effect of the tail rotor. It is difficult to see how that can be practically overcome, given the need for it as a powerful anti-torque measure.

5.2.2 Coaxial-rotor Helicopter

A coaxial rotor helicopter has symmetry in its rotor system and, in the case of the plan-symmetric helicopter, complete overall symmetry. It is therefore even simpler than for a HTOL aircraft to configure its FCS. Furthermore it is inherently less sensitive to gusts than any other configuration. Its method of aerodynamic control is shown in Figure 5.6 and a block diagram of an appropriate FCS is shown in Figure 5.7.

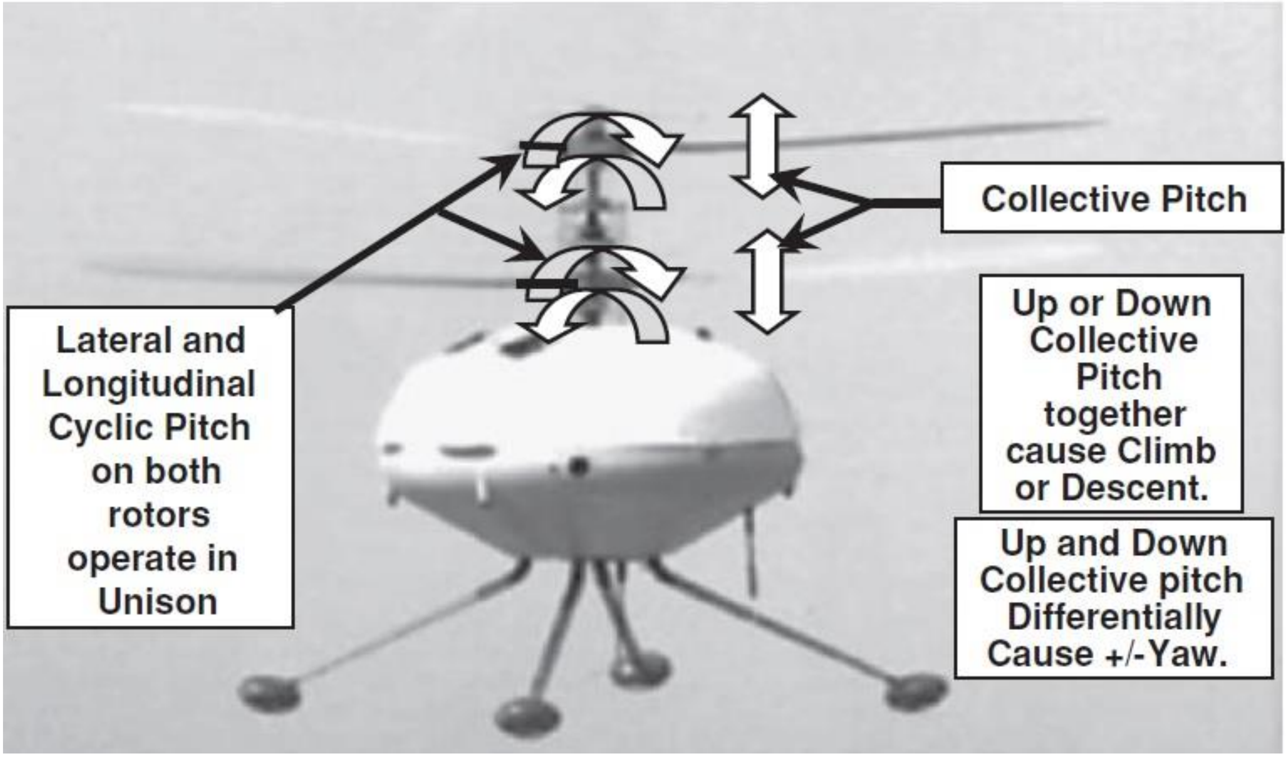


Figure 5.6: Plan-symmetric helicopter controls

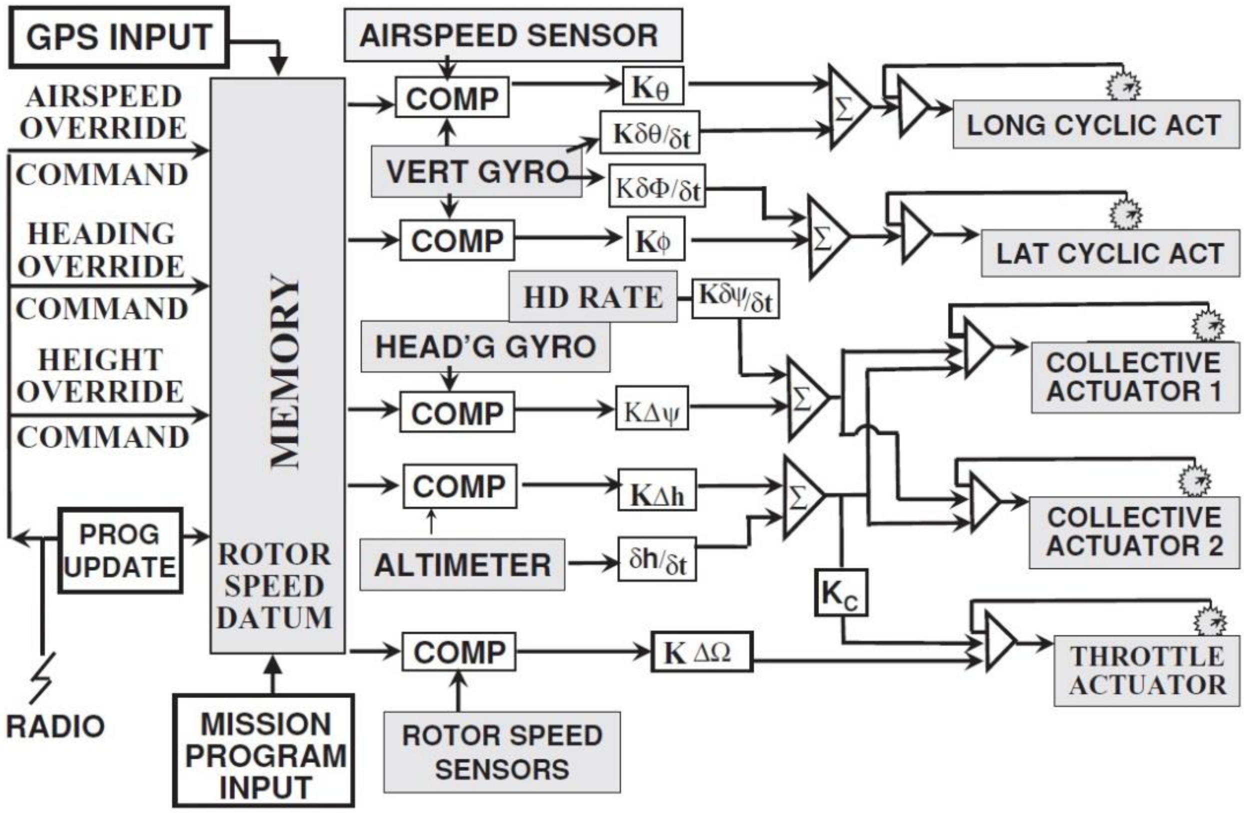


Figure 5.7: Coaxial-rotor helicopter AFCS

5.2.3 'Directional' Airframe Coaxial-rotor Helicopter (CRH)

'Directional' implies that it has an airframe having a preferred axis of flight, i.e. along which it has the lowest aerodynamic drag. With its rotor symmetry, it has none of the complex mode couplings of the SMR helicopter.

On the command to climb, the torque from each rotor remains sensibly equal so that little, if any, correction in yaw is required. In that event, it is achieved by a minor adjustment in differential collective pitch which removes any imbalance at source. Hence, unlike the SMR, there is no resulting side-force to balance. Similarly, entry into forward or sideways flight occasions no resultant side-force through rotor flapping. The flapping motion on each rotor is in equal and opposite directions thus the system is self-correcting. For these reasons, pilots flying crewed versions of the coaxial helicopter configuration, report on its ease of control compared with a SMR helicopter and, for the same reasons, the electronic flight control system is easier to develop.

There is a possible downside to the coaxial rotor helicopter. Its control in yaw relies upon the creation of a disparity in torque between the two rotors. In descent, less power is required to drive the two rotors and therefore less disparity in torque can be achieved, thus reducing the control power available. However, for all rates of descent short of full autorotation, the control available should remain adequate.

In full autorotation, calculations show that a small control power is available, but it is in the reverse direction. To overcome this problem, manned CRH are usually designed to be aerodynamically stable and incorporate rudders in the fin(s). In the event of total loss of engine power, unless very close to the ground, the pilot is required to put the aircraft immediately into forward flight where he has rudder control and conduct a run-on flared landing. This measure could be programmed into a UAV FCS.

5.2.4 Symmetrical Airframe Coaxial-rotor Helicopter

Otherwise known as a plan-symmetric helicopter (PSH), this is a special case of the CRHand, as explained elsewhere in this book, has several advantages over the directional CRH other than in aerodynamic drag of the fuselage. These advantages include a more compact aircraft for transport, more versatile operation of the payload, lower gust response and lower detectable signatures for stealth operation. It cannot be made aerodynamically stable in yaw, but is inherently neutrally stable. In normal flight conditions, it is stabilised spatially by the FCS. In full autorotation, unless corrective algorithms are added to the FCS to take account of the reversal in the control direction, the FCS would actually destabilise the aircraft.

A run-on landing, however, is unlikely to be practical for this type as it would require an undercarriage capable of such a landing and so is probably unsuitable for the configuration. However, it has the least response to gusts of all aircraft configurations, the response being zero in some directions and with no cross-coupling into other modes.

5.3 Convertible Rotor Aircraft

Convertible rotor aircraft may exist in two main variants - tilt-Rotor and tilt-Wing. Their means of control are similar. The most basic approach is for each rotor to have control of collective pitch and longitudinal cyclic pitch control only (Figure 5.8) as opposed to helicopters which normally have cyclic pitch control in both longitudinal and lateral planes. In addition, both types have a powered means of tilting the rotor shafts (and usually engines) from the vertical forwards to the horizontal. In the case of the tilt-wing aircraft, the wing tilts as well.

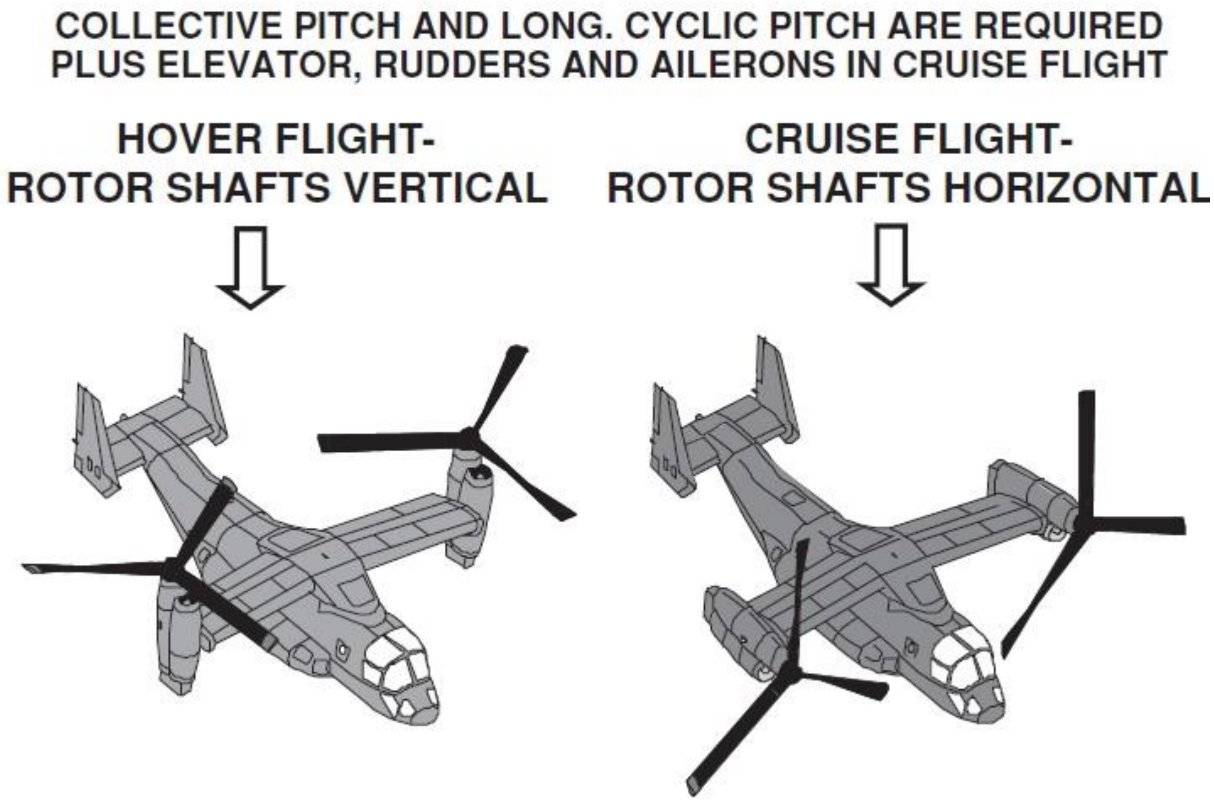


Figure 5.8: Tilt-rotor aircraft controls

The control strategy is as follows:

Table 5.1: Hover control strategy

Mode	Control
Climb or descent	Collective pitch change on both rotors
Fore and aft translation	Fore and aft longitudinal cyclic pitch change
Lateral translation	Differential collective pitch change
Heading change	Differential longitudinal cyclic pitch change

Table 5.2: Cruise Flight control strategy

Mode	Control
Climb or descent	Elevator deflection
Speed change	Collective pitch change
Heading change	Rudder deflection

The table shows the simplest solution to the means of control. There are further options:

a) By accepting the additional complexity of adding lateral cyclic pitch to finesse lateral translation in the hover and reduce the amount of roll incurred in the manoeuvre.

b) Differential collective pitch can be applied in cruise flight to assist in heading change especially in the transition between hover and cruise.

5.3.1 Transitional Flight

In any hybrid aircraft, the transition between hover flight and cruise flight is the most difficult regime to achieve and convertible rotor aircraft are no exception to this. Not only does it require the additional channel of control, i.e. the control of the actuators which tilt the rotor shaft axes at a controlled rate, but the FCS must phase in and out the control means for each flight mode in concert with, and appropriate to, the shaft tilt angle. Thus, during transition flight, both sets of controls (hover and cruise) must be operative in the correct ratios and in the correct phasing to ensure that the correct wing incidence is achieved. Any ancillary systems such as wing flaps must be phased in or out appropriately, hence the FCS for this type of aircraft is far more complicated than for either 'pure' HTOL or VTOL aircraft and is open to many different interpretations. Therefore no attempt is made here to show a FCS block diagram for these types.

5.4 Payload Control

In addition to maintaining control and stability of the aircraft, it is just as important to achieve that for the payload. Control of the aircraft is needed to get the aircraft over the target area, but will be useless unless the payload is properly controlled. The latter may be achieved using a system which is part of the aircraft FCS or by using a separate module. The choice will probably depend upon the degree to which the payload operation is integrated with the aircraft operation.

Control of the payload will include, for most imaging payloads, the means of bringing the sight-line accurately onto the target and keeping it there. This is probably carried out initially by 'manual' direction using actuation of the payload mounting about two axes. A gust-insensitive, spatially stable aircraft will facilitate this.

Subsequent maintaining of the sight-line on target will rely upon gyro-stabilization of the sight-line, possibly aided by a lock-on pattern recognition system in the E/O sensor and/or use of the differential GPS with computation involving the GPS coordinates of the target and the aircraft at each moment in time. Other control will include switching to release dispensable payloads; bring payload sensors 'on-line'; changing E/O settings; making adjustments to FOV; initiating, for example, scanning programs, etc.

The integration of the payload and aircraft control and stability systems is at its greatest in the PSH configuration which is, in effect, a flying payload turret. The same set of heading and vertical gyros, for example, support the control and stabilization of both aircraft and payload.

The FCS operates two sets of coordinate axes, those of the aircraft and those of the payload, even though the latter is fixed within the aircraft. Thus the payload sight-line may be pointing in one direction whilst the aircraft may fly in a totally different direction.

This facility enables the operation of a range of useful manoeuvres. For example in traversing a large expanse of sea or terrain, the payload sight-line may be programmed to scan at a range of frequencies over a range of amplitudes on either side of the aircraft line of flight to encompass a large field of regard in a reconnaissance mission. Another program may call for a continuous 360◦ rotation of the sight-line as the aircraft emerges vertically from the depths of a wood to scan for ‘items of interest’ in both near and far fields.

5.5 Sensors

Sensors, as shown in the FCS diagrams of Figures 5.2, 5.3, 5.5 and 5.7, include vertical attitude gyros, heading gyros, angular rate gyros when necessary, height and altitude sensors and airspeed sensors. Linear accelerometers may be used in some applications. Individual sensors may be used as described above or the sensors may form part of a ‘strapped down’ inertial measurement unit. It is not intended here to cover sensors in any detail as information is readily available from a number of different suppliers from whom specifications may be obtained. Some suppliers offer complete FCS ‘ready-made’ or at least custom-built for individual applications. In each case their qualities of accuracy, reliability, life, power supply, environmental protection and mass will be of importance to the UAV systems designer. Usually, though not always, the cost increases as the performance specification increases.

5.5.1 Height and Altitude Sensors

Sensors for measuring tape height, that is height above ground, include those measuring distance by timing pulses of radio, laser (figure 5.9) or acoustic energy (figure 5.10) from transmission to return. These vary in their accuracy, depending upon their frequency and power, but are usually more accurate than pressure sensors measuring altitude. Radio altimeters vary in their accuracy and range depending upon their antennae configuration.

Laser systems may have problems in causing eye damage and precautions must be taken in their selection and use. They may also lose function when operating over still water or certain types of fir trees when the energy is either absorbed or deflected so that no return is received. Acoustic systems usually have a smaller range capability and must also be separated in frequency from other sources of noise.

Barometric (or pressure) sensors for measuring pressure altitude are less accurate than the tape height sensors and have to be adjusted to take account of the atmospheric changes which take place hour by hour and from area to area. However in transitional flight at altitude this does not constitute a real problem and can be backed up by GPS data. These sensors are not suitable for accurate operation at low altitude, especially in the case of VTOL aircraft. The static air pressure measurement from a VTOL aircraft is greatly affected by the induced airflow around the aircraft, the direction of which also changes with vertical or lateral manoeuvres.

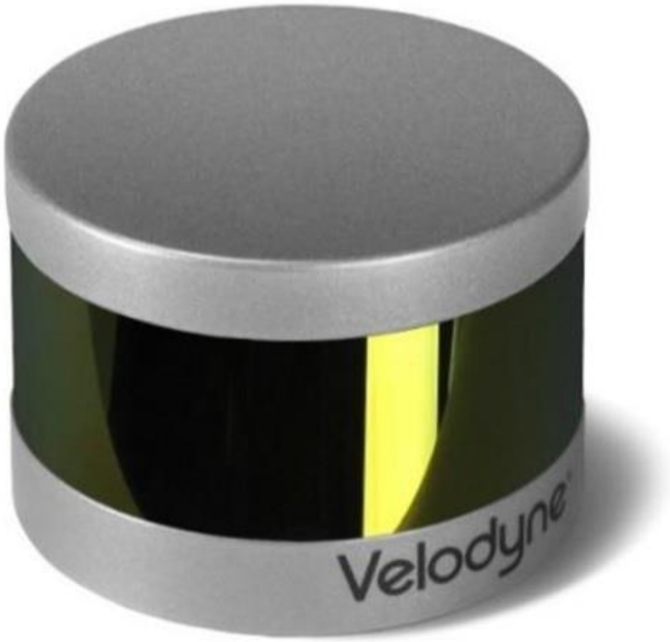


Figure 5.9: Laser based sensor Velodyne® VLP16

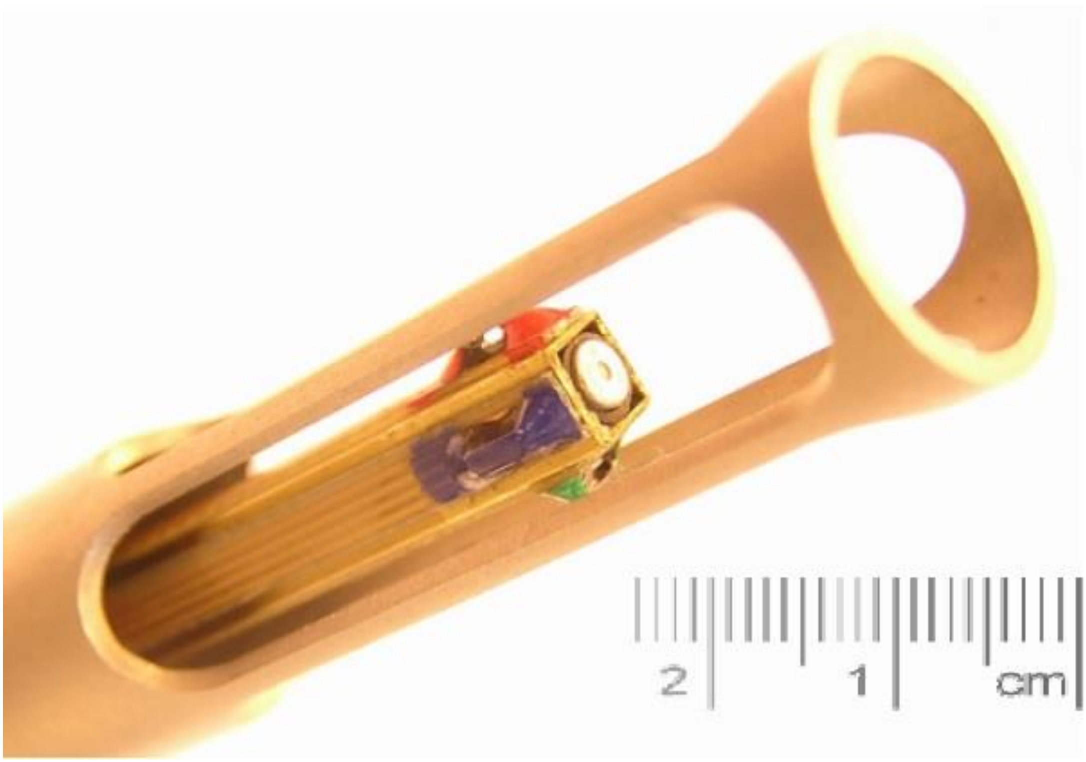
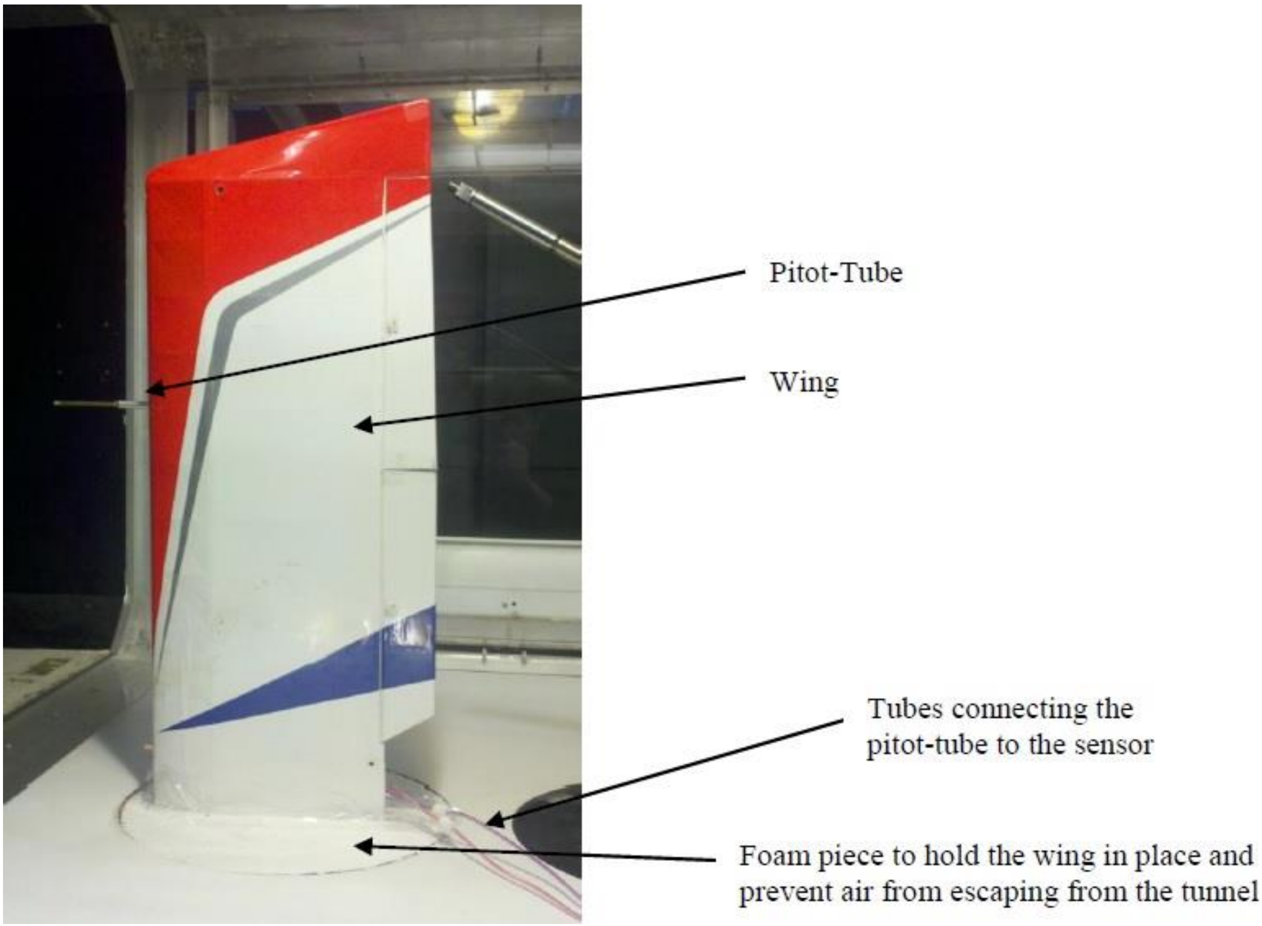


Figure 5.10: An acoustic vector sensor consisting of a sound pressure microphone and three orthogonally placed Microflown sensors

5.5.2 Airspeed Sensors

For HTOL aircraft a standard pitot-static (PS) system (figure 5.11) is acceptable provided that it is suitably positioned to read accurate static pressure either as part of a combined unit ahead of any aerodynamic interference or as a separate static vent elsewhere on the aircraft. The compensating PS head developed by Bristol Aircraft in the 1950s improves the accuracy of the former type of installation. In the case of VTOL aircraft the difficulty of measuring an accurate static pressure at different airspeeds, referred to above, also affects measurement of airspeed using a PS system. Apart from the inaccuracy of the classic PS system in measuring airspeed, and its inability to record speeds below about 15 m/s, fluctuating values from it can cause instability in the control system. Hence it is better to rely on data from a system integrated with GPS or better still from an omnidirectional air-data system that does not require knowledge of ambient static pressure.



5.11: Pitot-static (PS) system for UAV

5.5.3 Hover-position-hold Sensing

Holding station in a hover or near hover is often a requirement for a VTOL aircraft for take-off or for landing and also for several types of operations, current or projected, where surveillance from a fixed-point is required. If this is required at an established base, the task is solvable by means such as hovering over a beacon.

If the operation is required away from base, then options include the engagement of integrating accelerometers, pattern-recognition or, possibly in the future, photon-flow measurement on the E/O sensor or possibly Doppler interrogation of the radio altimeter, etc. These sensor inputs would be integrated into the FCS to operate the appropriate controls.

5.6 Autonomy

The 'jury' in the unmanned aircraft community seems to be 'still out' for the verdict on the definition of autonomy. Some suppliers of UAV systems claim that an aircraft has operated autonomously in carrying out a mission when it has flown a pre-programmed flight from take-off to landing without further instructions from outside. Others would label this type of activity as merely automatic and would say that to be autonomous the system must include an element of artificial intelligence. In other words the system must be able to make its own decisions without human intervention or pre-programming.

The main systems drivers for autonomy are that it should provide more flexible operation, in that the operator tells the system what is wanted from the mission (not how to do it) with the flexibility of dynamic changes to the mission goals being possible in flight with minimal operation replanning. This is coupled with reduction in reliance on time-critical communication and communication bandwidth, which in turn reduces the vulnerability of the system to communication loss, interruption or countermeasures. The goal is for the operators to concentrate on the job rather than operating the UAV.

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