UNMANNED AIR VEHICLES

III B. Tech V semester (R18)

BY

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COURSE OBJECTIVES:

The course should enable the students to	
I	Introduce to the student about the subsystems of Unmanned Air Vehicle Systems (UAS)
II	Familiarize the students about the aerodynamics and airframe configurations
III	Accustom the student to the wide variety of unmanned air vehicles
IV	Acquaint the student about the various communication, navigation, control and stability means of unmanned air vehicles

COURSE OUTCOMES (COs)

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
CO3	Recognize the 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

COURSE OUTCOMES (COs)

After successful completion of the course, students will be able to:

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
CO8	Analyze the attributes, performance, design issues and compromises of different types of aircrafts for UAV systems
CO9	Identify the appropriate communication and navigation systems for the UAVs as per the role requirements
CO10	Categorize the different techniques used to achieve the control and stability of UAV systems.
CO11	Apply the fundamental concepts of UAS in design and development of UAV systems for real-world application

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
PO3	**Design/Development of Solutions:** Design solutions for complex Engineering problems and design system components or processes that meet the specified needs with appropriate consideration for the public health and safety, and the cultural, societal, and Environmental considerations

PROGRAM OUTCOMES (POs)

PO 4	**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.
PO 12	**Life-Long Learning:** Recognize the need for and having the preparation and ability to engage in independent and life-long learning in the broadest context of technological change.

UNIT - I

INTRODUCTION TO UNMANNED AIRCRAFT SYSTEMS (UAS)

UNMANNED AIRCRAFT SYSTEMS

- 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

- The UAS' aircraft itself will have much in common with manned aircraft, but also several differences, which are result from the differences in operational requirements compared with manned aircraft

Example: need to take off from remote, short, unprepared airstrips
to fly for long periods at very high altitudes

UNMANNED AIRCRAFT SYSTEMS

The performance of the UAS' aircraft is often enhanced by

- not having to carry the **weight of equipment** and not having to carry **structure required** **to accommodate aircrew**, and having a **lower aerodynamic drag**
- advantageous scale effects associated with a smaller aircraft.

UNMANNED AIRCRAFT SYSTEMS

- 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*.**

Flying machine operated without an onboard pilot

Figure 1.1. Unmanned aircraft systems

Why UAS?

- Dull Roles
- Dirty Roles
- Dangerous Roles
- Covert Roles
- Research Roles
- Environmentally Critical Roles
- Economic Reasons

Why UAS?

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.

Dirty Roles applicable to both civilian and military applications, monitoring the environment for nuclear or chemical contamination puts aircrew unnecessarily at risk.

Crop-spraying with toxic chemicals is another dirty role

Why UAS?

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.

In such operations the **concentration of aircrew** upon the task may be compromised by the threat of attack. Loss of the asset is damaging, but equally damaging is the loss of trained aircrew and the political ramifications of capture and subsequent propaganda.

Power-line inspection and forest fire control are examples of applications in the civilian field for which experience sadly has shown that manned aircraft crew can be in significant danger

Operating in **extreme weather conditions**

Why UAS?

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.

Also in this category is the covert surveillance which arguably infringes the airspace of foreign countries in an uneasy peacetime. It could be postulated that in examples such as the Gary Powers/U2 aircraft affair of 1960, loss of an aircraft over alien territory could generate less diplomatic embarrassment if no aircrew are involved.

Why UAS?

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.

Testing subsequent modifications can also be effected more cheaply and more quickly than for a larger manned aircraft, and without any need for changes to aircrew accommodation or operation.

Why UAS?

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.

Typical of these are the regular inspection of power-lines where local inhabitants may object to the noise produced and where farm animals may suffer disturbance both from noise and from sighting the low-flying aircraft.

Why UAS?

Economic Reasons

Typically, the UAV is smaller than a manned aircraft used in the same rˆole, 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.

UAVs

Abraham Karem, Jew, *Israeli*, Father of UAV
Alumni of Technion – Israel Institute of Technology

RC Model/ Drone/ UAV

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 a nd 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.

RC Model/ Drone/ UAV

- 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-opticor 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. enginesor electronics.

Categories of Systems Based upon Air Vehicle Types

HALE – High altitude long endurance. Over 15 000 m altitude and 24+ hrs endurance

MALE – Medium altitude long endurance. 5000–15 000 m altitude and 24 hrs endurance

TUAV – **Medium Range** or **Tactical UAV** – with range of order between 100 and 300 km

Close-Range UAV – Ranges of up to about 100 km

MUAV or **Mini UAV** – UAV of below a certain mass probably below 20 kg

Categories of Systems Based upon Air Vehicle Types

Micro UAV or **MAV** – The MAV was originally defined as a UAV having a wing-span no greater than 150 mm

RPH – Remotely piloted helicopter or VTUAV, vertical take-off UAV.

UCAV – Unmanned Combat Air Vehicle (Fixed wing)

UCAR – Unmanned Combat Rotorcraft

The Systemic Basis of UAS

Technically, a UAV system comprises a number of elements, or sub-systems, of which the aircraft is but one

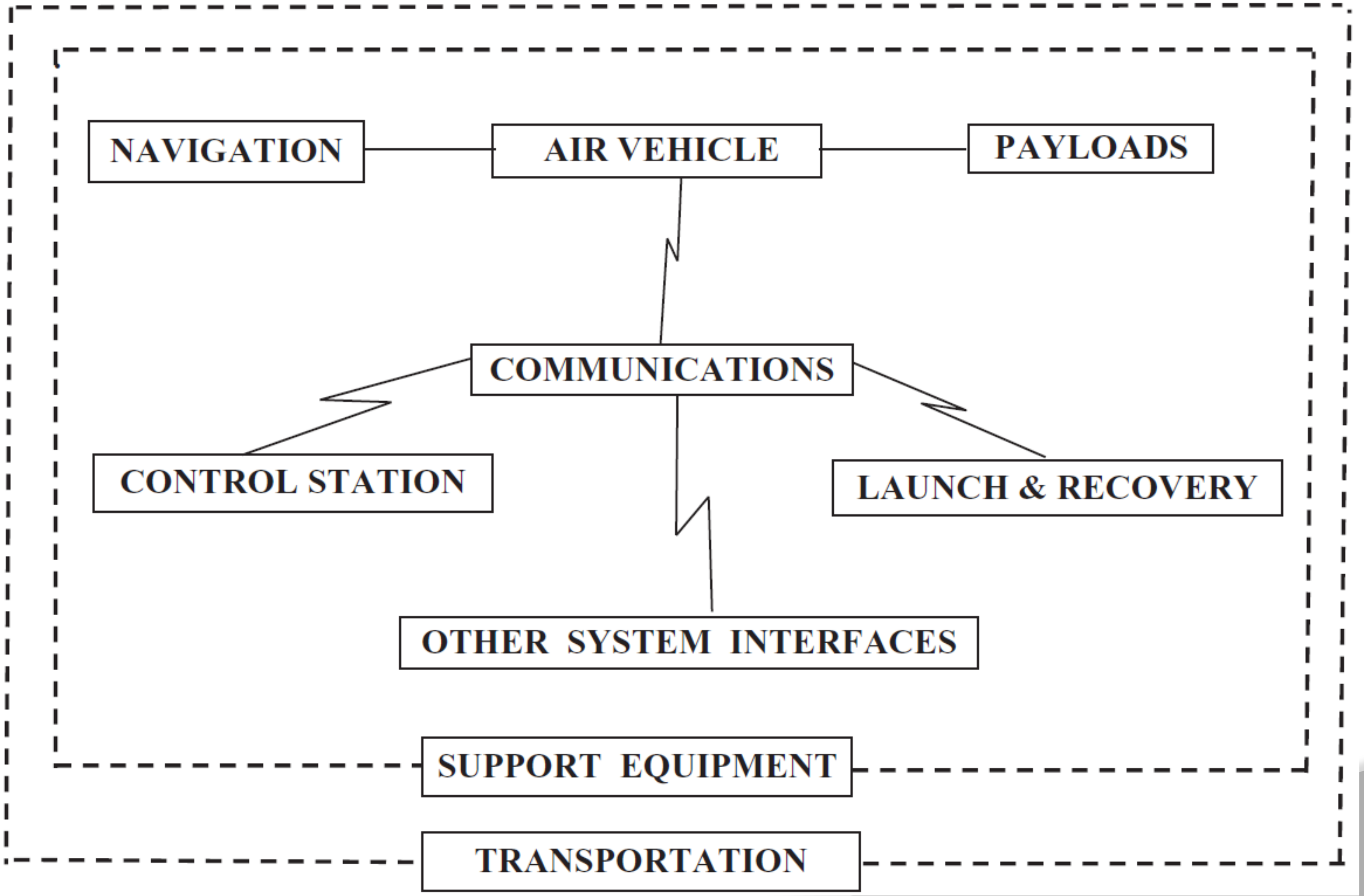


Figure 1.2. UAV system – functional structure

System Composition

Control Station (CS)

The control center of the operation and the man–machine interface

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.

Figure 1.3 .GCS - Ground control station

Control Station (CS)

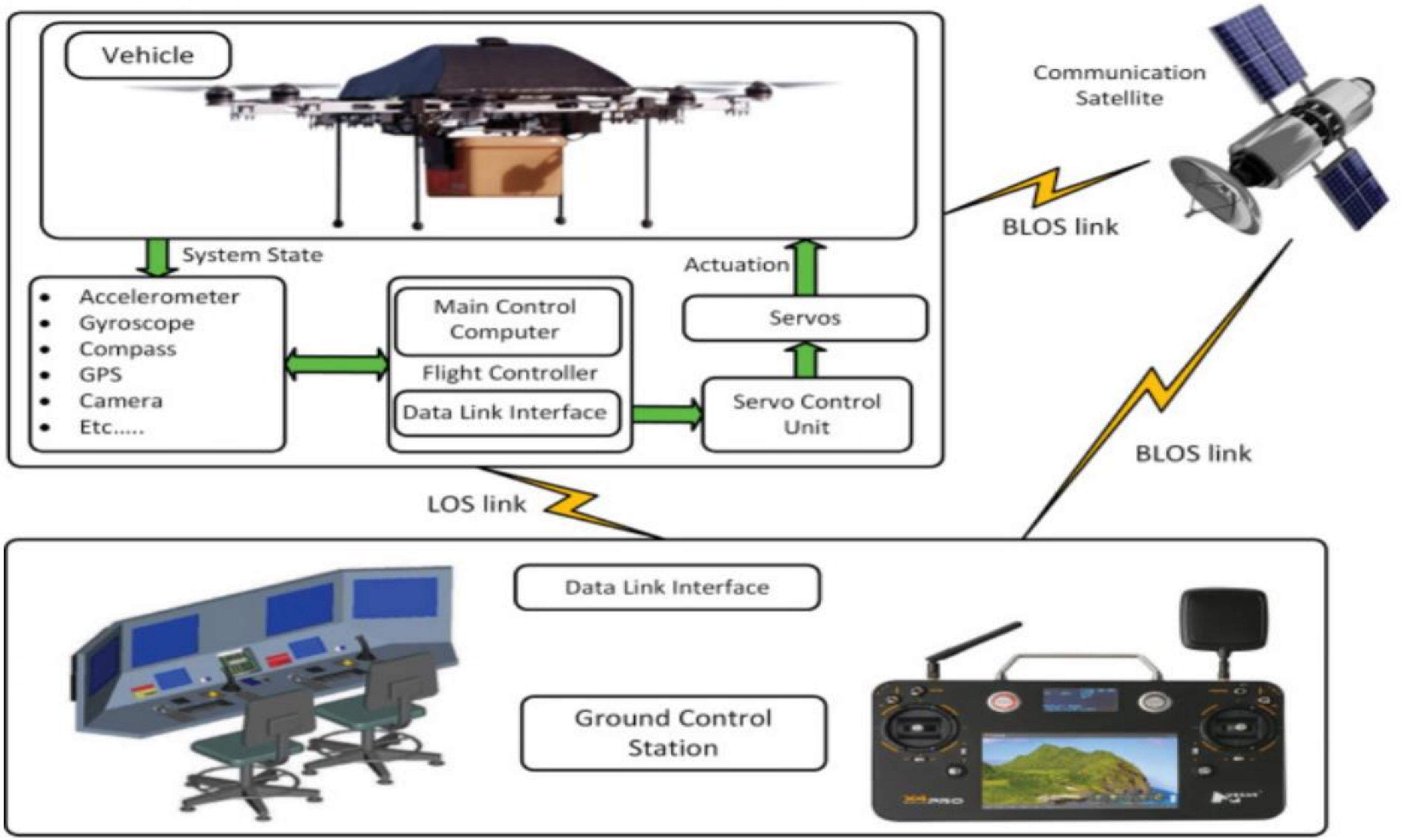


Figure 1.4. : High-level architecture of a UAV system

R. Altawy and A. M. Youssef. (2016). ACM Transactions on Cyber-Physical Systems, Vol. 1 (2): Article 7

Control Station (CS)

SCS - Shipboard control station

ACS - Airborne control station

Figure 1.5. SCS and ACS

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 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**

(d) combination of different types of sensors

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***

- communications link
- stabilization and control equipment,
- power plant and fuel
- electrical power supplies
- basic airframe structure and mechanisms needed for the aircraft to be launched, to carry out its mission, and to be recovered.

The Air Vehicle

Other significant determinants in the design of the aircraft configuration are the operational **range**, **airspeed and endurance** demanded of it by the mission requirement

Endurance and Range - fuel load
(Small fuel load and maximised performance - efficient propulsion system) and optimum airframe aerodynamics

Speed - a lighter-than-air aircraft,
or a heavier-than-air fixed-wing,
rotary-wing

A long endurance and long range mission - **a high-aspect ratio fixed-wing aircraft**

UCAVs (Unmanned Combat Air Vehicles) - operate **at high speed**
- likely to have **low aspect ratio wings**

Civilian uses of UAVs – **Low speeds - Vertical take-off and landing**

The Air Vehicle

Figure 1.6. Airframe configurations

Navigation Systems

- Operators should know ‘*where the aircraft is*’ at any moment in time
- Aircraft should know ‘*where it is*’ during autonomous flight
- Global Positioning System (**GPS**) which accesses positional information from a system of earth-satellites with simple form of inertial navigation system (**INS**)

Navigation Systems

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 fall-back options.

These methods include:

(a) Radar tracking - 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

Navigation Systems

Radar tracking

Fig 1.7. Transponder and Portable aircraft transponder tracking unit

Navigation Systems

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

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

Launch, Recovery and Retrieval Equipment

(a) Launch equipment –

for air vehicles

- which do **no**t have a **vertical flight** capability,
- **no**r 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.

Launch Equipment

Hydraulic rail launcher

Pneumatic launcher

Catapult take-off

Figure 1.7. Launch equipment

Launch, Recovery and Retrieval Equipment

(b) Recovery equipment - 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***.

An alternative form of recovery equipment - ***a large net***.

(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.

Recovery Equipment

Figure 1.8. Recovery equipment

Retrieval equipment

Figure 1.8. Sky Hook Retrieval Equipment

Communications

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,

Possible alternatives

- by light in the form of a ***laser beam*** or
- via ***optical fibers***.

Communications

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.

Communications

The tasks of the data links are usually as follows:

(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

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.

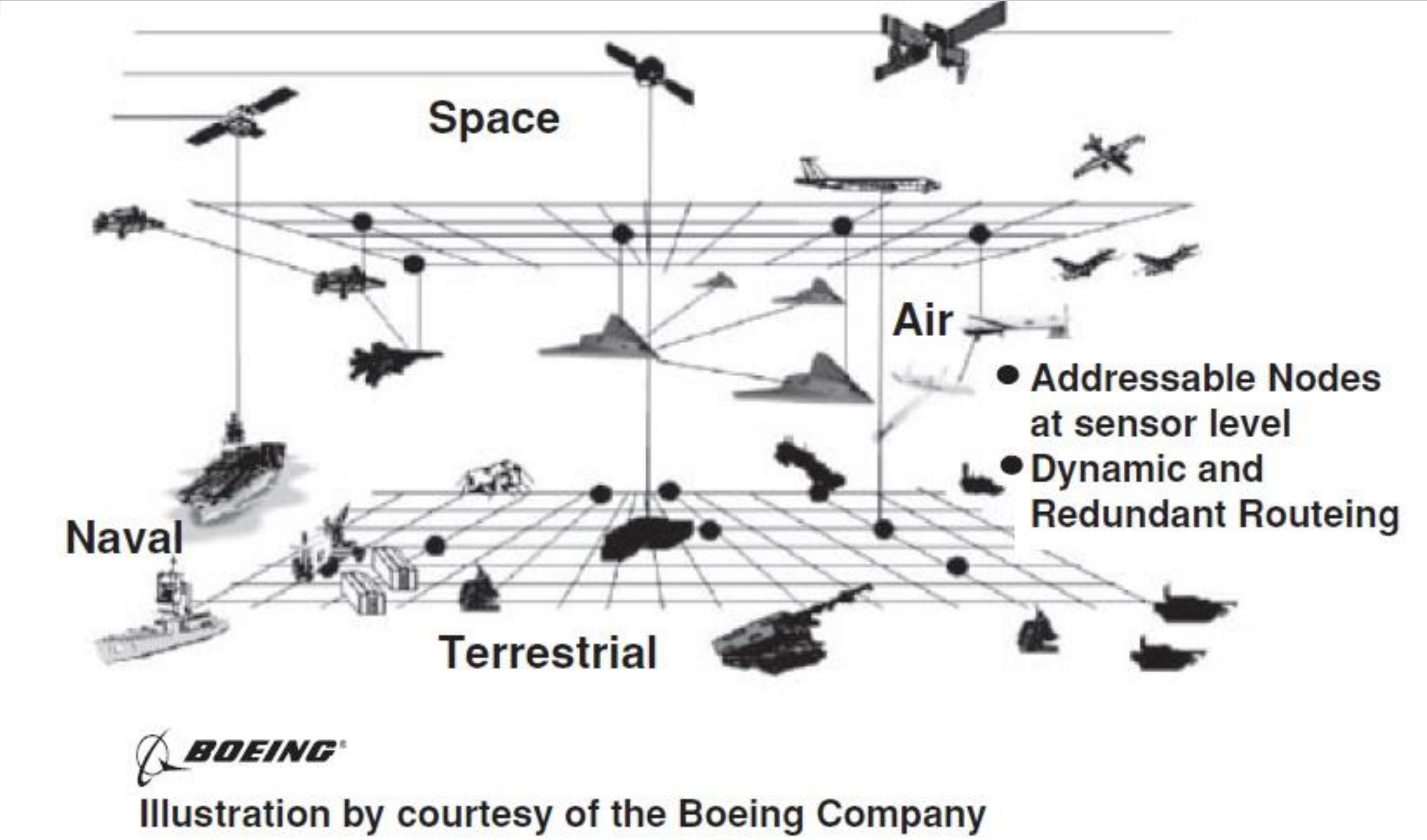
It is likely that the UAV system may be operated by the services (both military and civilian) in different countries which may require different radio frequencies or security coding.

Interfacing with Other Systems

A UAV system exists in order to carry out a task. It is unlikely that the task may ‘stand alone’. 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.

Interfacing with Other Systems



- Addressable Nodes at sensor level
- Dynamic and Redundant Routeing

Illustration by courtesy of the Boeing Company

Figure 1.9. Network-centric architecture (Boeing)

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.

UAV Operations Manual

Australian Government

Civil Aviation Safety Authority Australia

Figure 1.10. Support Equipment

Transportation

A UAV system is often required to be mobile. Therefore transport means must be provided for all the sub-systems discussed above.

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.

Transportation

Figure 1.11. Transportation

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 recognize 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.

Introduction to Design and Selection of the System

Design- Conceptual Phase

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?

Design- Conceptual Phase

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?

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.

Preliminary Design

- 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.

Preliminary Design

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.

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:
  - aerodynamics
  - 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.

Detail Design

- 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.

Detail Design

- The **jigs and tools** required for manufacture will be specified and **will be designed** unless ‘bought-out’.

- <u>Test Schedules will be drafted</u> for the test phases and initial thoughts applied to the contents of the operating and maintenance manuals.

Selection of the System

Air Vehicle – Payload

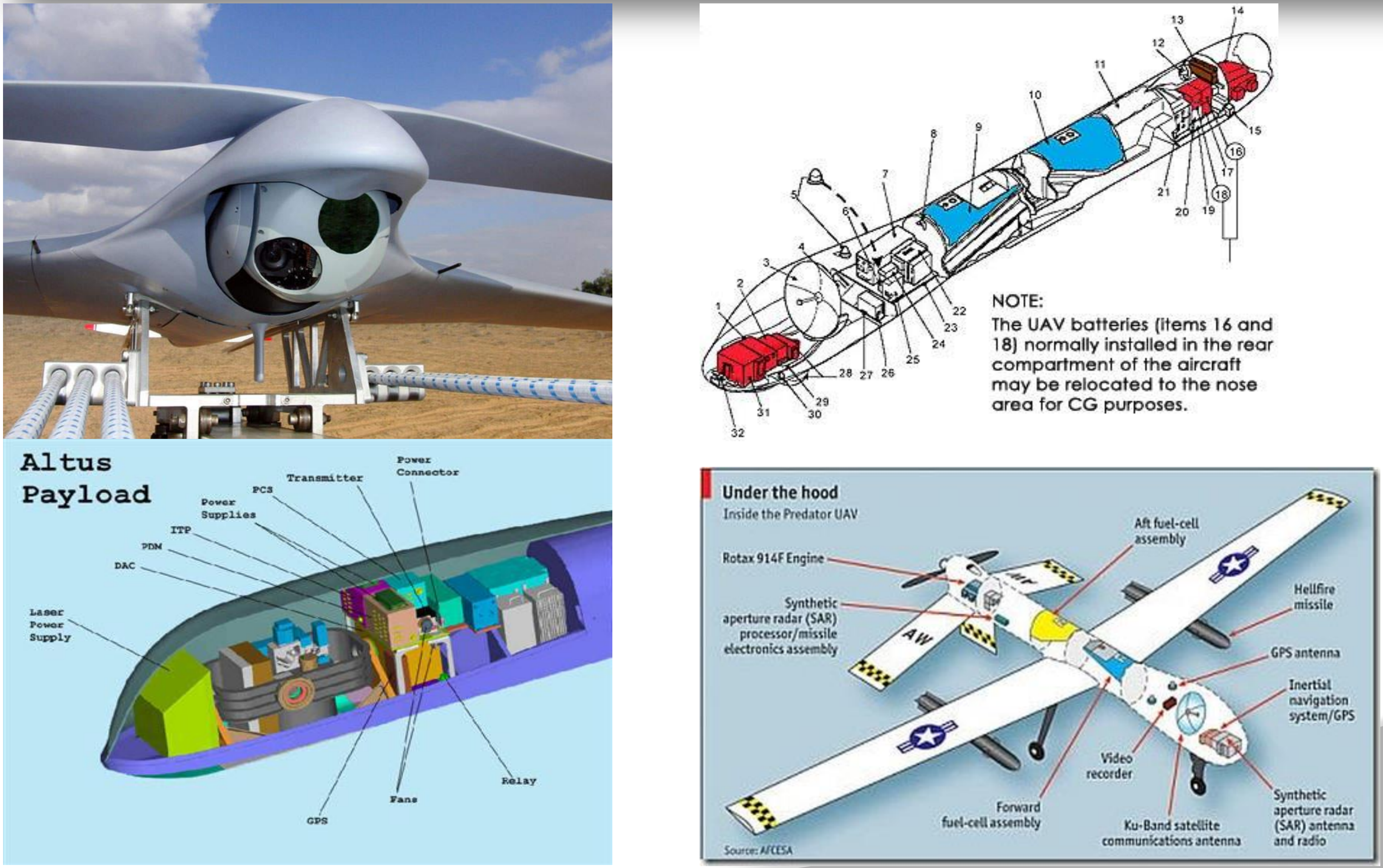
- The size and mass of the payload and its requirement for electrical power supplies is often the premier determinant of the layout, size and all–up-mass (AUM) of the aircraft. This is perhaps rightly so, as its tasking is the sole reason for the existence of the UAV system.

- The payload may range in mass from a ***fraction of a kilogram up to 1000 kg*** and in **volume** from a few cubic centimeters (**cm**^{3}) to more than a cubic metre (**>m**^{3}), especially in the case of armed air vehicles.

Air Vehicle – Payload

- 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.

Payloads



NOTE:
The UAV batteries (items 16 and 18) normally installed in the rear compartment of the aircraft may be relocated to the nose area for CG purposes.

Altus Payload

Under the hood

Inside the Predator UAV

Source: AFCESA

Figure 1.12. Payloads

Payloads

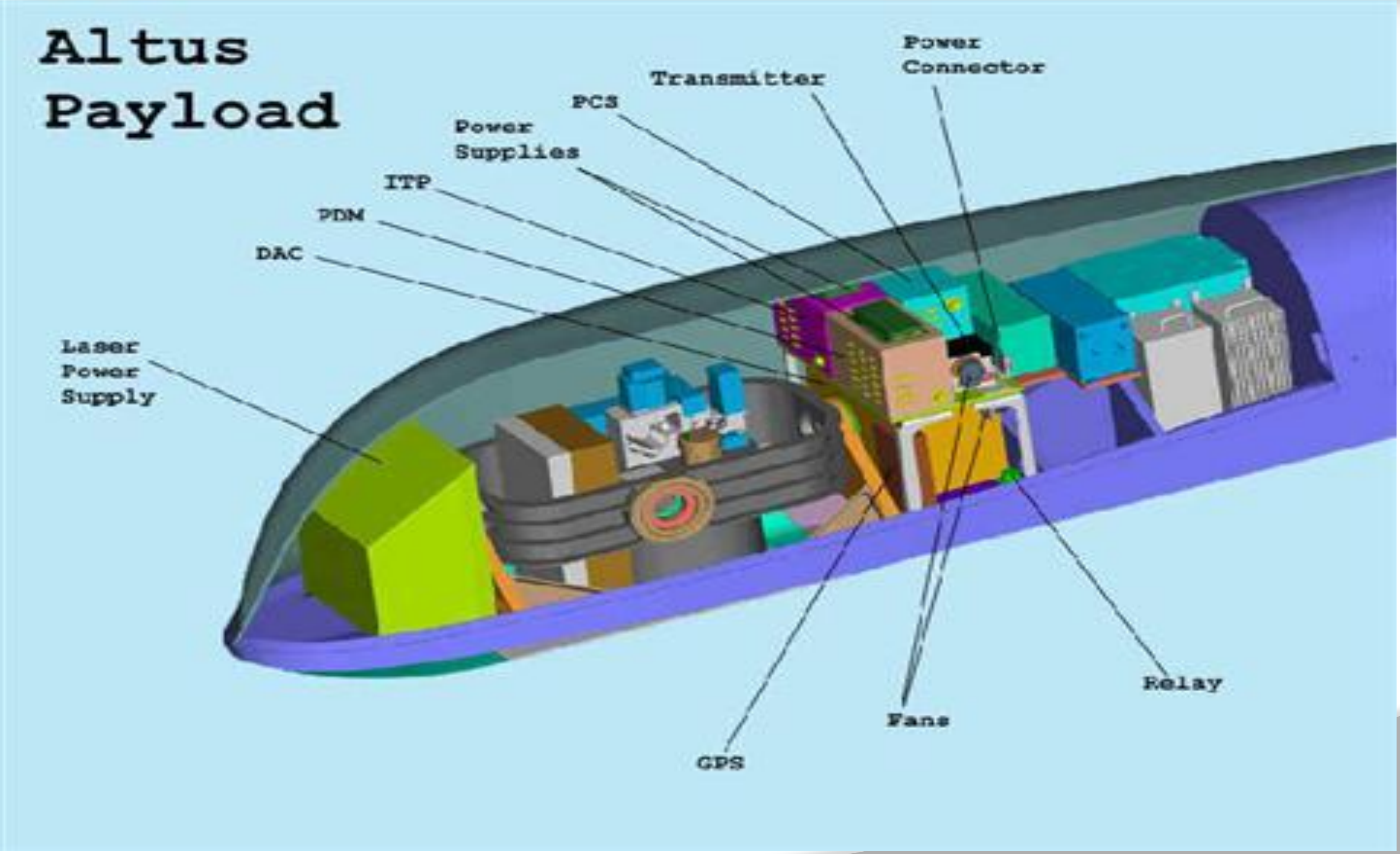


Figure 1.12. Payloads

Payloads

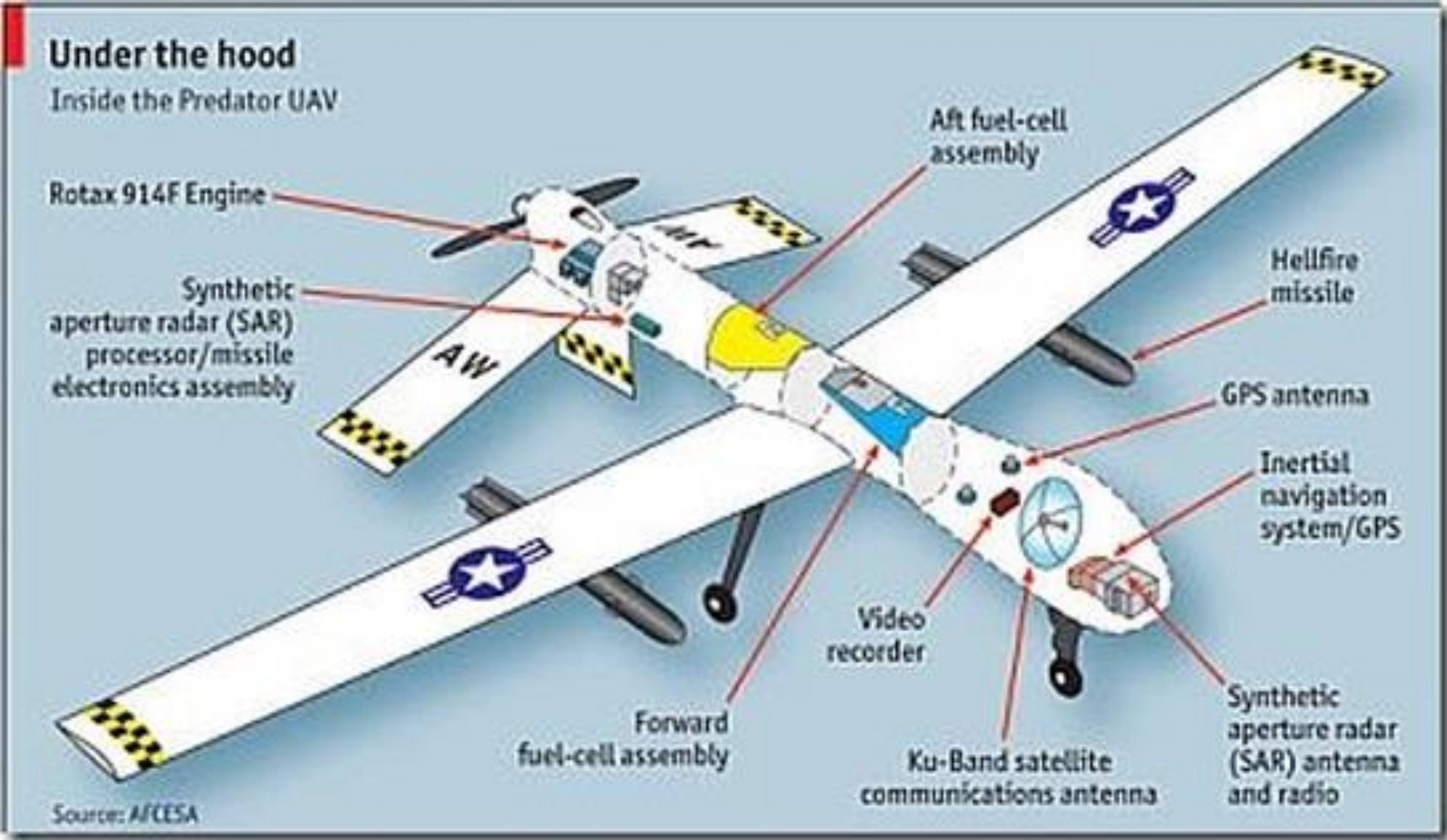


Figure 1.12. Payloads

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 powerplant.
- 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.

Air Vehicle – Endurance- Influencing Factors

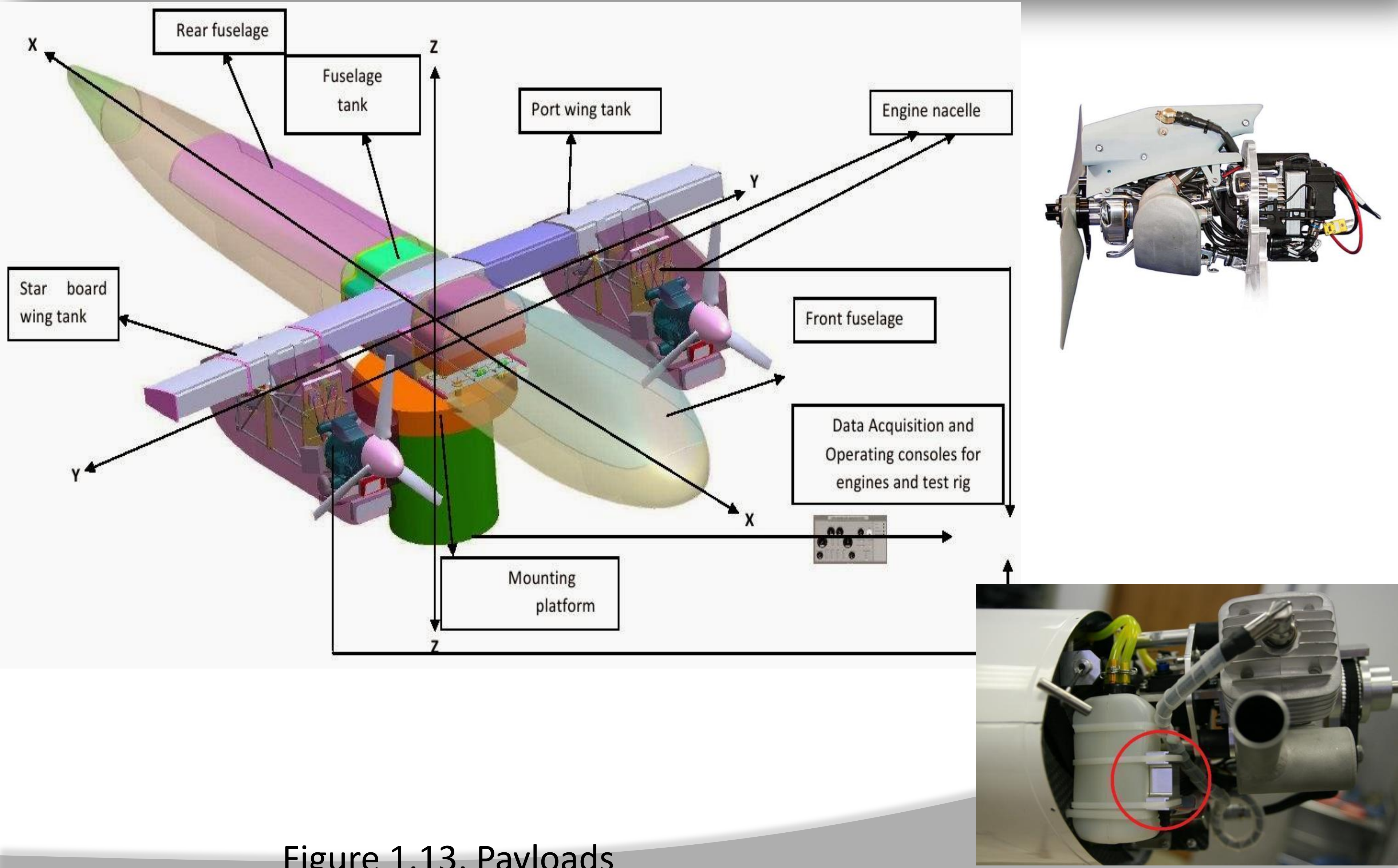


Figure 1.13. Payloads

Air Vehicle – Radius of Action

- 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 effect the **electrical power** and frequency range needed for the radio-links.

Air Vehicle – Radius of Action

- The design and positioning of the radio antennae will reflect these requirements and could have an *affect 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*

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.

Air Vehicle – Speed Range

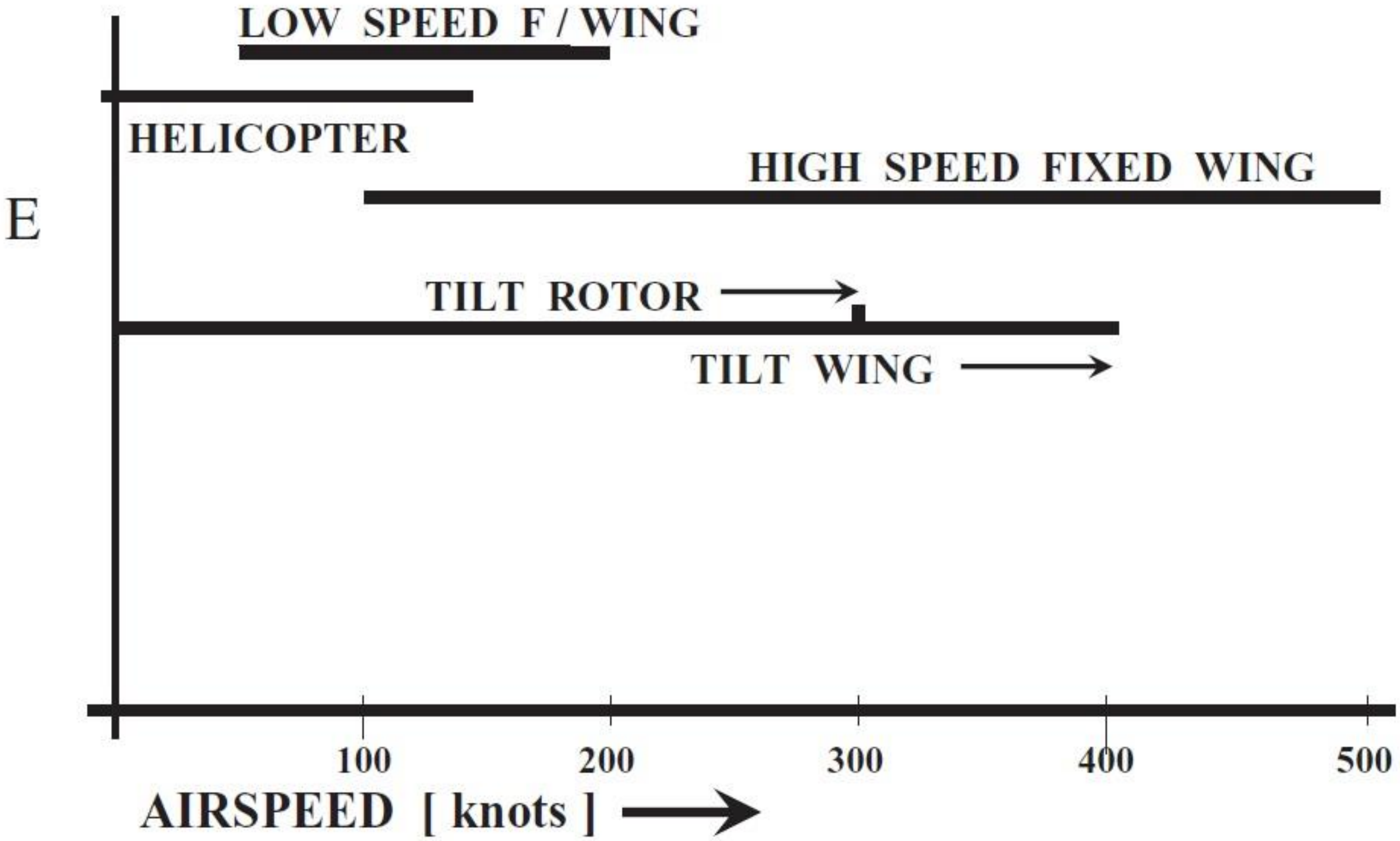


Figure 1.14. Speed ranges of aircraft types

Air Vehicle – Speed Range

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.

Overall System

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.

Overall System

The length of the runway required for will depend upon the

aircraft acceleration and

lift-off speed.

The size, power and sophistication of the launcher will depend upon

the ***aircraft mass*** and

minimum flight speed

Environmental Conditions

(i) it is important to recognise, during the system design, the impact that the environment will have on all elements of that system; and

(i) it is necessary to recognise the impact that the UAV system may have on the environment.

Environmental Conditions

(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.

Maintenance

The **frequency and length of time** during which a **UAV system is nonoperable** due to its undergoing maintenance are significant factors in

(i) the usefulness and

(ii) costs of the deployment of the system.

These are factors which must be addressed **during the initial design of the system**,

(a) involve control of the system liability to damage, system reliability, component lives,

(b) costs and supply, and the time taken for component replacement and routine servicing.

System Selection as Categories

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 air speeds. They may perform reconnaissance, ground attack or air-superiority (UCAV) missions.

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.

d) MAV and NAV which may be hand-launched and of very short range and endurance.

Applications of UAVs- 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

Military roles- 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

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

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

Lift-induced Drag

- 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.

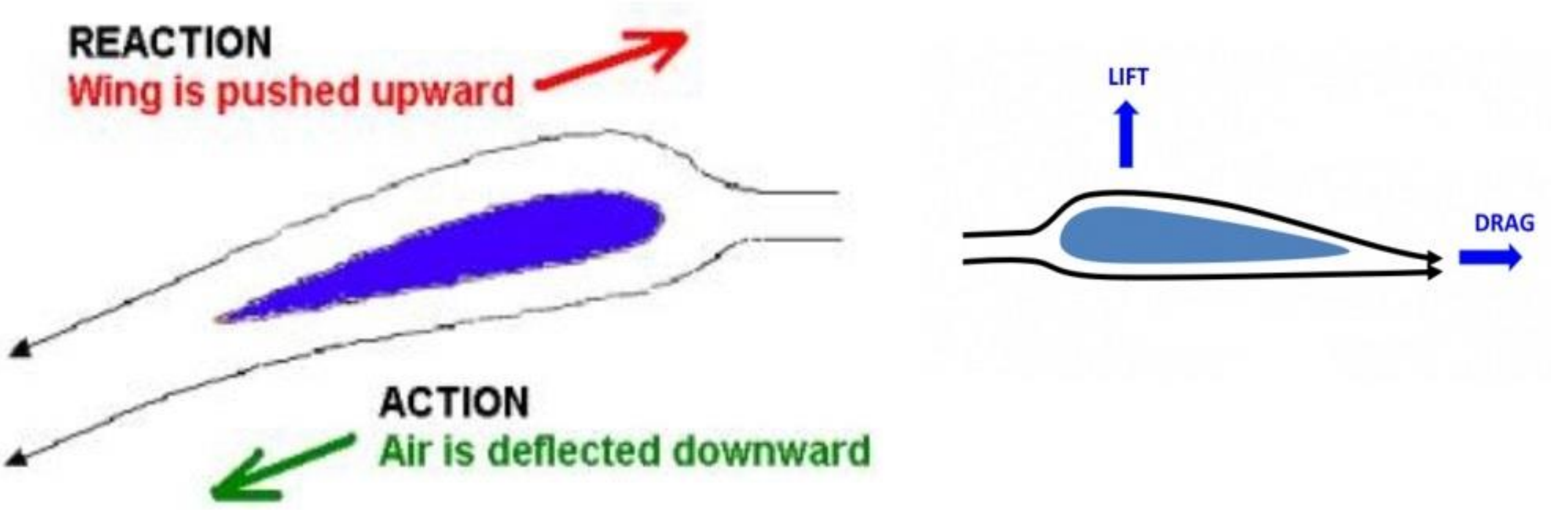


Fig. 2.1. Lift Generating Mechanism

Lift-induced Drag

- This is illustrated in Figure 2.1 and 2.2 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*.

Lift-induced Drag

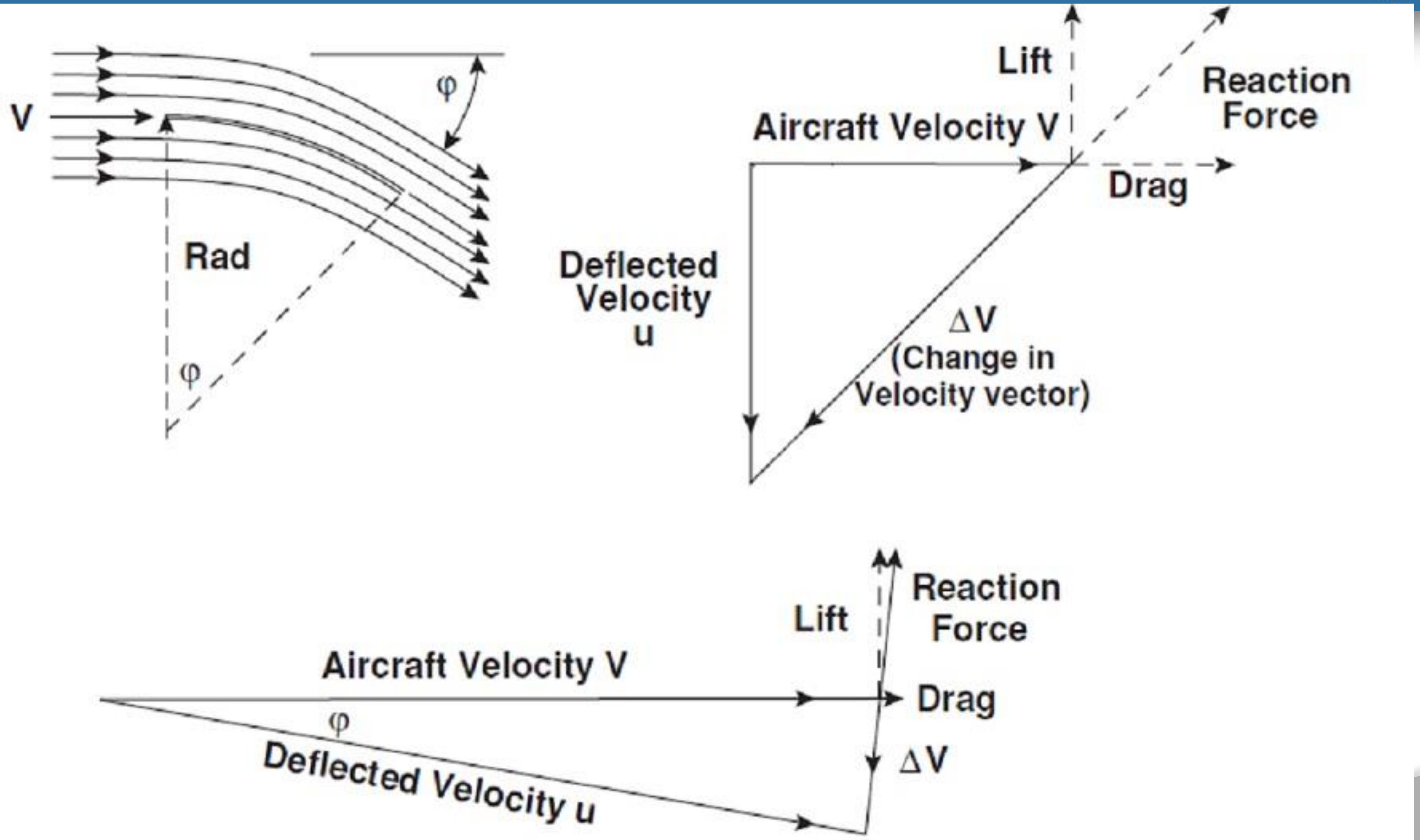


Figure 2.2: Creation of lift (and drag) by air deflection

Lift-induced Drag

- 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
- for the low values of air density at high altitudes, the aircraft **must fly fast and/or have a large wing-span** b to entrain a large mass of air

Lift-induced Drag

- The induced drag D_i of an aircraft wing varies as the square of the span loading (lift generated, L divided by span length [b]), the reciprocal of the air density ρ kg/m^2, and the square of the reciprocal of the airspeed V m/s.

$D_i = k_i.(L/b)^2/q\pi$ or $D_i = k_i.(L/b)^2/ ½\, \rho\pi V^2$

Where k_i is a non-dimensional factor, 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: $q = ½\ \rho V^2$.

Lift-induced Drag

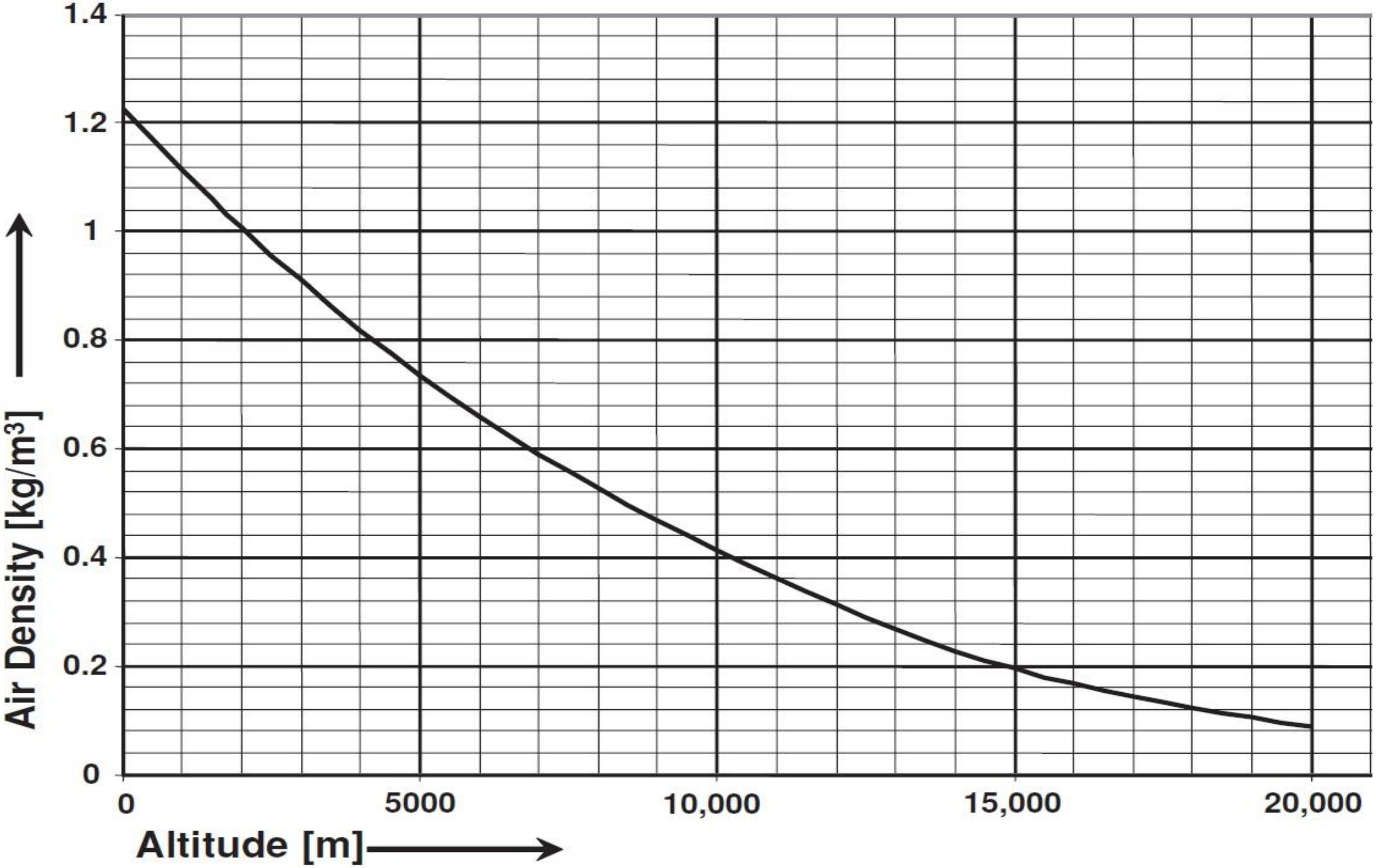


Figure 2.3: The standard atmosphere

Lift-induced Drag

- 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.
- 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.

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

Parasitic Drag

Skin Friction Drag (Friction Drag): Drag caused by the friction of a fluid against the surface of an object that is moving through it.
It is directly proportional to the area of the surface in contact with the fluid and increases with the square of the velocity.

Resistant force exerted on an object moving in a fluid

Form Drag: The drag caused by the separation of the boundary layer from a surface and the wake created by that separation. It is primarily dependent upon the shape of the object.

The pressure differential between the leading and trailing edges of the plate causes the plate to be pushed in the direction of the relative wind and retards forward motion. This is form drag.

Parasitic Drag

Interference Drag: Drag that is generated by the mixing of airflow streamlines between airframe components such as the wing and the fuselage, the engine pylon and the wing or, in the case of a military or other special purpose aircraft, between the airframe and attached external stores such as fuel tanks, weapons or sensor pods.

parasitic drag varies, on an aircraft of defined configuration, with the *air density* and with the square of the *airspeed*.

Parasitic Drag

The parasitic drag may be estimated for any level flight condition using the expression:

$$D_p = q\, C_{Dp} .\, S$$

Where *S* is the wing area and

q is the aerodynamic head: $q = 1/2 \rho V^2$ and

C_{Dp} is the parasitic drag coefficient

Parasitic Drag

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 CL, so that the parasitic drag equation then becomes

$$D_\mathrm{p} = \left(C_{\mathrm{Dp}} + k_\mathrm{p} C_\mathrm{L}^2\right) q\, S$$

V_{min} (Constraints on V, Speed of Aircraft)

[1]. **Induced drag reduces** as the square of the reciprocal of the airspeed,

$$D_i = k_i.(L/b)^2/q\pi \quad \text{or} \quad D_i = k_i.(L/b)^2/\tfrac{1}{2}\rho\pi V^2$$

$$D_i \propto 1/V^2 \text{ (Inversely)}$$

whilst the **parasite drag varies** with the square of the airspeed

$$D_p = q\, C_{Dp}.\, S, \text{ (directly)} \qquad D_p = \left(C_{Dp} + k_p C_L^2\right) q\, S$$

Thus there is an intermediate airspeed, where the induced drag equals the parasitic drag and the total drag is a minimum.

V , Speed of the aircraft : $D = D_i + D_p$ [V, speed – Less Drag]

V_{min} (Constraints on V, Speed of Aircraft)

[2] 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.

Power = Drag x Airspeed [V, speed – Less Power]

[3] 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. (Fuel/ Distance)

[V, speed –Fuel, more distance]

V_{min} (Constraints on V, Speed of Aircraft)

Speed ……Low Drag

Speed …… Low Power requirement

Speed …… Low Fuel consumption

All these **(Speed)** 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**.

Minimum Flight Speed

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.

The value of the absolute minimum flight speed is obtained by

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

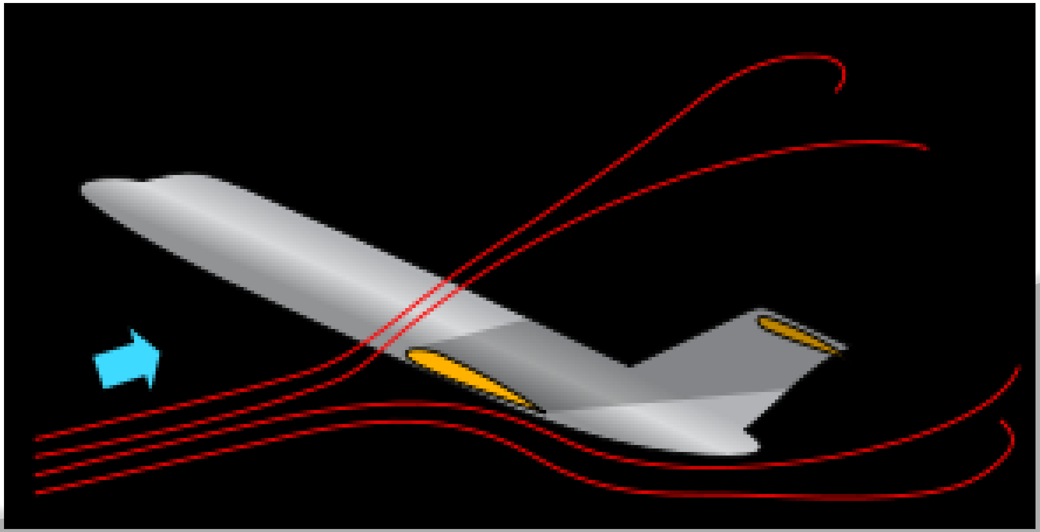
Minimum Flight Speed

- It is 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.



Practical Minimum Flight Speed

A more realistic value of V_{min} can be specified either by allowing a margin in speed or in lift coefficient.

This results in a value of V_{min} given by:

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

where C_{Lo} (operating CL) has been chosen to have a value of about 0.2 less than the $CL._{max}$ for the selected aerofoil section.

Minimum Flight Speed

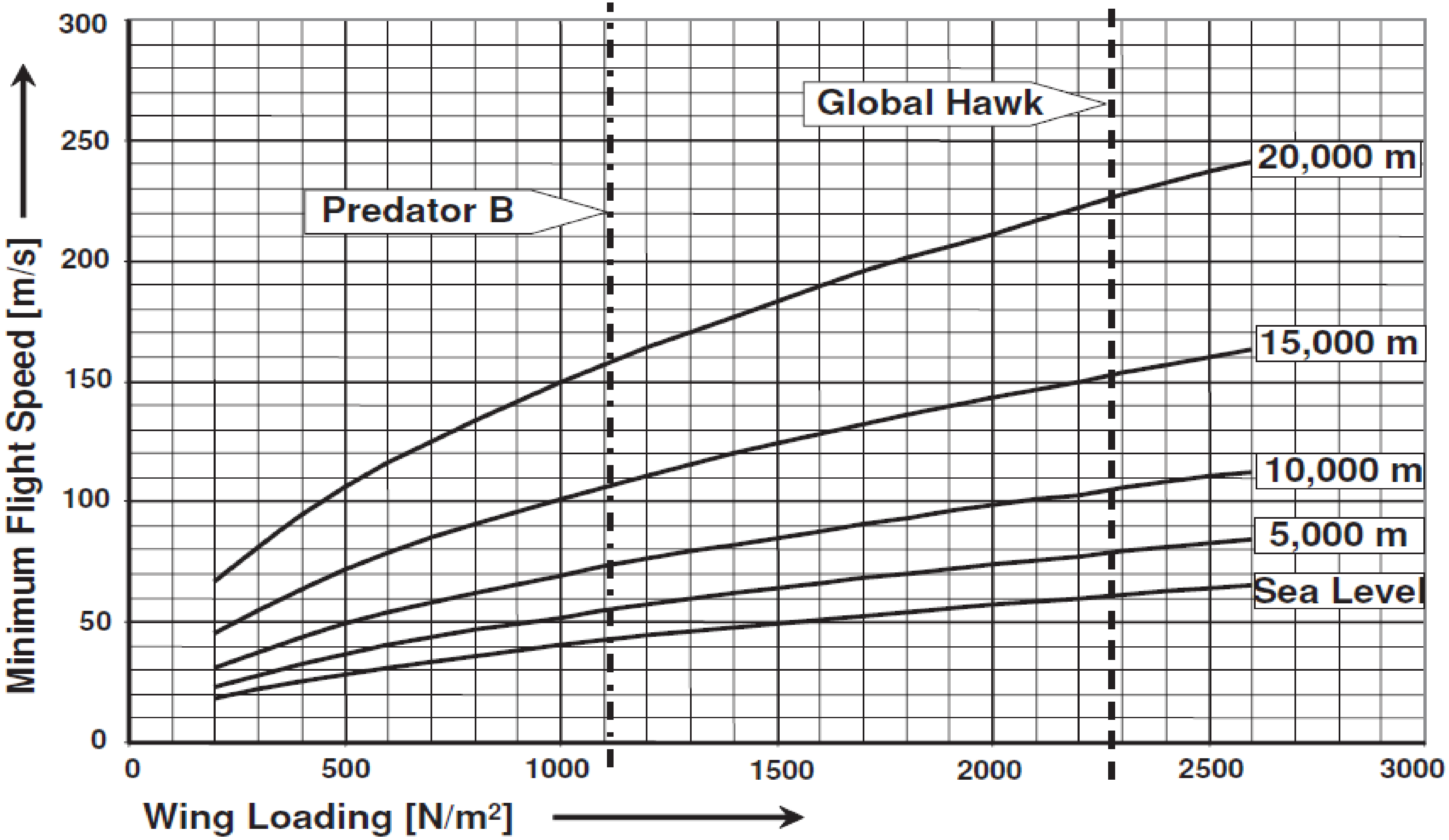


Figure 2.4: Minimum Flight Speed

Long-endurance, Long-range Role Aircraft

GLOBAL HAWK – HALE

PREDATOR - MALE

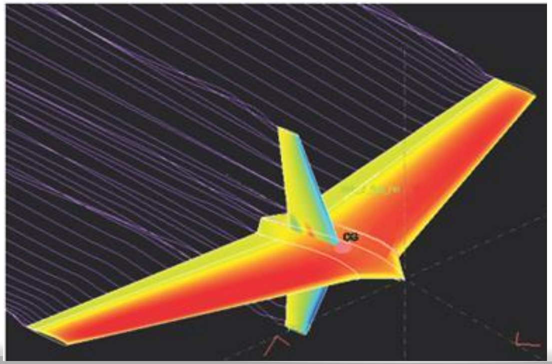
Rotary-wing Aerodynamics, Lift Induced Drag

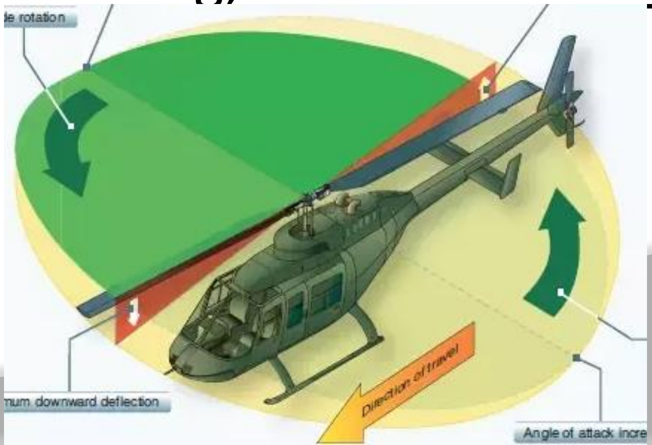
The aerodynamics of rotary-wing aircraft are, by nature, more complex than the aerodynamics of fixed-wing aircraft.

Intention is to outline some of the essential truths

- ‘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.

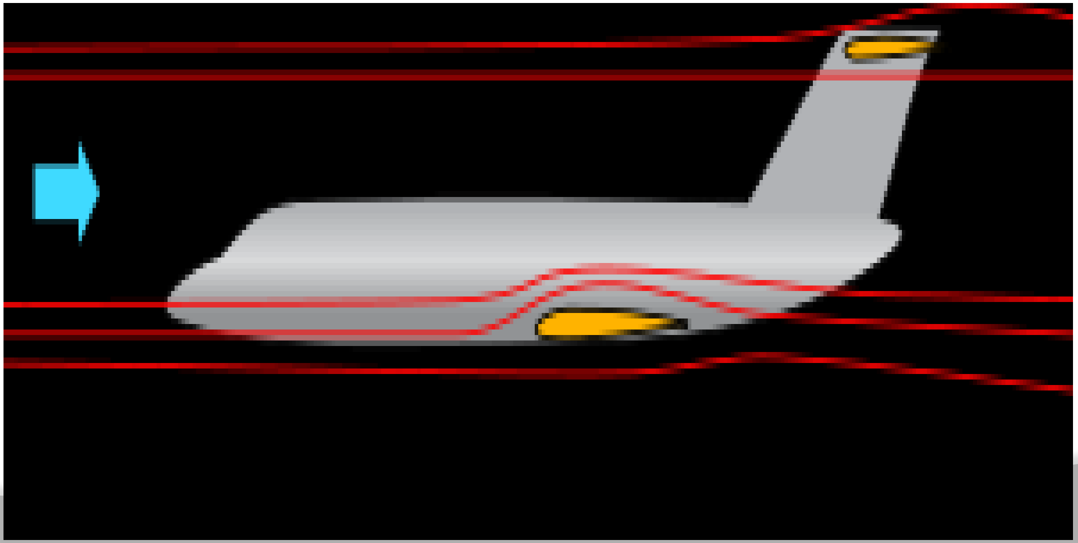


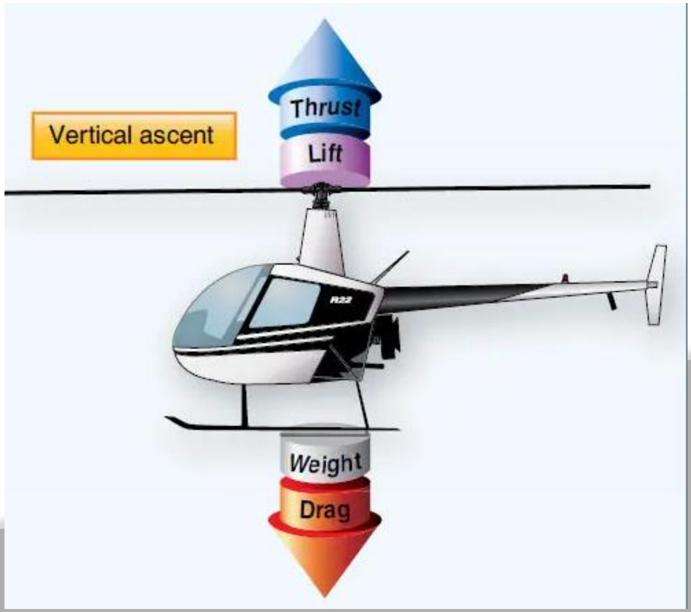


Rotary-wing Aerodynamics

Rotary wing draws in ‘new’ air from above in order to add energy to it and accelerate it downwards,

Fixed wing receives the new air horizontally to accelerate it downwards

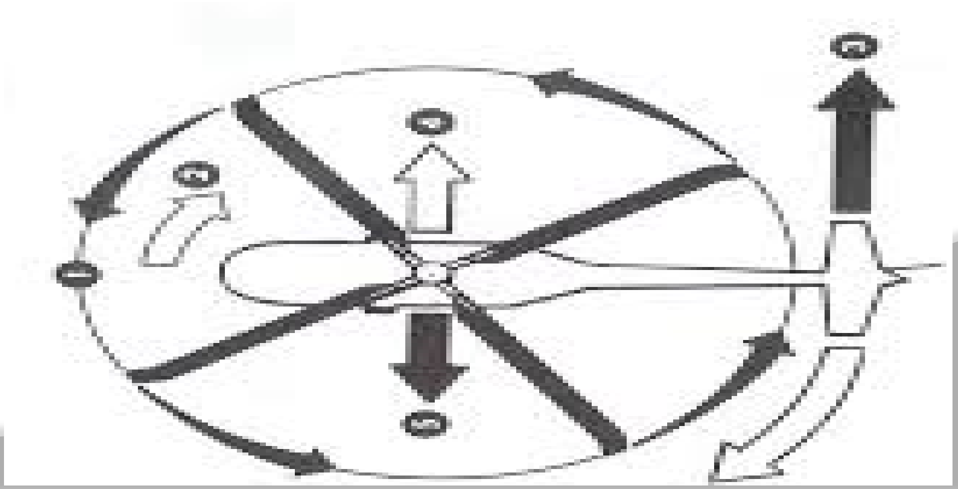




Rotary-wing Aerodynamics

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/m^2, i.e. lift produced divided by the disc area, may be seen as the equivalent of span loading for the fixed wing.



Rotary-wing Aerodynamics

The velocity induced at the helicopter rotor in the hover is given by:

$$v_{\mathrm{i}} = k_{\mathrm{n}}(p/2\rho)^{1/2}$$

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 1.1 usually being appropriate to rotors of moderate disc loading p.

Rotary-wing Aerodynamics

The induced power in hover flight is then given by

$$P_i = k_n . T\, v_i,$$

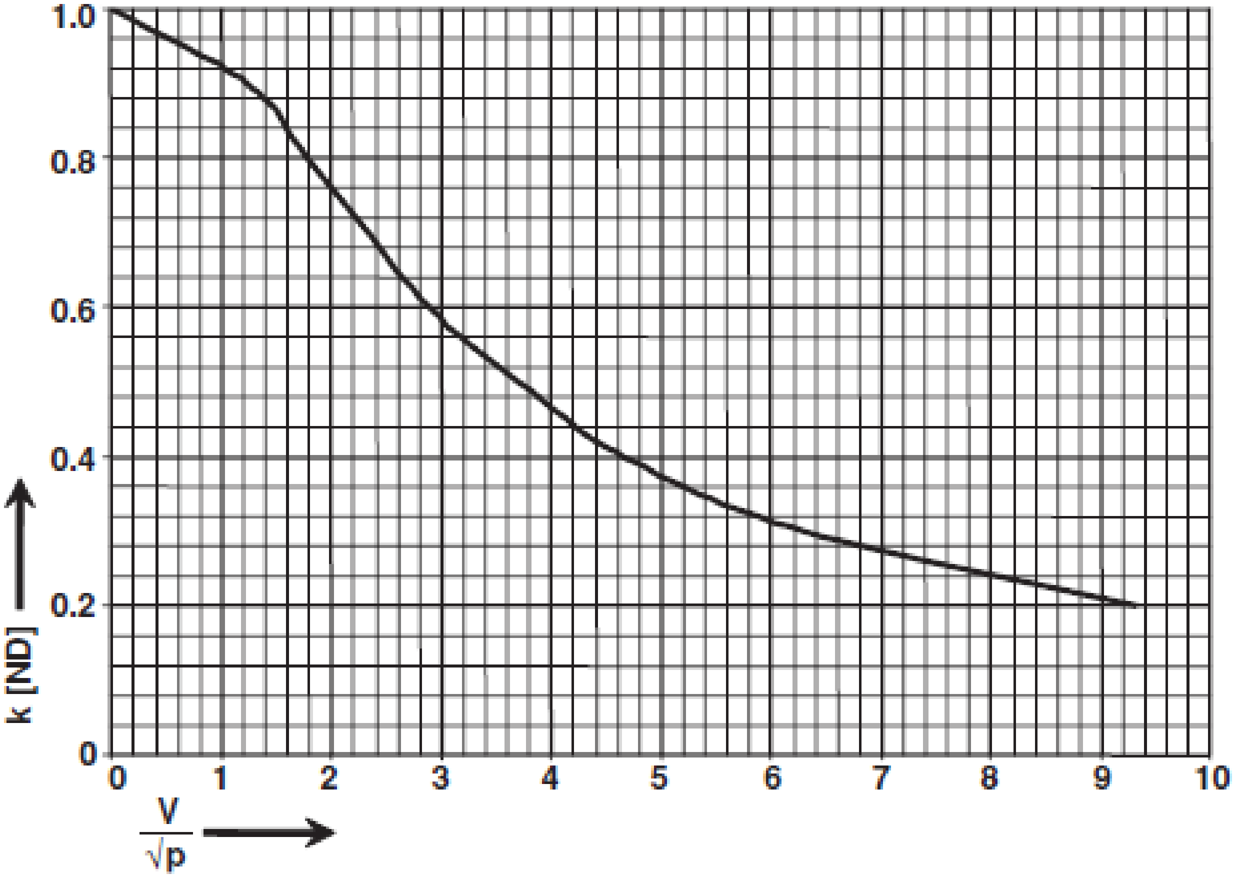
where T is the thrust produced by the helicopter rotor.

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.

$$D_i = k_i.(L/b)^2/q\pi \quad \text{or} \quad D_i = k_i.(L/b)^2/ \tfrac{1}{2}\rho\pi V^2$$

Rotary-wing Aerodynamics

There For speeds between 0 to 70 kmph



an induced factor k is plotted against a function of aircraft forward speed and disc loading (V÷ √p), The induced power calculated for the hover is multiplied by the factor k to obtain the induced power obtaining at the intermediate airspeeds.

Rotary-wing Aerodynamics

Parasitic Drag, the same elements, form drag, friction drag, etc., as discussed for the estimate of fixed-wing aircraft performance, apply to the rotary-wing aircraft .

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, etc., then comprise the parasitic drag which is calculated in the same way as for a fixed-wing aircraft.

Rotary-wing Aerodynamics

Profile Drag or Power

Hover Flight

$$\text{Profile power } P_o = \frac{1}{8}\rho\,\delta A V_T^3$$

where A is the total blade area and

V_T is the speed of the rotor tip

δ is the drag coefficient .

Rotary-wing Aerodynamics

Profile Drag or Power

Forward Flight

$$P_{0\mu} = P_0(1 + 4.73\,\mu^2).$$

μ is the ‘advance ratio’ – i.e. the ratio of the forward speed to the rotor tip speed,

P_0- Profile power in hover flight

Response to Air Turbulence

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

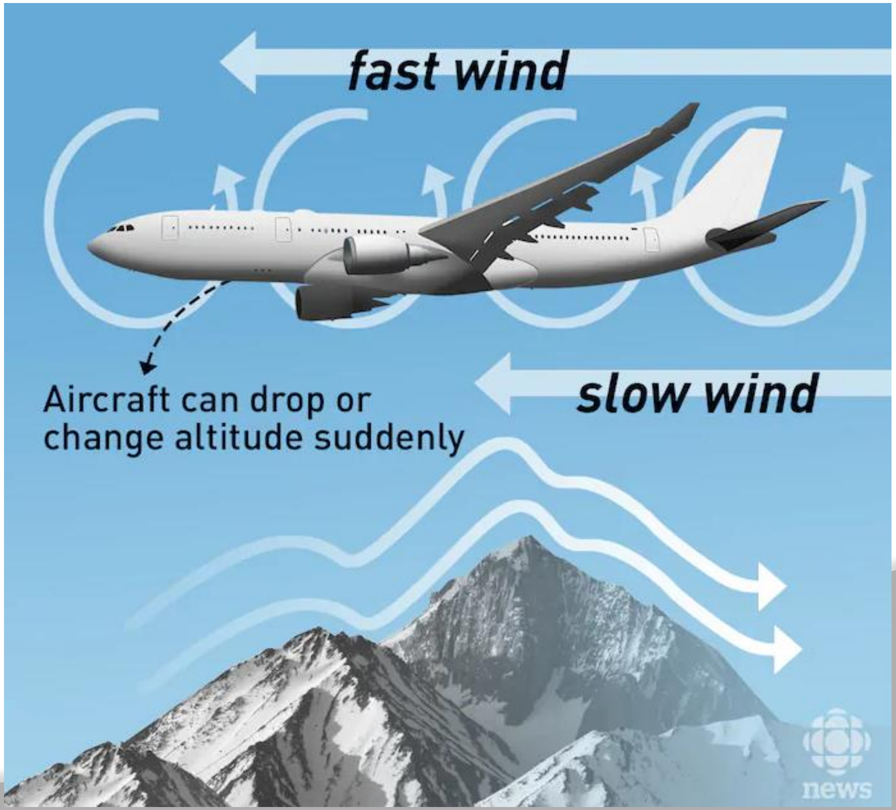
a) if it is designed to have strong aerodynamic stability;

b) if it has large aerodynamic surface areas, coupled with a high aspect ratio of those surfaces, compared with the mass of the aircraft.

Response to Air Turbulence

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 will move with the air-mass**.

The aircraft will therefore be very responsive to air turbulence (gusts).



Response to Air Turbulence

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**

This will require:

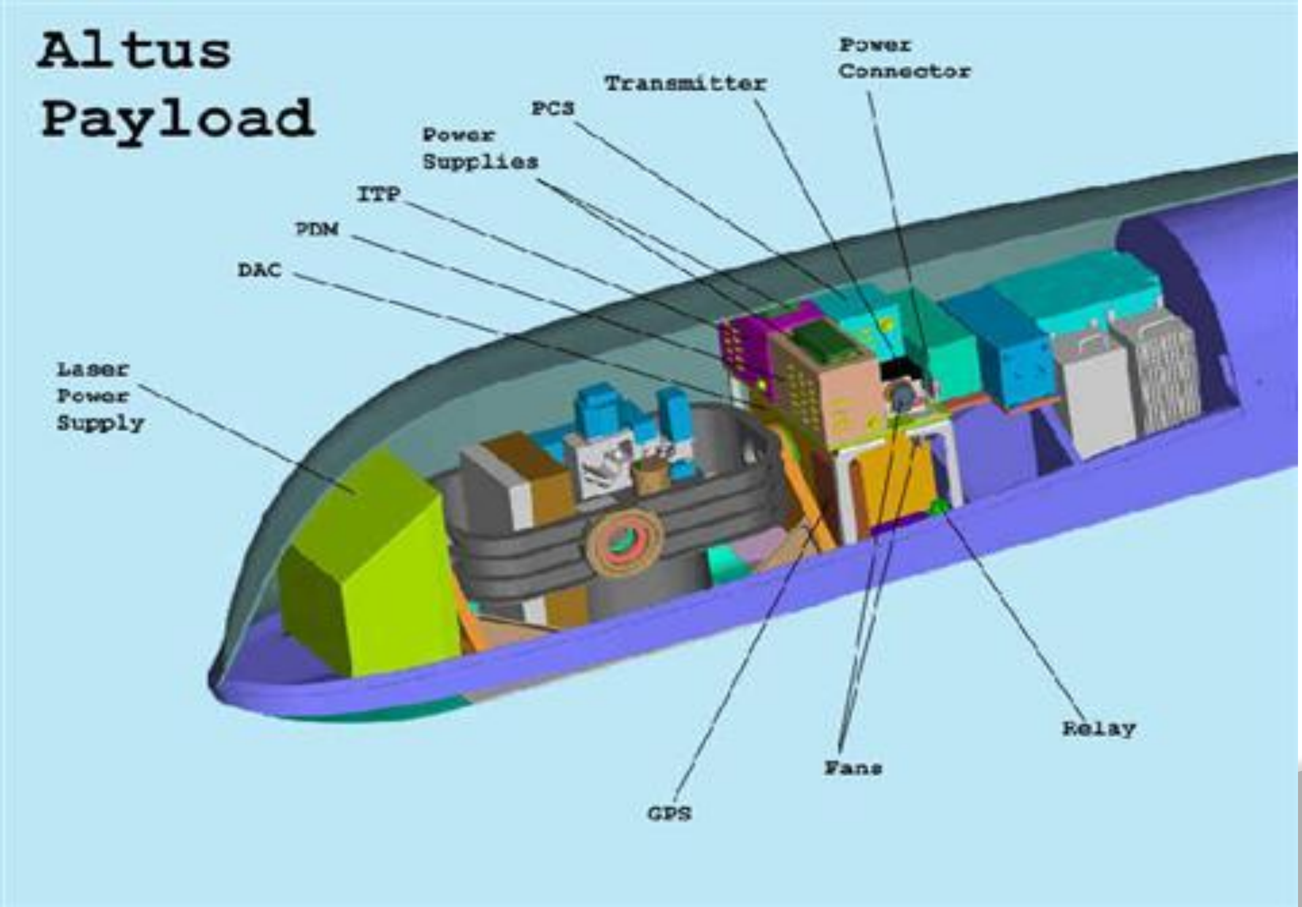
- **sensors** to measure aircraft attitudes **in the three axes of pitch, roll and yaw with speed and altitude and/or height data input.**

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.

Response to Air Turbulence

if it has large aerodynamic surface areas, coupled with a high aspect ratio of those surfaces, compared with the mass of the aircraft.



Response to Air Turbulence

How does an aircraft with large surface area to mass ratio react to gust?

How does an aircraft with low surface area to mass ratio react to gust?

More mass-----more inertia
Dense packaging of UAV -----is an advantage!

Response to Air Turbulence

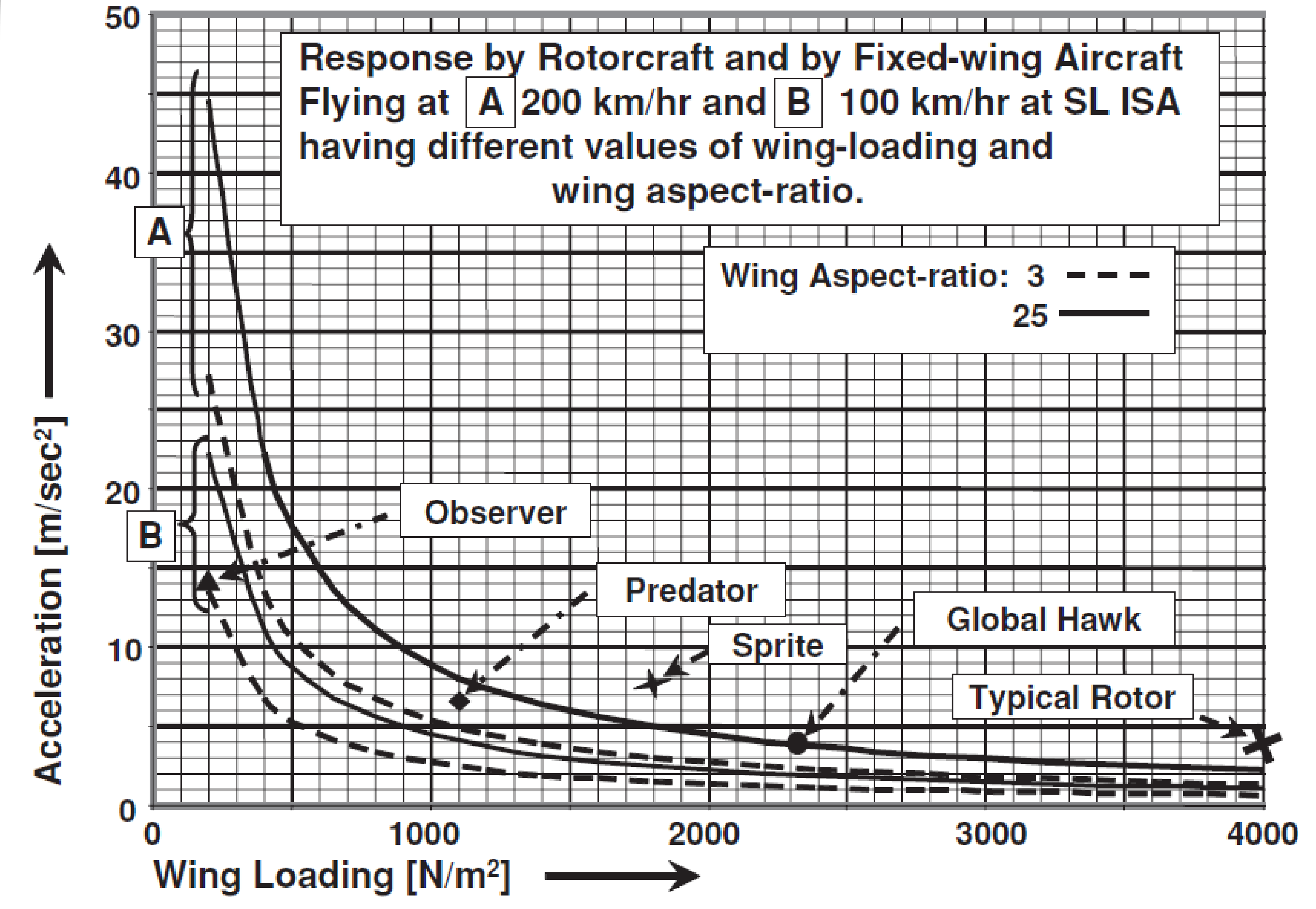


Figure 2.5: Aircraft vertical response to a vertical gust

Long-endurance, Long-range Role Aircraft

GLOBAL HAWK – HALE

PREDATOR - MALE

Observer

Figure 3.40 : Pioneer three-view drawing

ML Aviation SPRITE

Figure 3.46 : ML Aviation SPRITE

Gust Effect Calculation

The vertical acceleration in response to a 1 m/s vertical gust is approximately given by the expression:
acceleration = K1 × K2 × V/w_m, where K1 and K2 are constants:
K1 = ½ ρa and K2 = AR ÷ (AR +2.4).
a, two-dimensional aerofoil lift curve slope (= 5.73).

V (m/s) is the forward speed of the aeroplane or 2/3 of the rotor tip speed of the helicopter.
w_m (kg/m2) 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/m^2 divided by the gravitational acceleration g.

Airframe Configurations

HTOL aircraft configurations

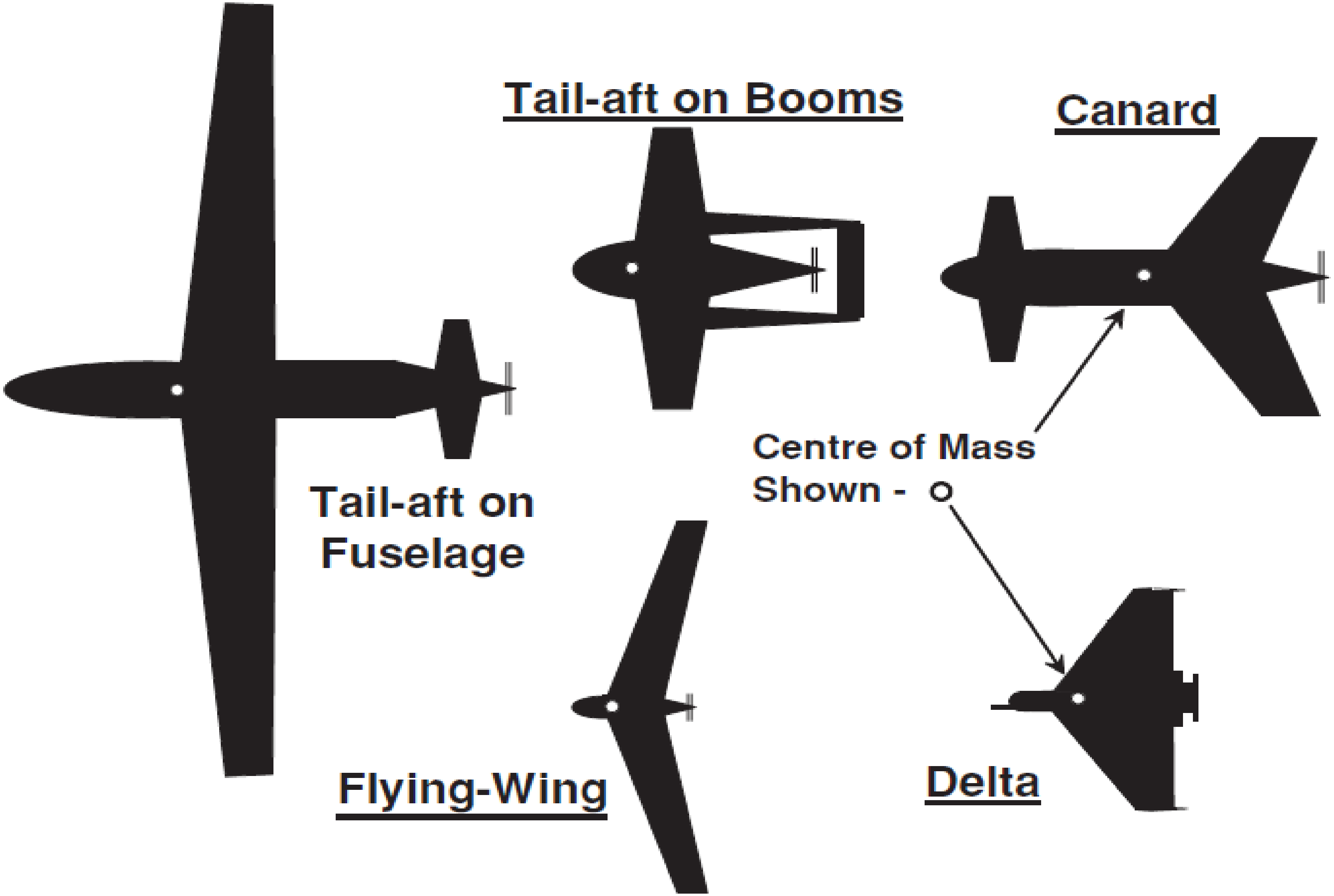


Figure 2.6: HTOL aircraft configurations

Main Wing Forward with Control Surfaces aft

This is accepted as the conventional arrangement.

- The aircraft centre of mass is **forward of the wing centre 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 **weathercock stability in yaw** with wing dihedral giving stability in roll

Main Wing Forward with Control Surfaces aft

Main Wing Forward with Control Surfaces aft

Main Wing Forward with Control Surfaces aft

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

Main Wing Forward with Control Surfaces aft

- 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 (payload) 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

Main Wing Forward with Control Surfaces aft

Hunter

Shadow

Canard Configuration

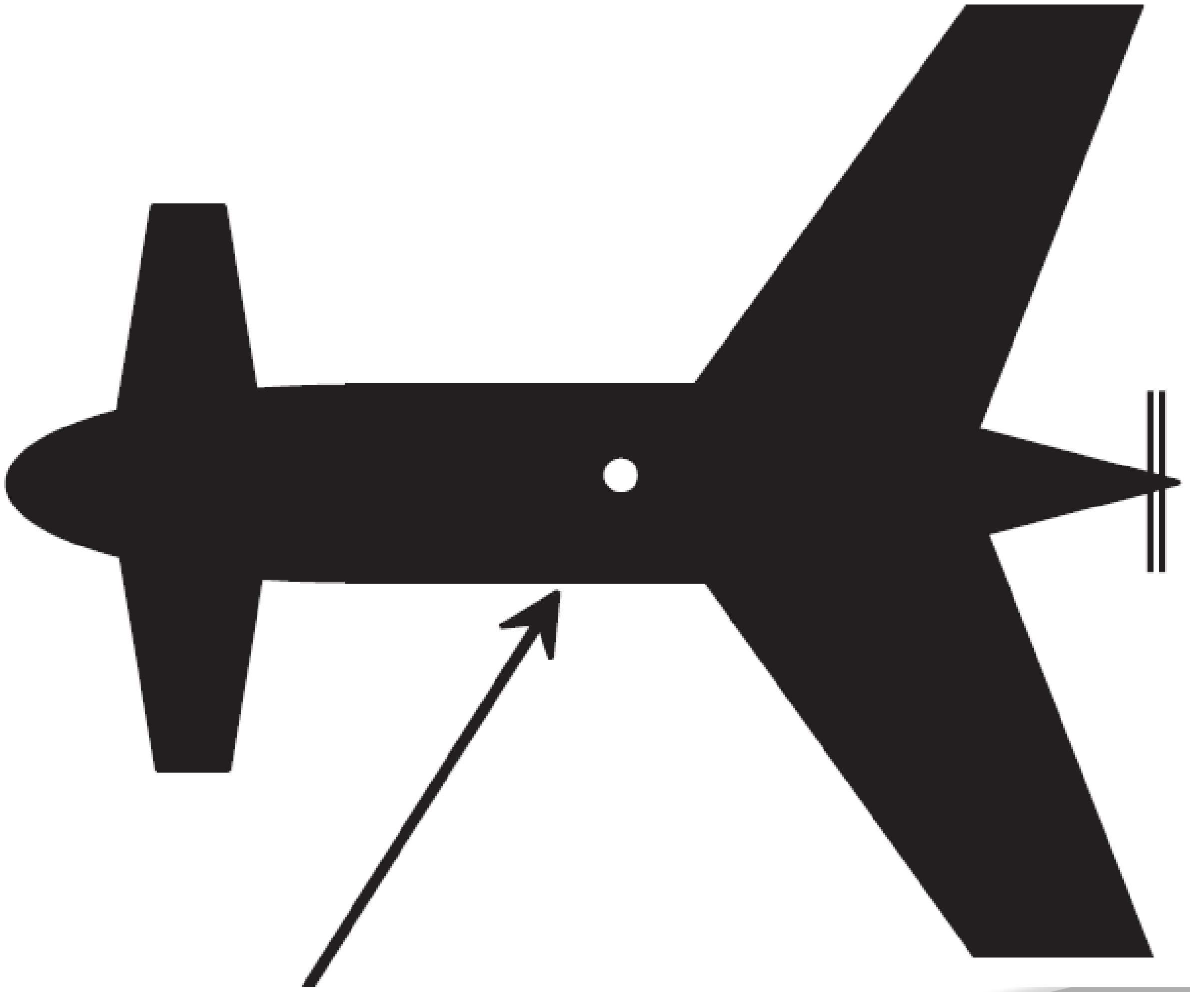


Figure 2.7: Canard Configuration

Canard Configuration

A canard configuration has the horizontal stabiliser mounted forward of the wing. The aircraft centre of mass is also forward of the wing and the balance is achieved with the foreplane (horizontal stabiliser) 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.

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

Figure 2.8: Blue Horizon UAV

Canard 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.

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

Flying Wing or “Tailless” Configurations

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.

Flying Wing or “Tailless” Configurations

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.

Northrop Grumman RQ-180 Low-Observable Flying-Wing Stealth UAS/UAV

AVIC 601-S Chinese low-observable flying wing UAV

Delta-wing Configuration

The delta-wing configuration, such as in the Observer UAV 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**.

Delta-wing Configuration

Observer

VTOL Configurations

Single-main-rotor or 'Penny-farthing'

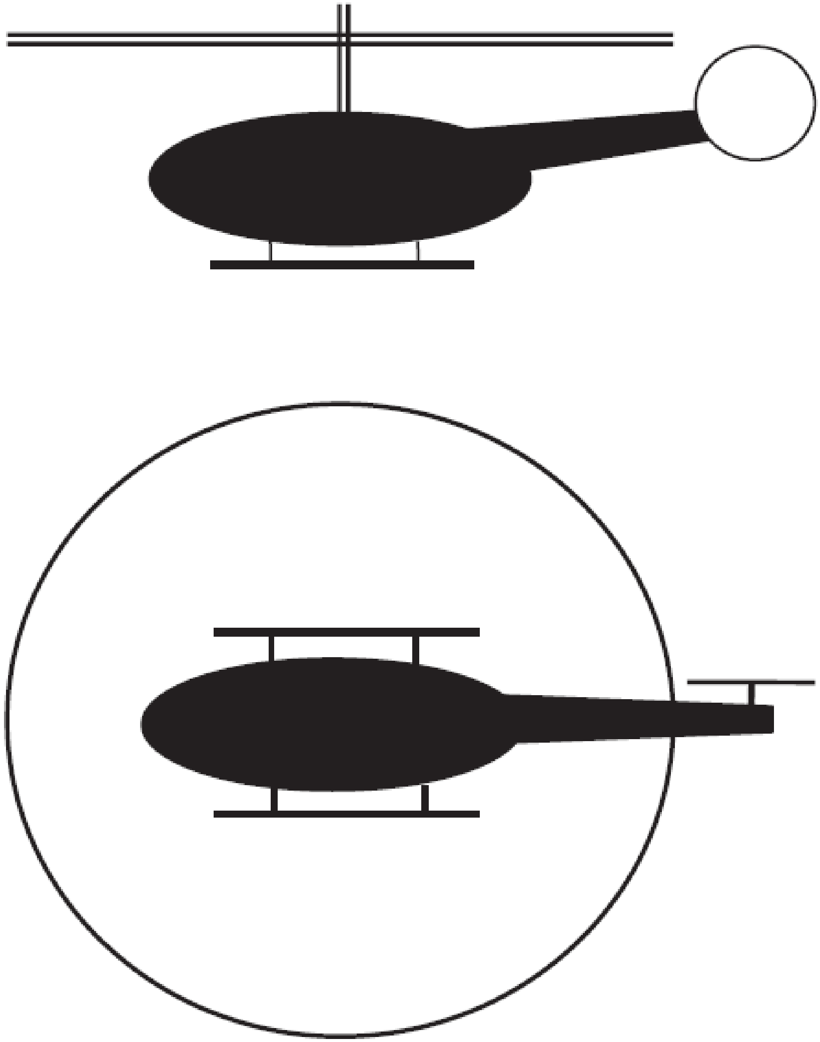
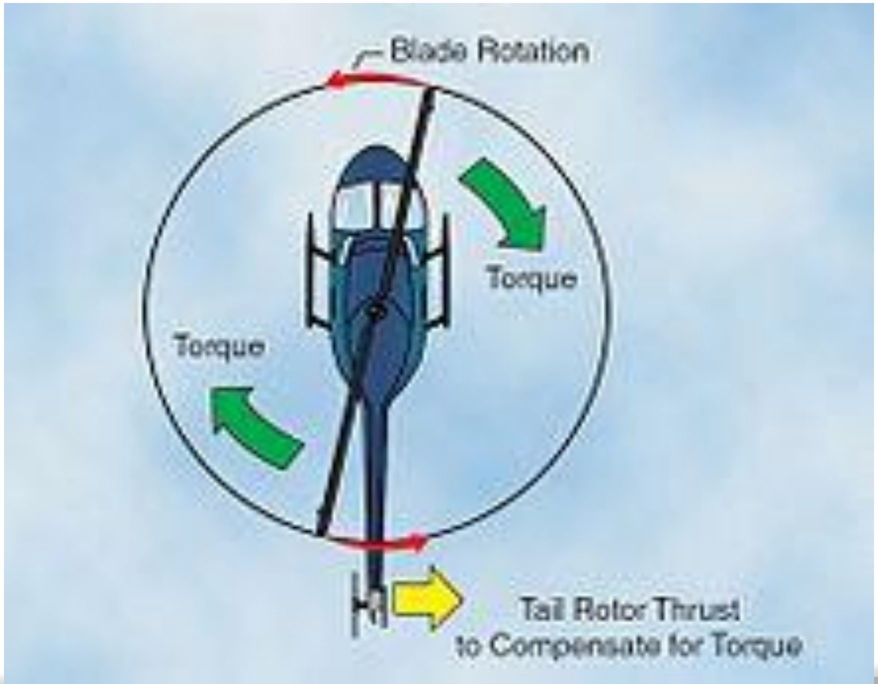
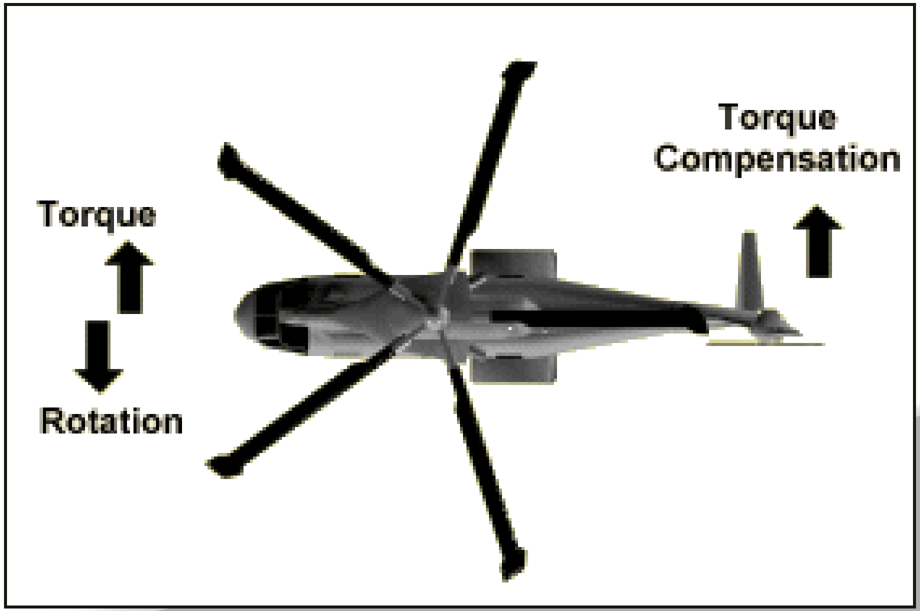


Figure 2.9: Single-main-rotor

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 further 10% onto the main rotor power demands.





Single-main-rotor or ‘Penny-farthing’

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 600–15 000 kg which currently covers the majority of rotorcraft requirements.

Single-main-rotor

Figure 2.10: Fire Scout

Tandem Rotor

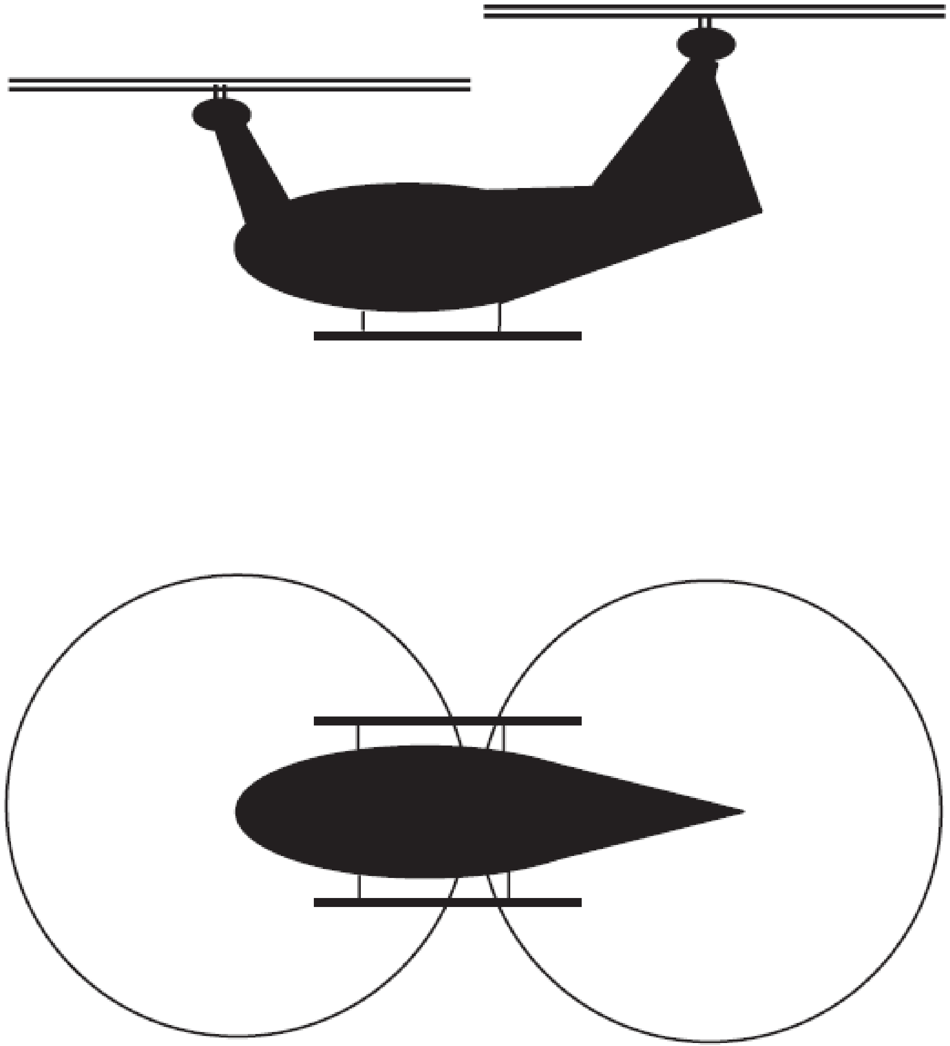


Figure 2.10: Tandem rotor

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.

This configuration is more symmetric in control than the ‘single rotor’ and is more power efficient.

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.

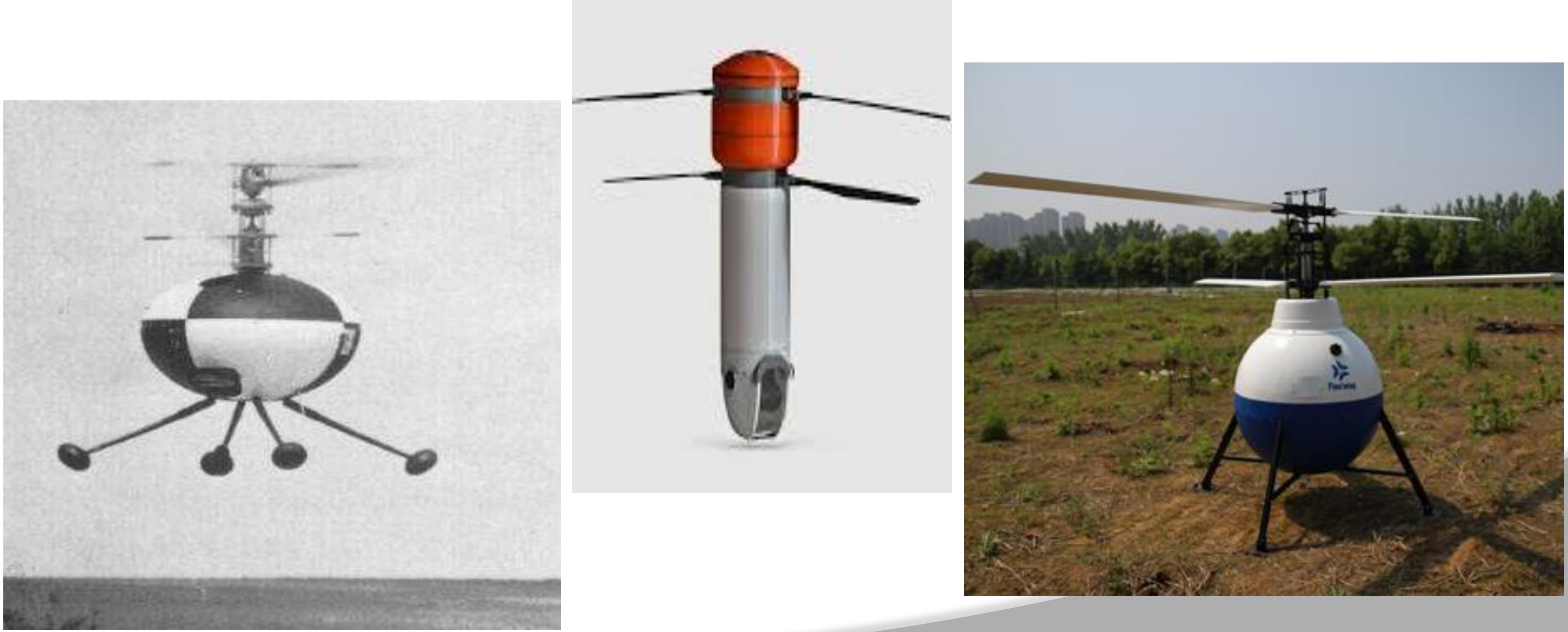
Coaxial Rotor

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***.

Hence the **automatic flight control system (AFCS) algorithms are no more complex than that of a typical HTOL aircraft.**

Coaxial Rotor

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. the coaxial configuration used less power in hover flight than did the single-rotor



Quad-rotor

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.

Quad-rotor

Hybrid Airframe Configurations

200 kt (370 km/hr)

Long range

Hybrid Airframe Configurations

Convertible Rotor Aircraft

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.

Smart UAV

Hybrid – Convertible - Tilt rotor

Bell Eagle Eye, TR911X

Hybrid – Convertible - Tilt rotor

V22 OSPREY

Hybrid – Convertible- Tilt wing

- ‘**Tilt rotor**’, retains the wing fixed horizontally to the fuselage and the rotors, with their pylons, are tilted relatively to the wing
- ‘**Tilt wing**’, power-plants and rotors to be constructed as an assembly and for the assembly to be hinged on the upper fuselage.

Kaman K-16B

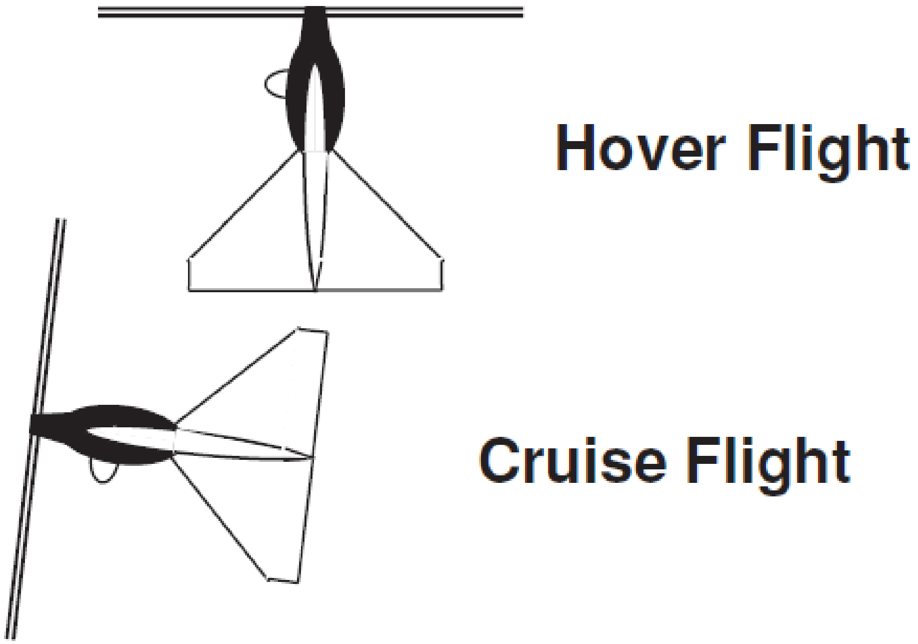
Hiller X-18

Hybrid- Tilt wing

Hybrid- Tilt wing

Tilt-wing-body Aircraft

In the case of crewed aircraft it is desirable to retain the fuselage sensibly horizontal for both flight crew and passengers. No such constraint exists for the UAV. It is therefore theoretically possible to tilt the whole aircraft



Ducted Fan Aircraft

The ducted fan aircraft, 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 minimise rotation of the body by a resultant torque

The greater problem would be the attitude control of the body as the vanes may lack sufficient force or response to ensure a controllable, stable system.

Jet-life Aircraft

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.

Jet-life Aircraft

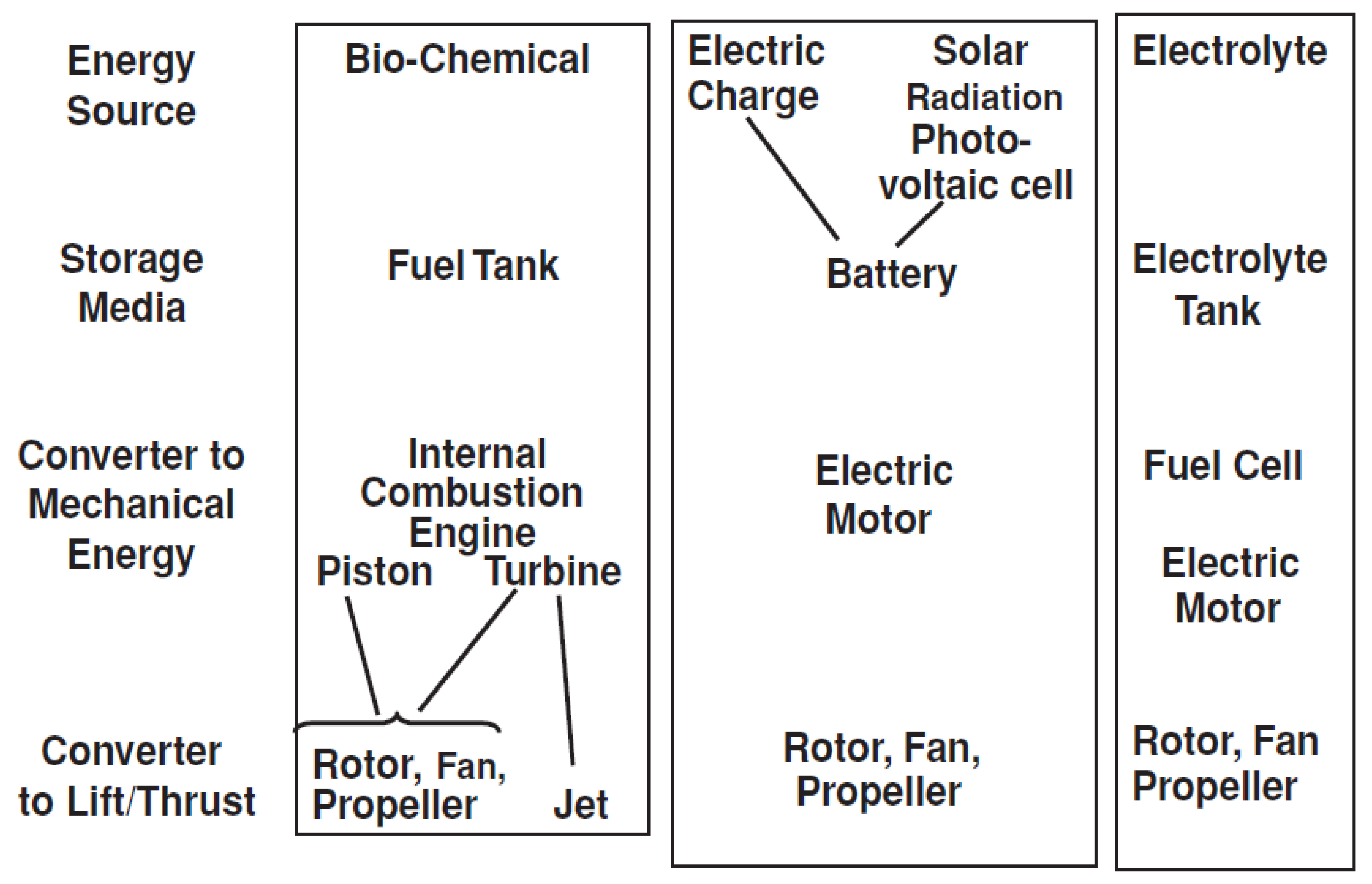
Harrier fighter aircraft

Jet-life Aircraft

Harrier fighter aircraft

Selection of Power-plants

Selection of Power-plants



Energy Source	Bio-Chemical	Electric Charge Solar Radiation Photo-voltaic cell	Electrolyte
Storage Media	Fuel Tank	Battery	Electrolyte Tank
Converter to Mechanical Energy	Internal Combustion Engine Piston Turbine	Electric Motor	Fuel Cell Electric Motor
Converter to Lift/Thrust	Rotor, Fan, Propeller Jet	Rotor, Fan, Propeller	Rotor, Fan Propeller

Figure 2.13: Power- generation Systems

Selection of Power-plants

- Piston Engines
    - Two-stroke engines
    - Four-stroke engines
    - Stepped piston engines
    - Rotary engines

- Gas-turbine Engines
    - Turbo-jet engines
    - Turbo-shaft engines
    - Turbo-fan engines

- Electric Motors

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, Some use valves for controlling the airflow, others do not.

- **Both types** can be designed to use petroleum fuels or, 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.

Two-stroke and Four-stroke engines

- 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.**

- Running a piston engine at full power and speed will tend to increase the specific consumption compared with lower powers and speeds

- 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

Two-stroke and Four-stroke engines

- 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.

- The **torque peaks** of the two-stroke unit are much smaller than those of the comparable **four-stroke** unit.

- Linear vibration has also to be considered and will be largely a function of the number of cylinders of the engine.

Stepped Piston, Two-stroke, Engines

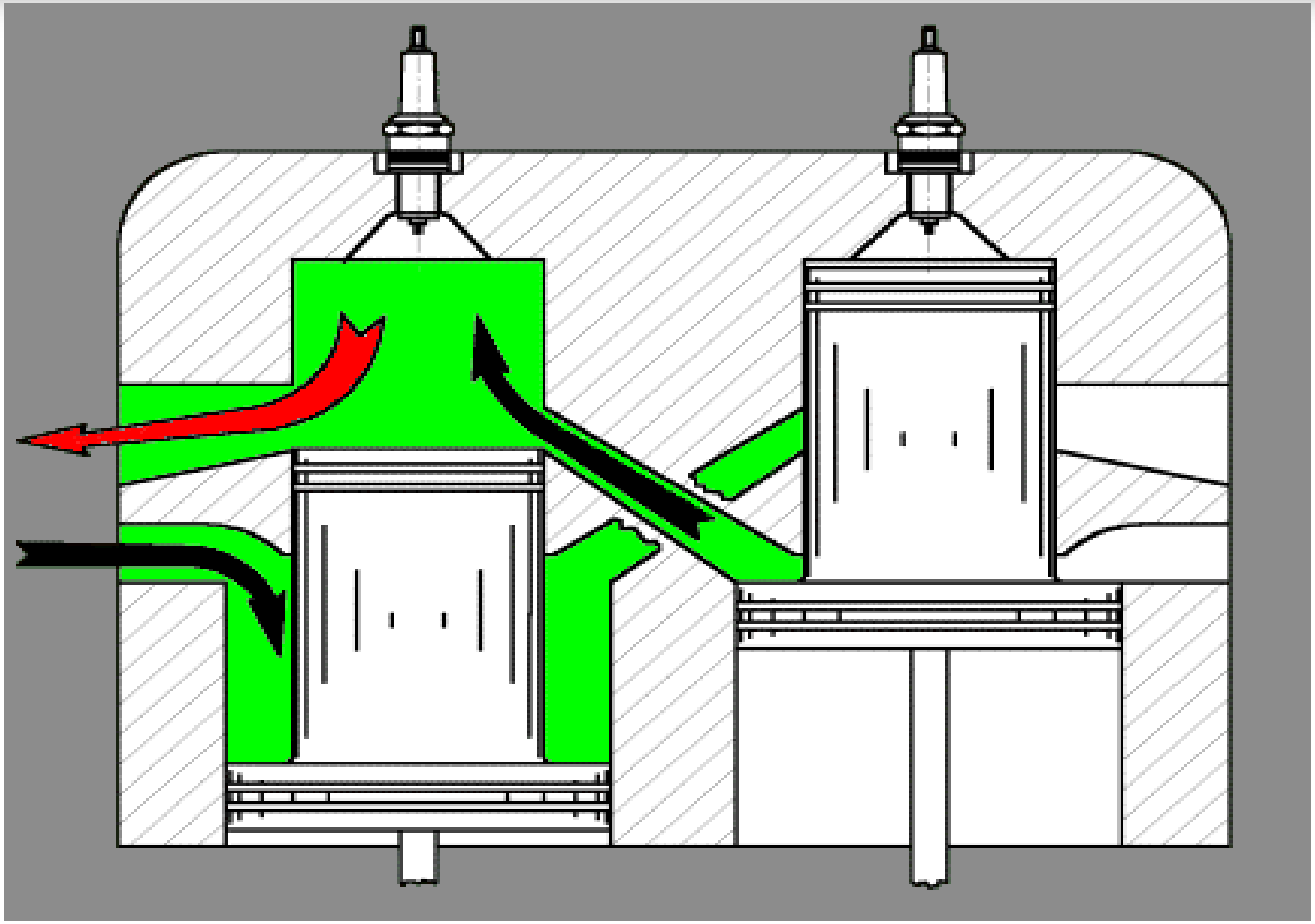


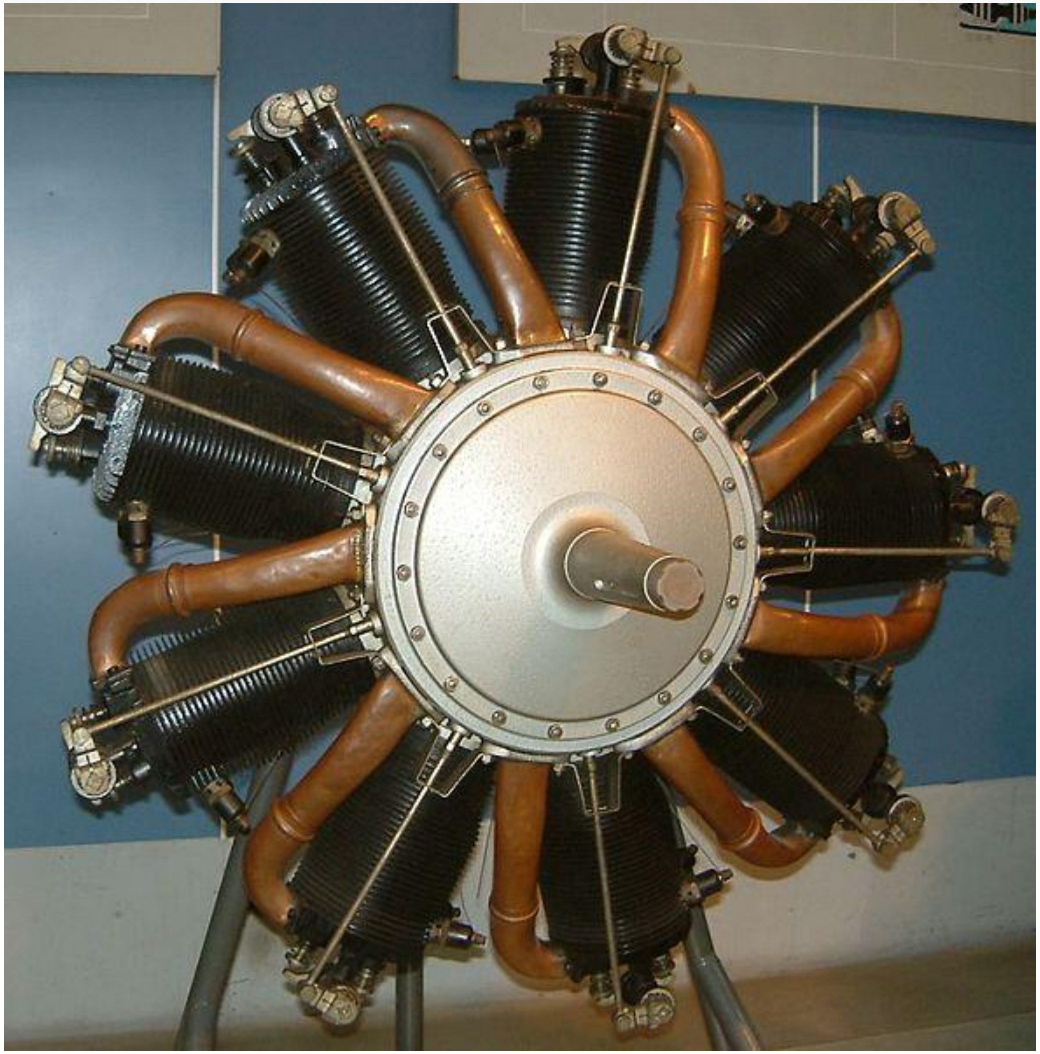
Figure 2.15: Stepped piston, two-stroke, engine

Stepped Piston, Two-stroke, Engines

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.

Rotary Engines



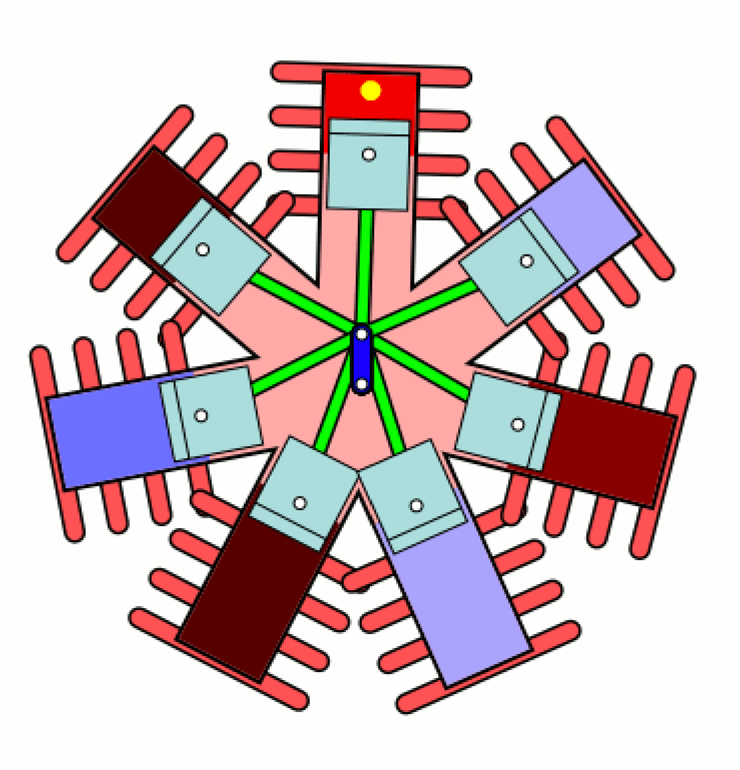


Figure 2.16: Rotary engine

Rotary Engines

Figure 2.17: Hermes-180, Israeli tactical close range UAV

Rotary Engines

- 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.

Gas-turbine Engines

Gas-turbine engines are fundamentally quieter than piston engines and produce smooth power at low mass/power ratios.

(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.

(iii) 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.

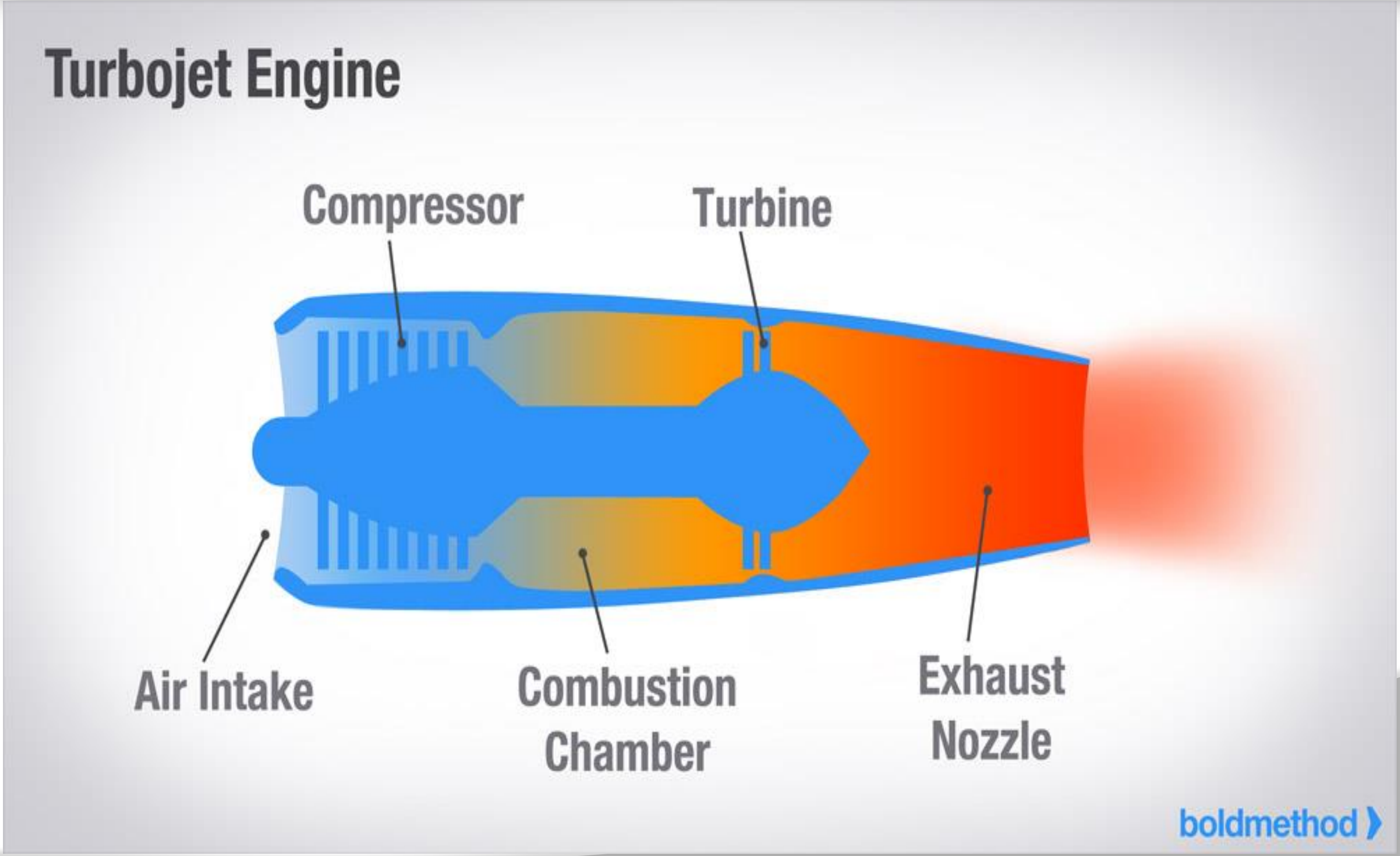
Gas-turbine Engines

The 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:

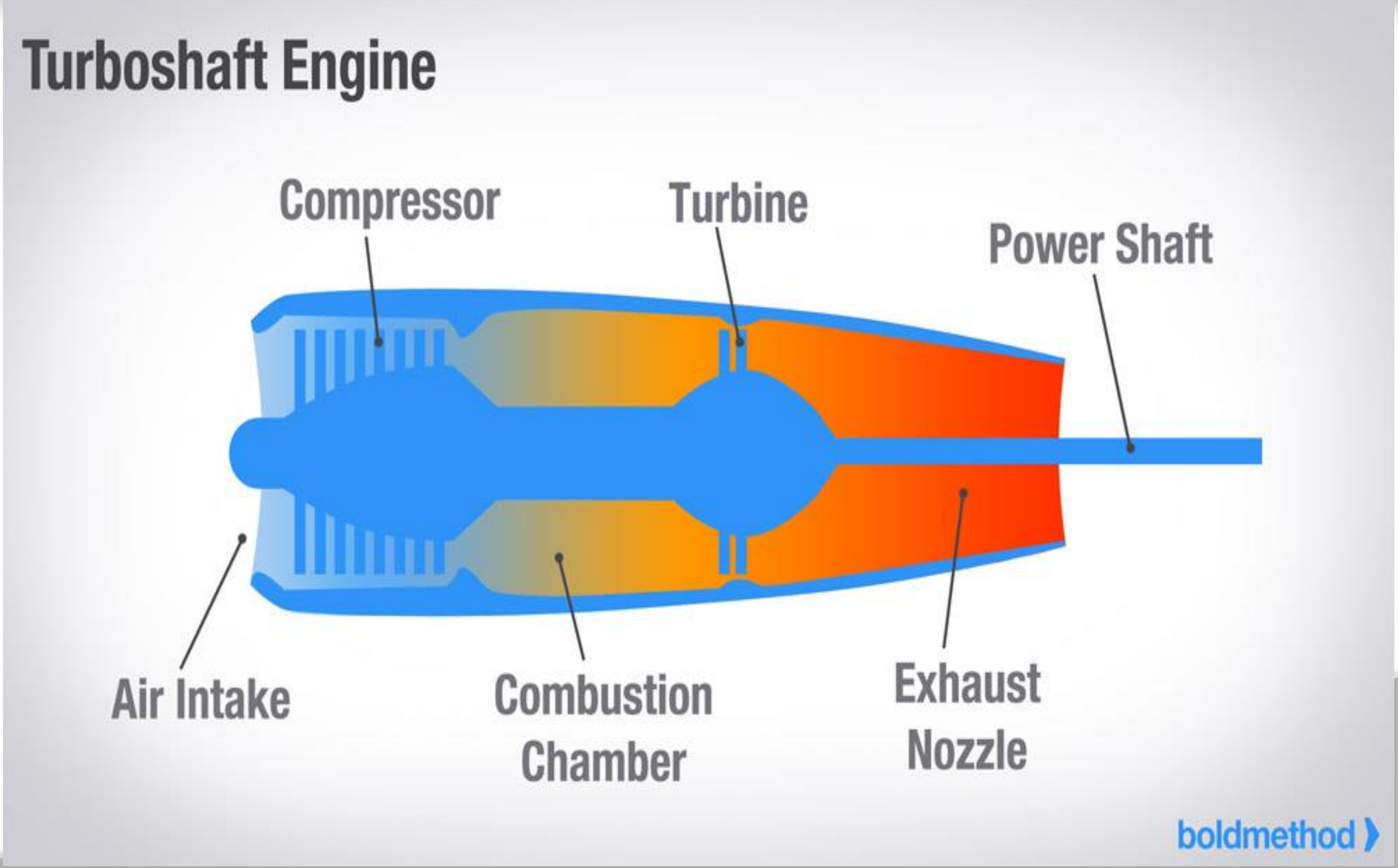
(i) turbo-jet units which are designed to produce thrust (kN) from a high-velocity jet for direct propulsion;

(ii) Turbo-shaft units which produce power (kW) in an output shaft which may drive a propeller or helicopter rotor to provide thrust

Gas-turbine Engines- Turbojet



Gas-turbine Engines- Turboshaft

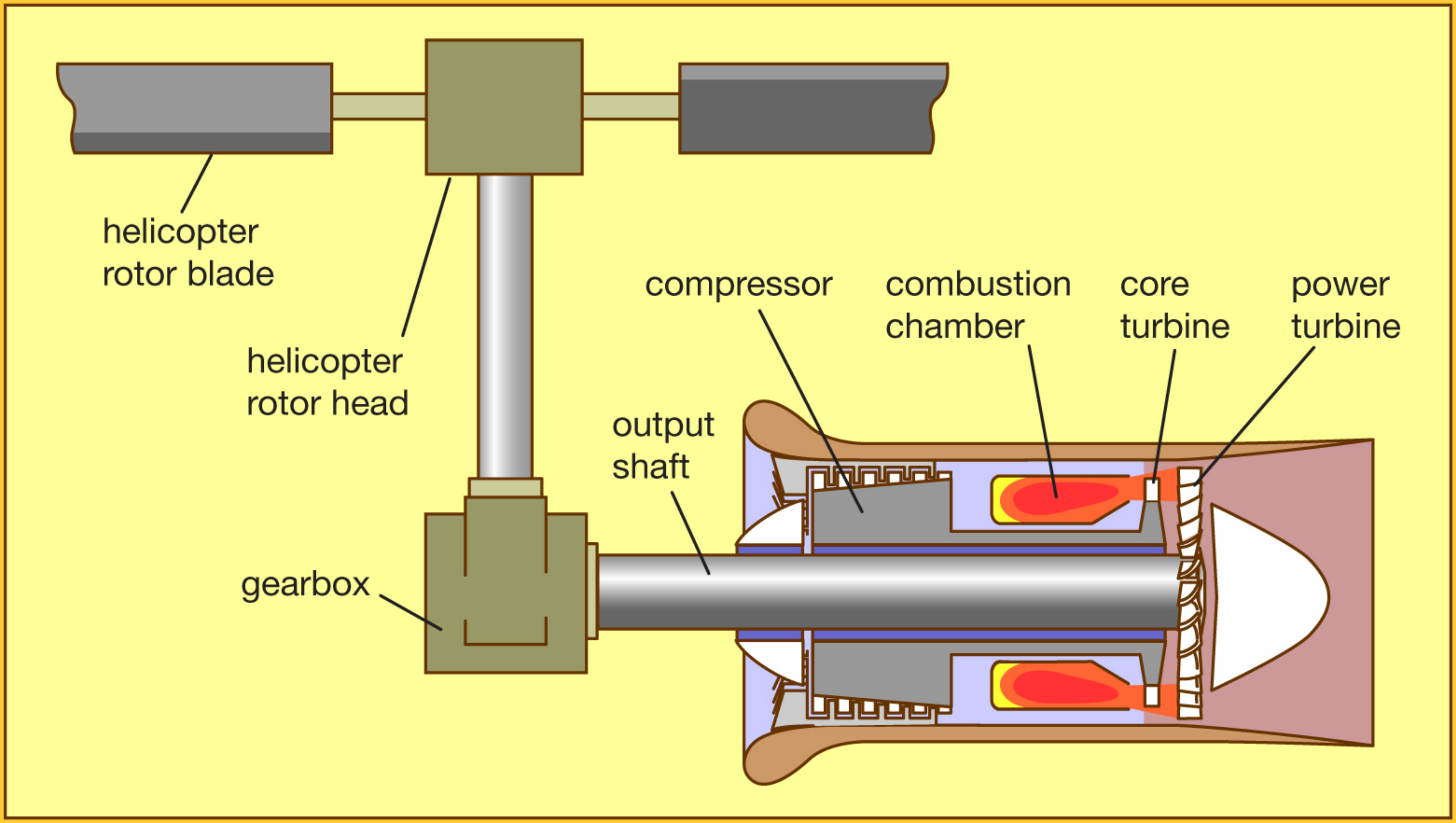


Gas-turbine Engines- Turboshaft

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.

Gas-turbine Engines- Turboshaft



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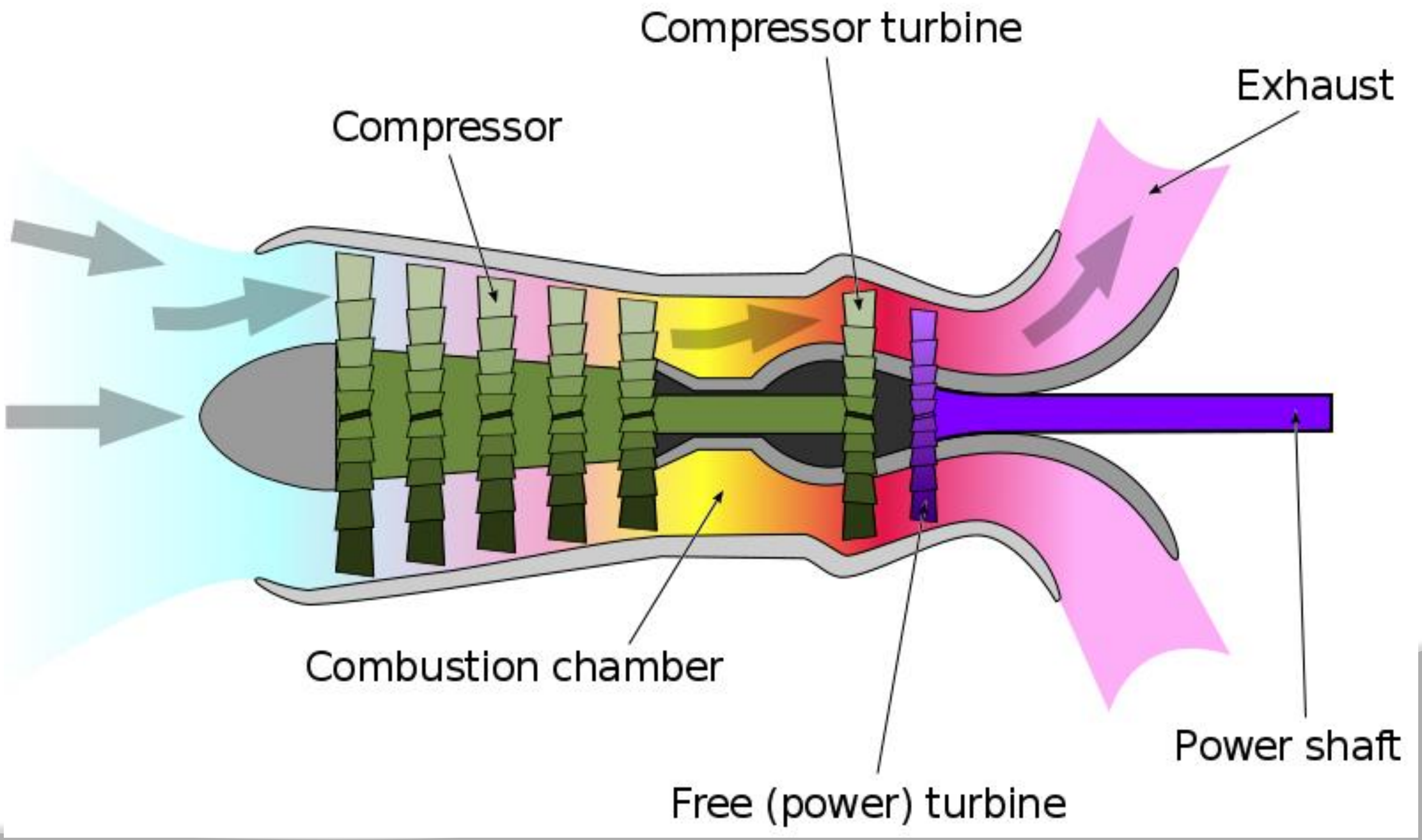
Gas-turbine Engines- Turboshaft

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.

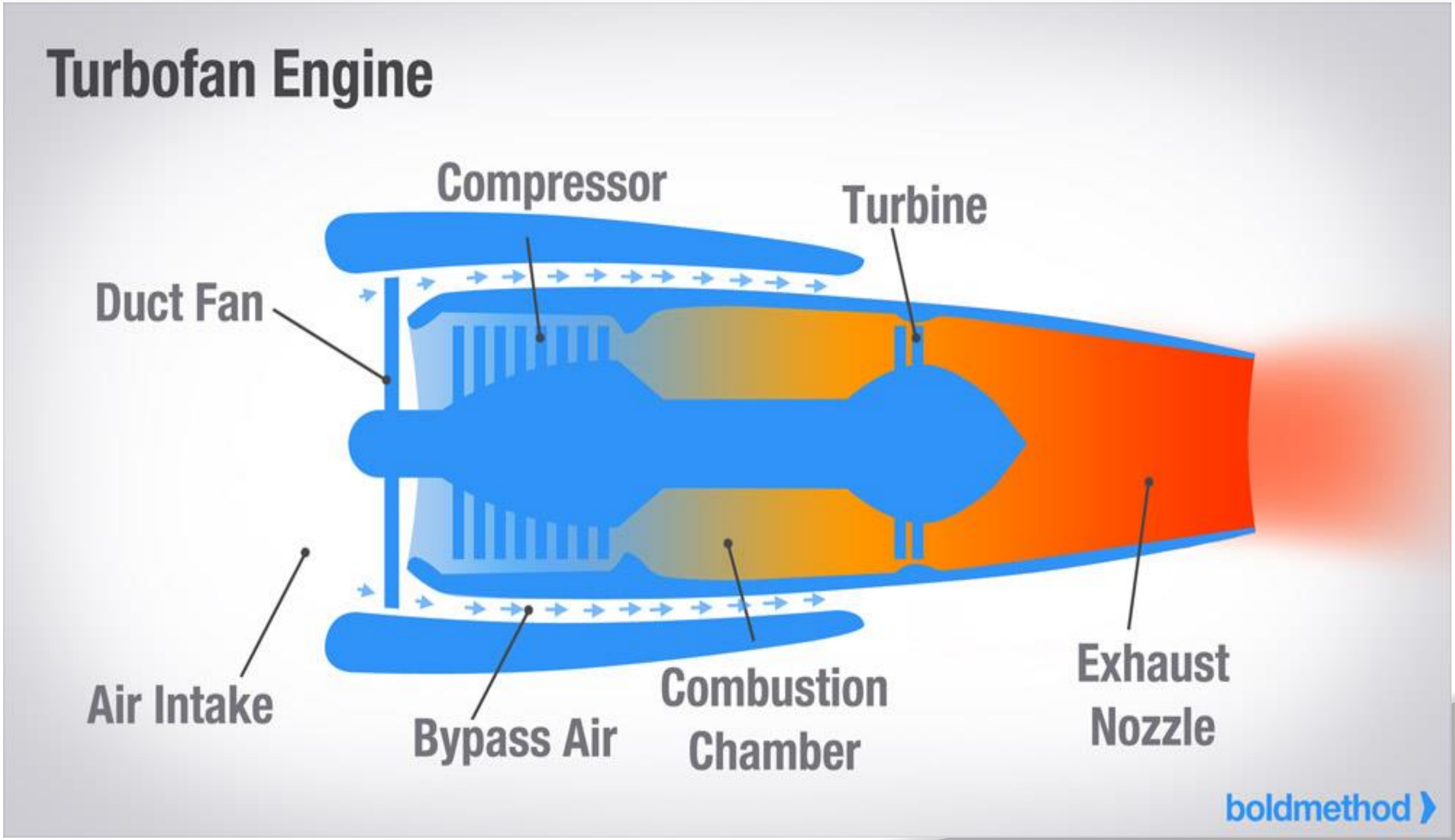
Turboshaft -free-power-turbine (FPT)



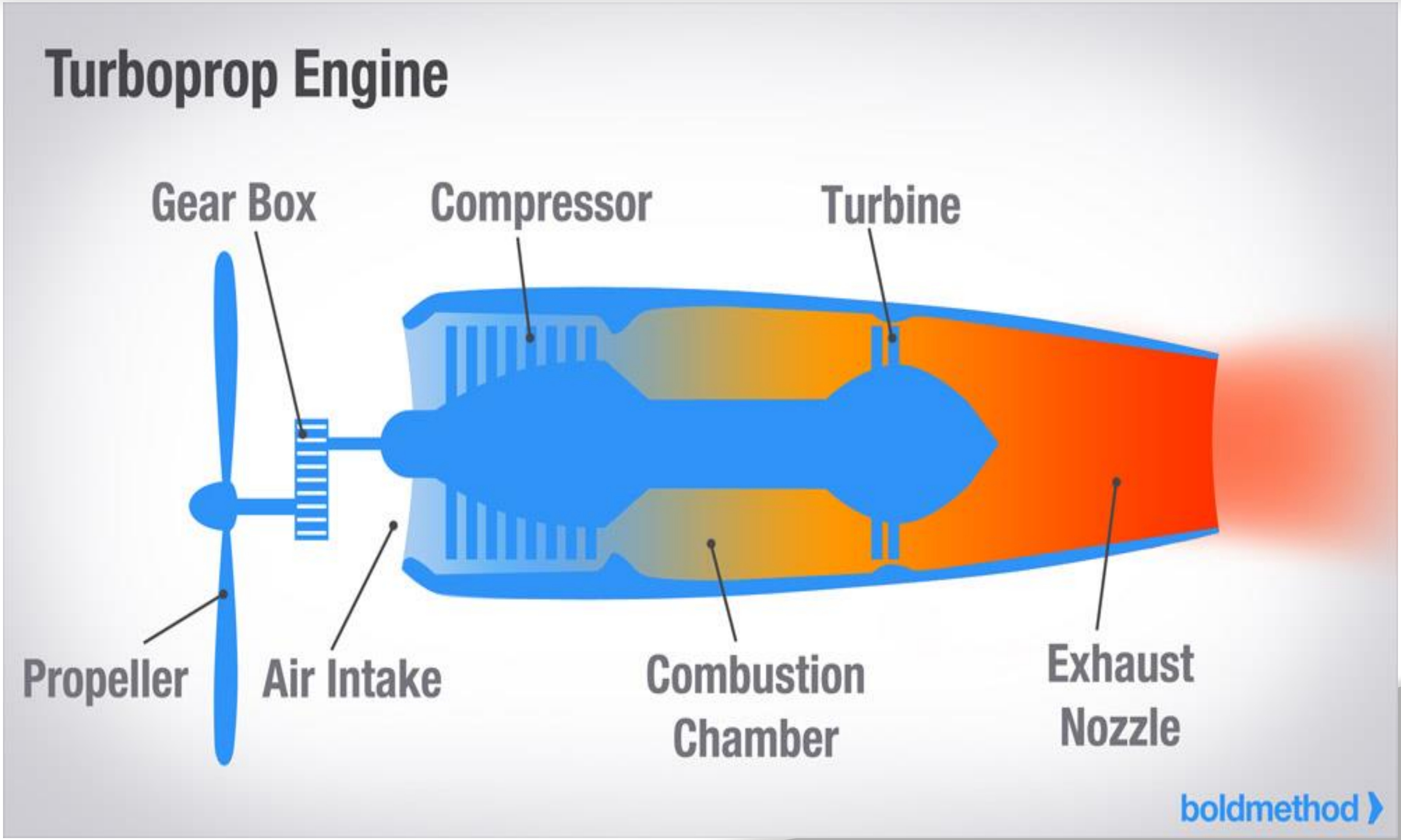
Gas-turbine Engines - Turbofan

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.

Gas-turbine Engines - Turbofan



Gas-turbine Engines - Turboprop



Gas-turbine Engines

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.

Gas-turbine Engines

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.

Gas-turbine Engines

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 Firescout 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.

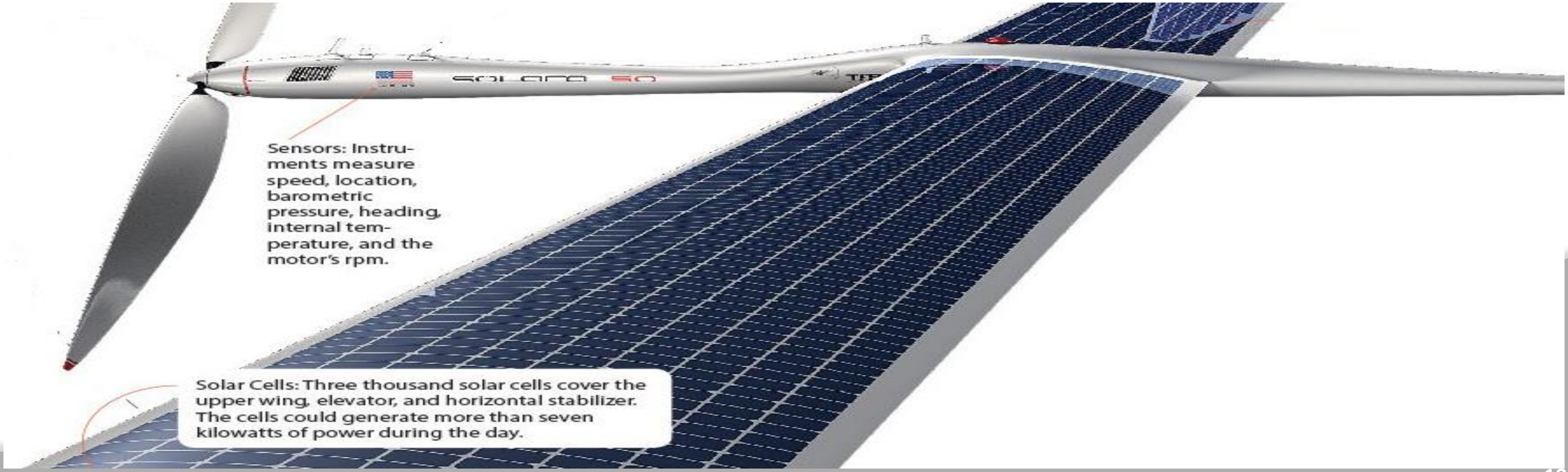
Battery Power

Currently only micro- and mini-UAV are powered by batteries and electric motors. 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

Global Hawk Block 20

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.



Sensors: Instruments measure speed, location, barometric pressure, heading, internal temperature, and the motor's rpm.

Solar Cells: Three thousand solar cells cover the upper wing, elevator, and horizontal stabilizer. The cells could generate more than seven kilowatts of power during the day.

Scale Effects

All-up mass (AUM), Manned Aeroplanes

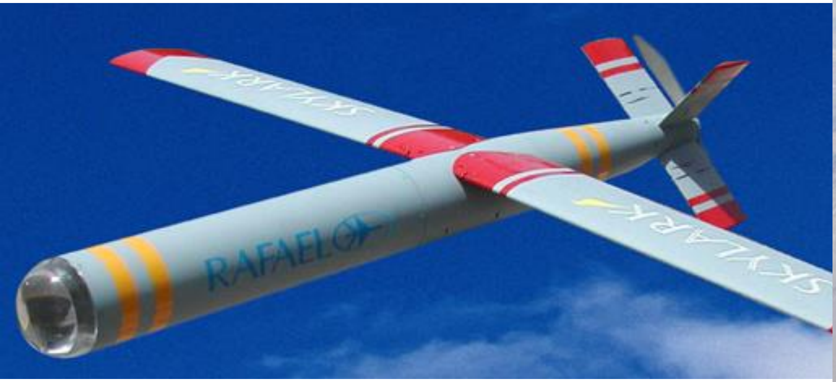
All-up mass (AUM), manned aeroplanes range in size from the smallest single-seater such as the

- Titan Tornado of about 340 kg
- Airbus A380 – 5,90,000 kg
- Antonov An 225 - the 6,40,000kg

All-up mass (AUM), Unmanned Aeroplanes

- 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 counterparts.



All-up mass (AUM), unmanned aeroplanes

Similarly for rotorcraft –

whilst ***manned versions*** range in mass from the 623 kg (Robinson R22) to the 97,000 kg (Mil 12 helicopter)

The **unmanned versions** range only generally from

20 kg (EADS Scorpio 6) to **200 kg** (Schiebel Camcopter).

Mass domains of manned and unmanned aircraft

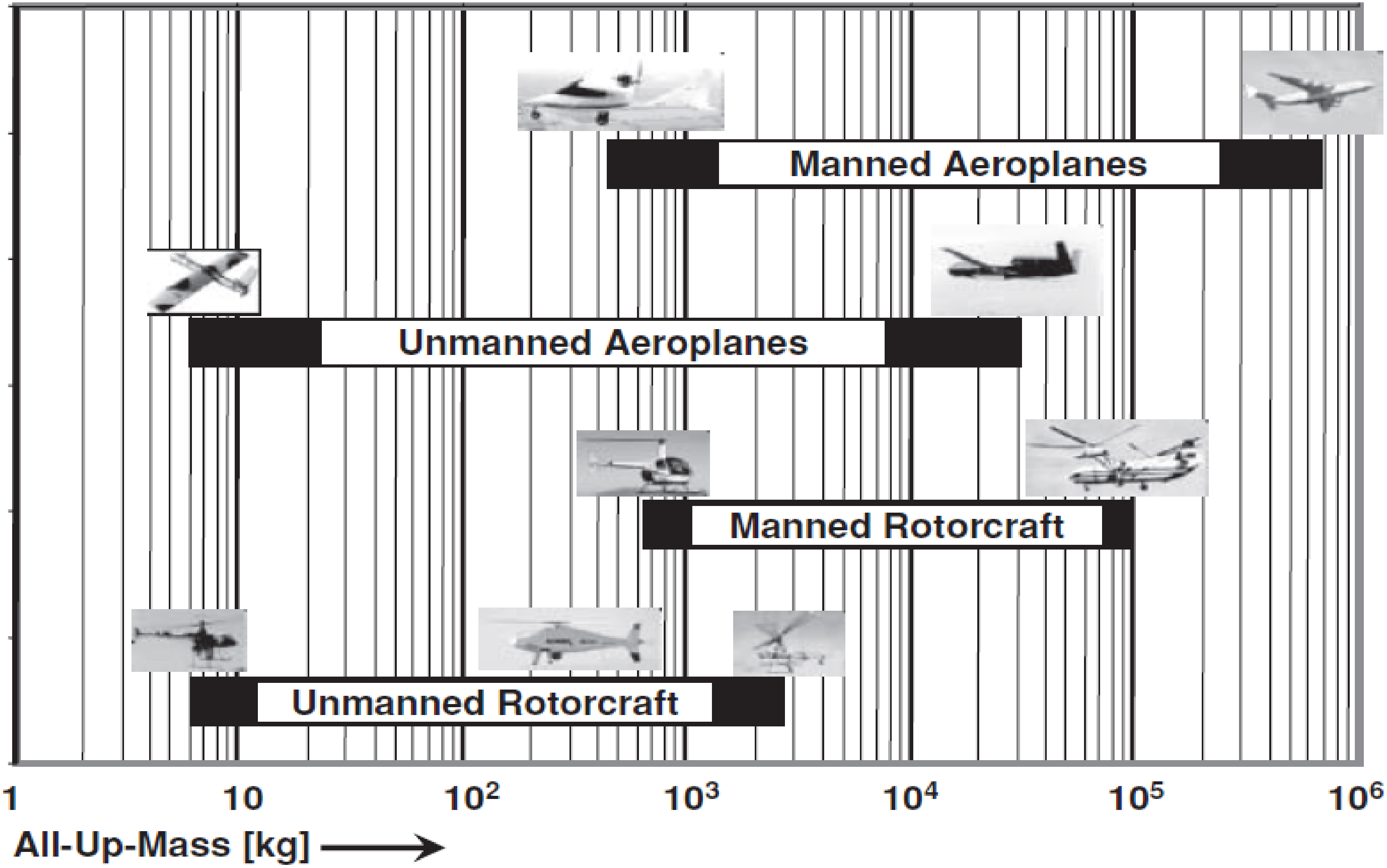


Figure 2.11: Mass domains of manned and unmanned aircraft

Froude Scaling

Wren

Swan

Elephant, by Yathin S Krishnappa

Mouse

Froude Scaling

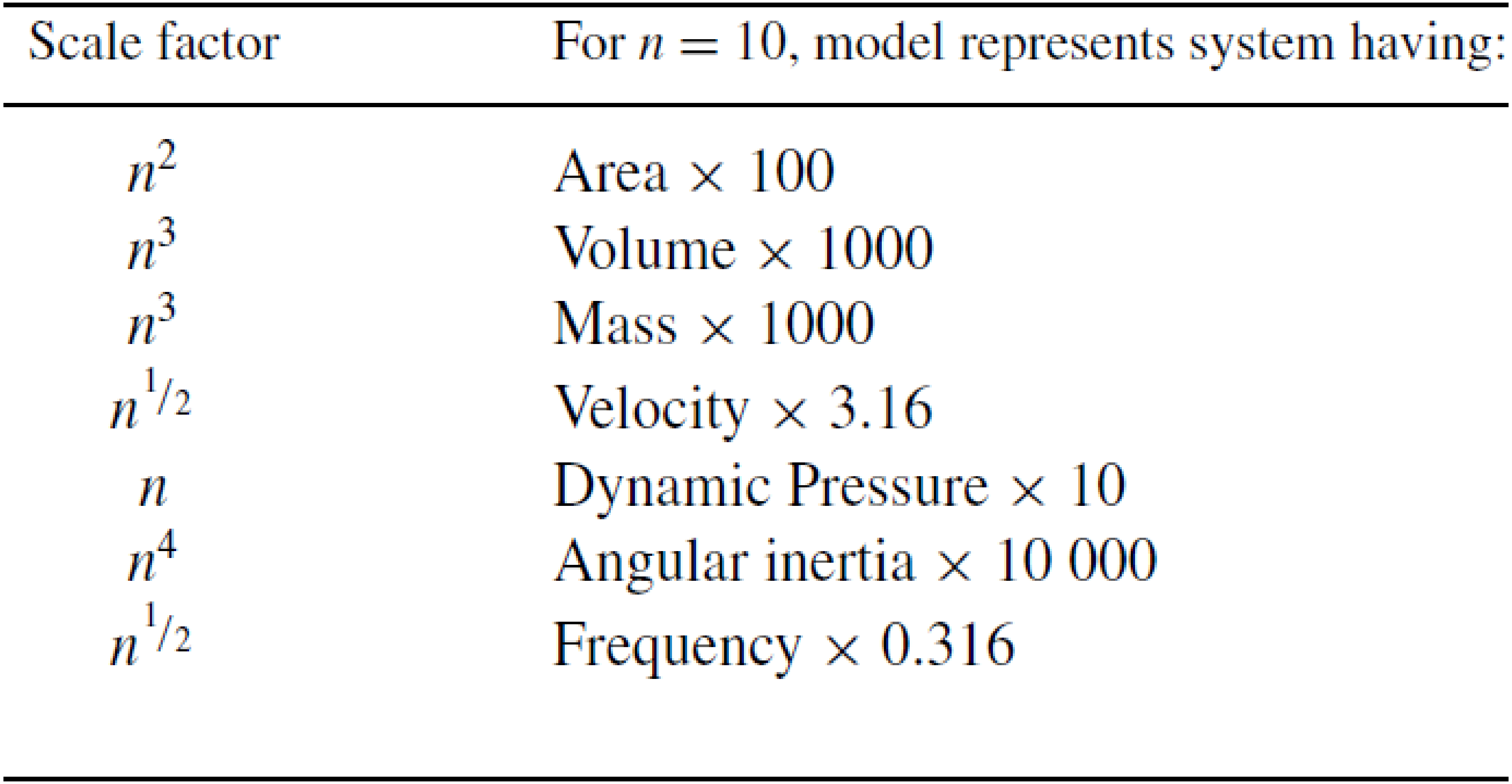
Linear dimension ratio is L_a/L_m = n (scale factor)

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.

Scale Factor



Scale factor	For $n = 10$, model represents system having:
n^2	Area × 100
n^3	Volume × 1000
n^3	Mass × 1000
$n^{1/2}$	Velocity × 3.16
n	Dynamic Pressure × 10
n^4	Angular inertia × 10 000
$n^{1/2}$	Frequency × 0.316

Figure 2.12: Scale factors

Packaging Density

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

The packaging density of cockpit for most light manned aircraft to an overall value about 100 kg/m^3 or less.,

… providing them with room for access and to operate, reduces the effectiveness

Packaging Density

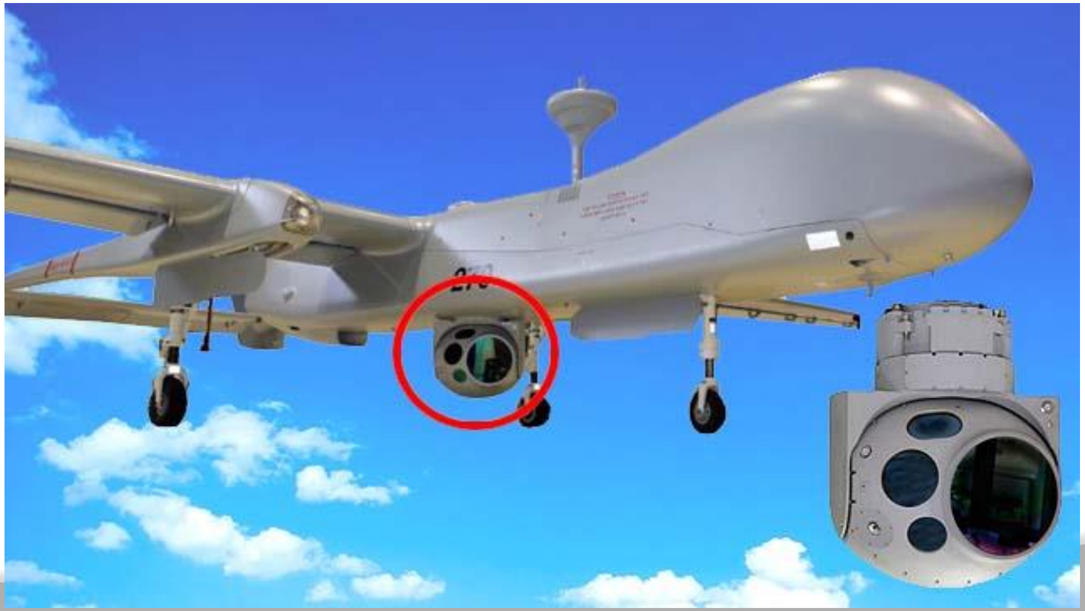
the electronics and optics for a UAV :

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 **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 **5000–6000 kg/m^3**, although still requiring some room for access, cooling, etc**.**

Packaging Density



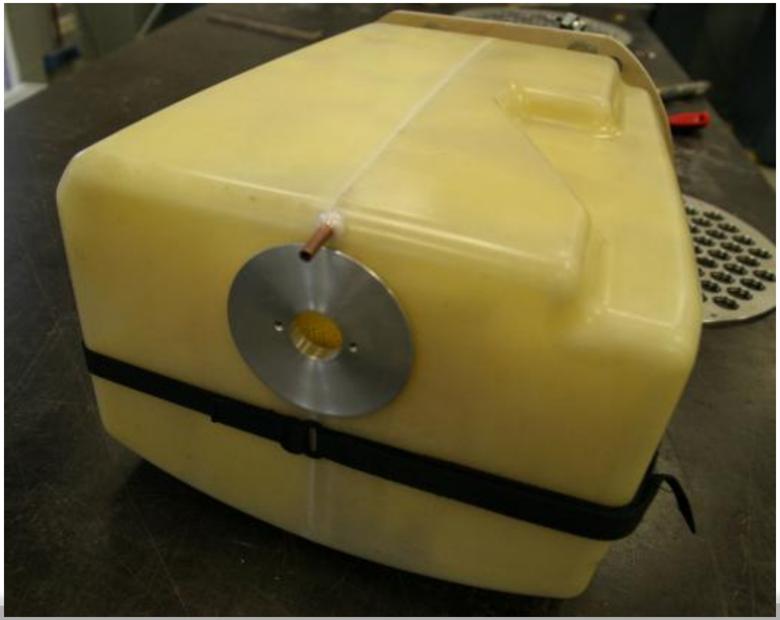
Packaging Density

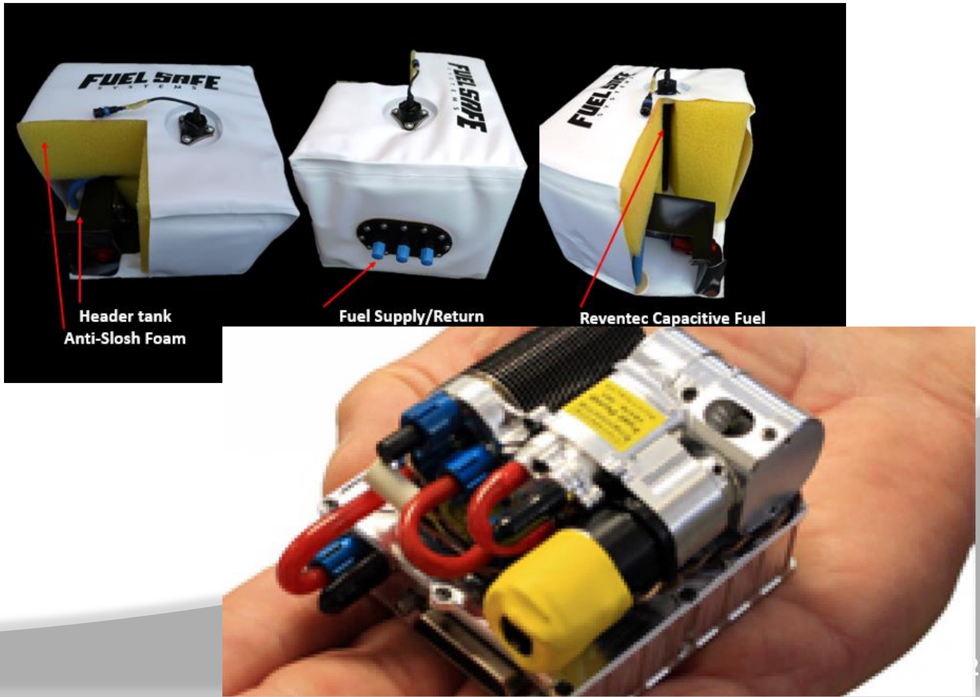
Structures such as wings, tail booms and empennage tend to have low

- 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 this increases *only slowly* as the aircraft size increases.
- The packaging 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.

Packaging Density

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**.





Packaging Density

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: AUM - 700 kg , packaging density -120 kg/m^3.
- A fixed-wing UAV, such as the **Observer :** AUM -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**.

Packaging Density

Structures and Mechanisms

An efficient aerodynamic solution for the **smaller** UAV is a challenge but, *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.

Structures and Mechanisms

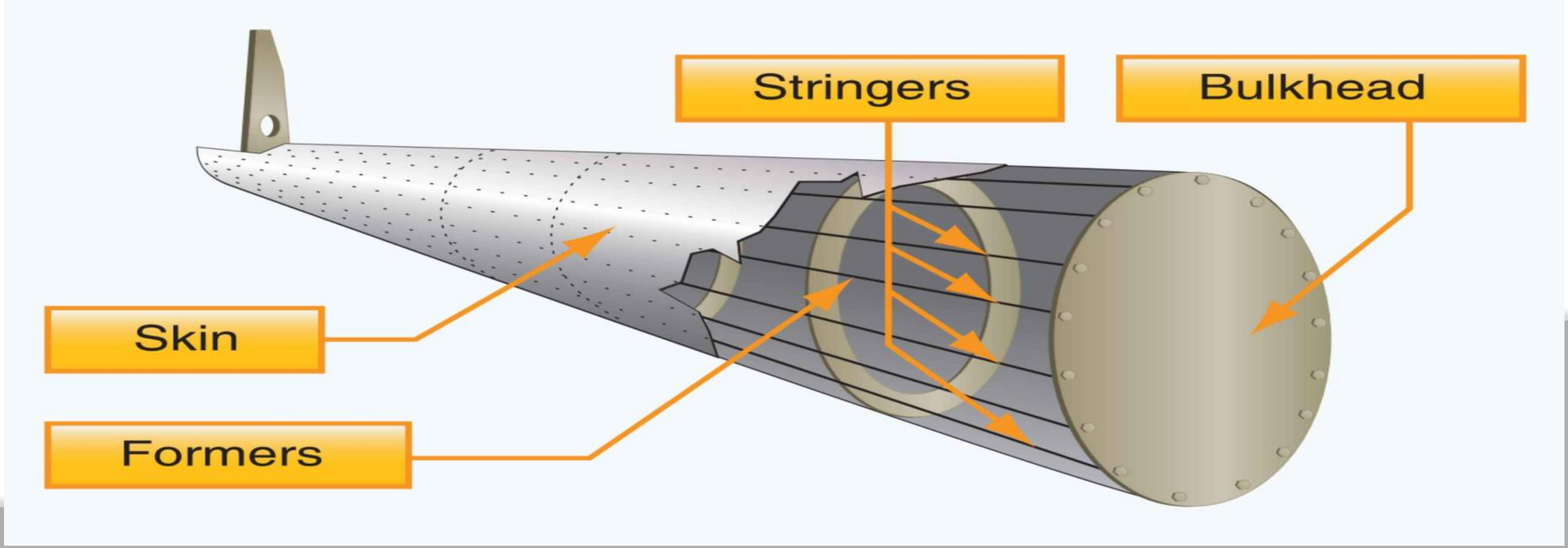
Fabric-covered tubular framework

Monocoque construction in light alloys- shells (or skins)

To prevent local buckling of the skins between frames (or formers), stringers were added

To protect from dents in the surfaces, it became necessary to accept the use of thicker skins to prevent this, but at a weight penalty.

Structures and Mechanisms



Structures and Mechanisms

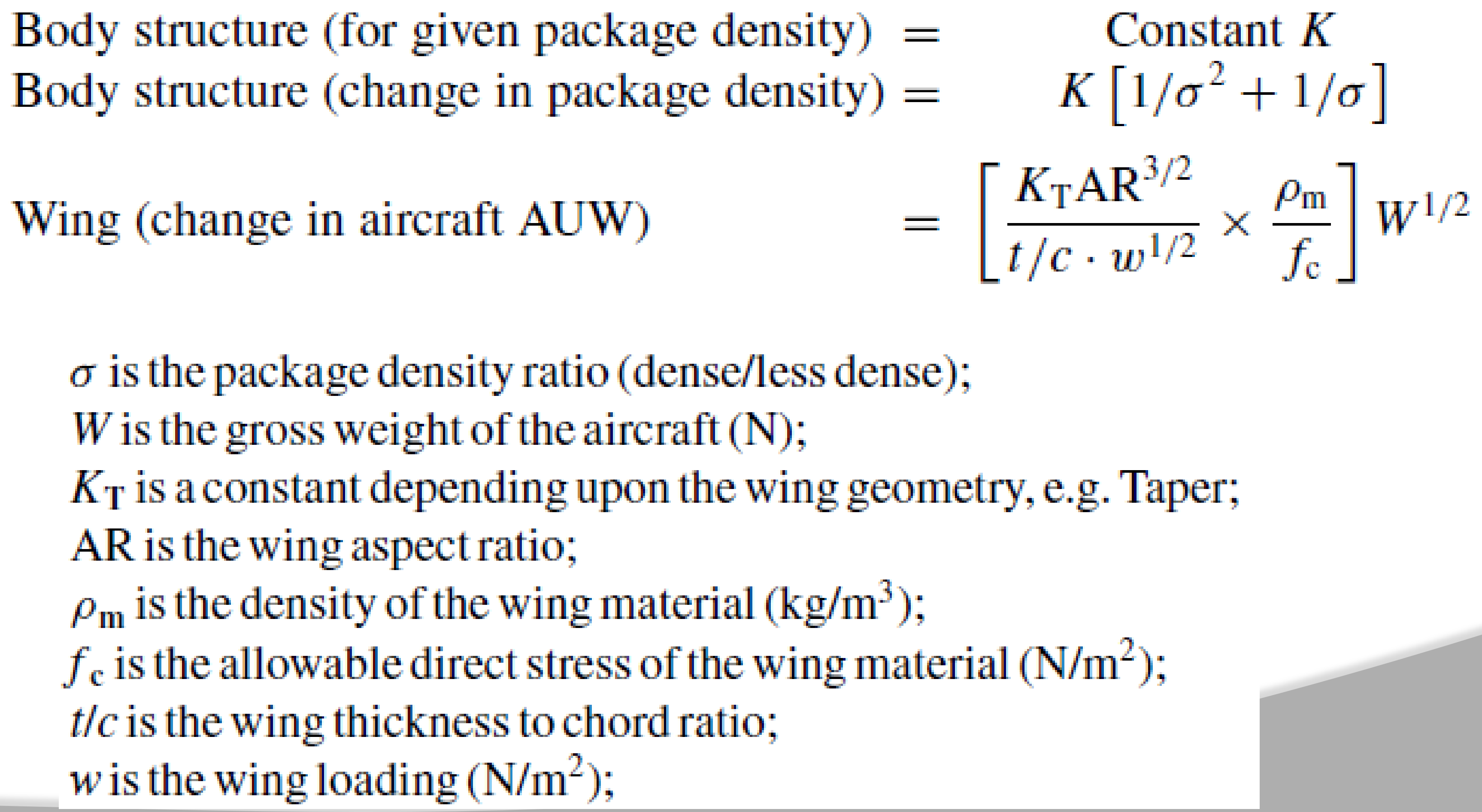
The advent of composite materials of lower density helped to alleviate this problem as the skins could be made thicker without an increase in weight

initially, the materials such as glass-fibre 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

carbon-fibre matrices, plastic–aluminium alloy composites

Structures and Mechanisms

Weight fraction, derived from the scaling laws



$$\text{Body structure (for given package density)} = \text{Constant } K$$

$$\text{Body structure (change in package density)} = K\left[1/\sigma^2 + 1/\sigma\right]$$

$$\text{Wing (change in aircraft AUW)} = \left[\frac{K_\mathrm{T}\mathrm{AR}^{3/2}}{t/c \cdot w^{1/2}} \times \frac{\rho_\mathrm{m}}{f_\mathrm{c}}\right] W^{1/2}$$

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);

Structures and Mechanisms

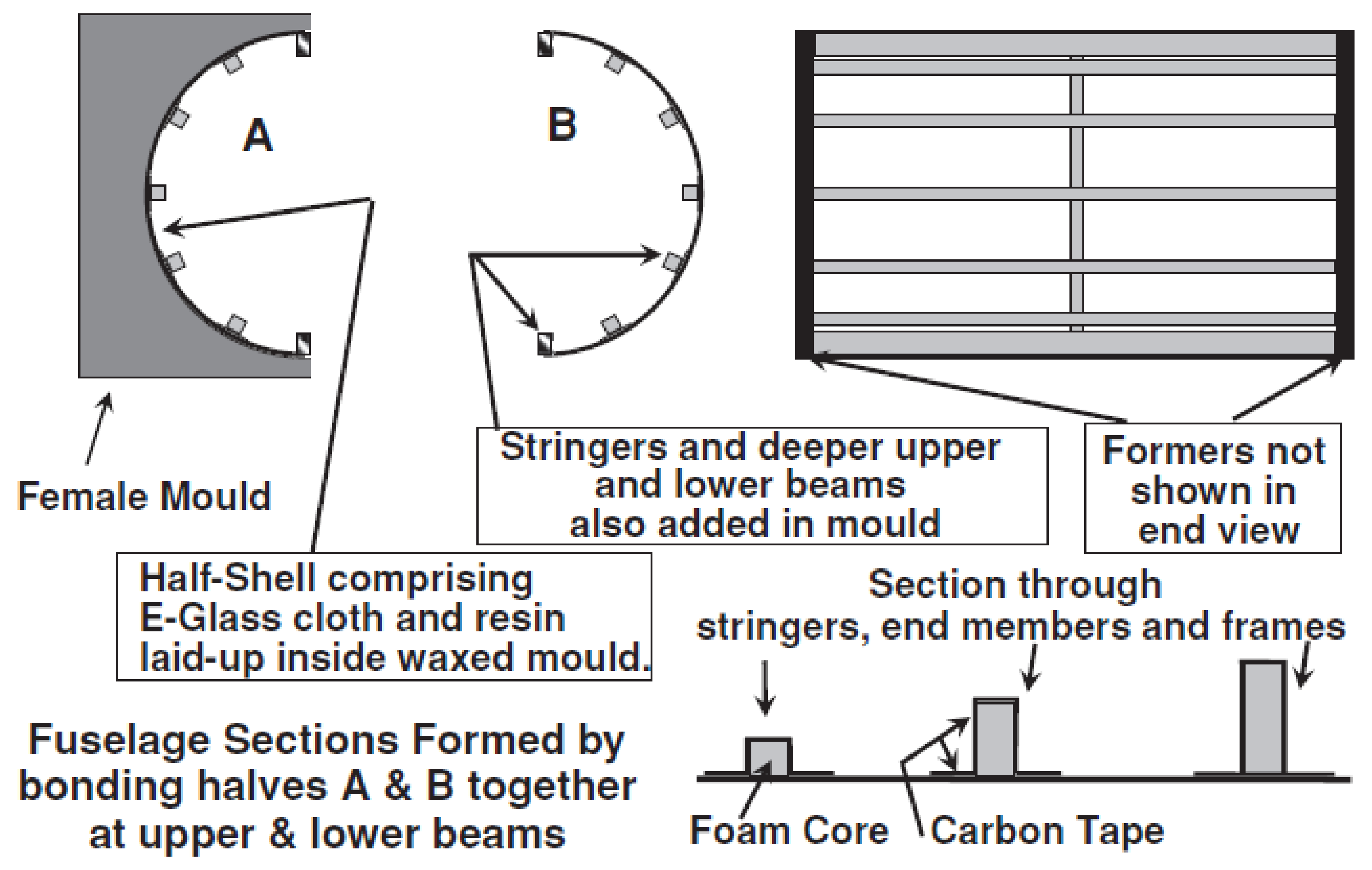


Figure. Structural techniques using composite materials

Structures and Mechanisms

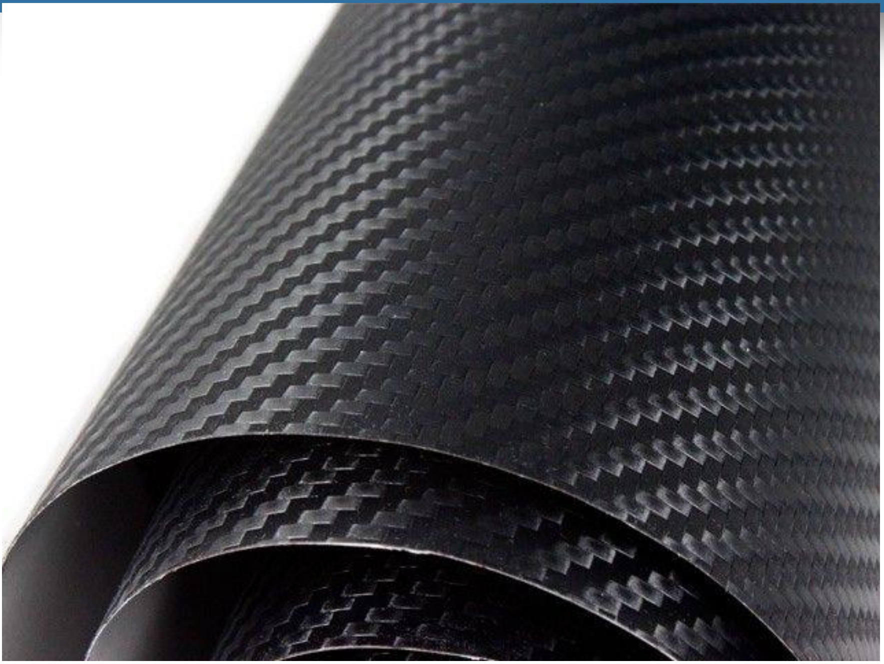
An alternative material which has about half the density yet offers similar stiffness to carbon/glass combination is a glass-fibre or carbon-fibre reinforced polycarbonate. It can be thermo-moulded and its forming into structure is less labour intensive than is the case with laid-up materials.

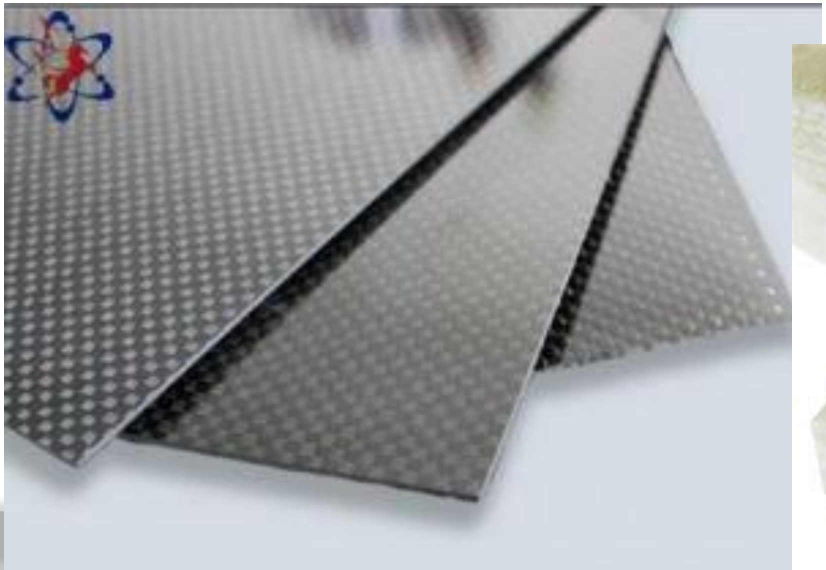
Similar construction methods may be applied to the lifting surfaces.

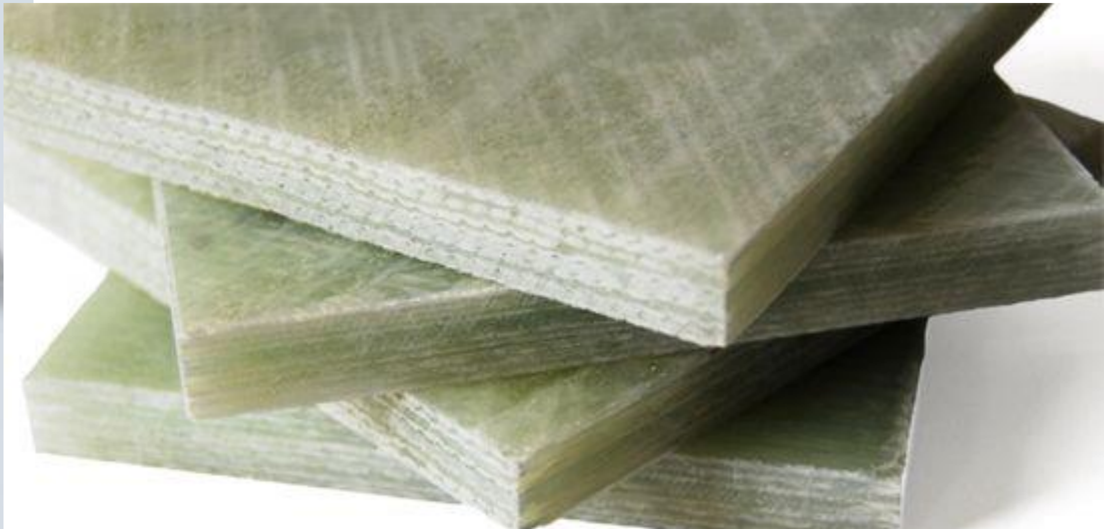
Carbon composites for outer shells of wings and fuselages

Sandwich construction is another option with a nylon honeycomb layer sandwiched between two layers of carbon-fibre or carbon-fibre and glass-fibre mix.

Structures and Mechanisms







Structures and Mechanisms- Accurate Tolerances

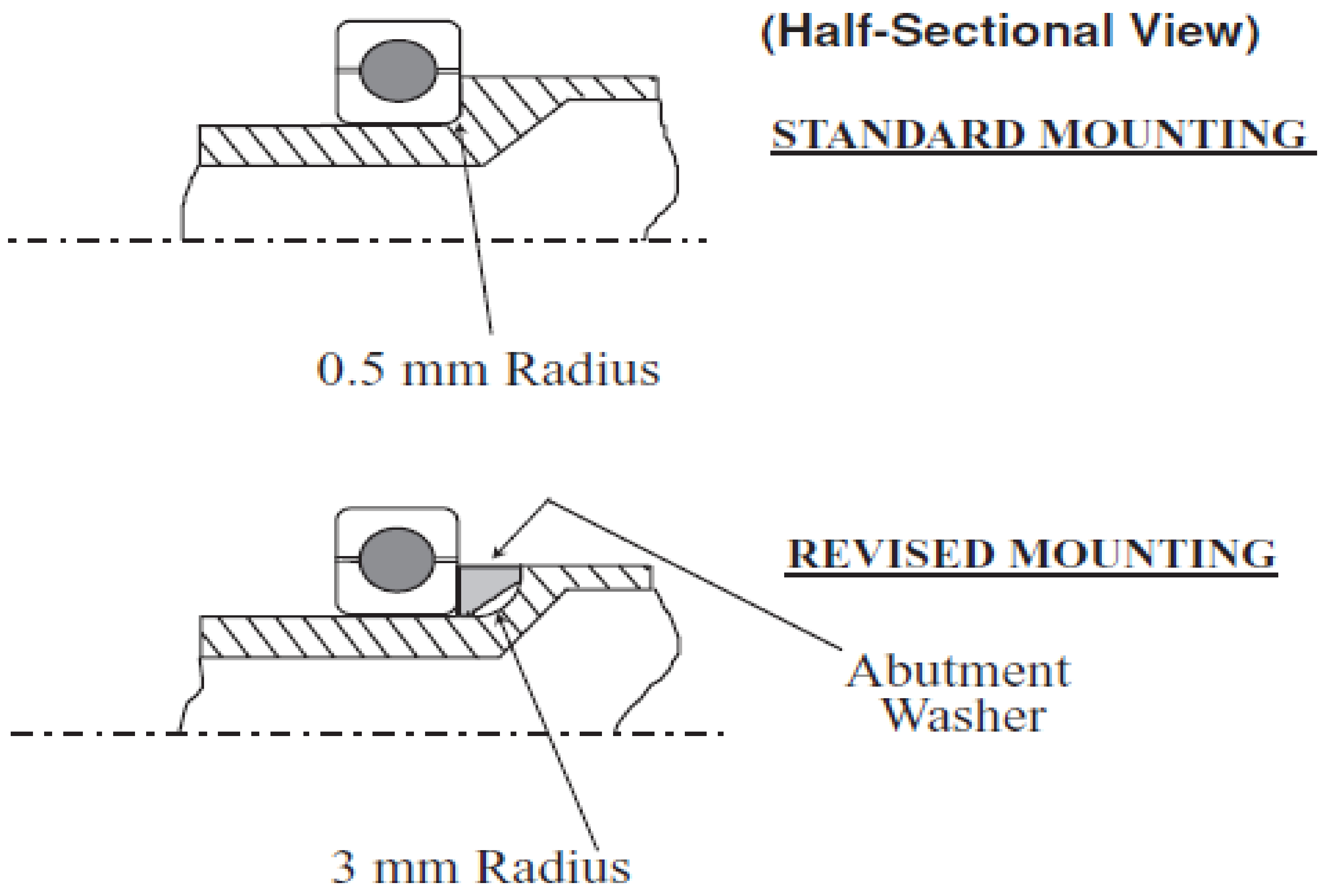


Figure. Revision of bearing mount design

Wear and Fatigue

Structure Design prerequisite:

It not only adequately and efficiently performs its required function, but that it continues to do so, reliably, for a 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.***

Wear and Fatigue

The wear rate on bearing surfaces is usually estimated from load–velocity charts.

- 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

Wear and Fatigue

- One effect of scale, 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.

Wear and Fatigue

- 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.

Undercarriage Design

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

Undercarriage Design

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 judgement 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.

Undercarriage Design

UAV designer should consider these factors and design for a vertical impact velocity of **no less than 2 m/s** and an undercarriage **deflection** yielding a maximum of **4g deceleration**

If the undercarriage has wheels, they are likely to be smaller than the wheels of a manned aircraft.

Undercarriage Design

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.

alamy

Undercarriage Design

Undercarriage Design

Undercarriage configurations range from the very simple to the relatively complex.

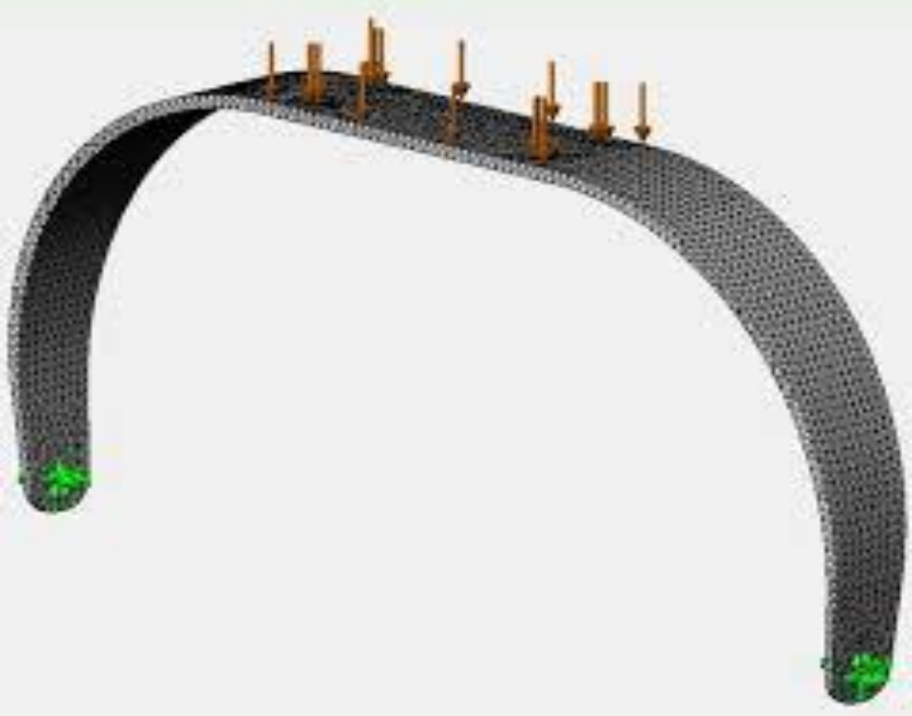
The simplest will be those employed in land-based VTOL aircraft. These may be a fixed tubular skid type with **flexible plates to absorb** the initial energy of impact, and use ***friction between metal plates*** or with the ***composites*** to provide a limited amount of damping

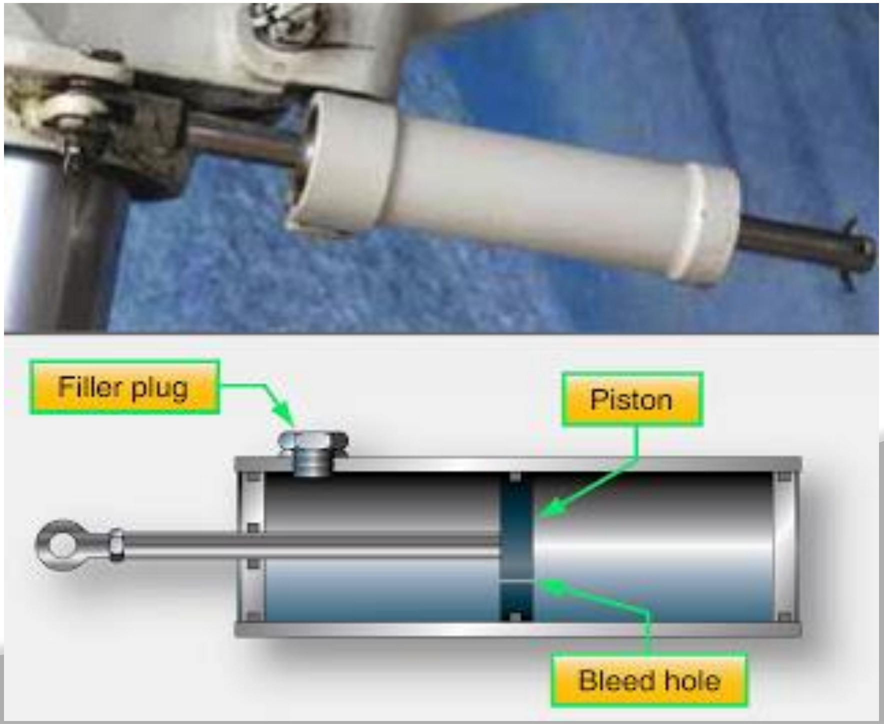
Undercarriage Design

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.

Undercarriage Design

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.





Undercarriage Design

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 <u>VTOL aircraft merely to assist in manoeuvring the aircraft on the ground or deck</u>

Undercarriage Design

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 destabilising effect in high-speed flight.

Undercarriage Design

- The direction of retraction 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.

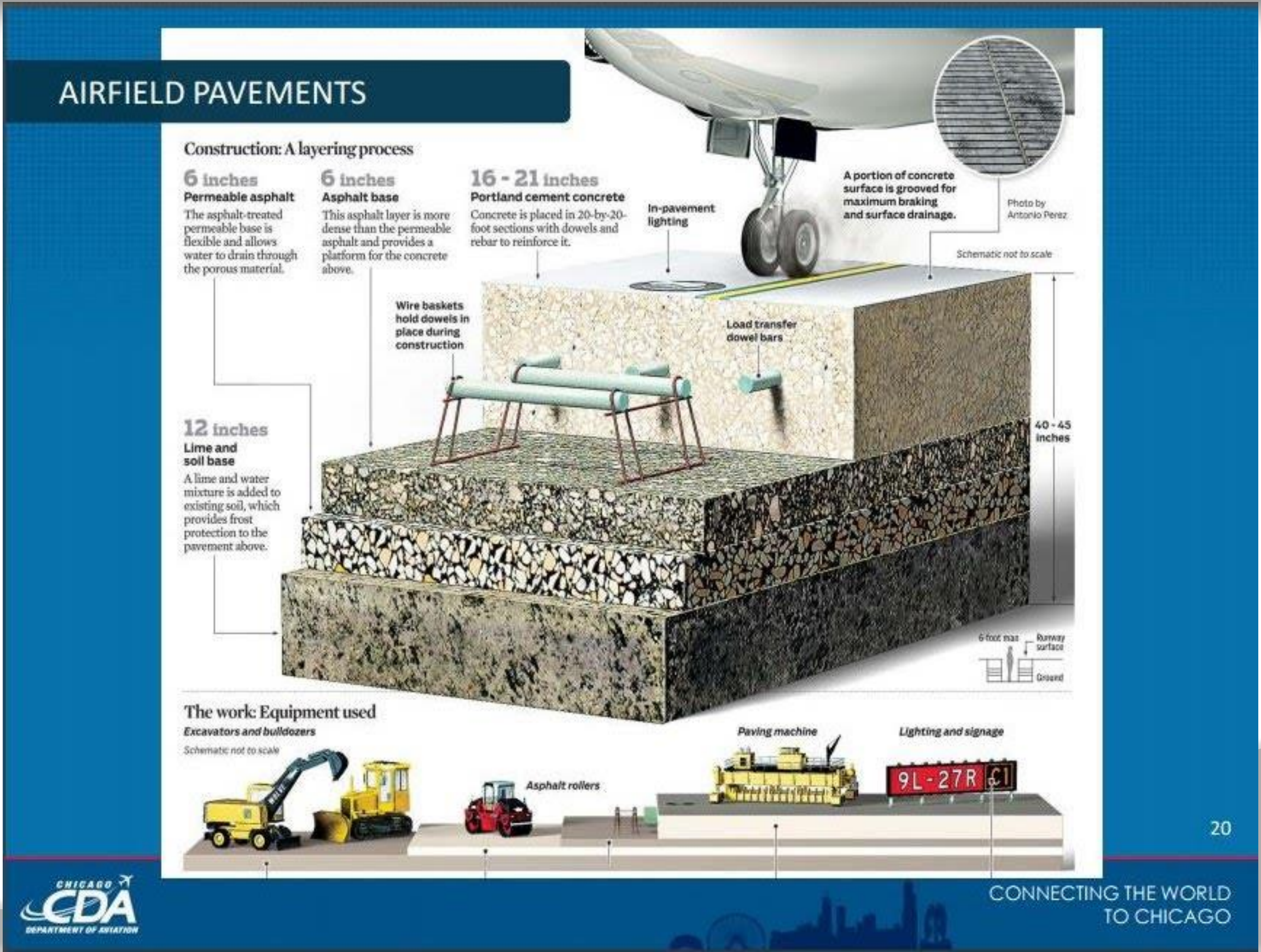
Undercarriage Design

- Another aspect to consider with aircraft operating from land is the **degree of firmness of the ground** on which it will have to be moved. This is usually specified as the **Californian bearing ratio (CBR)**.
- Suffice it to say that operation on or from soft ground will require larger wheels and lower pressure tyres than for operations from firm ground.

Undercarriage Design

Undercarriage Design

Undercarriage Design



AIRFIELD PAVEMENTS

Construction: A layering process

6 inches
Permeable asphalt
The asphalt-treated permeable base is flexible and allows water to drain through the porous material.

6 inches
Asphalt base
This asphalt layer is more dense than the permeable asphalt and provides a platform for the concrete above.

16 - 21 inches
Portland cement concrete
Concrete is placed in 20-by-20-foot sections with dowels and rebar to reinforce it.

12 inches
Lime and soil base
A lime and water mixture is added to existing soil, which provides frost protection to the pavement above.

A portion of concrete surface is grooved for maximum braking and surface drainage.

Photo by Antonio Perez

Schematic not to scale

The work: Equipment used

Schematic not to scale

Undercarriage Design

- 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

Undercarriage Design

Undercarriage Design

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.

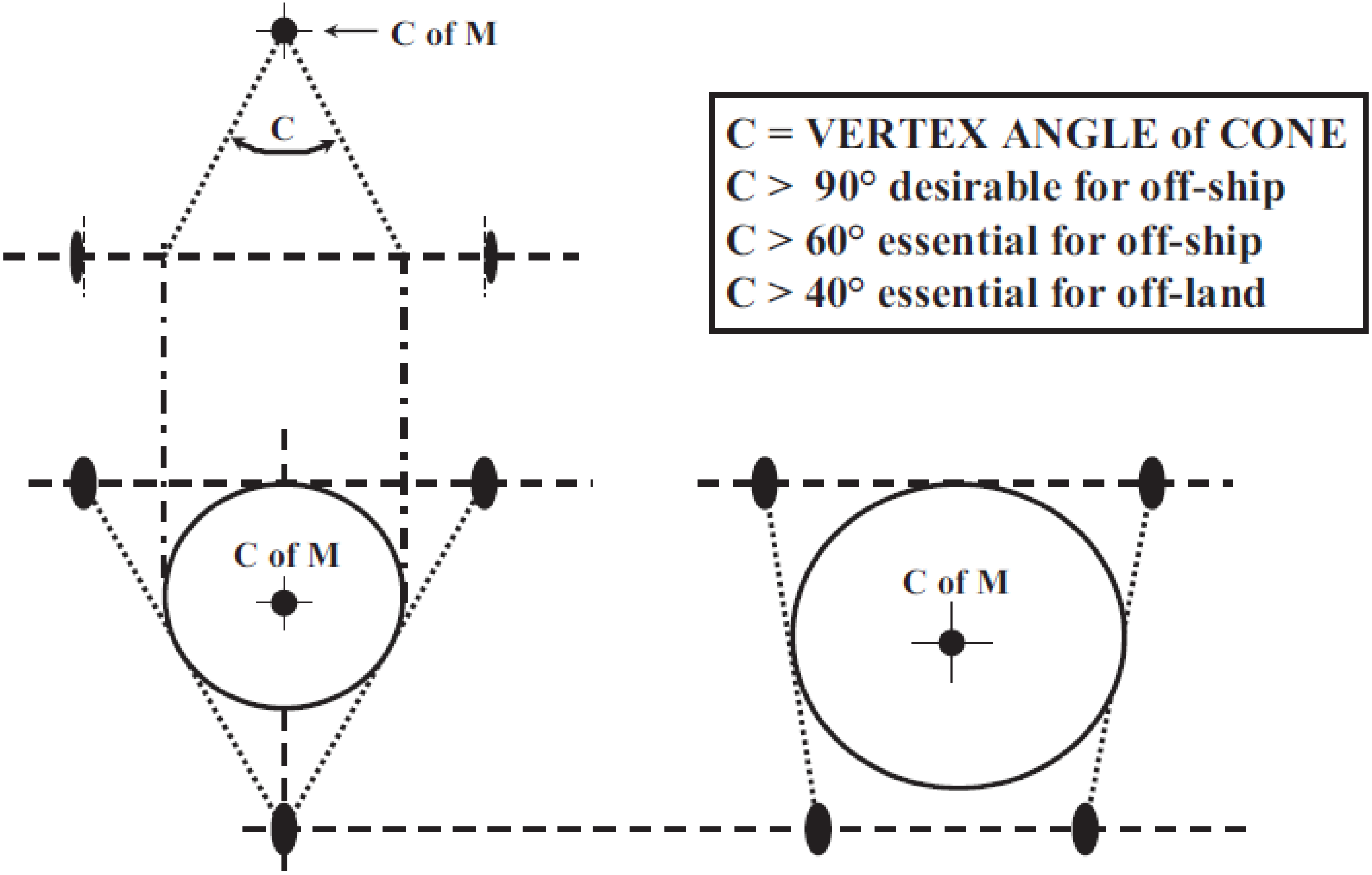
Undercarriage Design

Undercarriage Design

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.

Undercarriage Design



C = VERTEX ANGLE of CONE
C > 90° desirable for off-ship
C > 60° essential for off-ship
C > 40° essential for off-land

PLAN VIEW -- TRI-WHEEL

PLAN VIEW -- QUADRI-WHEEL

Undercarriage Design

It may be noted that, a four-legged undercarriage will provide a larger stability cone for a similar undercarriage spread as does a three-legged undercarriage. For this reason, several naval helicopters have four-legged undercarriages.

Undercarriage Design

The design of an undercarriage for rotary wing aircraft must take into account the **interaction between**

- **the dynamics of the rotor**, if it is articulated, and
- **the aircraft on its undercarriage**.

This phenomenon is known as ground resonance and

its prevention requires the provision of a degree of damping in both the undercarriage and the rotor in-plane motion

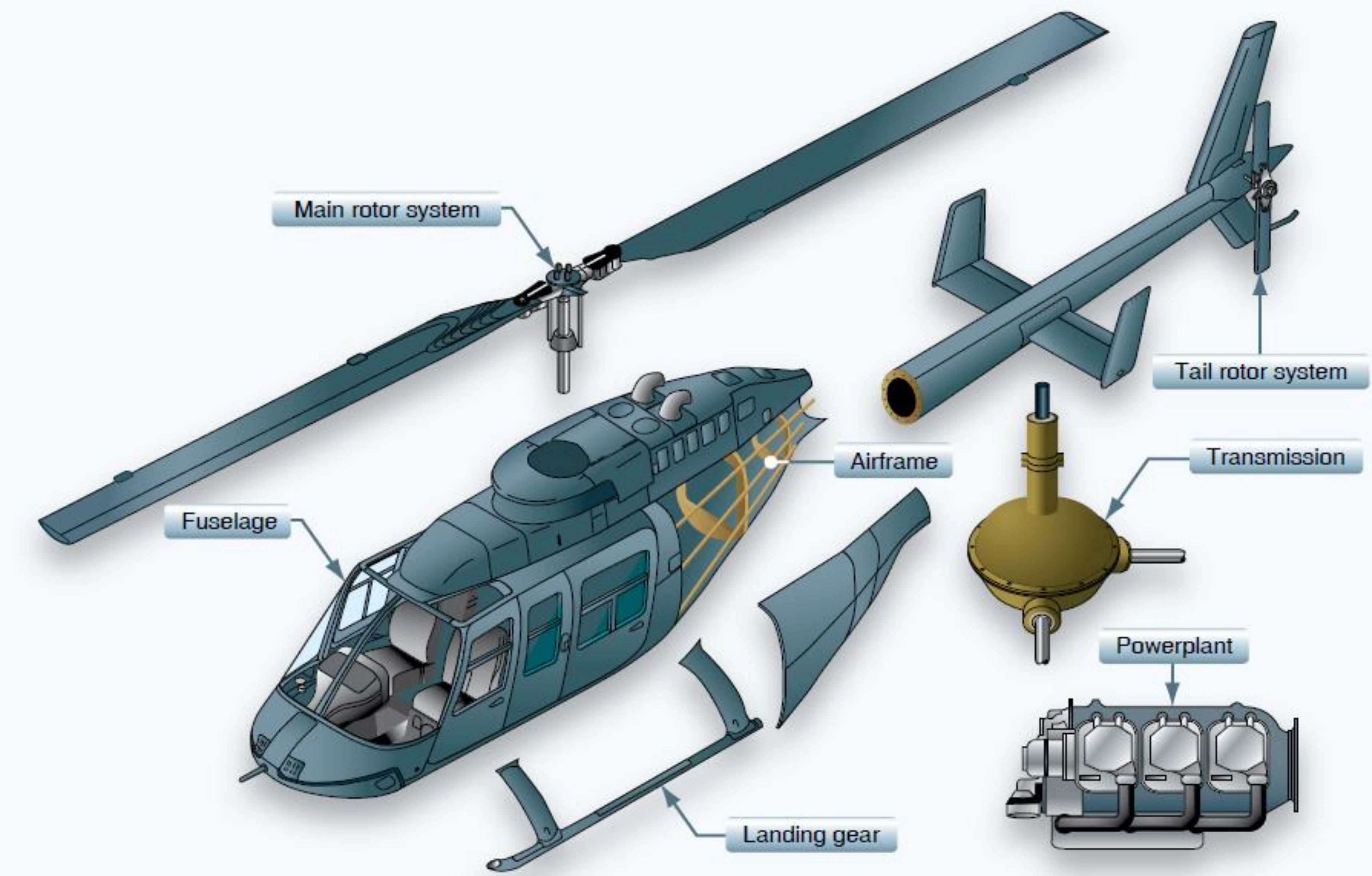
*The mass fraction may range from about **2%** for the simple to **5%** for the complex*

Helicopter Rotor Design

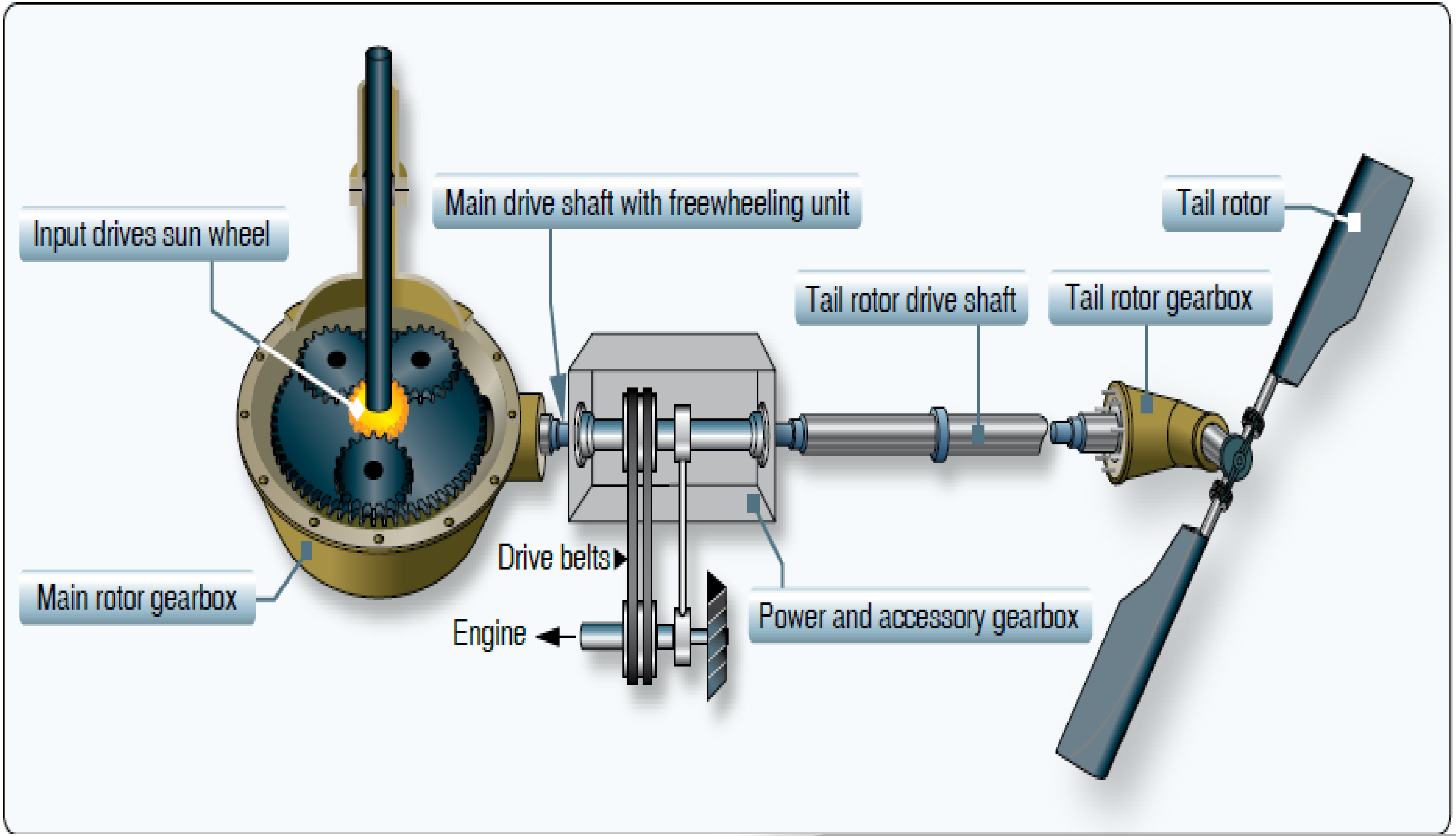
Helicopter Rotor Design

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.

Helicopter Rotor Design

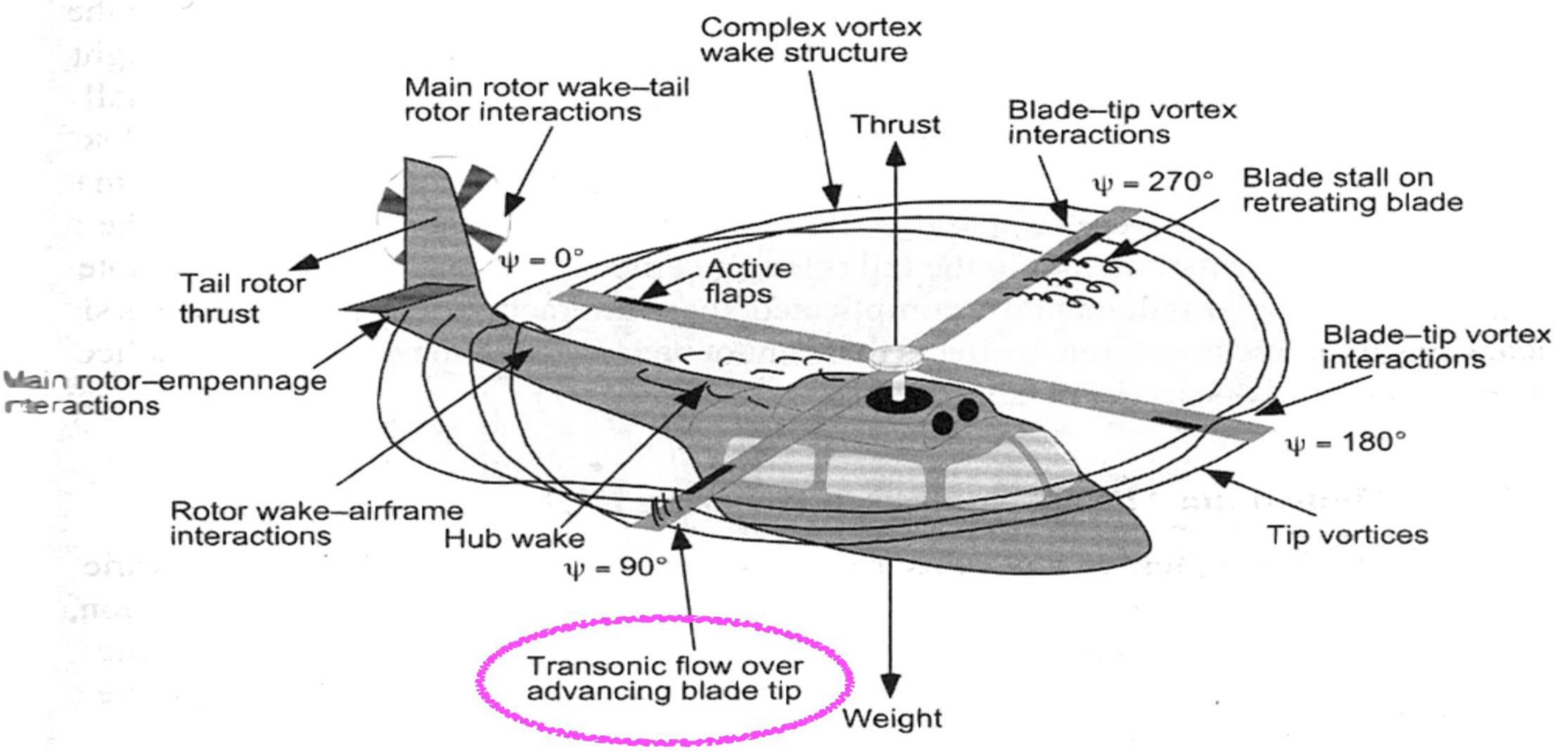


Helicopter Rotor Design



Helicopter Rotor Design

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.



Helicopter Rotor Design

$$\text{Rotorcraft gears and shafts} = K\left[\frac{0.43}{V_{\mathrm{T}}} + \frac{0.0085}{p^{1/2}}\right] W^{1/2}$$

$$\text{Rotor blades and hub} = \left[\frac{22}{\beta_0 V_{\mathrm{T}}^2 p^{1/2}}\right] W^{1/2}$$

K, Body structure Constant (for given package density)

W is the gross weight of the aircraft (N);

V_T is the tip speed of the rotor (m/s);

p is the disc loading of the rotor (N/m2);

β_0 is the coning angle of the rotor blades (rad).

Helicopter Rotor Design

As the aircraft design gross mass **(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 of the rotor and require more power and thus a larger and heavier engine.

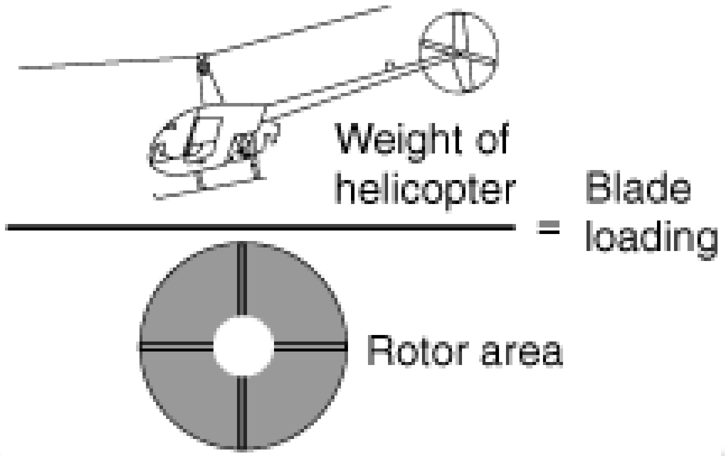
The weight increase with size of a rotor is at a generally greater rate than an engine weight increases with power.

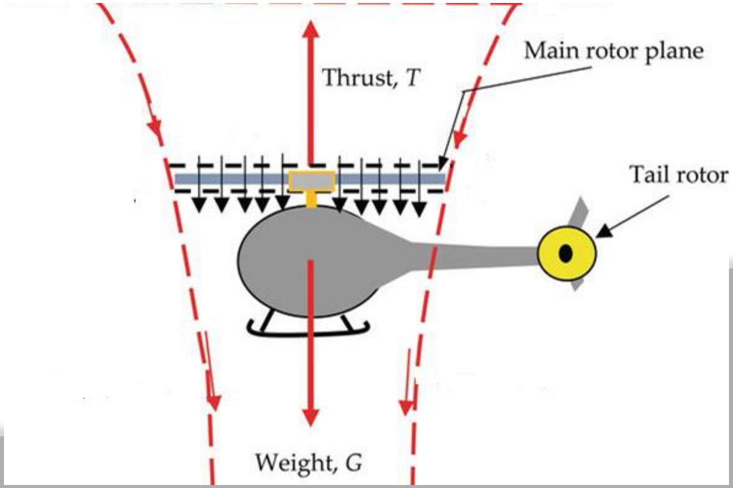
Therefore there is a trade-off of power-plant weight with rotor weight.

Helicopter Rotor Design

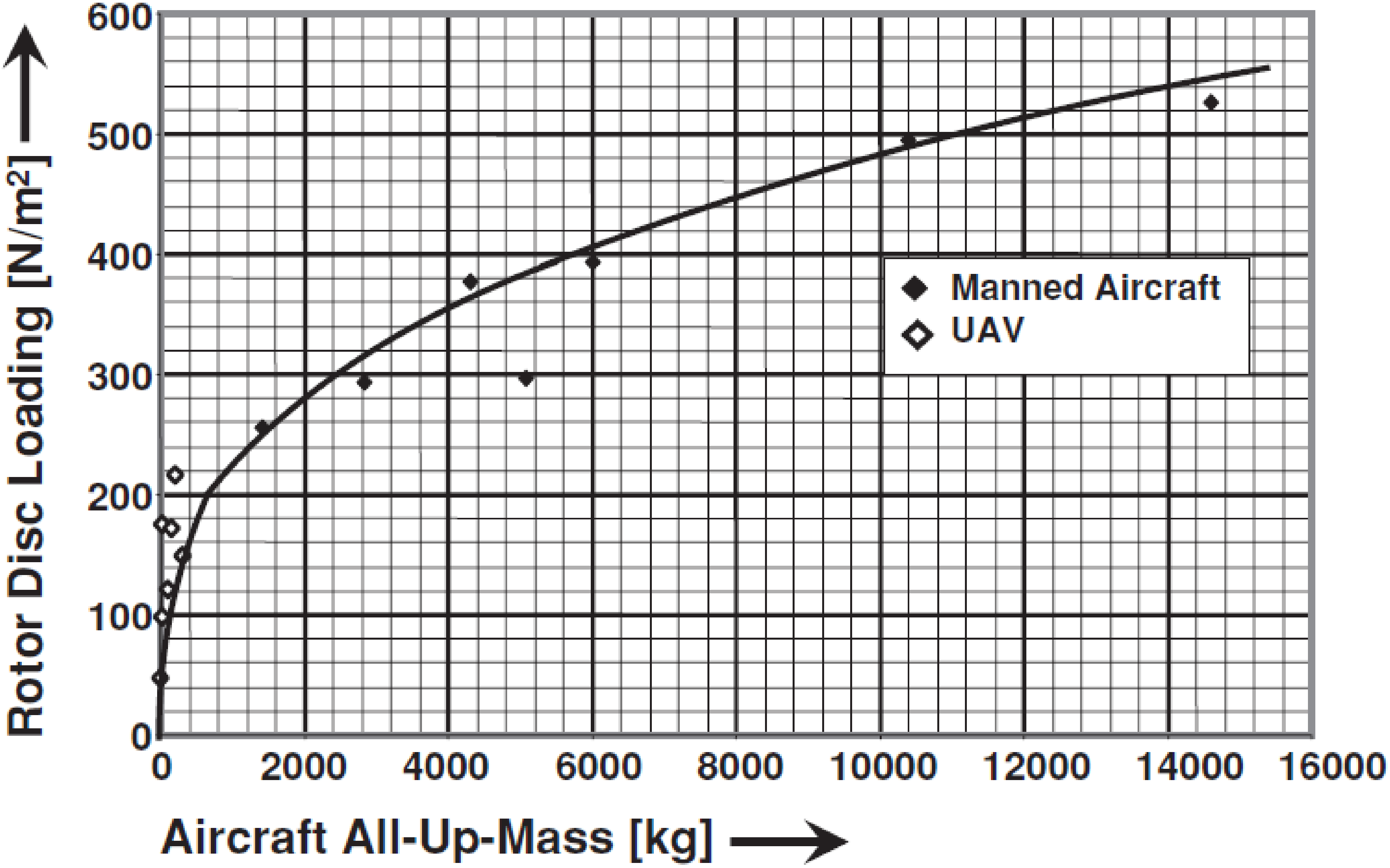
The result is that the designer will choose a disc loading which produces the lowest combined rotor and power-plant weight for the endurance required of the aircraft.

Disc loading will be seen to tend upwards with aircraft DGM although aircraft designed for long endurance will be below that trend.





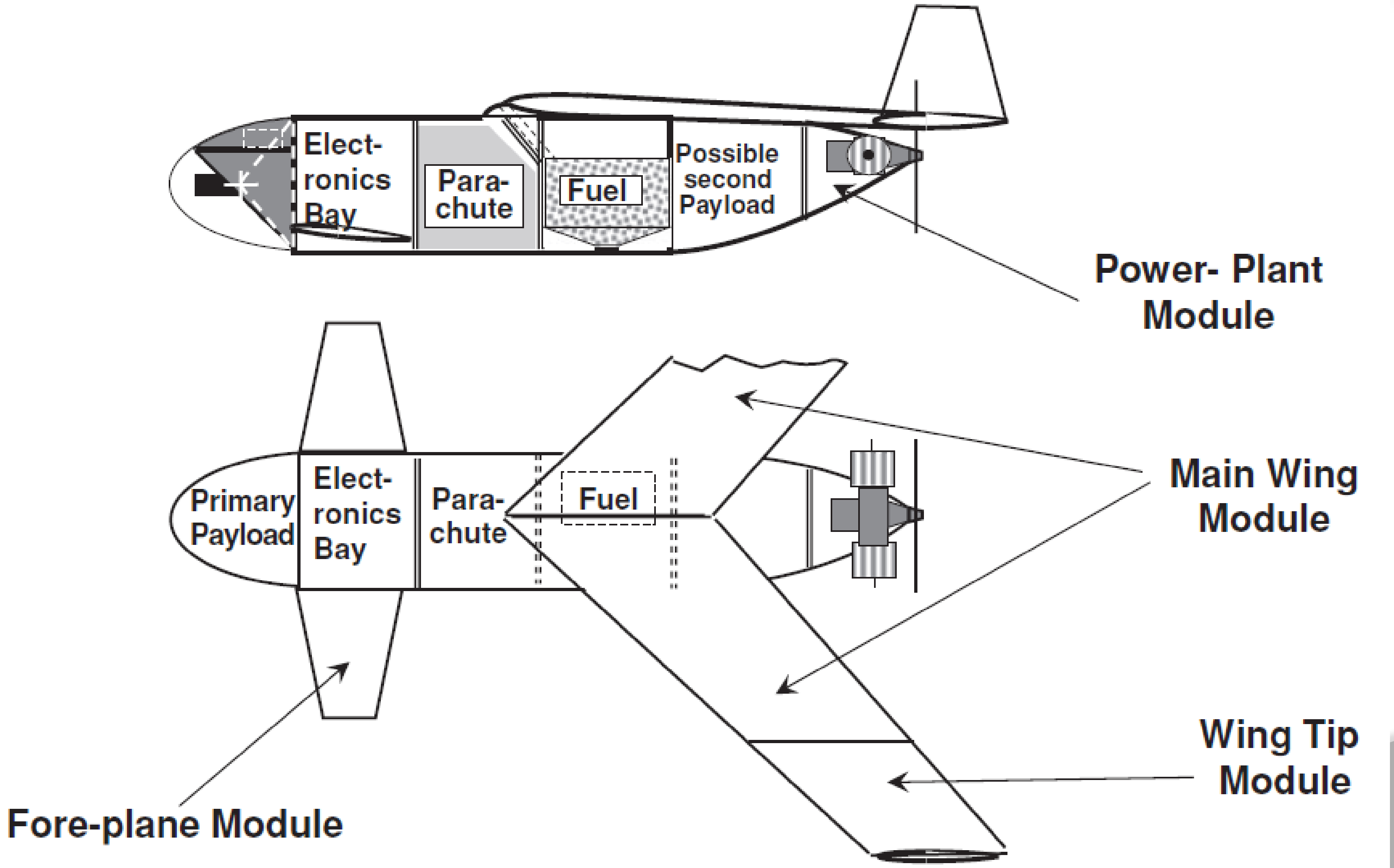
Helicopter Rotor Design



Modular Construction

Modular construction’ is a term used to describe the use of factory-produced pre-engineered (UAS) units (separate manufacture of the several modules) by different suppliers, and in different countries, that are delivered to site. This allows for the ***manufacture and testing, to agreed standards, of complete modules by different suppliers, and in different countries***, and **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.

Modular Construction



Modular Construction

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.

Modular Construction

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..

Modular Construction (MALE)

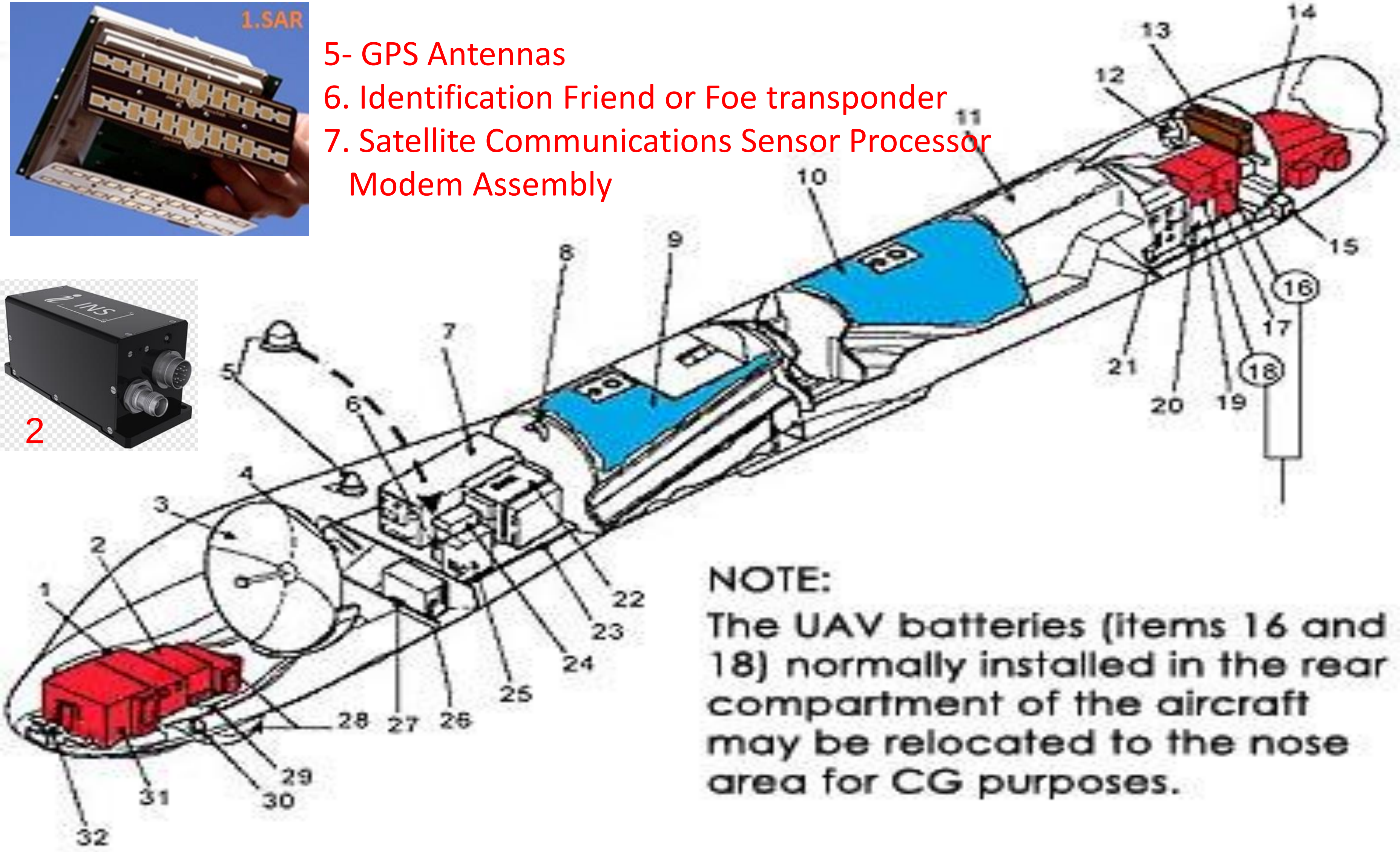
1.SAR

5- GPS Antennas

6. Identification Friend or Foe transponder

7. Satellite Communications Sensor Processor Modem Assembly

2



NOTE:
The UAV batteries (items 16 and 18) normally installed in the rear compartment of the aircraft may be relocated to the nose area for CG purposes.

Modular Construction (MALE)


6.Identification Friend or Foe transponde

13. Oil Cooler/Radiator

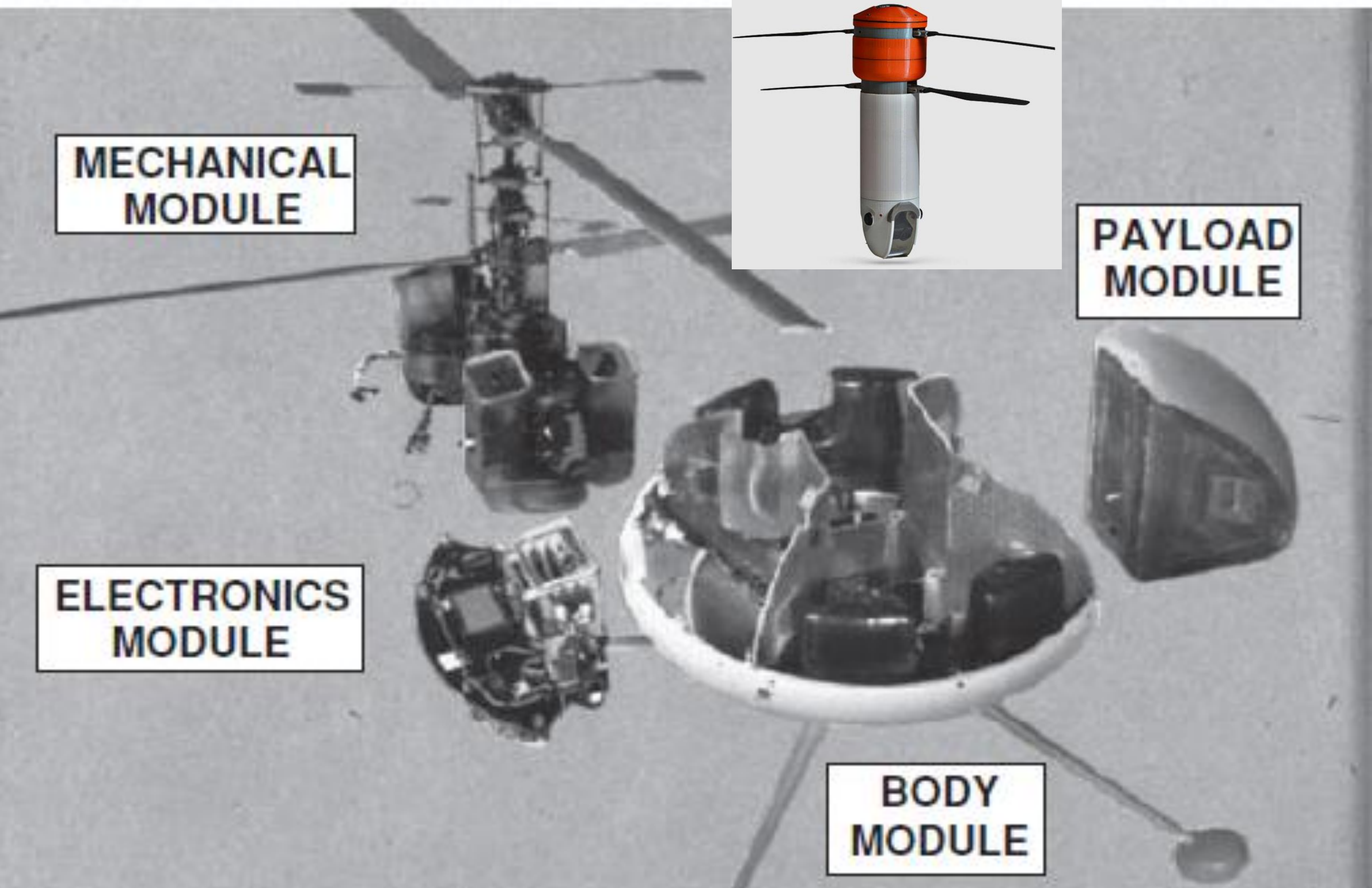

18. Battery (Assembly)

14. Engine

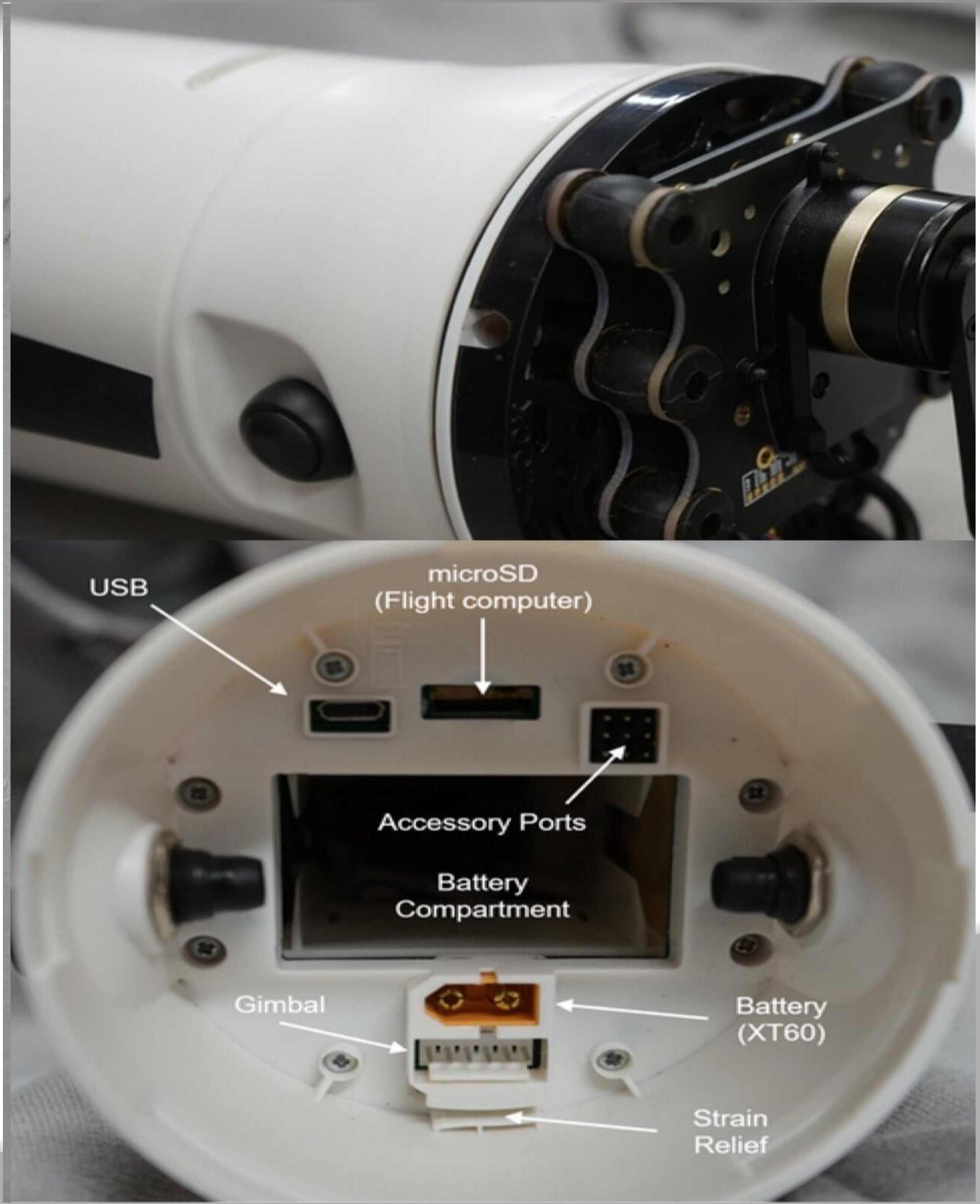
26. Video Encoder

30. Ice detector

Modular Construction (VTOL)



Modular Construction



Modular Construction

As the illustration shows, the aircraft comprises four main modules:

a) the body module,

b) the mechanical module,

c) the electronics module, and

d) a range of alternative payload modules.

Modular Construction

The **body** is constructed entirely of **composite material**, being a matrix of resin-reinforced glass and carbon fibres. It is by far the cheapest of the four modules.

It is essentially an endoskeleton structure **with a central box having a vertical pillar at each corner**.

The mechanical module attaches to the upper end of each pillar, whilst ***one leg of the four-legged undercarriage plugs into*** the lower end of each tubular pillar.

Modular Construction

The volume of the circular body is essentially divided into ***four segments by four vertical diaphragms*** which act as ‘brackets’ to carry the **electronics** and **payload modules**, and to provide insulation from the other **two** segments which are occupied by **each power-plant**.

There is no ‘front’ of the aircraft as it is symmetric in plan view and can fly equally readily in any direction. However, to simplify the description, we will refer to the *segment which carries the detachable payload as the ‘front’*.

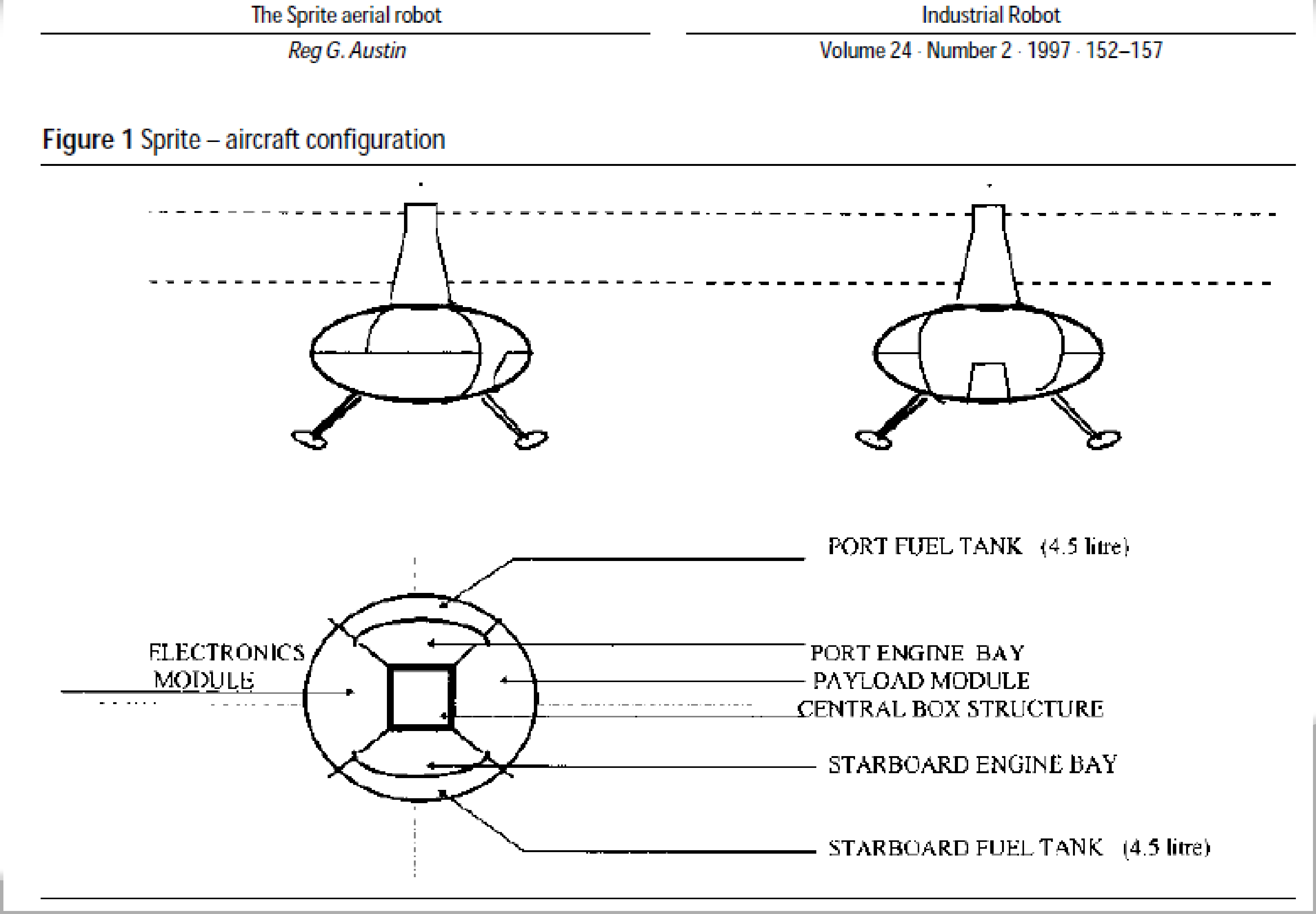
Modular Construction

Opposite the **payload module**, and balancing it, is the electronics module, whilst the **mechanical module** gear-box **straddles** the **central box section**.

The **rotor drive shafts** rise centrally from the gear-box and the ***two power-plants*** occupy each of the lateral segments.

The body is completed by four removable covers which form the upper surface of the body and provide access to the modules for attention in situ or removal.

Modular Construction



The Sprite aerial robot

Reg G. Austin

Industrial Robot

Volume 24 · Number 2 · 1997 · 152–157

Figure 1 Sprite – aircraft configuration

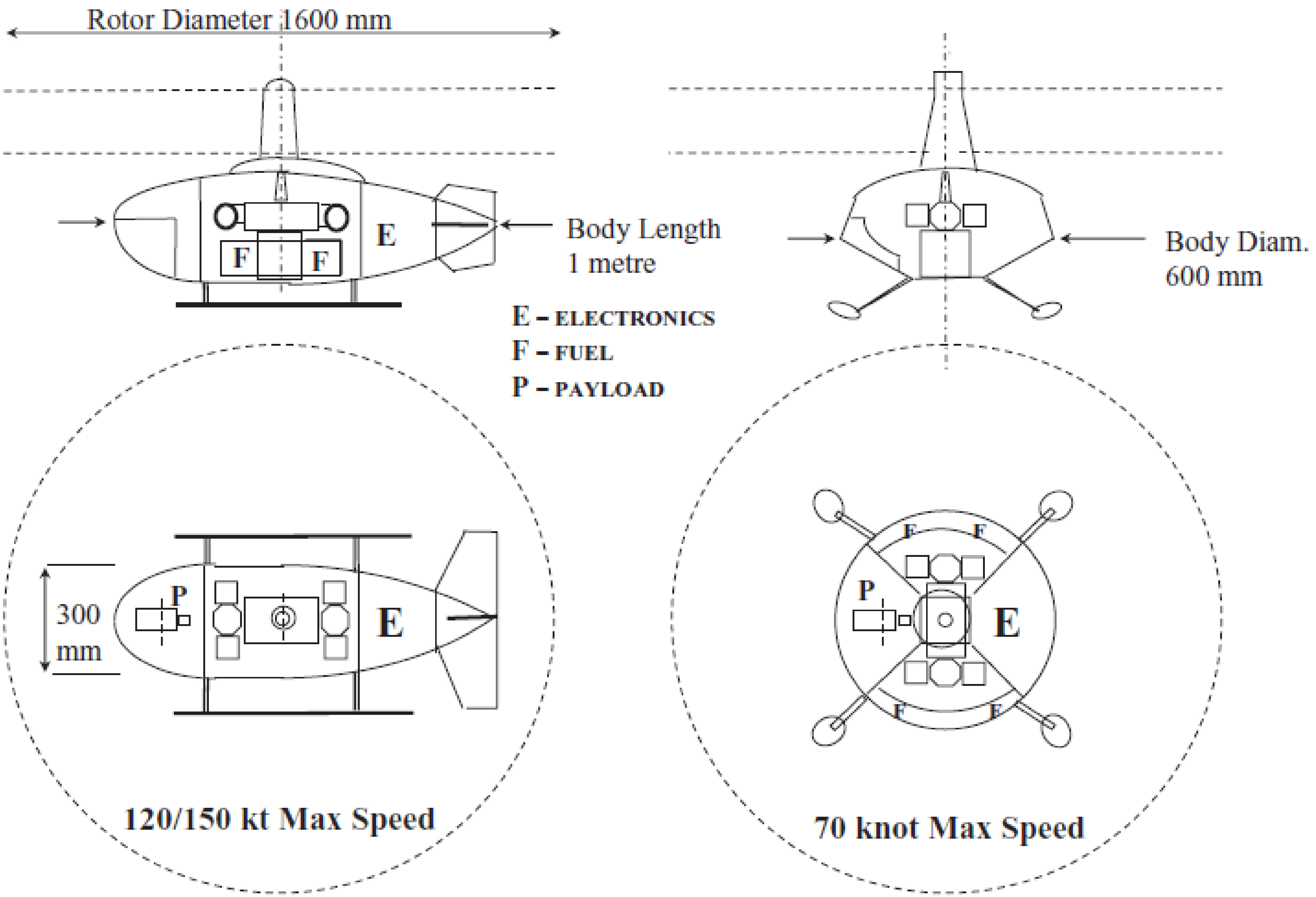
Modular Construction

This arrangement enables the mechanical module

- to **carry the weight of the body** and **its contents** from the top of the box-pillars in flight,
- whilst the **weight** of the whole aircraft in landing is **transmitted** directly down through the **pillars to the undercarriage**.
- The design concept provides a lightweight, cheap structure and a very compact aircraft with the desirably high density of packaging

These are the features which give the helicopter UAV its small size, for a given payload and performance, compared with the equivalent small aeroplane UAV

Modular Construction



Modular Construction

All-Up-Mass	36kg
Rotor span	1.60m
Engine power	2 x 5.25kW
Maximum speed	126km/hr
Loiter speed	0 - 60km/hr
Max. Endurance	3 hours

A wide range of Interchangeable payloads include:-
Colour TV Camera,
Low Light Level TV Camera,
Thermal imaging TV Camera,
NBC Monitor + LLLTV,
Laser Target Designator + LLLTV,
Radar Confusion Transmission + TV
all with full hemisphere field of regard.
1 or 2 (optional) 500W rotor-driven alternators supply electrical power.

As the launch and recovery of the aircraft is via an automatic vertical take-off and landing, the whole system is contained within and operated by two operators from a single all-terrain vehicle.

Modular Construction

Another configuration considered was the installation of the modules in a tilt-wing airframe somewhat similar to the Aerovironment Sky Tote, but with a delta-wing.

Modular Construction

The advantage of this ability of the aircraft **to emerge in different configurations** is that *an operator can operate* ***more than one type and choose the variant which provides the best capability for a particular role***.

The airframe body is by far the cheapest of the modules and the others can literally be moved into whichever airframe is to be operated.

- To meet airworthiness regulations it is necessary to define the ‘build standard’ of each aircraft before flight, and for a UAV system, probably of the whole system

Ancillary Equipment

UAV need a similar range of ancillary equipment as manned aircraft except for those items relevant to aircrew accommodation and functioning.

- Appropriately sized electrical alternators,
- actuators,
- air-data systems,
- attitude and altitude sensors,
- batteries,
- fasteners,
- external lighting, antennae, etc.

UNIT-III

Long-endurance, Long-range Role Aircraft

Long-endurance, Long-range Role Aircraft

Figure 3.1: Long-endurance, long-range, HALE

Global Hawk Block 20

Global Hawk Block 20

by Northrop-Grumman.
Wing-span 39.9m
Length 14.5m
MTOM 14,628kg
Max. Endurance 35hr
Max Altitude 19,800m
Payload - mass 1,360kg
Stabilised, high-magnification
Optical and I.R. TV.
Synthetic Aperture Radar

Global Hawk Block 20

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

Long-endurance, Long-range Role Aircraft

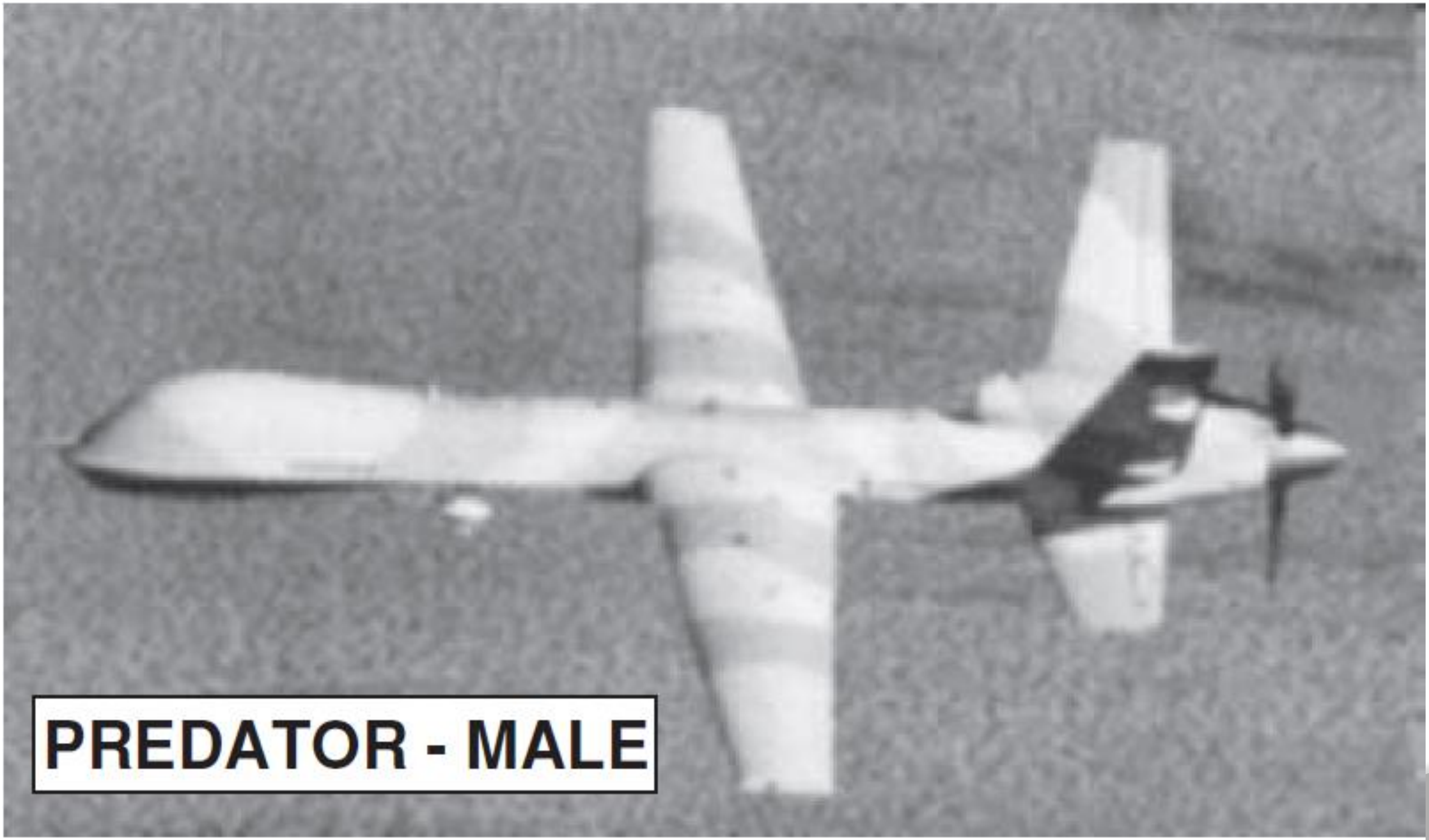


Figure 3.2: : Long-endurance, long-range, MALE

Predator B

Predator B

by General Atomics Inc.
Wing-span 20m
Length 10.6m
MTOM 4,536kg
Max. Endurance 32hr
Ceiling 12,000m
Payload :- mass 230kg
Stabilised, High-mag.
Optical and I.R. TV.
S.A.R.

Three main concerns of the airframe designer

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.;

To obtain long range, 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.

Three main concerns of the airframe designer

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’.

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.

Three main concerns of the airframe designer

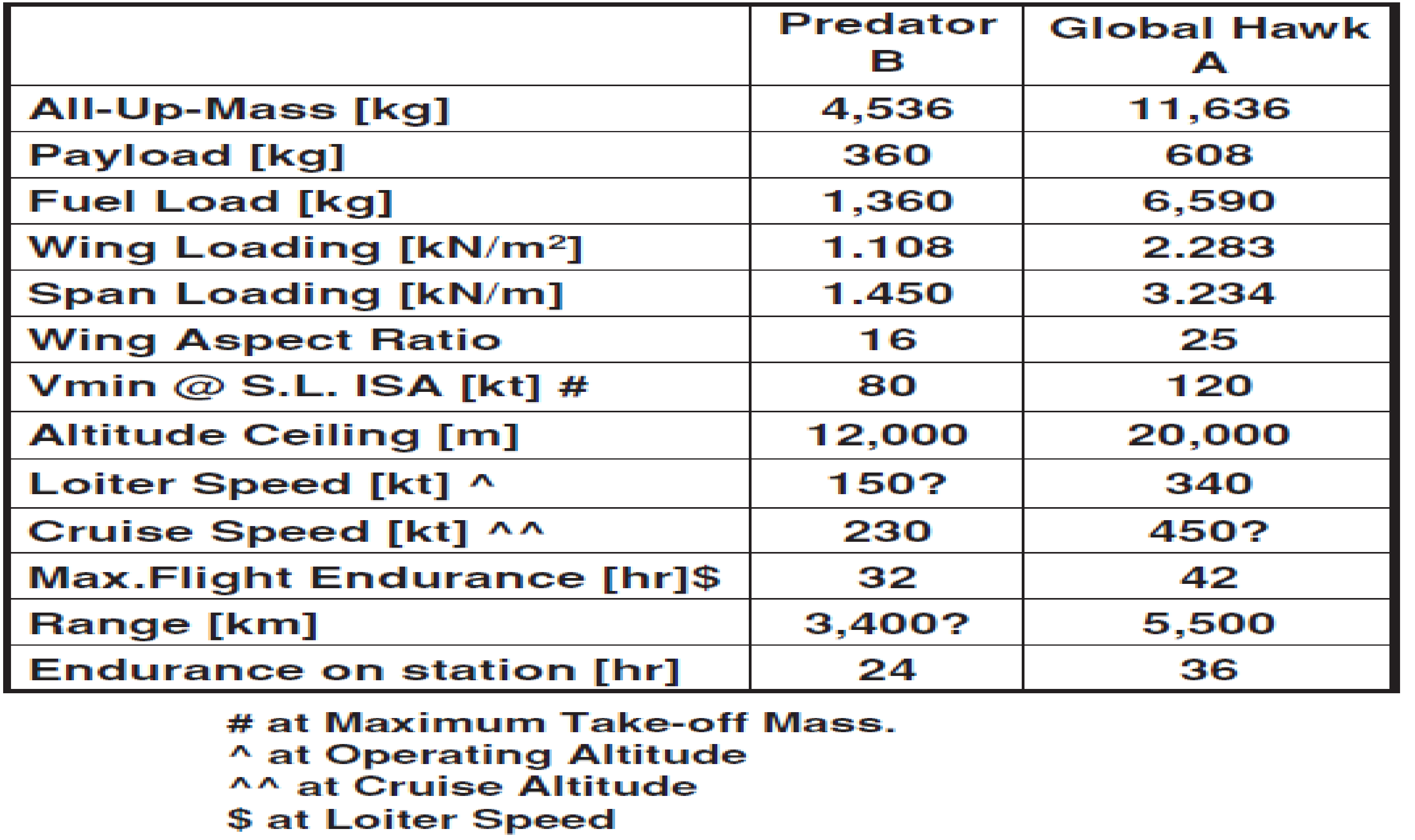
c) install a reliable **power-plant** which provides an adequate level of power, yet is **light in weight and is fuel efficient**, particularly under the conditions at which the aircraft will spend the majority of its time operating.

The lightest engine may not result in the lightest overall package if the light engine uses more fuel.

Three main concerns of the airframe designer

- 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.***

Performance of HALE UAV



	Predator B	Global Hawk A
All-Up-Mass [kg]	4,536	11,636
Payload [kg]	360	608
Fuel Load [kg]	1,360	6,590
Wing Loading [kN/m^2]	1.108	2.283
Span Loading [kN/m]	1.450	3.234
Wing Aspect Ratio	16	25
Vmin @ S.L. ISA [kt] #	80	120
Altitude Ceiling [m]	12,000	20,000
Loiter Speed [kt] ^	150?	340
Cruise Speed [kt] ^^	230	450?
Max.Flight Endurance [hr]$	32	42
Range [km]	3,400?	5,500
Endurance on station [hr]	24	36

at Maximum Take-off Mass.
^ at Operating Altitude
^^ at Cruise Altitude
$ at Loiter Speed

Figure 3.3: Comparison of Leading Particulars of Predator and Global-Hawk UAV

Performance of HALE UAV

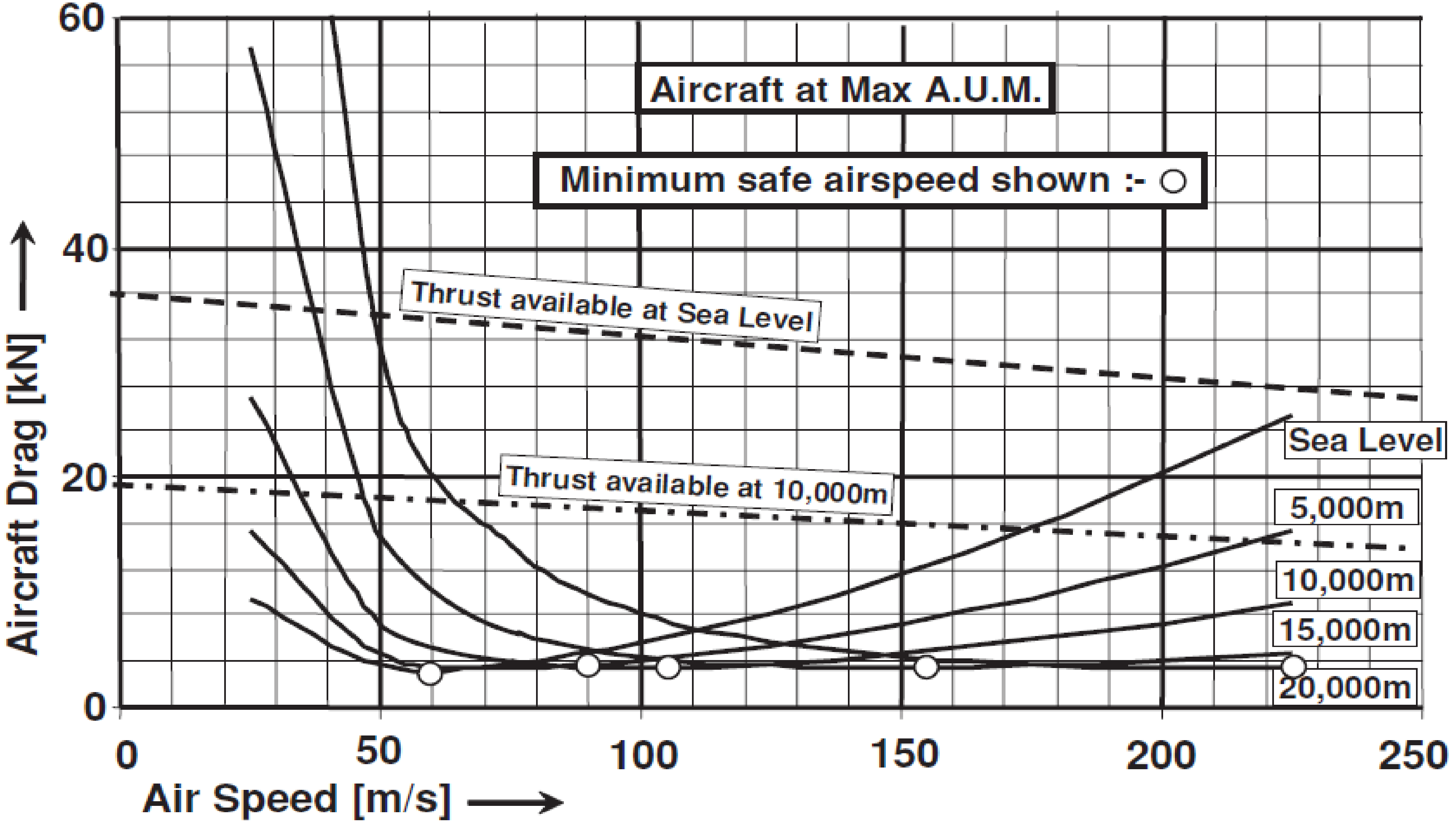


Figure 3.4:HALE UAV variation of aircraft drag with airspeed and altitude (ISA)

Performance of HALE UAV

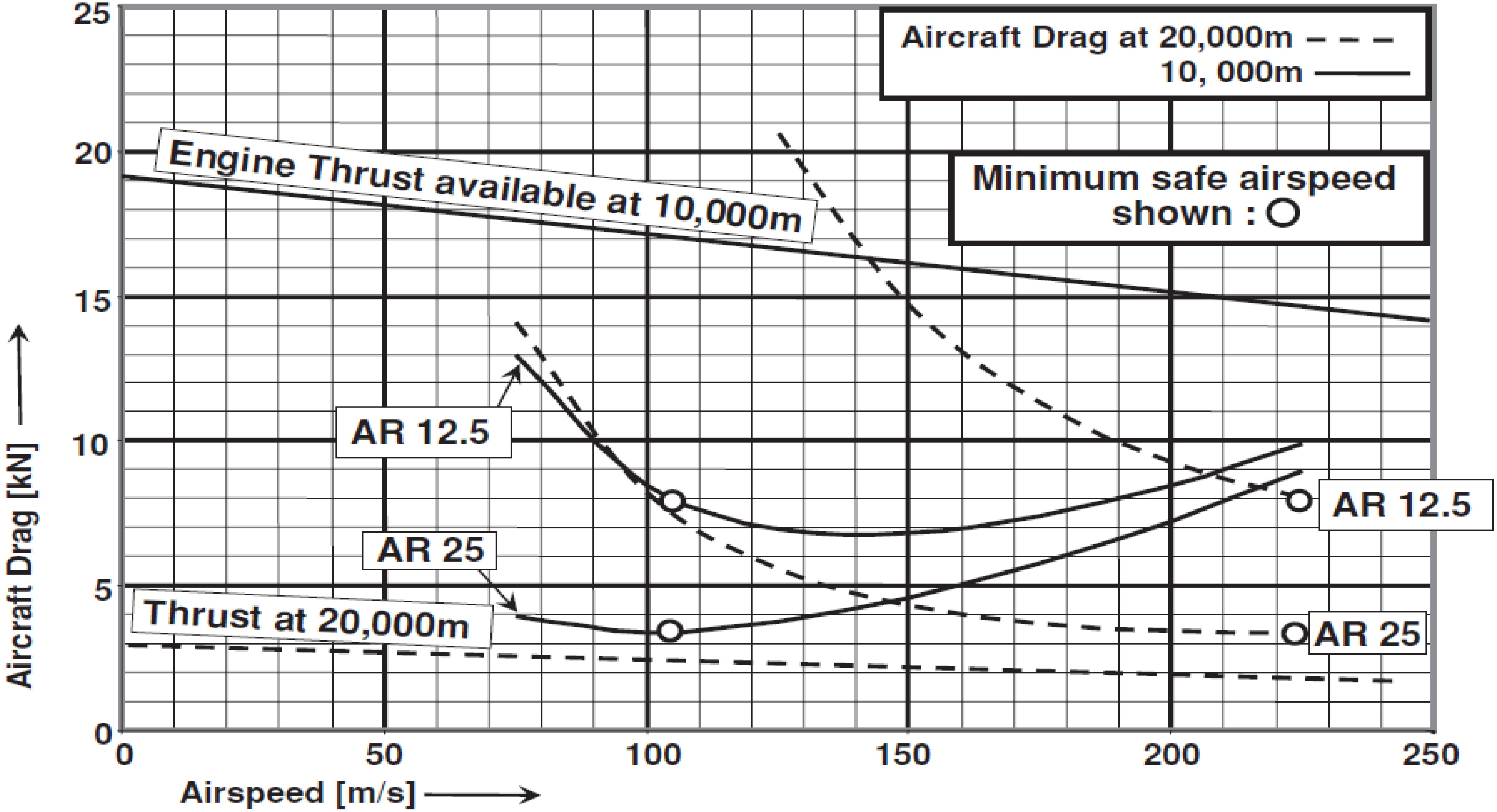


Figure 3.5: HALE UAV: effect of wing aspect ratio on aircraft drag at high altitudes (aircraft at gross mass)

Performance of HALE UAV

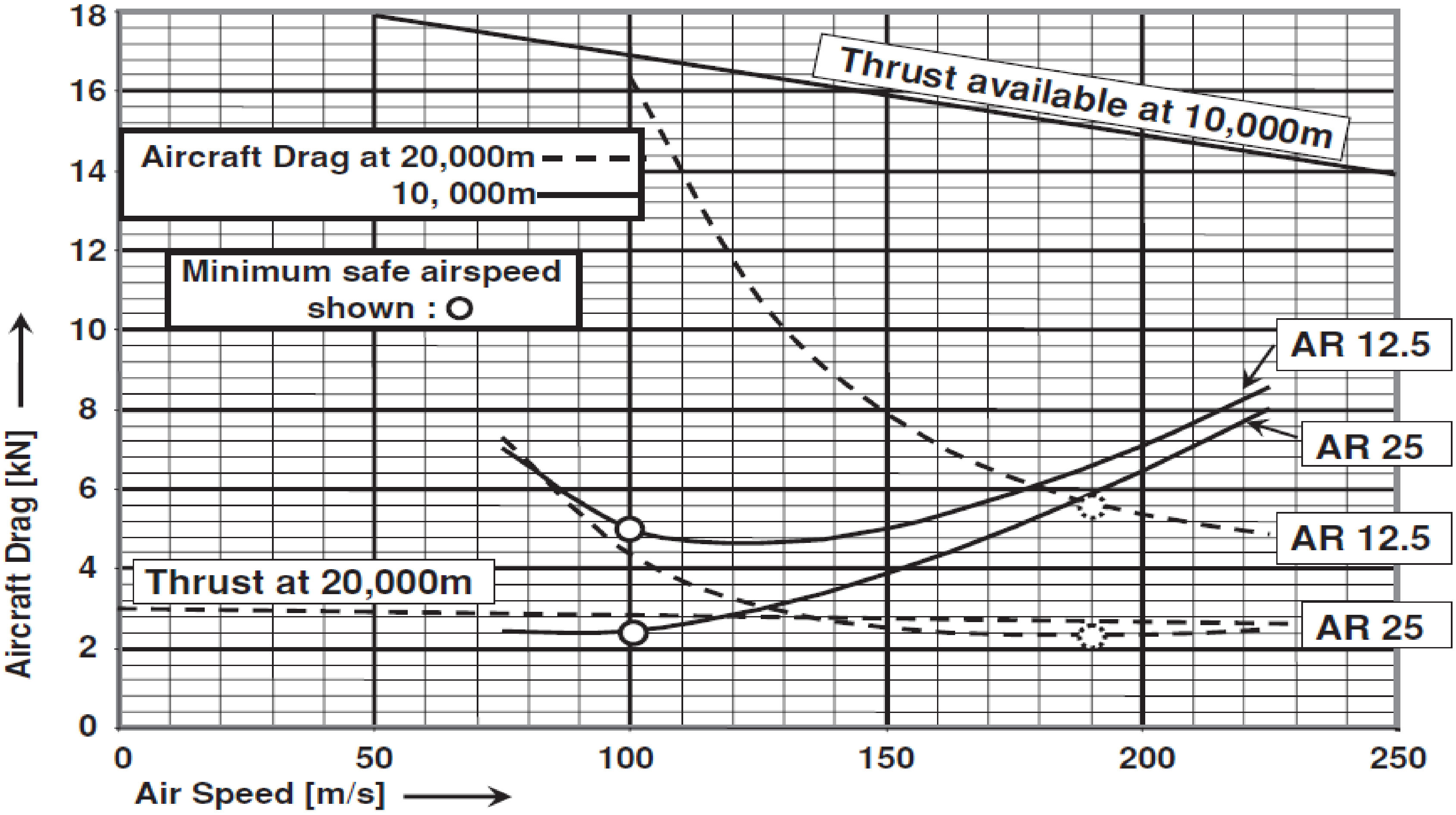


Figure 3.6: HALE UAV: effect of wing aspect ratio on aircraft drag at high altitudes (aircraft mass with half fuel)

Performance of HALE UAV

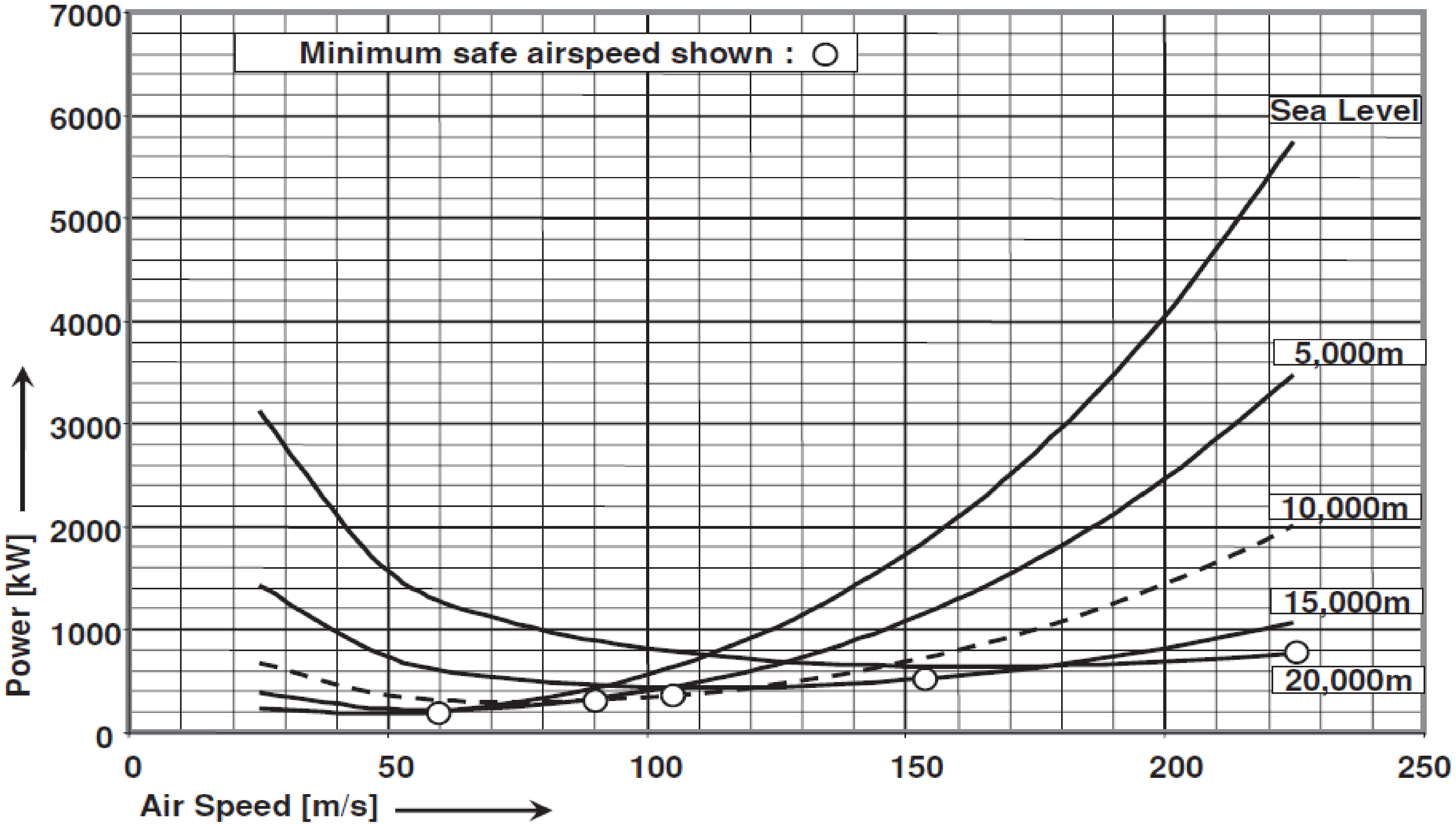


Figure 3.7: HALE UAV: power required to maintain height. Variation with airspeed and altitude – 114 kN AUW, ISA conditions

Medium-range, Tactical Aircraft

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**

Medium-range, Tactical Aircraft

- 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**.

Medium-range, Tactical Aircraft

- 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’.
- 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.

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.

Fixed-wing Aircraft

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 stabilization and control, are mounted on twin tail-booms.

Hunter RQ5A

Figure 3.8 : Hunter RQ5A UAV

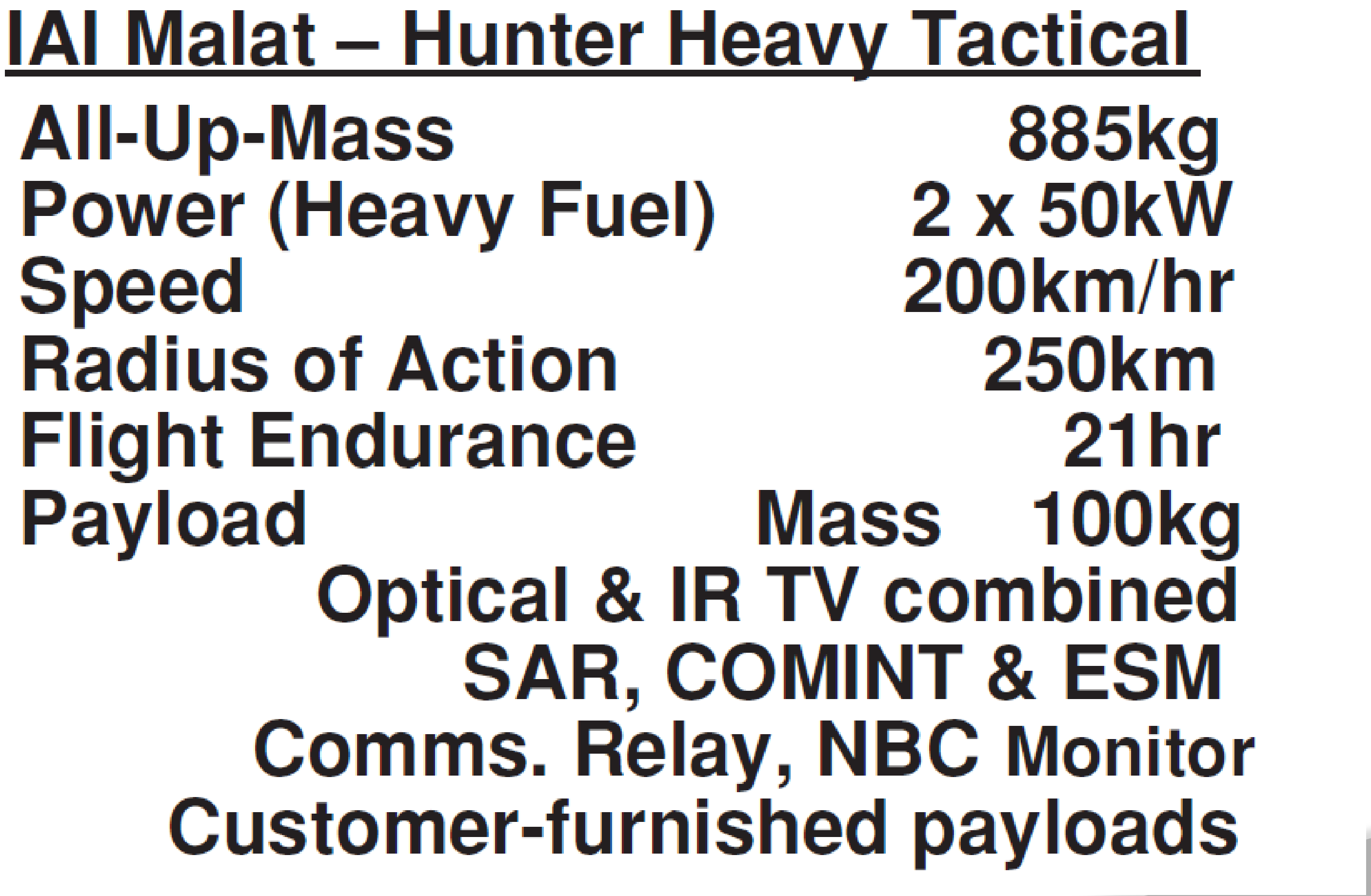
Hunter RQ5A

Figure 3.9 : Hunter RQ5A UAV

Hunter RQ5A

Figure 3.10: Hunter RQ5A UAV , by IAI-Israel Aerospace Industries.

Hunter RQ5A



IAI Malat – Hunter Heavy Tactical

All-Up-Mass	885kg
Power (Heavy Fuel)	2 x 50kW
Speed	200km/hr
Radius of Action	250km
Flight Endurance	21hr
Payload	Mass 100kg
	Optical & IR TV combined
	SAR, COMINT & ESM
	Comms. Relay, NBC Monitor
	Customer-furnished payloads

Figure 3.11: Technical details of Hunter RQ5A UAV.

SEEKER-II (Denel Dynamics/Aerospace)

Figure3.12 : SEEKER-II by Denel Aerospace

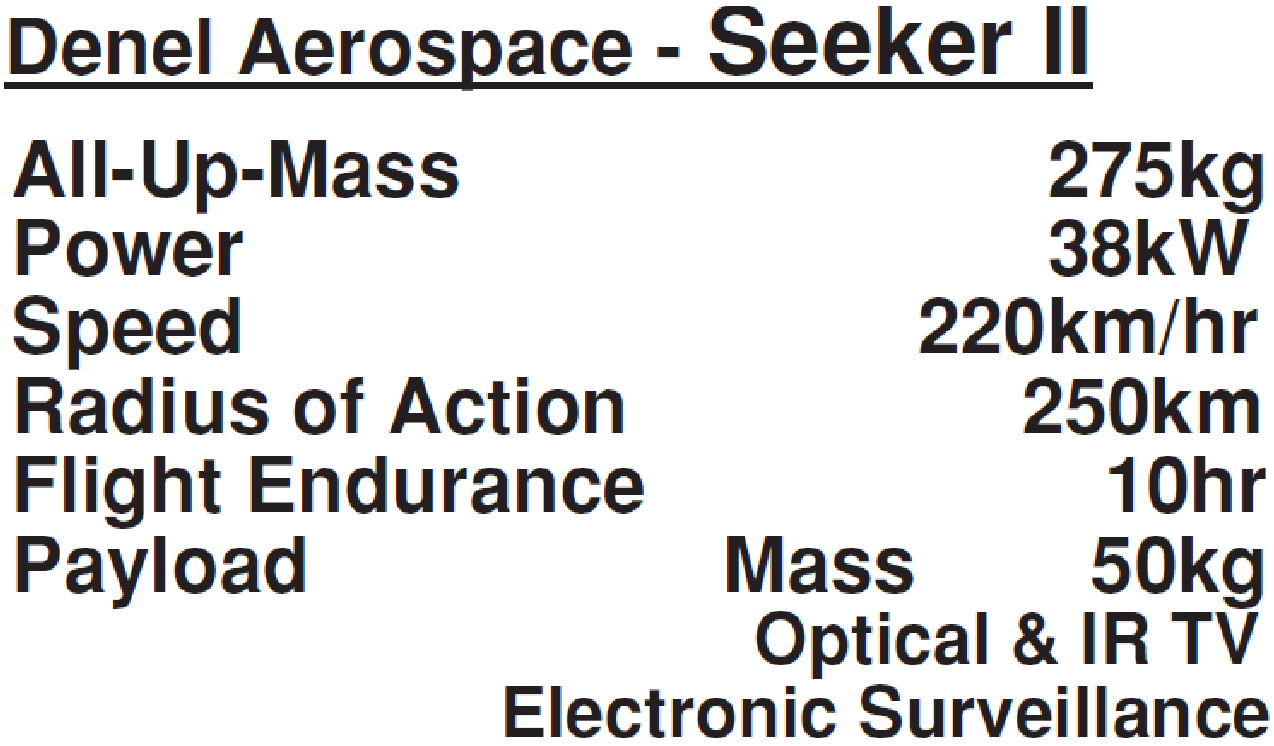
SEEKER-II (Denel Dynamics/Aerospace)

Figure 3.13: SEEKER-II by Denel Dynamics, South Africa

SEEKER-II (Denel Dynamics/Aerospace)

Figure 3.14 : SEEKER-II by Denel Dynamics, South Africa

SEEKER-II (Denel Dynamics/Aerospace)



Denel Aerospace - Seeker II

All-Up-Mass		275kg
Power		38kW
Speed		220km/hr
Radius of Action		250km
Flight Endurance		10hr
Payload	Mass	50kg
		Optical & IR TV
		Electronic Surveillance

Figure 3.15 : SEEKER-II by Denel Dynamics, South Africa

RANGER (by RUAG)

Figure 3.16: Ranger UAV by RUAG, Switzerland
(SWIS-ISREAL Joint Venture)

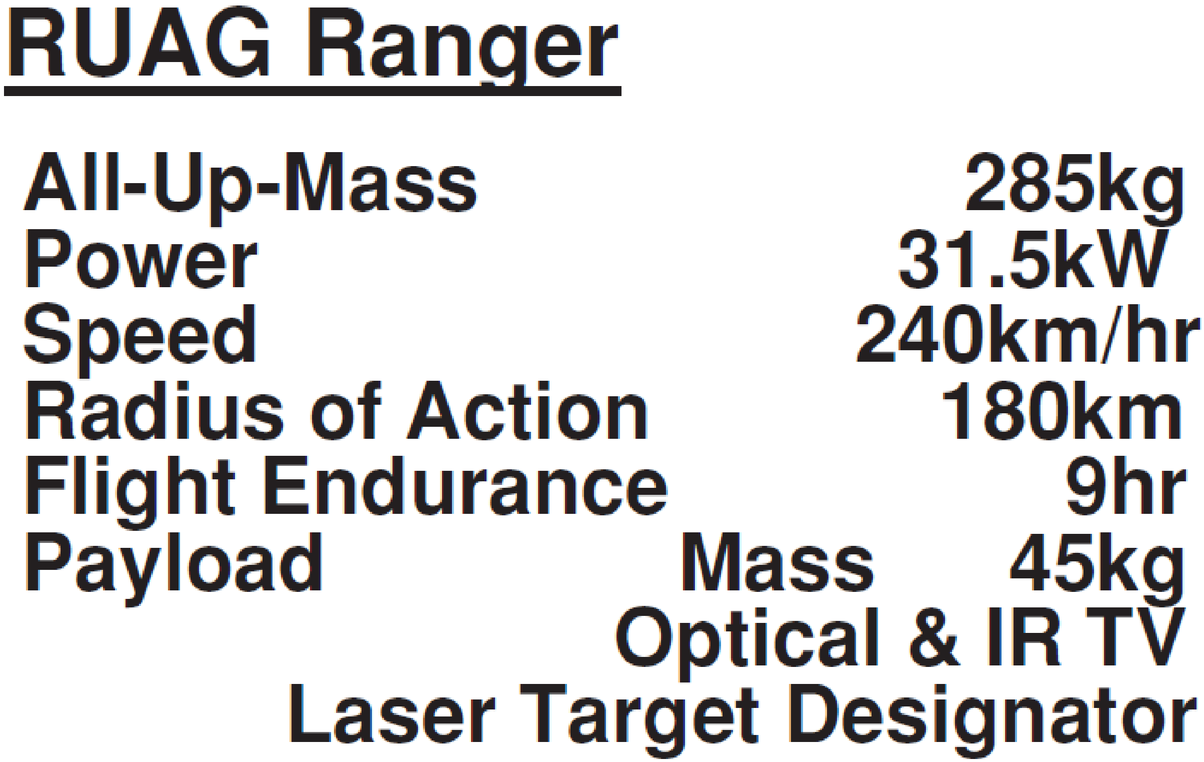
RANGER (RUAG)

Figure 3.17 : Ranger UAV by RUAG, Switzerland , uses hydraulic launcher

RANGER (RUAG)

Figure 3.18: Ranger UAV by RUAG, Switzerland

RANGER (RUAG)



RUAG Ranger

All-Up-Mass		285kg
Power		31.5kW
Speed		240km/hr
Radius of Action		180km
Flight Endurance		9hr
Payload	Mass	45kg
	Optical & IR TV	
	Laser Target Designator	

Figure 3.19: Ranger UAV by RUAG, Switzerland

SHADOW 600 (by AAI/TEXTRON)

Figure 3.20 : Shadow 600 UAV by AAI- American Armaments .Inc., US

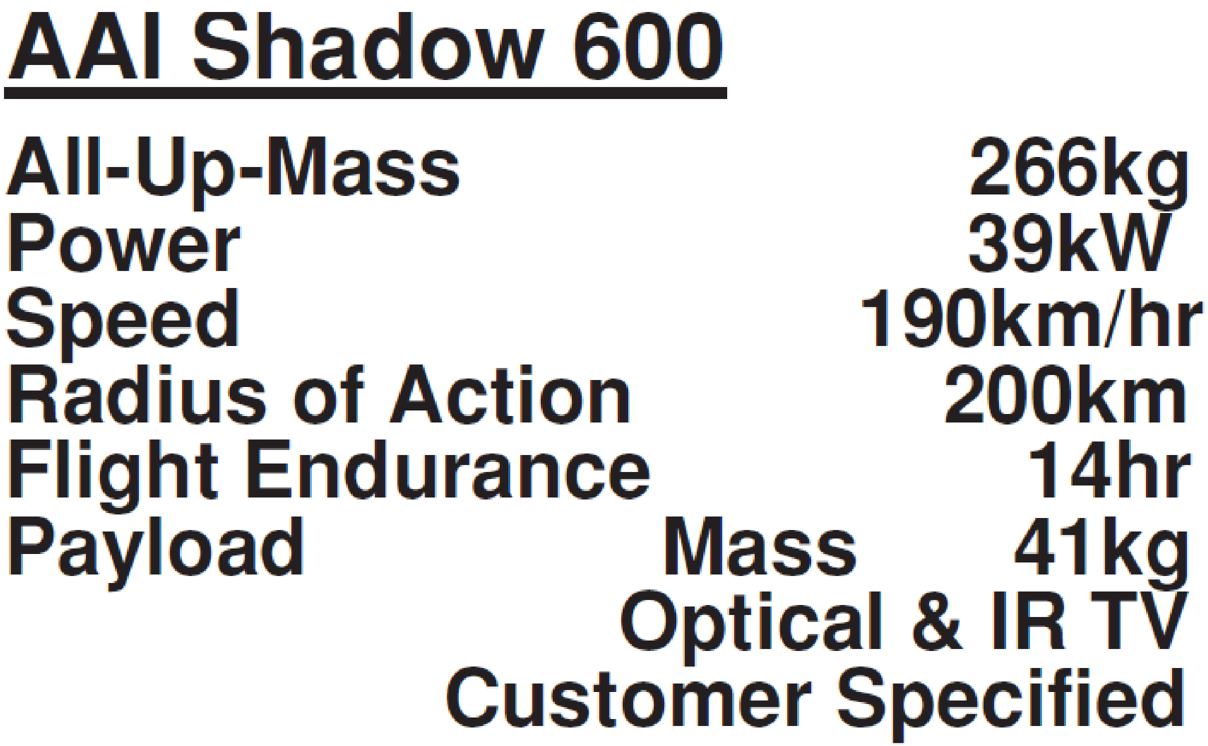
SHADOW 600 (by TEXTRON)

Figure 3.21 : Shadow 600 UAV by Textron, US

SHADOW 600 (by TEXTRON)

Figure 3.22 : Shadow 600 UAV by Textron, US

SHADOW 600 (by TEXTRON)

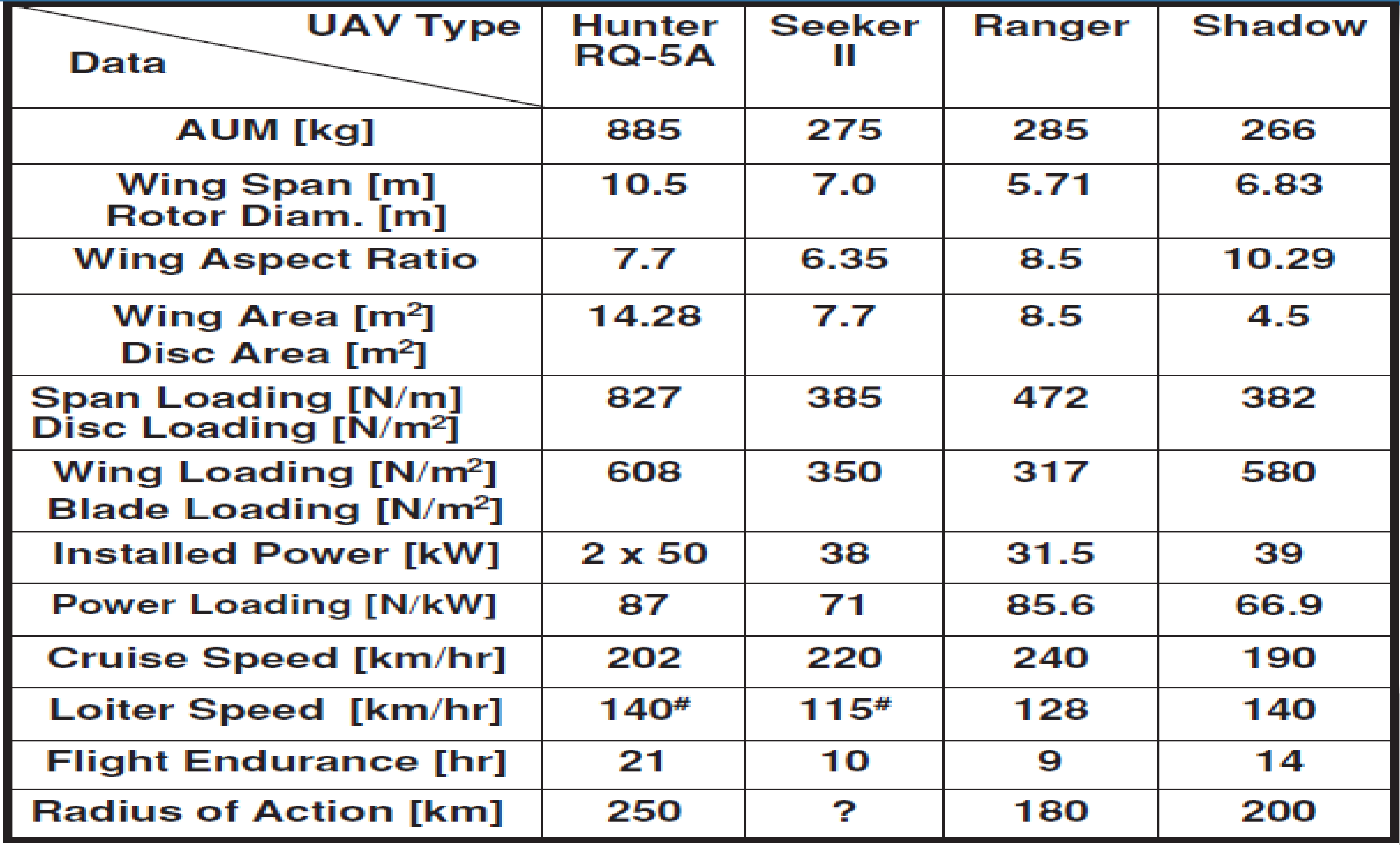


AAI Shadow 600

All-Up-Mass	266kg
Power	39kW
Speed	190km/hr
Radius of Action	200km
Flight Endurance	14hr
Payload	Mass 41kg
	Optical & IR TV
	Customer Specified

Figure 3.23 : Shadow 600 UAV by Textron, US

Medium-range, Tactical Fixed Wing Aircrafts



UAV Type Data	Hunter RQ-5A	Seeker II	Ranger	Shadow
AUM [kg]	885	275	285	266
Wing Span [m] Rotor Diam. [m]	10.5	7.0	5.71	6.83
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
Span Loading [N/m] Disc Loading [N/m^2]	827	385	472	382
Wing Loading [N/m^2] Blade Loading [N/m^2]	608	350	317	580
Installed Power [kW]	2 x 50	38	31.5	39
Power Loading [N/kW]	87	71	85.6	66.9
Cruise Speed [km/hr]	202	220	240	190
Loiter Speed [km/hr]	140#	115#	128	140
Flight Endurance [hr]	21	10	9	14
Radius of Action [km]	250	?	180	200

Figure 3.24 : Medium-range, Tactical Fixed Wing Aircrafts

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.

VTOL (Rotary-winged) Aircraft

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.

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

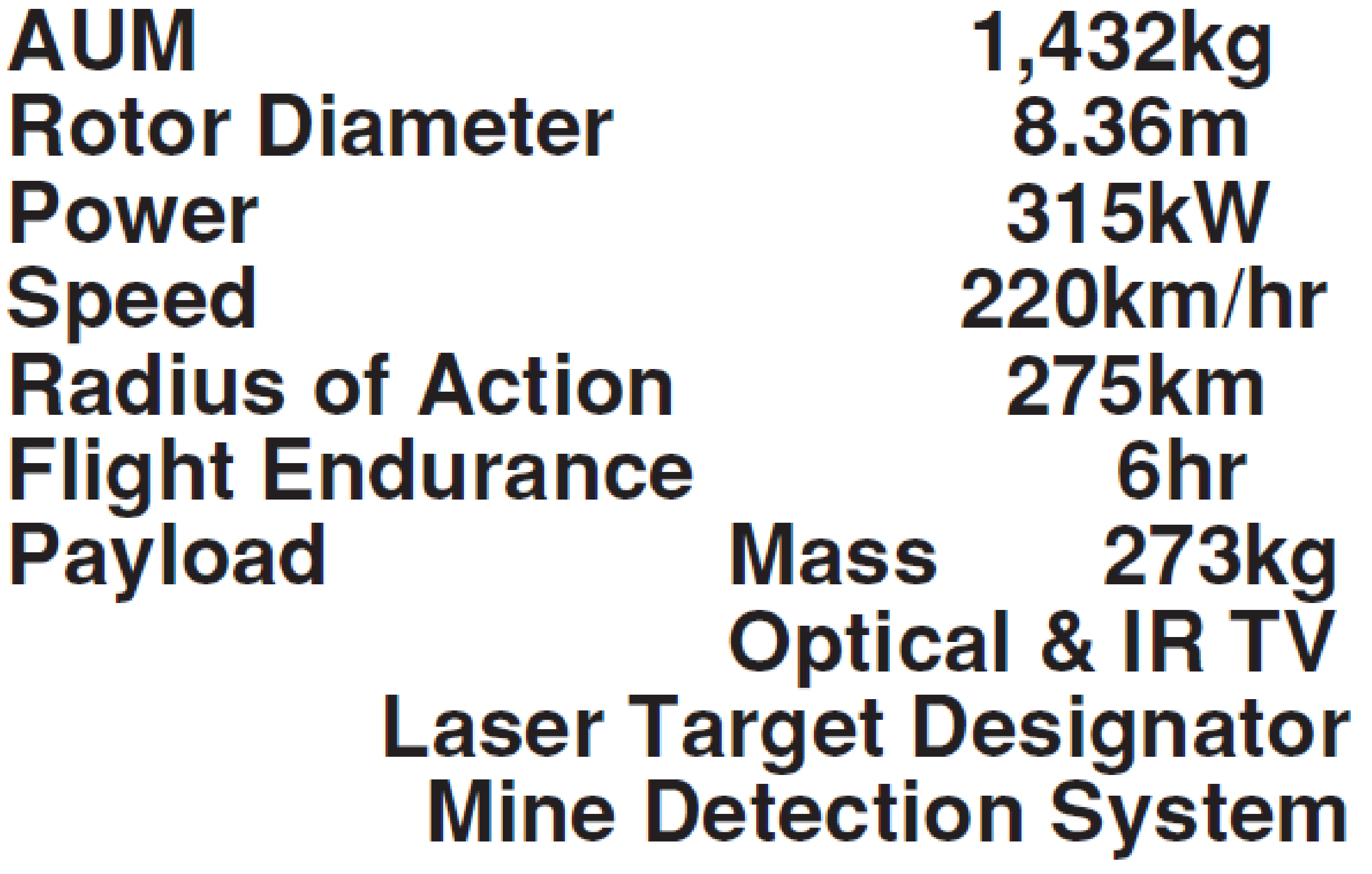
Northrop Grumman Fire scout

Figure 3.25 : Northrop Grumman Fire scout

Northrop Grumman Fire scout

Figure 3.26 : Northrop Grumman Fire scout

Northrop Grumman Firescout



AUM	1,432kg
Rotor Diameter	8.36m
Power	315kW
Speed	220km/hr
Radius of Action	275km
Flight Endurance	6hr
Payload	Mass 273kg
	Optical & IR TV
	Laser Target Designator
	Mine Detection System

Figure 3.27 : Northrop Grumman Fire scout

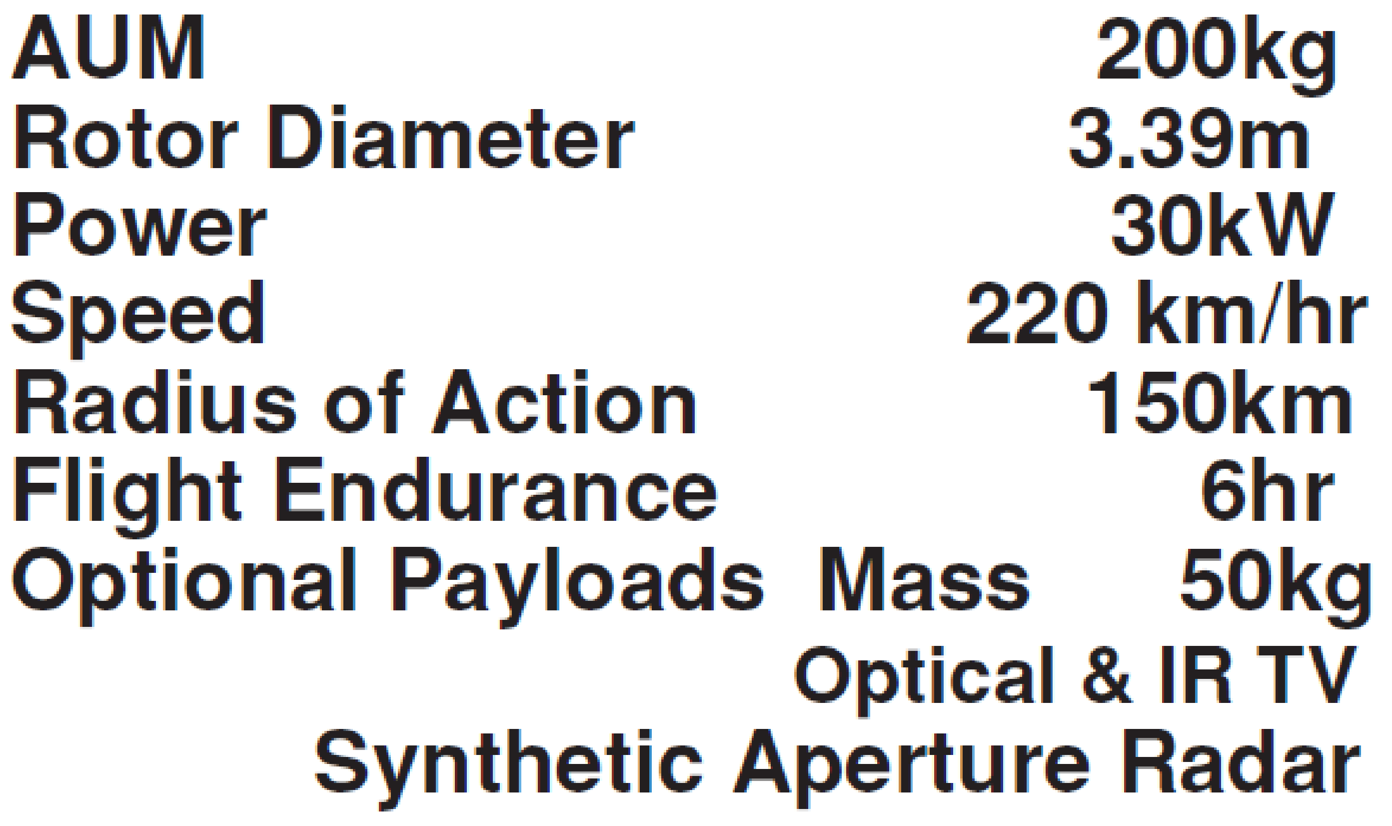
Schiebel Camcopter S100

Figure 3.28 : Schiebel Camcopter S100

Schiebel Camcopter S100

Figure 3.29 : Schiebel Camcopter S100

Schiebel Camcopter S100



AUM	200kg
Rotor Diameter	3.39m
Power	30kW
Speed	220 km/hr
Radius of Action	150km
Flight Endurance	6hr
Optional Payloads Mass	50kg
	Optical & IR TV
	Synthetic Aperture Radar

Figure 3.30 : Technical details of Schiebel Camcopter S100

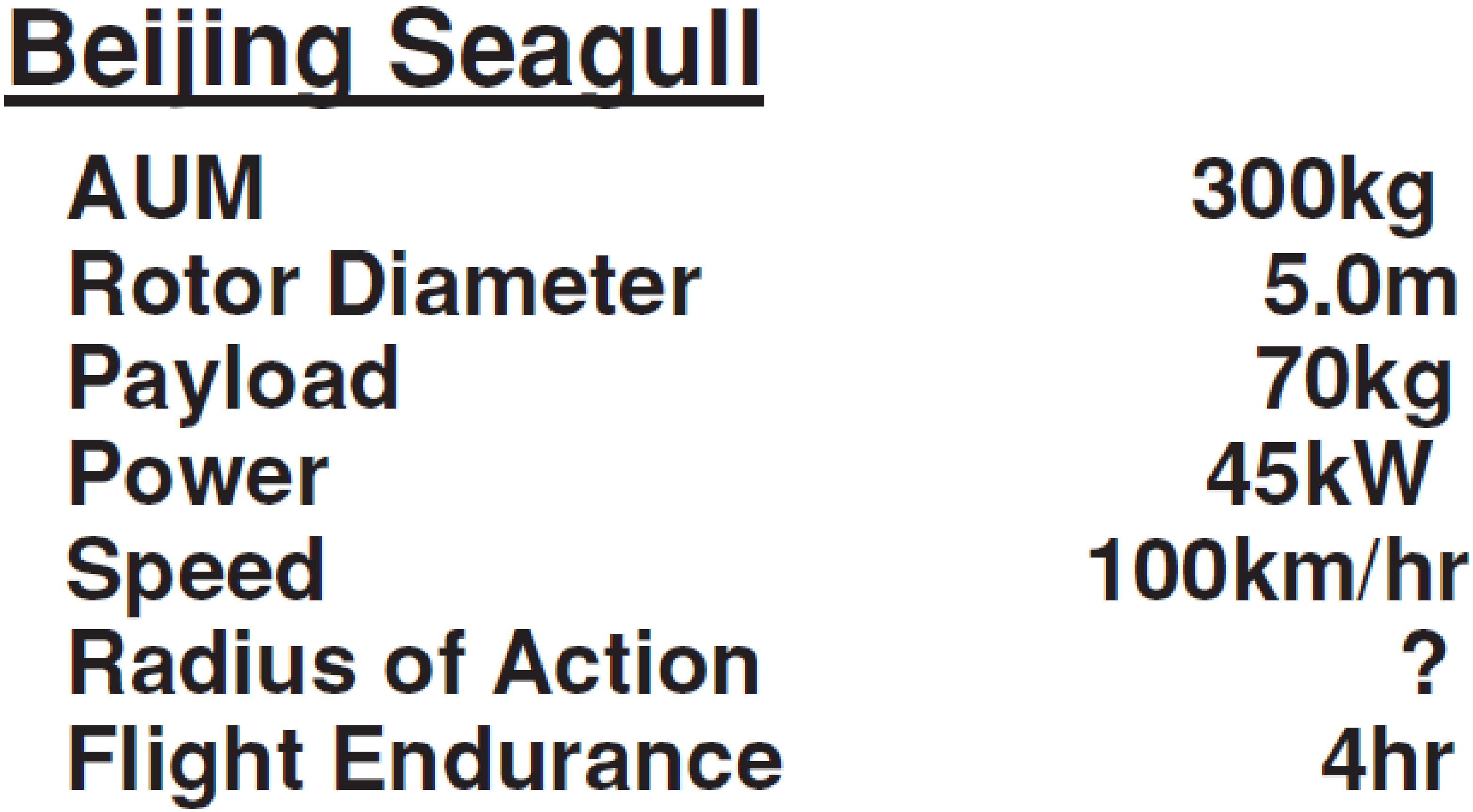
Beijing Seagull

Figure 3.31 : Beijing Seagull

Beijing Seagull

Figure 3.32 : Beijing Seagull

Beijing Seagull



Beijing Seagull

AUM	300kg
Rotor Diameter	5.0m
Payload	70kg
Power	45kW
Speed	100km/hr
Radius of Action	?
Flight Endurance	4hr

Figure 3.33 : Technical details of Beijing Seagull

Bell Aerosystems Sea Eagle

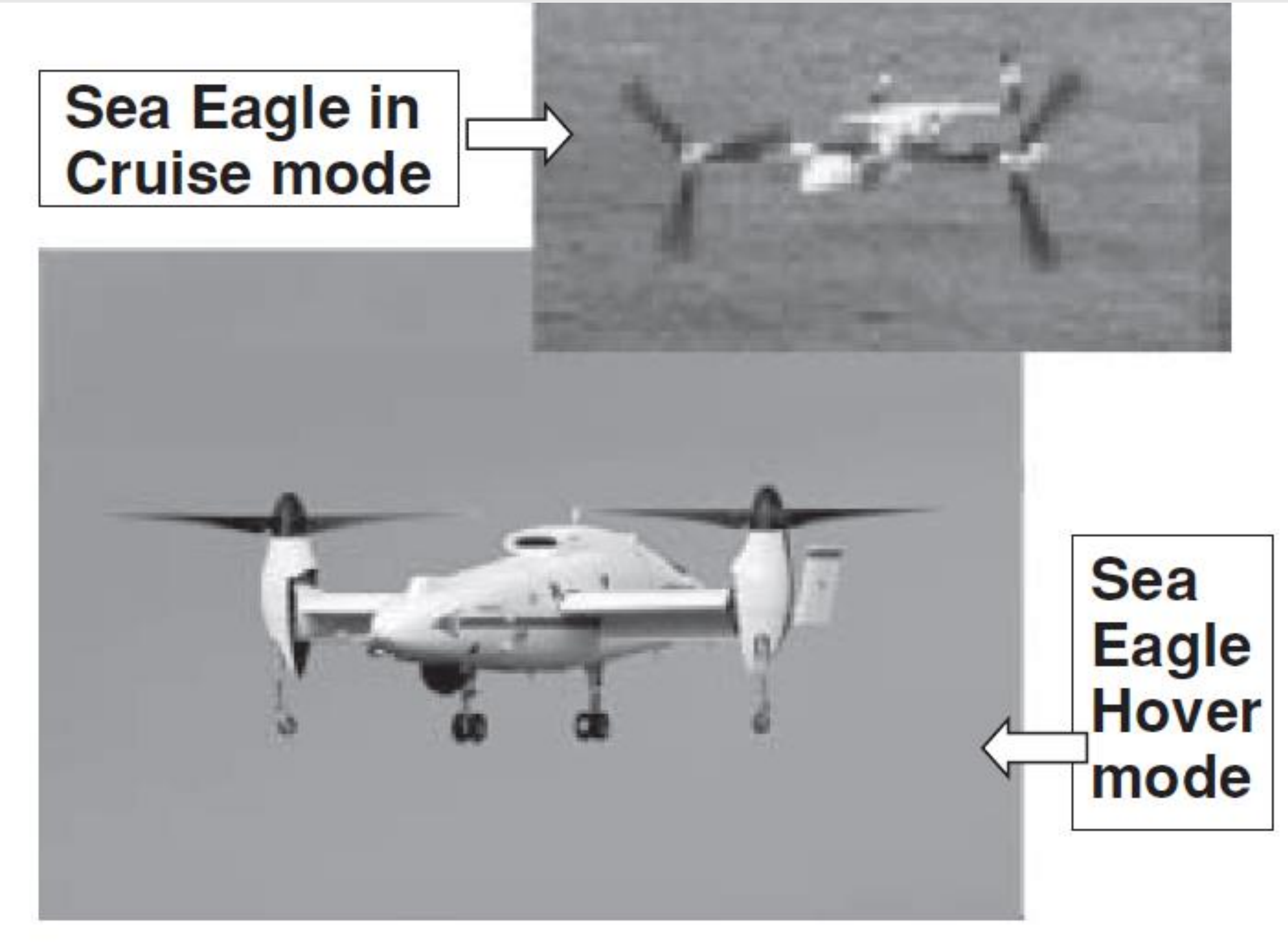


Figure 3.34 : Bell Aerosystems Sea Eagle

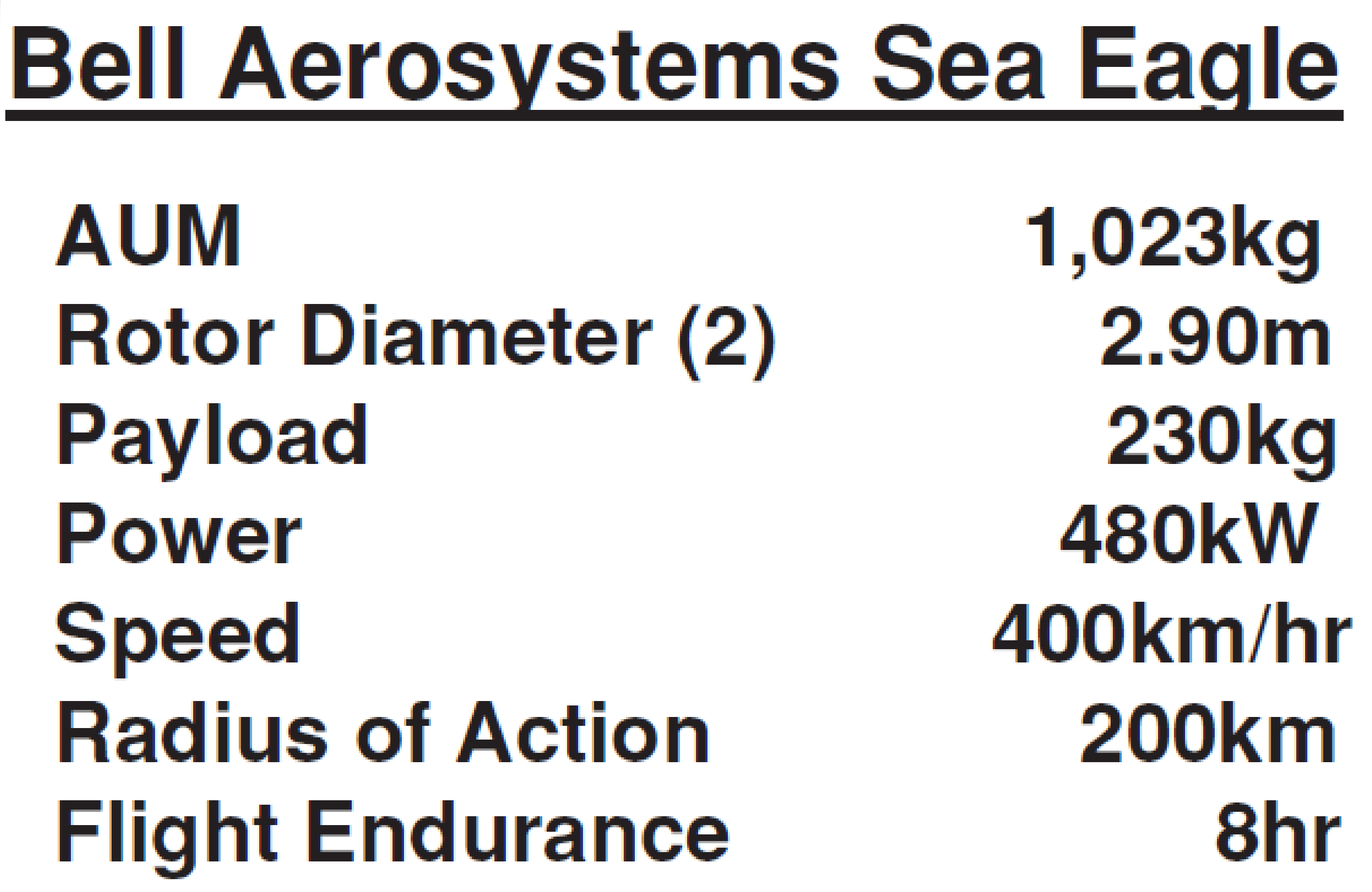
Bell Aerosystems Sea Eagle

Figure 3.35 : Bell Aerosystems Sea Eagle

Bell Aerosystems Sea Eagle

Figure 3.36 : Bell Aerosystems Sea Eagle

Bell Aerosystems Sea Eagle

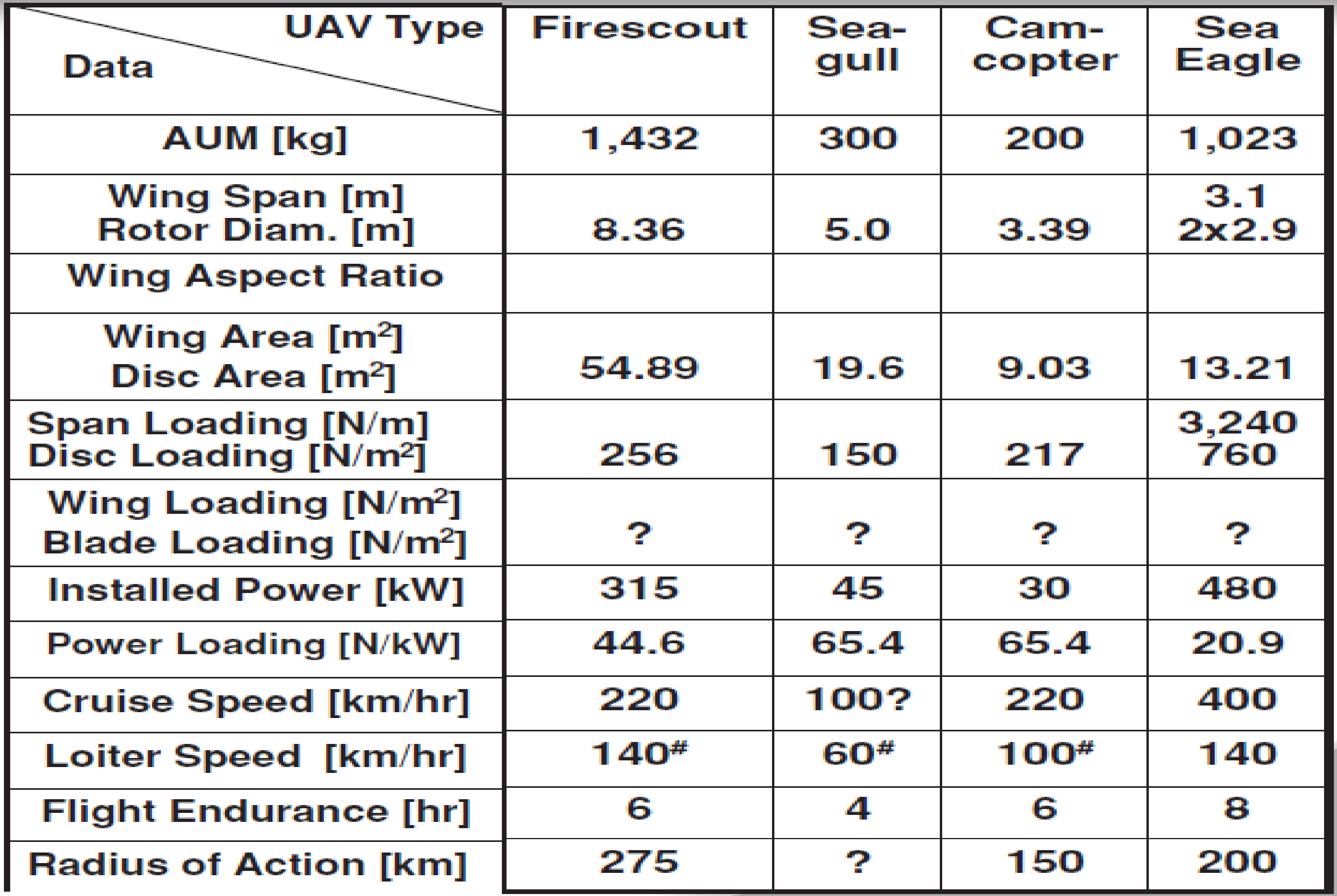


Bell Aerosystems Sea Eagle

AUM	1,023kg
Rotor Diameter (2)	2.90m
Payload	230kg
Power	480kW
Speed	400km/hr
Radius of Action	200km
Flight Endurance	8hr

Figure 3.37 : Bell Aerosystems Sea Eagle

VTOL (Rotary-winged) Aircraft



UAV Type Data	Firescout	Sea-gull	Cam-copter	Sea Eagle
AUM [kg]	1,432	300	200	1,023
Wing Span [m] Rotor Diam. [m]	8.36	5.0	3.39	3.1 2x2.9
Wing Aspect Ratio				
Wing Area [m²] Disc Area [m²]	54.89	19.6	9.03	13.21
Span Loading [N/m] Disc Loading [N/m²]	256	150	217	3,240 760
Wing Loading [N/m²] Blade Loading [N/m²]	?	?	?	?
Installed Power [kW]	315	45	30	480
Power Loading [N/kW]	44.6	65.4	65.4	20.9
Cruise Speed [km/hr]	220	100?	220	400
Loiter Speed [km/hr]	140#	60#	100#	140
Flight Endurance [hr]	6	4	6	8
Radius of Action [km]	275	?	150	200

Figure 3.38 : Bell Aerosystems Sea Eagle

VTOL (Rotary-winged) Aircraft

- 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 for their mass.

VTOL (Rotary-winged) Aircraft

- With the exception of the tilt-rotor Sea Eagle and the Seagull, ***all types have a similar cruise speed of about 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.

Close-range/Battlefield Aircraft

VTOL (Rotary-winged) Aircraft

- This type of system with its **multitude of roles**, 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.
- **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.

VTOL (Rotary-winged) Aircraft

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

Pioneer three-view drawing

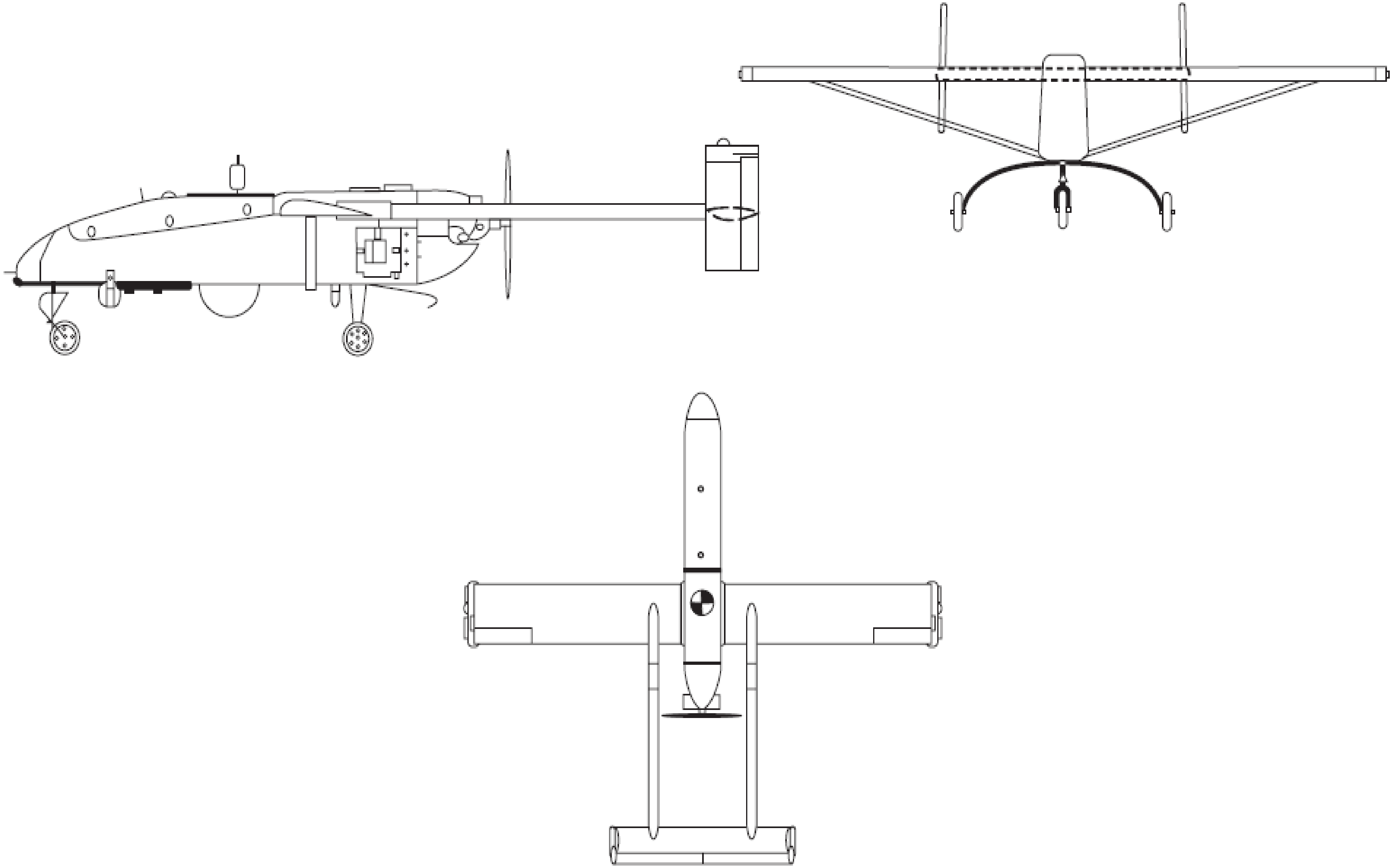


Figure 3.39 : Pioneer three-view drawing

Pioneer three-view drawing

General characteristics

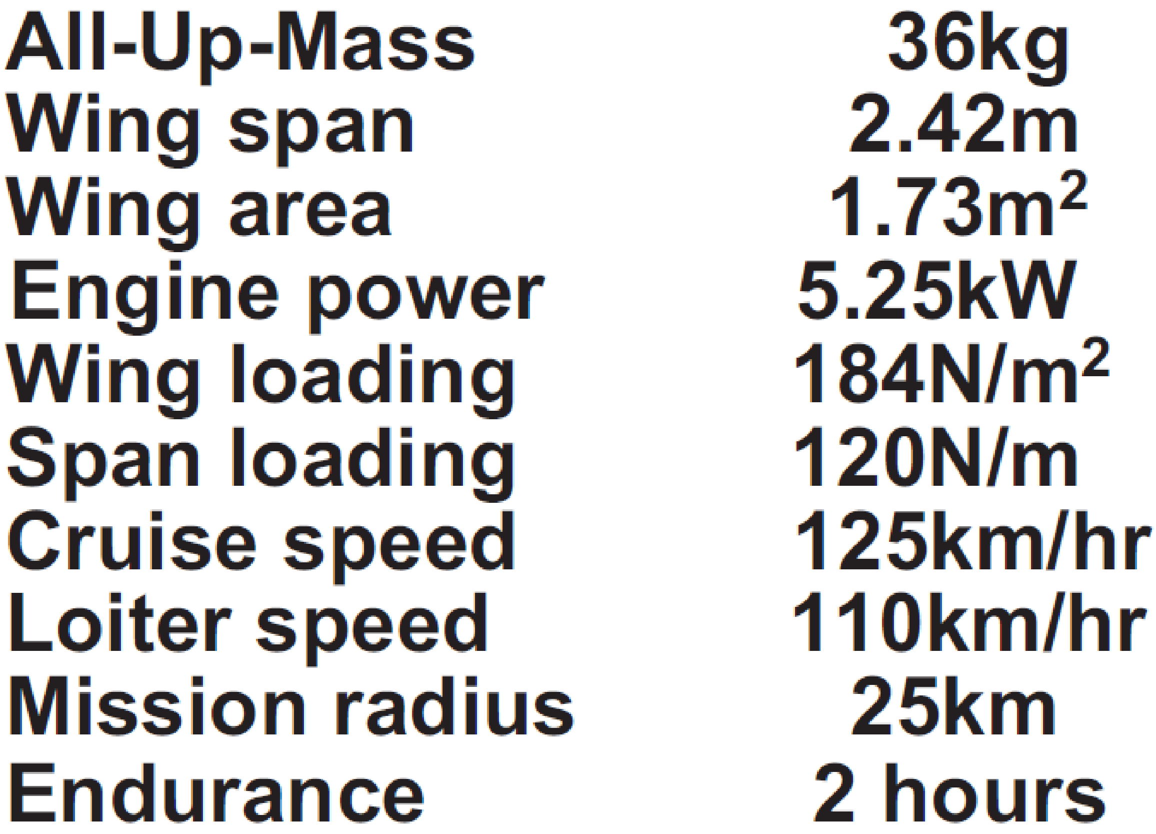
Length: 4.3 m (14 ft)
Wingspan: 5.151 m (16 ft 10.8 in)
Height: 1.006 m (3 ft 3.6 in)
Airfoil: NACA 4415
Gross weight: 205 kg
Fuel capacity: 44 to 47 l (12 to 12 US gal.)
Powerplant: 1 × ZF Sachs 2-stroke 2-cylinder horizontally-opposed piston engine, 19 kW (26 hp) or UEL AR-741 rotary engine; 28.3 kW (38.0 hp)

Performance
Range: 185 km , Service ceiling: 4,600 m (15,100 ft)
Used in Persian Gulf War, 1991

Observer

Figure 3.40 : Pioneer three-view drawing

Observer



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

Figure 3.41 : Technical details of Observer

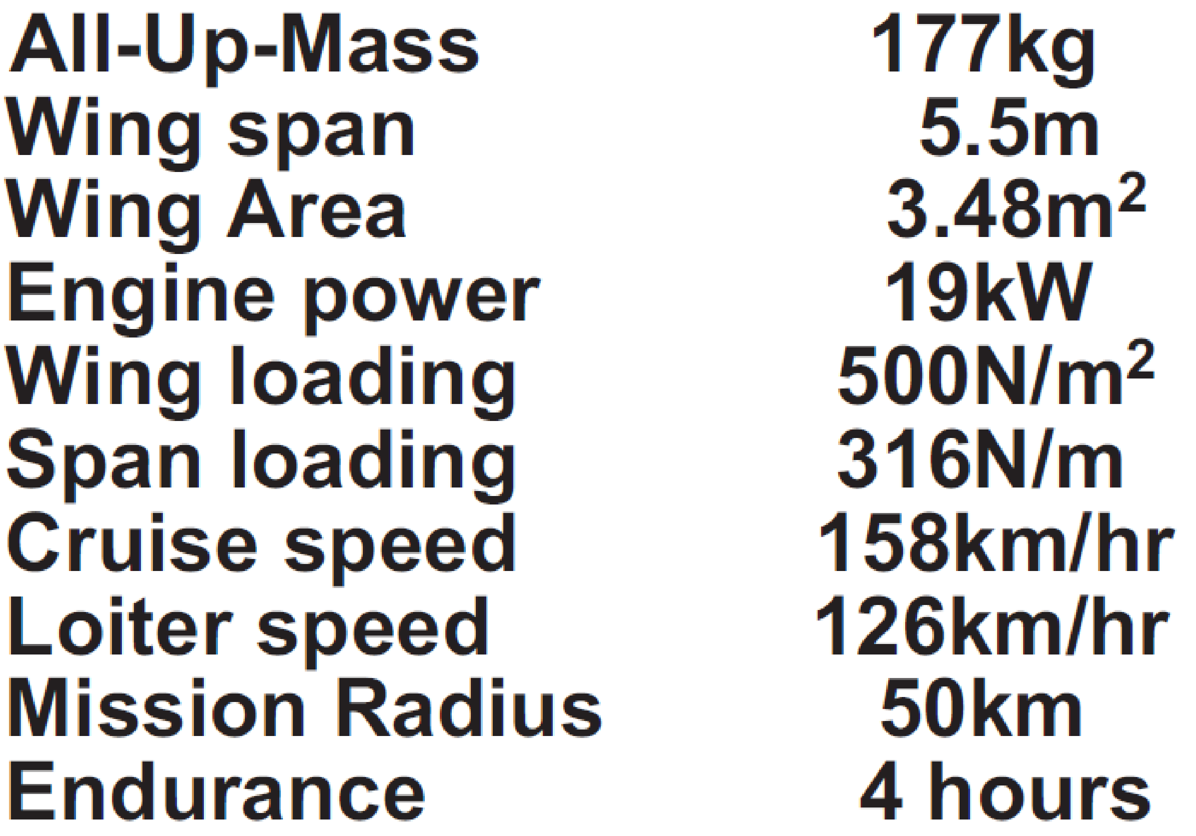
Observer

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 stabilizing it electronically in space coordinates.

Phoenix

Figure 3.42 : Technical details of Observer

Phoenix



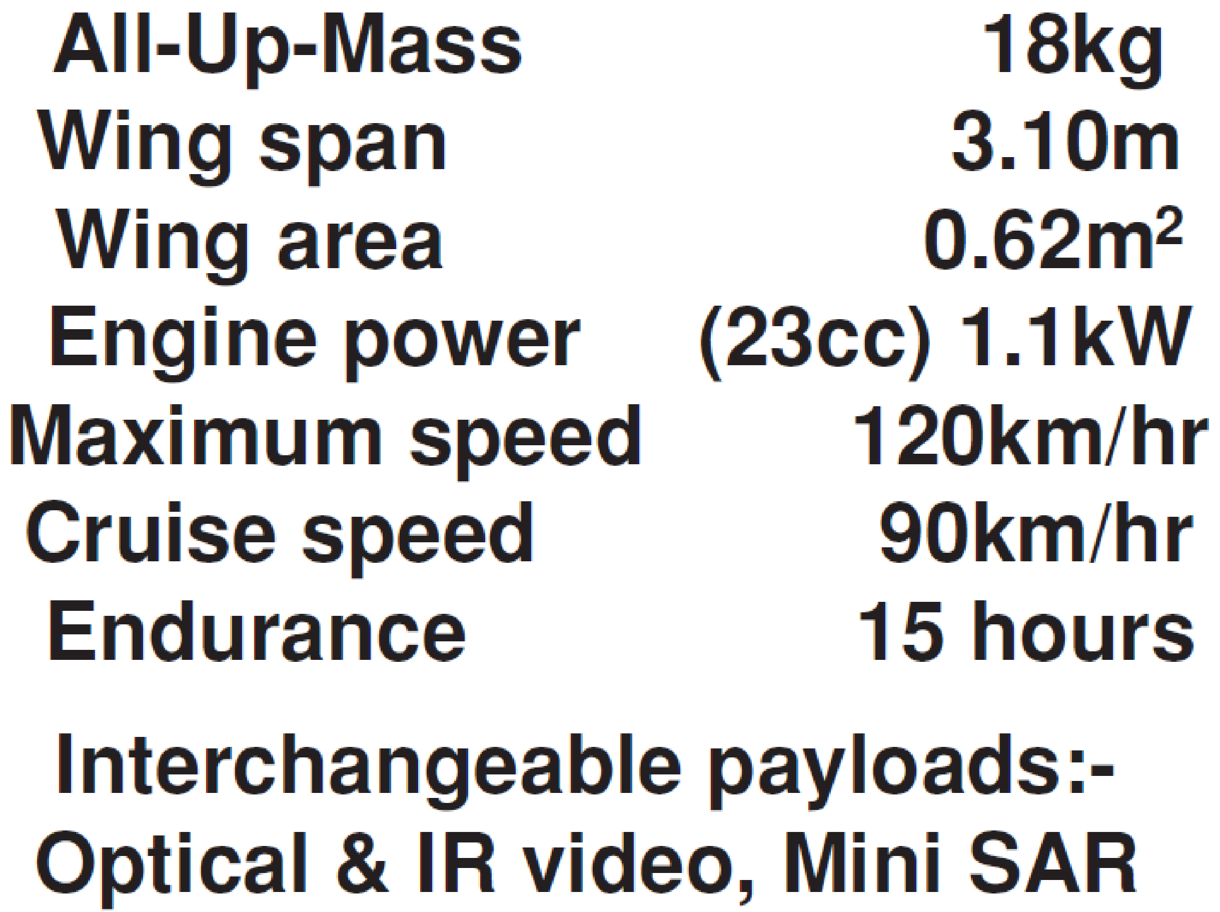
All-Up-Mass	177kg
Wing span	5.5m
Wing Area	$3.48m^2$
Engine power	19kW
Wing loading	$500N/m^2$
Span loading	316N/m
Cruise speed	158km/hr
Loiter speed	126km/hr
Mission Radius	50km
Endurance	4 hours

Figure 3.43 : Technical details of Phoenix

Scan Eagle

Figure 3.44 : Scan Eagle

Scan-Eagle



All-Up-Mass	18kg
Wing span	3.10m
Wing area	0.62m^2
Engine power	(23cc) 1.1kW
Maximum speed	120km/hr
Cruise speed	90km/hr
Endurance	15 hours

Interchangeable payloads:-

Optical & IR video, Mini SAR

Figure 3.45 : Technical details of Scan Eagle

Scan Eagle

- The Scan Eagle system uses an innovative sky-hook recovery method, but this adds a further vehicle and equipment to the system.

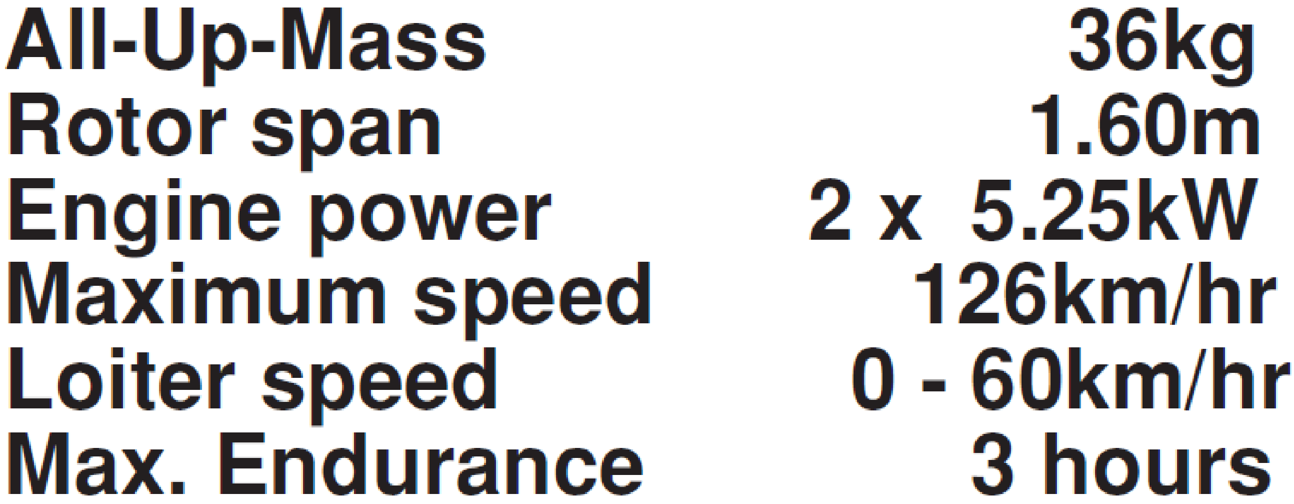
- The ‘flying wing’ configuration was presumably chosen in view of the demands of the recovery system as an empennage might have fouled the sky-hook

VTOL Aircraft Systems

ML Aviation SPRITE

Figure 3.46 : ML Aviation SPRITE

Sprite



All-Up-Mass	36kg
Rotor span	1.60m
Engine power	2 x 5.25kW
Maximum speed	126km/hr
Loiter speed	0 - 60km/hr
Max. Endurance	3 hours

Figure 3.47 : ML Aviation SPRITE

Sprite

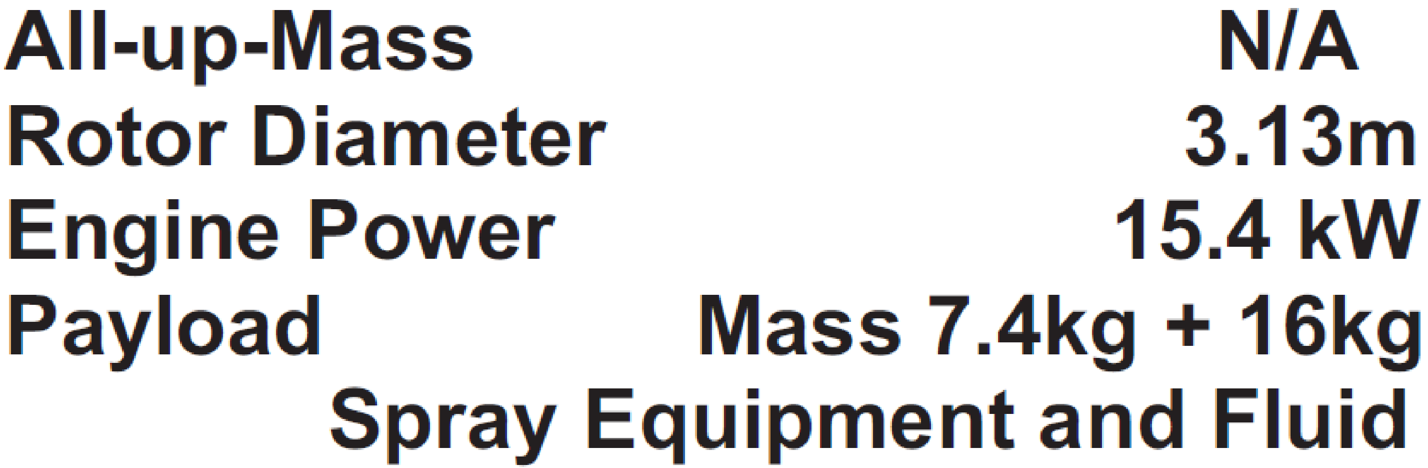
- The Sprite aircraft is **designed to have neutral aerodynamic stability** and **relies upon the AFCS** to provide positive spatial stability. It has demonstrated extreme steadiness when operating in turbulent air.

- The Sprite UAV also offers **extremely low detectable signatures**.

Yamaha R Max

Figure 3.48 : ML Aviation SPRITE

Yamaha R Max



All-up-Mass	N/A
Rotor Diameter	3.13m
Engine Power	15.4 kW
Payload	Mass 7.4kg + 16kg Spray Equipment and Fluid

Figure 3.49 : Technical details of Yamaha R Max

Yamaha R Max

R Max was expressly ***designed for spraying crops*** with fluid. It can carry 30 kg of fluid and spray gear and is over 21/2 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.**

EADS (France) SCORPIO 30

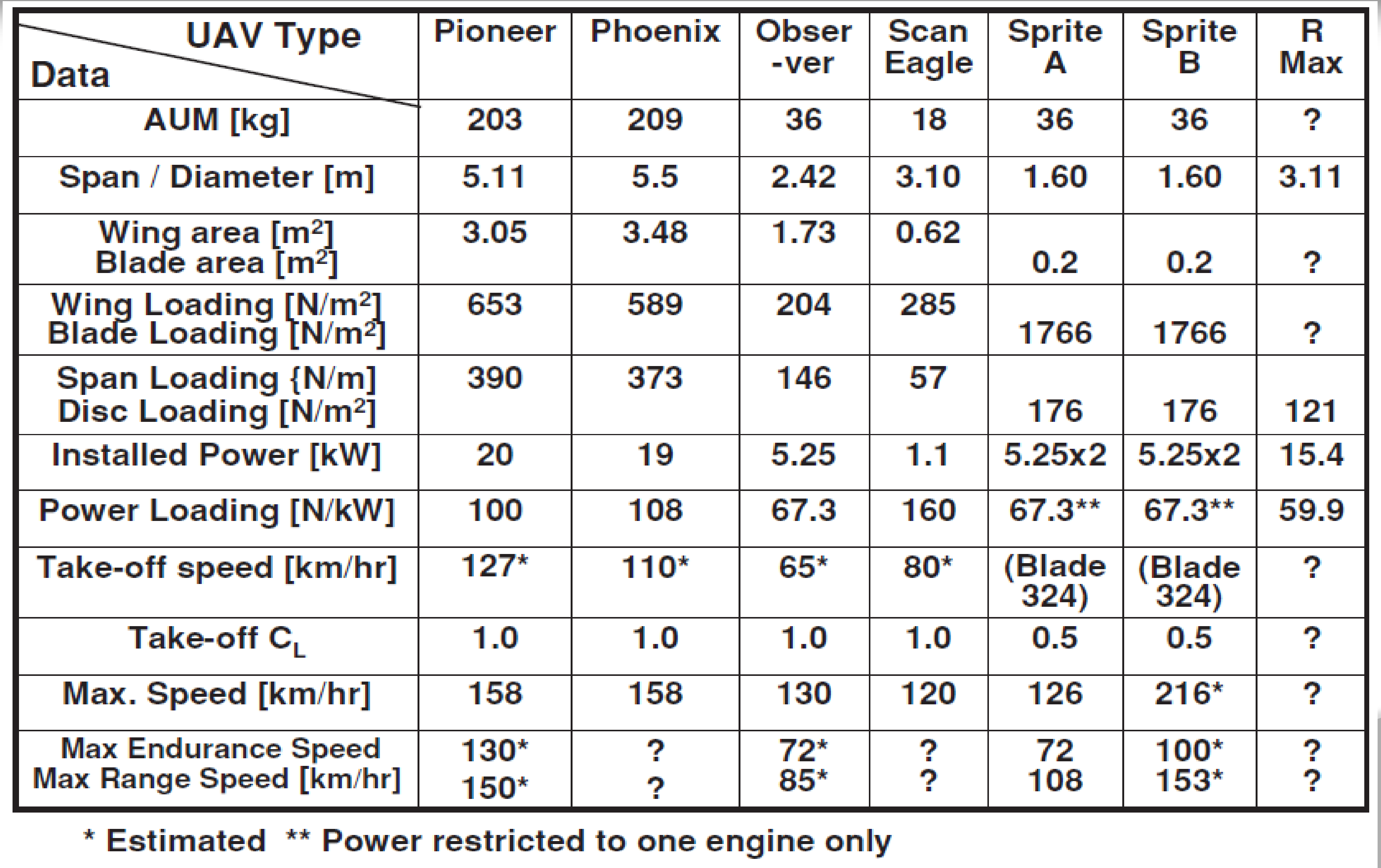
Figure 3.50 : EADS (France) SCORPIO 30

EADS (France) SCORPIO 30

All-up-Mass	38kg
Rotor Diameter	2.20m
Max Speed	50km/hr
Endurance	2hr.
Payload	Mass Unknown Optical and I.R. TV

Figure 3.51 : Technical details of EADS (France) SCORPIO 30

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

Figure 3.52 : Close-range UAV technical data

Close range UAVL: power/speed comparison

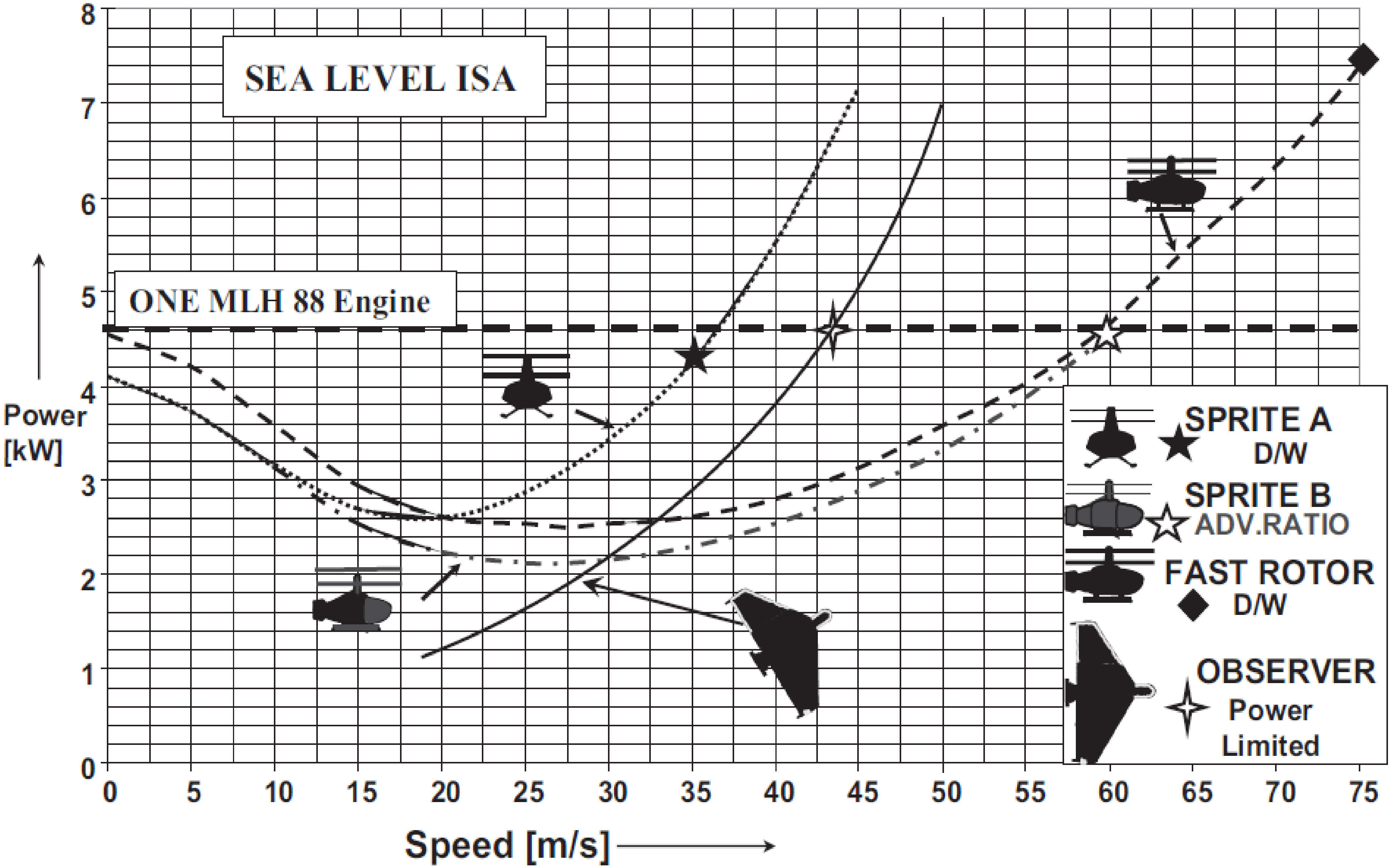
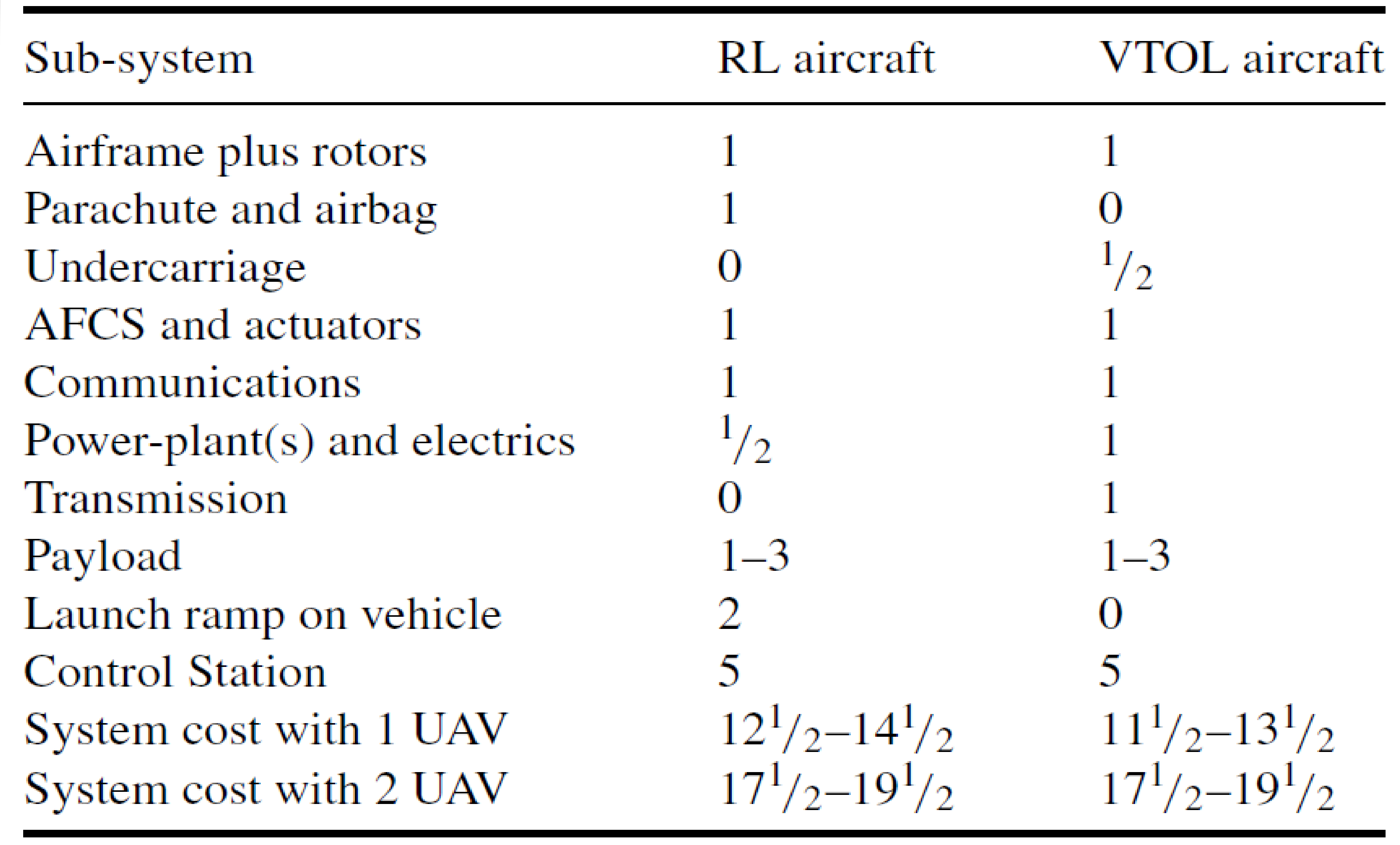


Figure 3.53 : Close range UAVL: power/speed comparison

Close range UAV Comparison



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	$17^{1}/_{2}$–$19^{1}/_{2}$	$17^{1}/_{2}$–$19^{1}/_{2}$

Figure 3.53 : Close range UAV Comparison

UNIT – IV

COMMUNICATIONS NAVIGATION

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.

By Laser

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

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.

By Fibre-optics

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.

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.

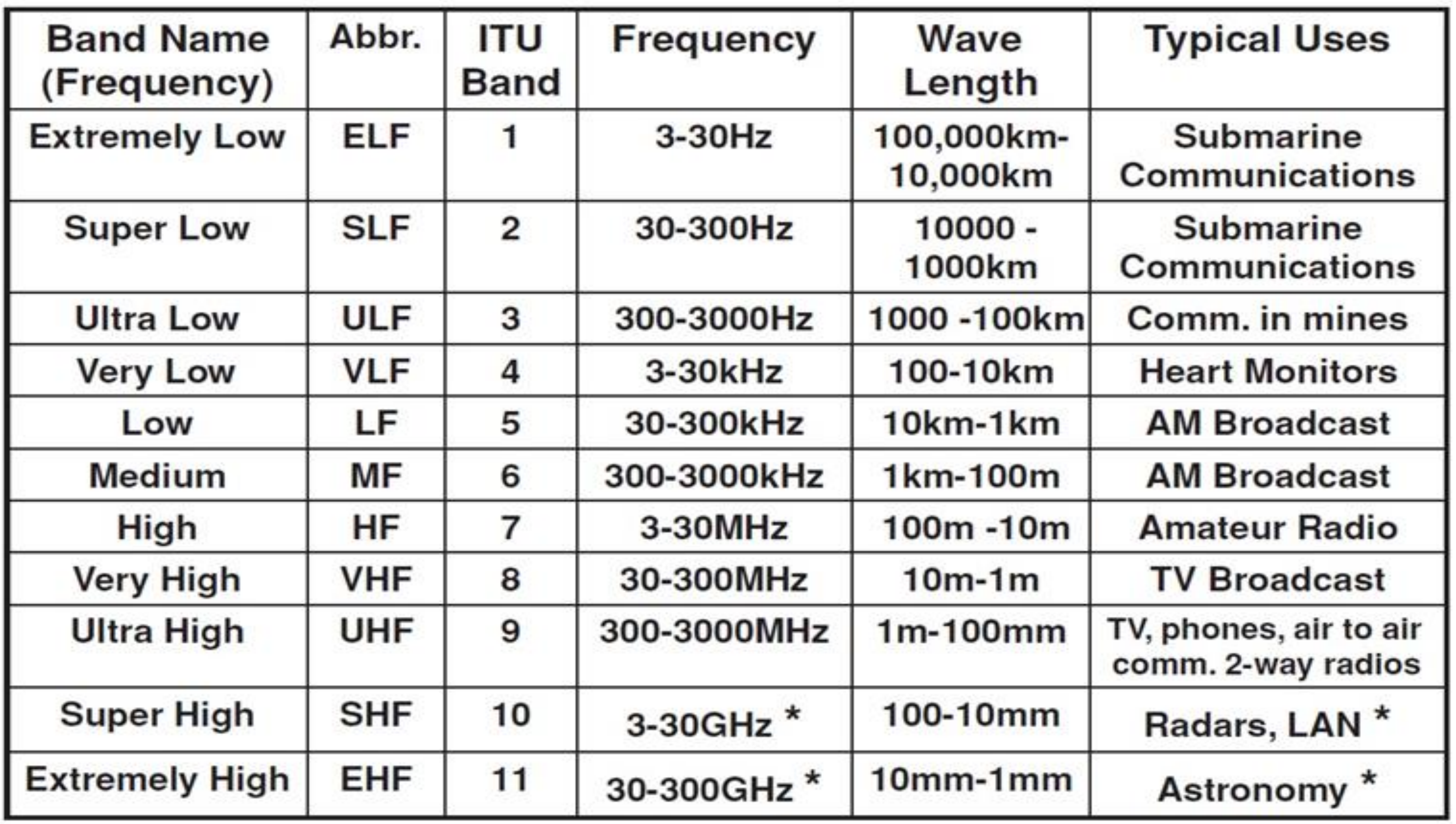
Radio Communication

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.

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.

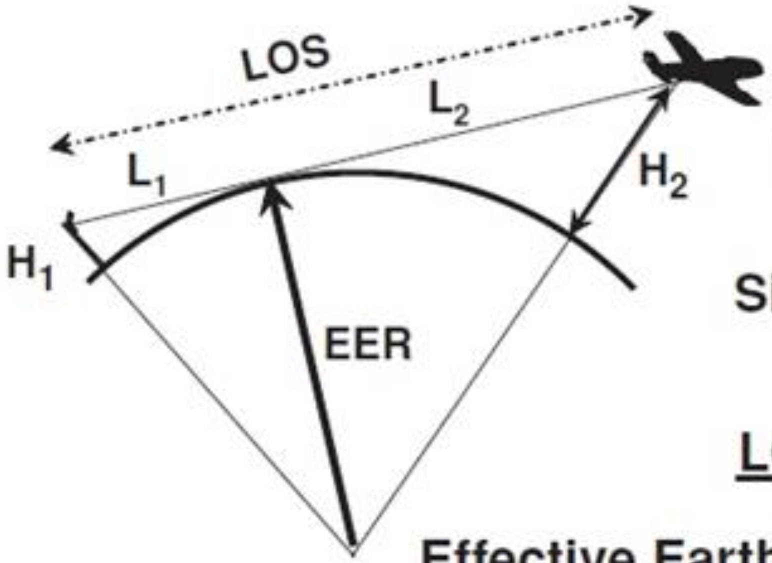
Radio frequency spectra



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 *

Figure.4.1. Radio frequency spectra

Radio LOS derivation



$$L_1^2 = (EER + H_1)^2 - EER^2$$

$$L_1 = \sqrt{[(2 \times EER \times H_1) + H_1^2]}$$

Similarly,

$$L_2 = \sqrt{[(2 \times EER \times H_2) + H_2^2]}$$

$$\underline{LOS = L_1 + L_2}$$

Effective Earth Radius (EER) may be taken as 8,500km for typical radio frequencies.

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

where H1 and H2 represent the heights of the radio antenna and air vehicle respectively.

Figure 4.2: Radio LOS derivation

Radio line-of-sight

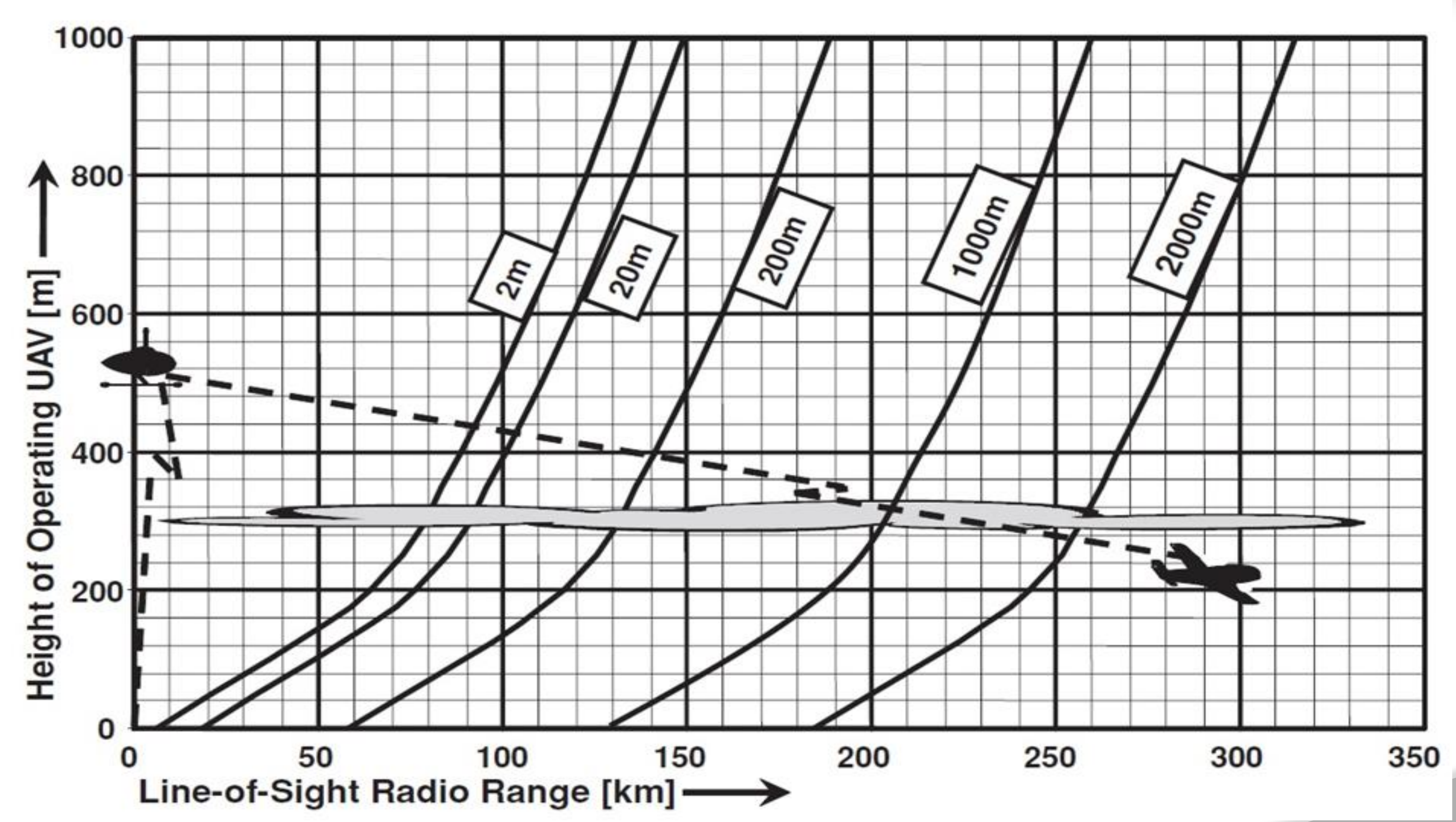


Figure 4.3: Radio line-of-sight

Radio Frequency Band Designations

There are at least three systems in use to designate frequency bands

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

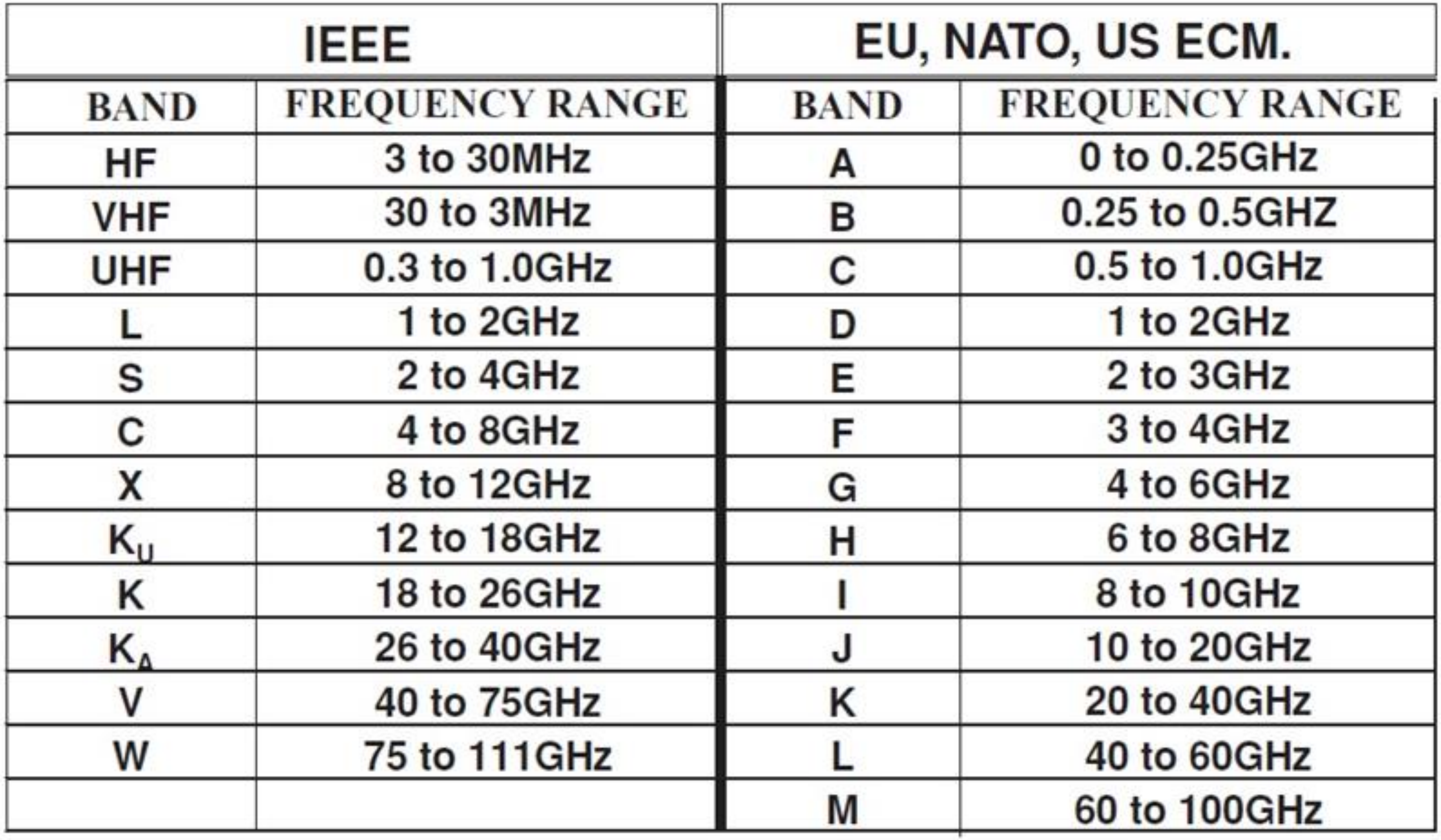
b) The Institute of Electrical and Electronics Engineering (IEEE) designations were the original band ranges developed in World War 2, but do not cover the lower radio ranges below HF.

c) The NATO and EU Designations are the more recent series, but do not cover the VHF and HF radio frequencies;

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.

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

Figure 4.4. Radio frequency band designation

Radio frequency band designation

- 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. 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.

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.

Radio Range Limited by Power

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 maximizing 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

Radio Range Limited by Power

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.

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.

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.

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.

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.

Vulnerability

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.

Vulnerability

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.

Vulnerability

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.

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.

- This arrangement will often be the case for military operation and also may be the situation for some civilian applications.

- Such operations may employ a number of interoperable systems and give rise to the term ‘system of systems’ (SoS).

Interoperable systems

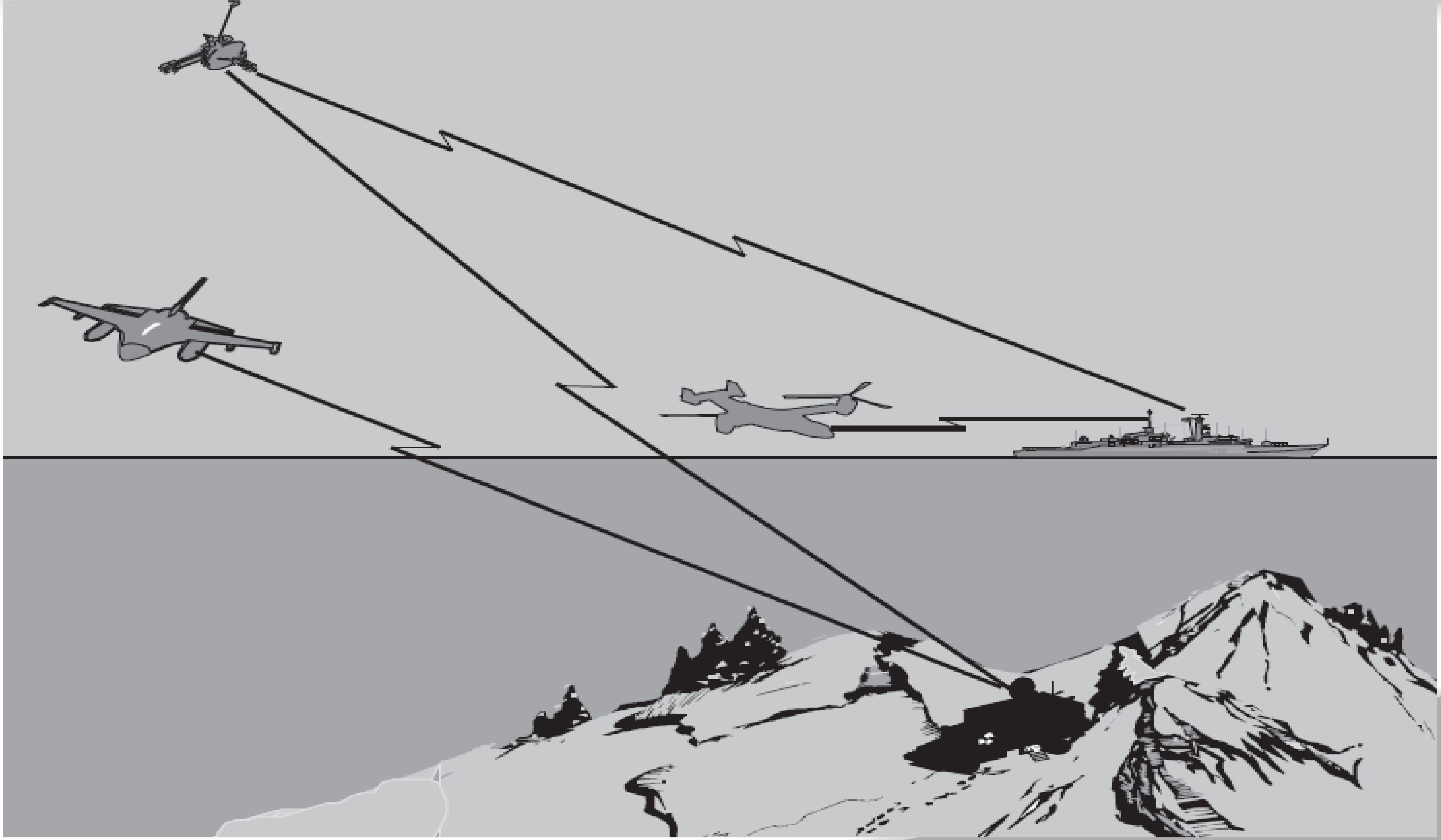


Figure 4.5. Interoperable systems

Interoperable systems

- 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.

Interoperable systems

- 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.

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.

Communications Data Rate and Bandwidth Usage

- 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

Communications Data Rate and Bandwidth Usage

- 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

- 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.

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.

Antenna Types

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.

Antenna Types

(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.

Antenna Types

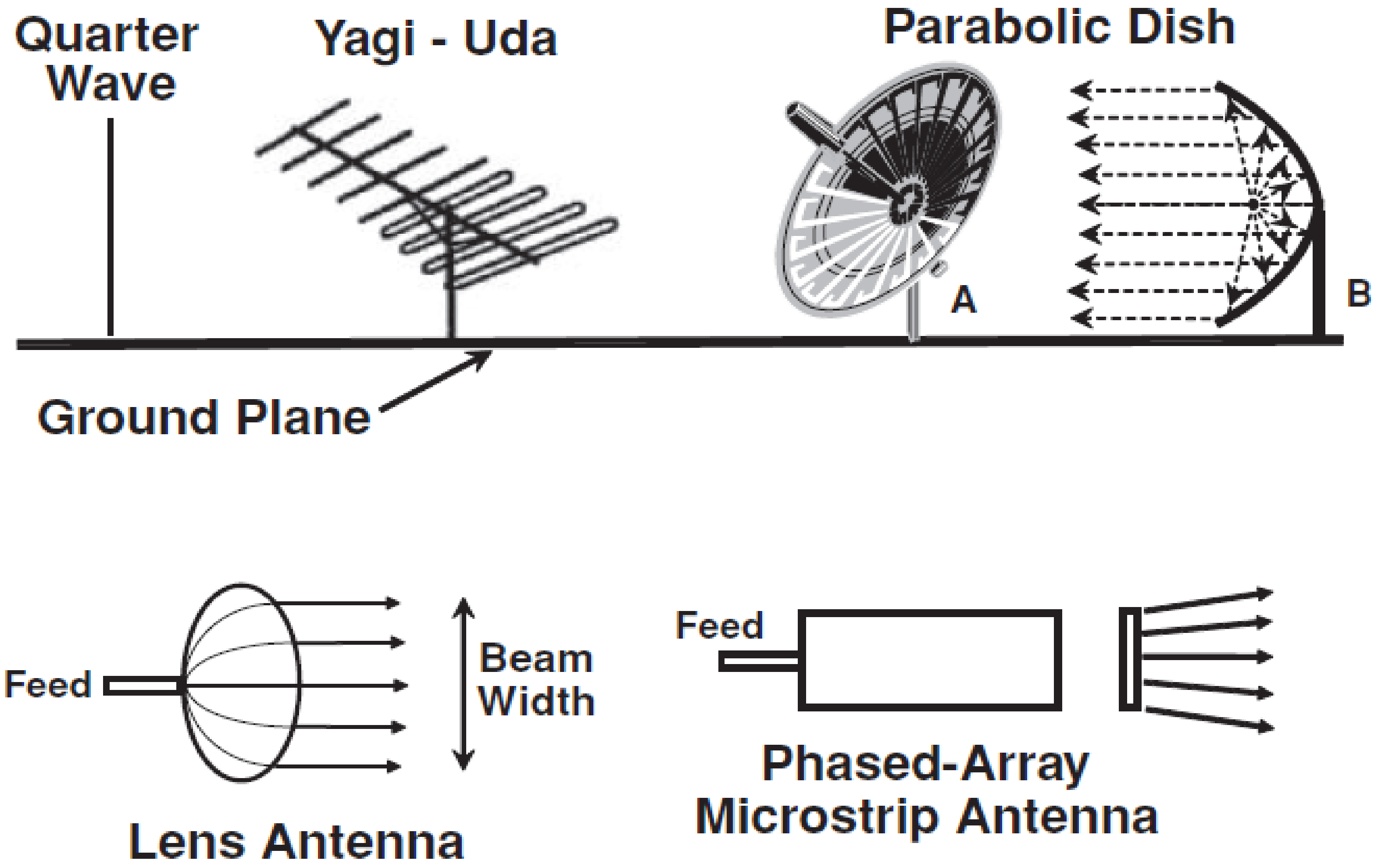


Figure 4.6. Applicable antenna types

Typical Yagi Construction

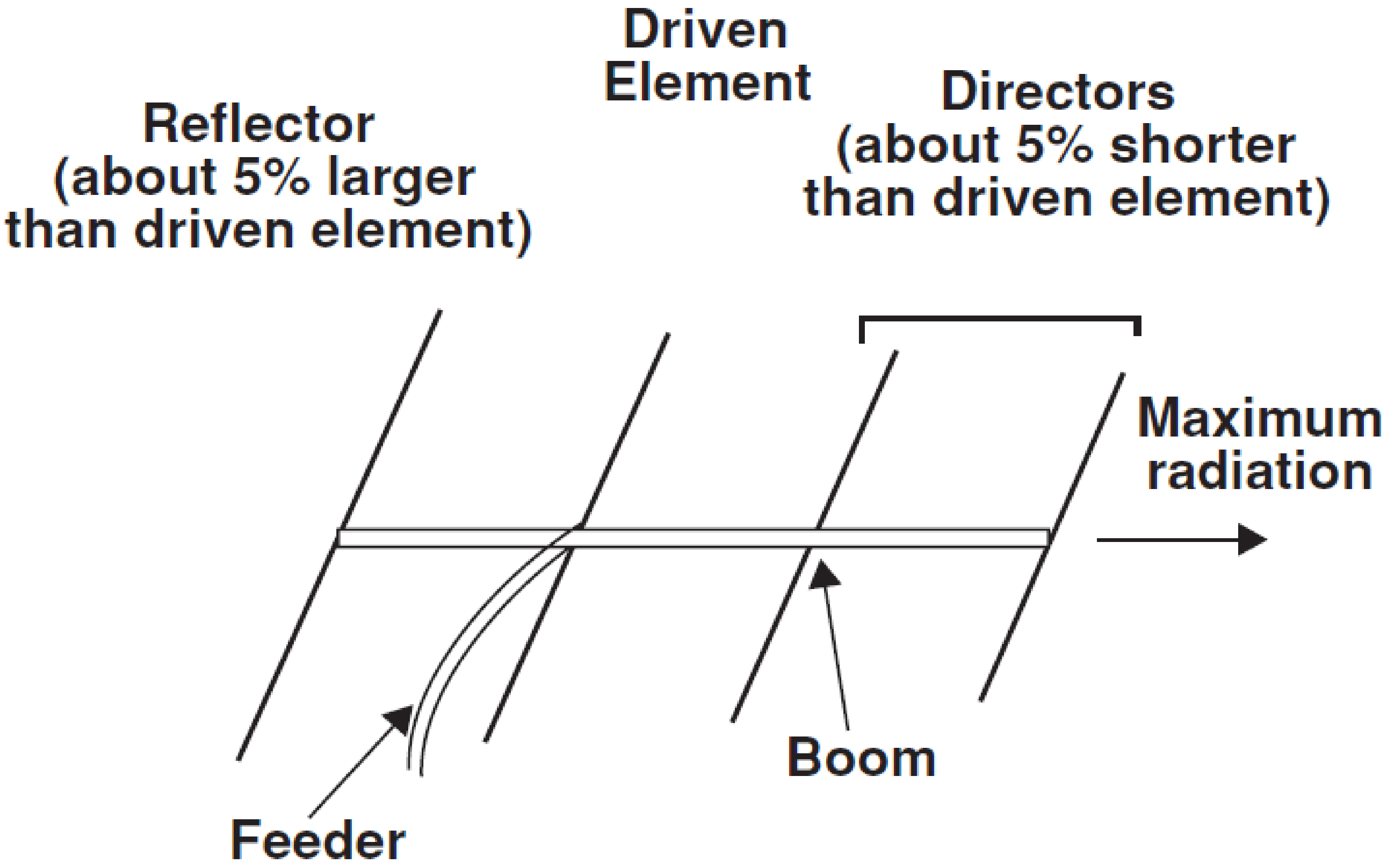


Figure 4.7. Typical Yagi Construction

Typical Yagi Antenna Radiation Pattern

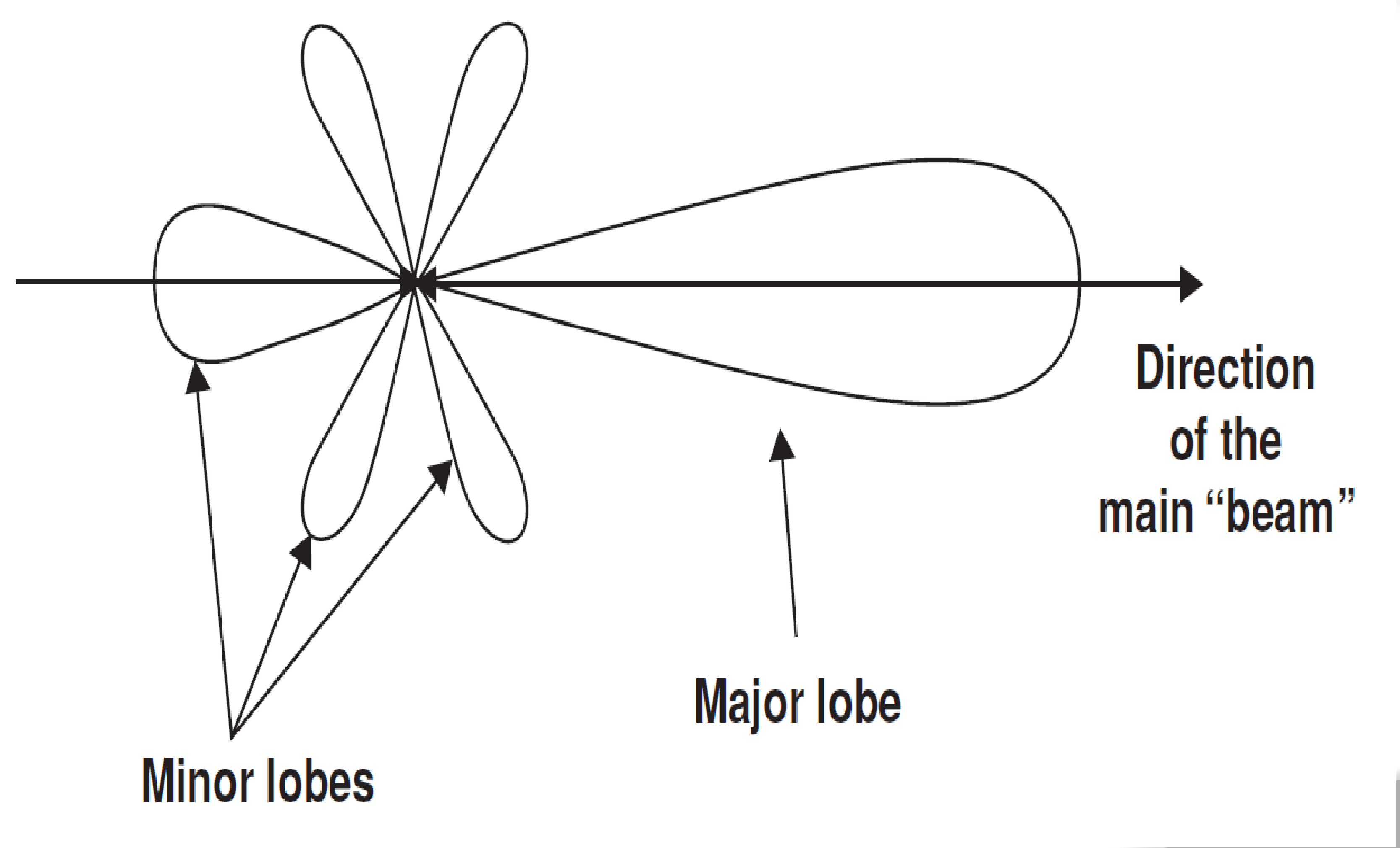
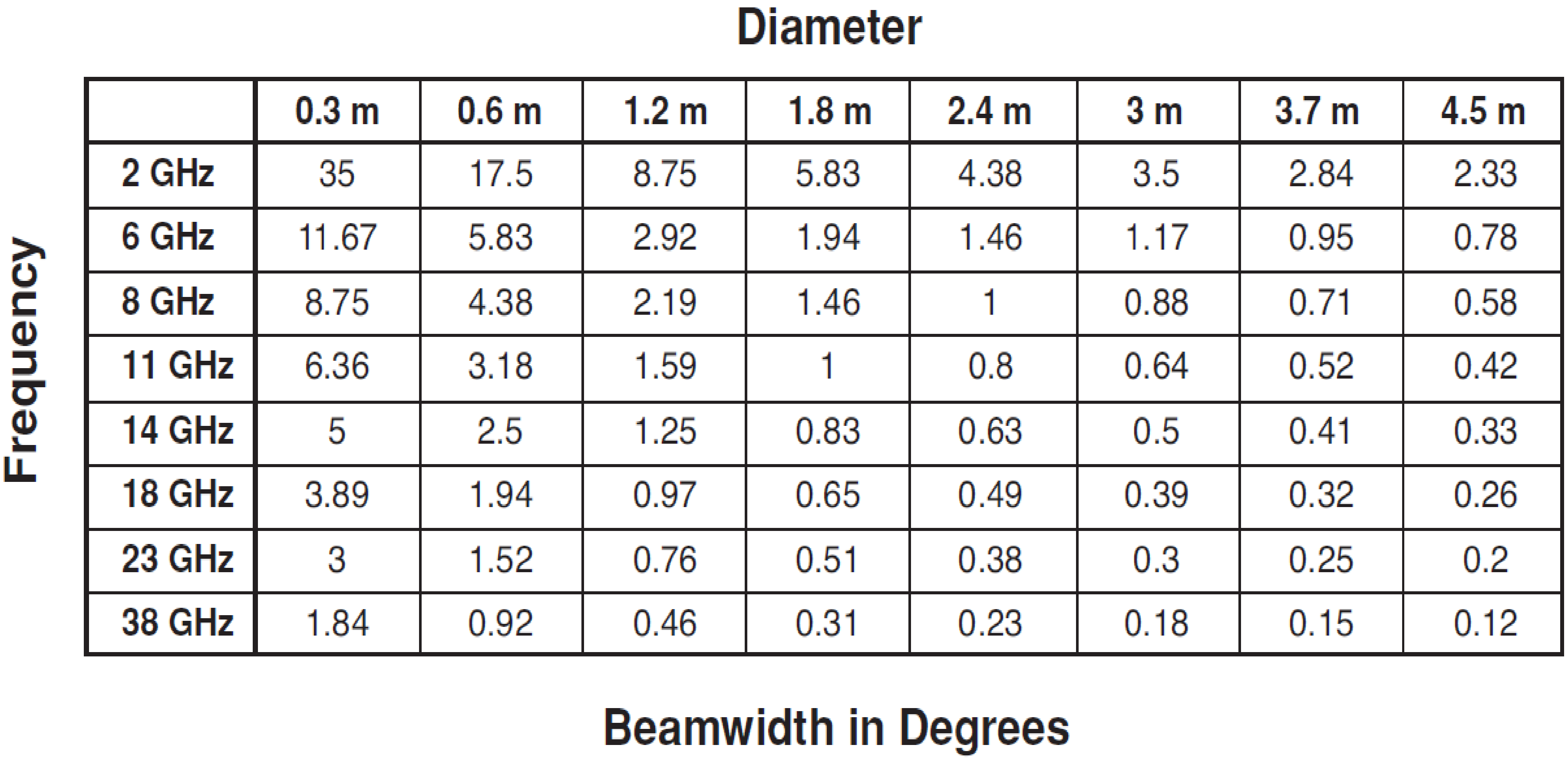


Figure 4.7. Typical Yagi Antenna Radiation Pattern

Antenna characteristics



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

Beamwidth in Degrees

Figure 4.8. Variation of Parabolic Antenna Beamwidth with Radio Frequency and Antenna Diameter

Yagi-Uda antenna

(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.

Parabolic dish antennae

(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. By changing the disc diameter, for a given radio frequency, beams of various widths may be generated as listed in Figure 4.8. 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.

Lens antenna works

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

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.

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.

NAVSTAR Global Positioning System (GPS)

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 1.6 GHz. 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.

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.

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.

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.

Inertial Navigation

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.

Inertial Navigation

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.

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.

Radio Tracking

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.

Way-point Navigation

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.

Way-point Navigation

b) Input instructions to the UAVFCS to command the UAV to 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.

Way-point Navigation

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

Control and Stability

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.

Control and Stability

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.

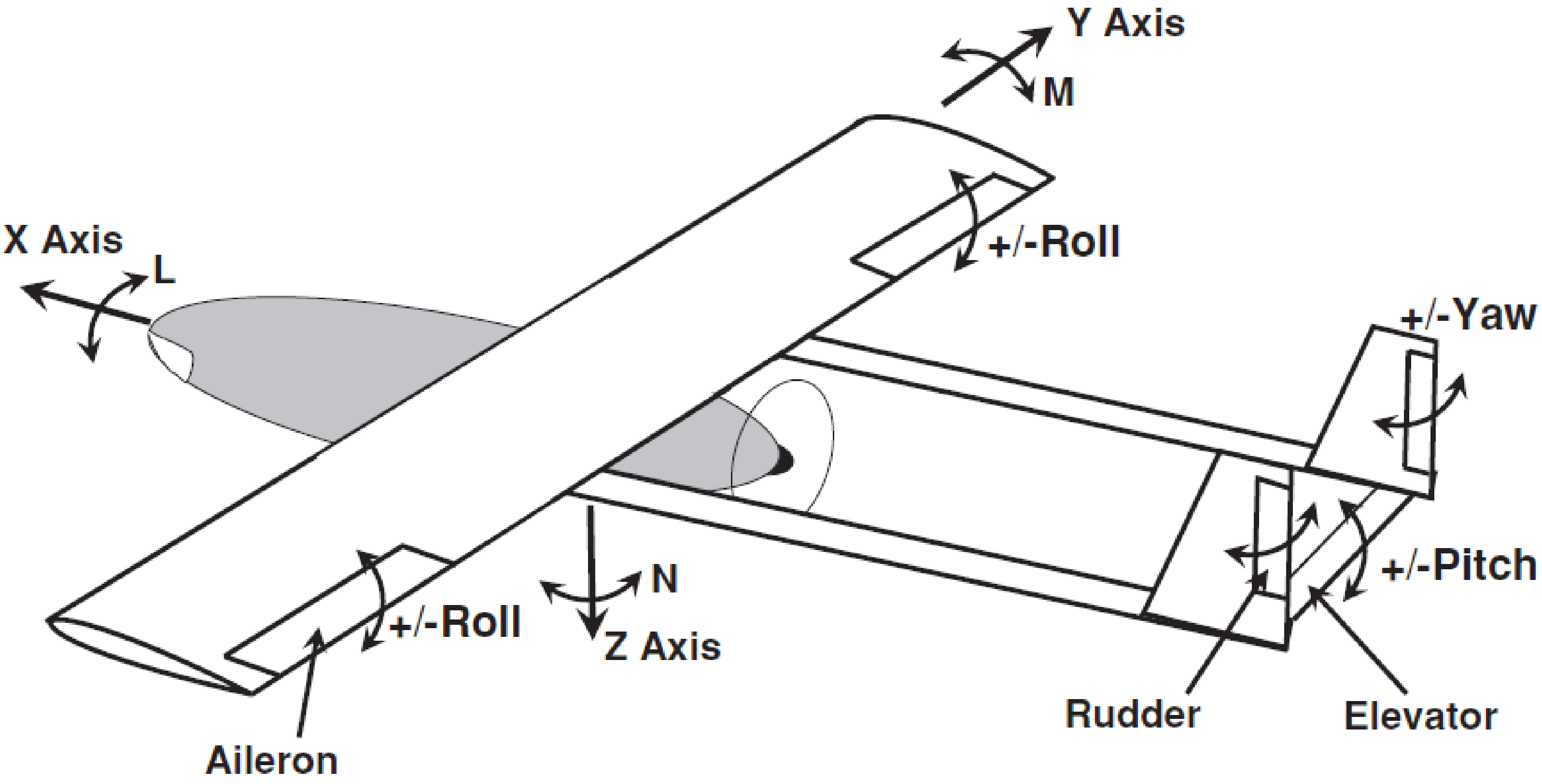
HTOL Aircraft

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.

HTOL aircraft aerodynamic control surfaces



Ailerons produce rolling moment L
Elevators produce pitching moment M
Rudders produce yawing moment N

Figure 5.1. HTOL aircraft aerodynamic control surfaces

HTOL Aircraft

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.

HTOL Aircraft

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.

HTOL Aircraft

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.

The movable control surfaces are used to steer and stabilize the aircraft in the normal manner relative to spatial coordinates. 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.

HTOL Aircraft

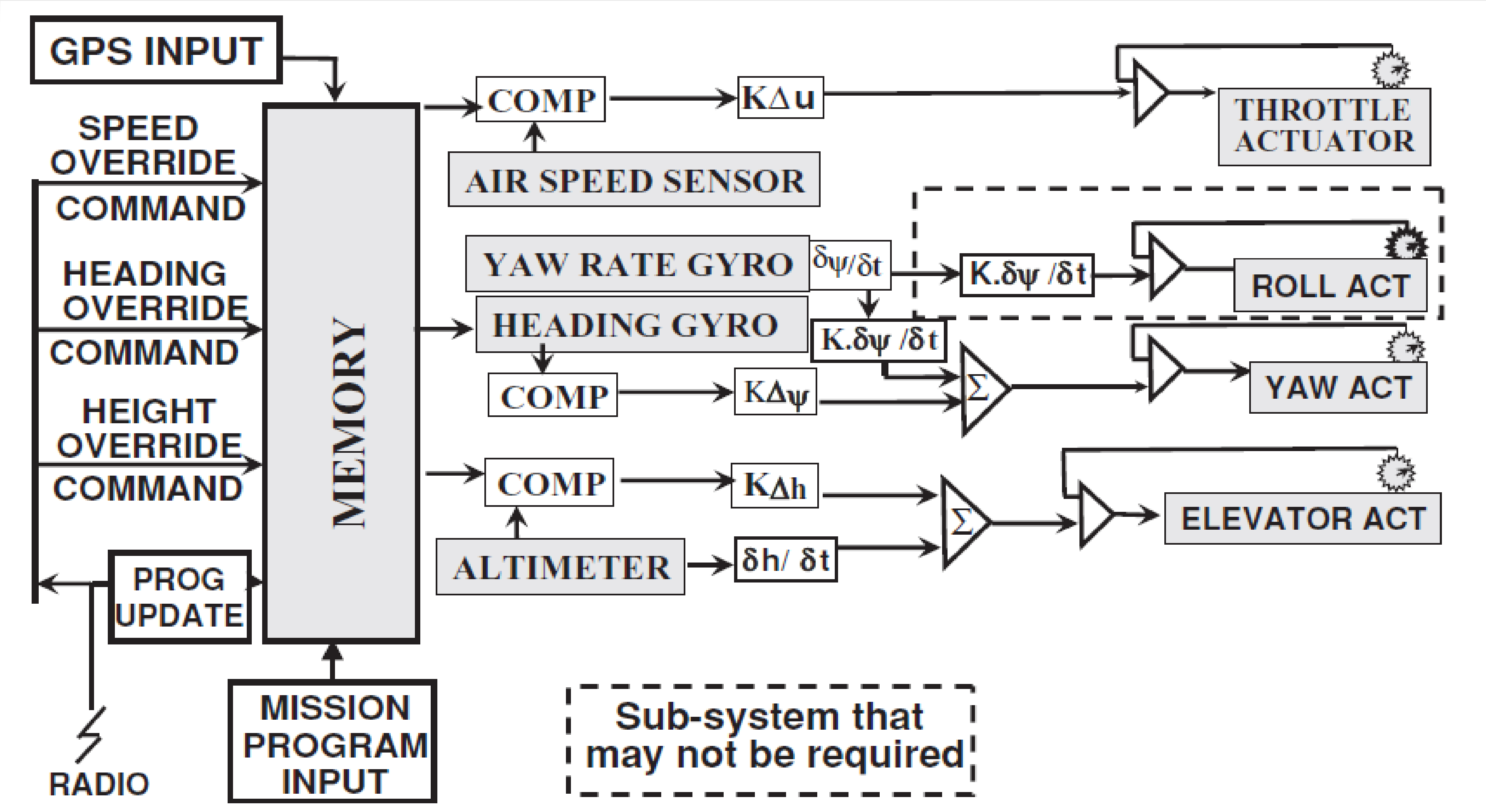


Figure 5.2. HTOL aircraft basic AFCS

HTOL Aircraft

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.

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.

- 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.

HTOL Aero-stable Configuration

- 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.

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.

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.

- 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.

The Height or Altitude Channel

- 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.

The Height or Altitude Channel

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.

The Height or Altitude Channel

- 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.

The Height or Altitude Channel

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.

The Height or Altitude Channel

- 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.

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.

HTOL Spatially Stabilised Configuration

- 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.

HTOL Spatially Stabilised Configuration

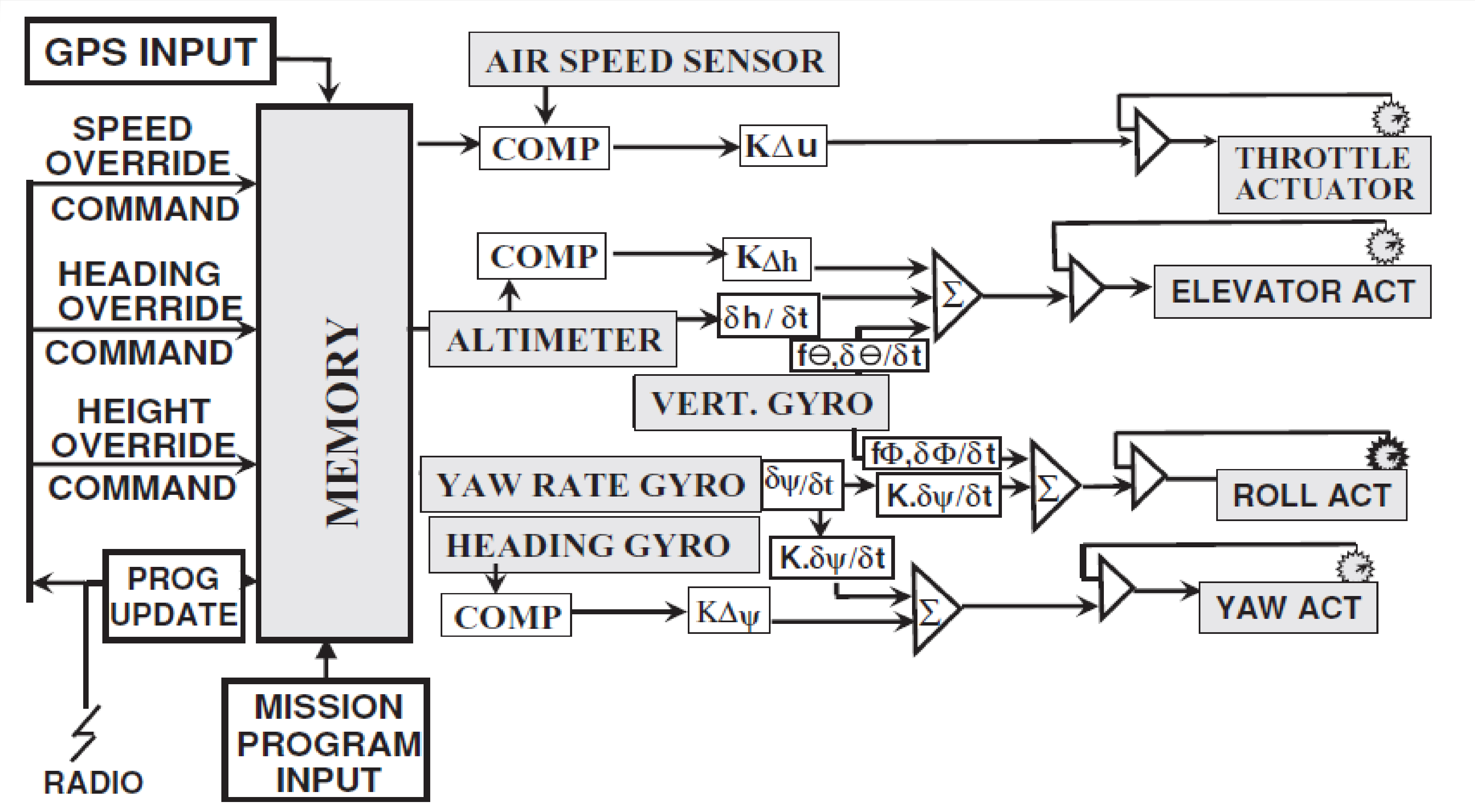


Figure 5.3. Spatially stabilized HTOL aircraft AFCS

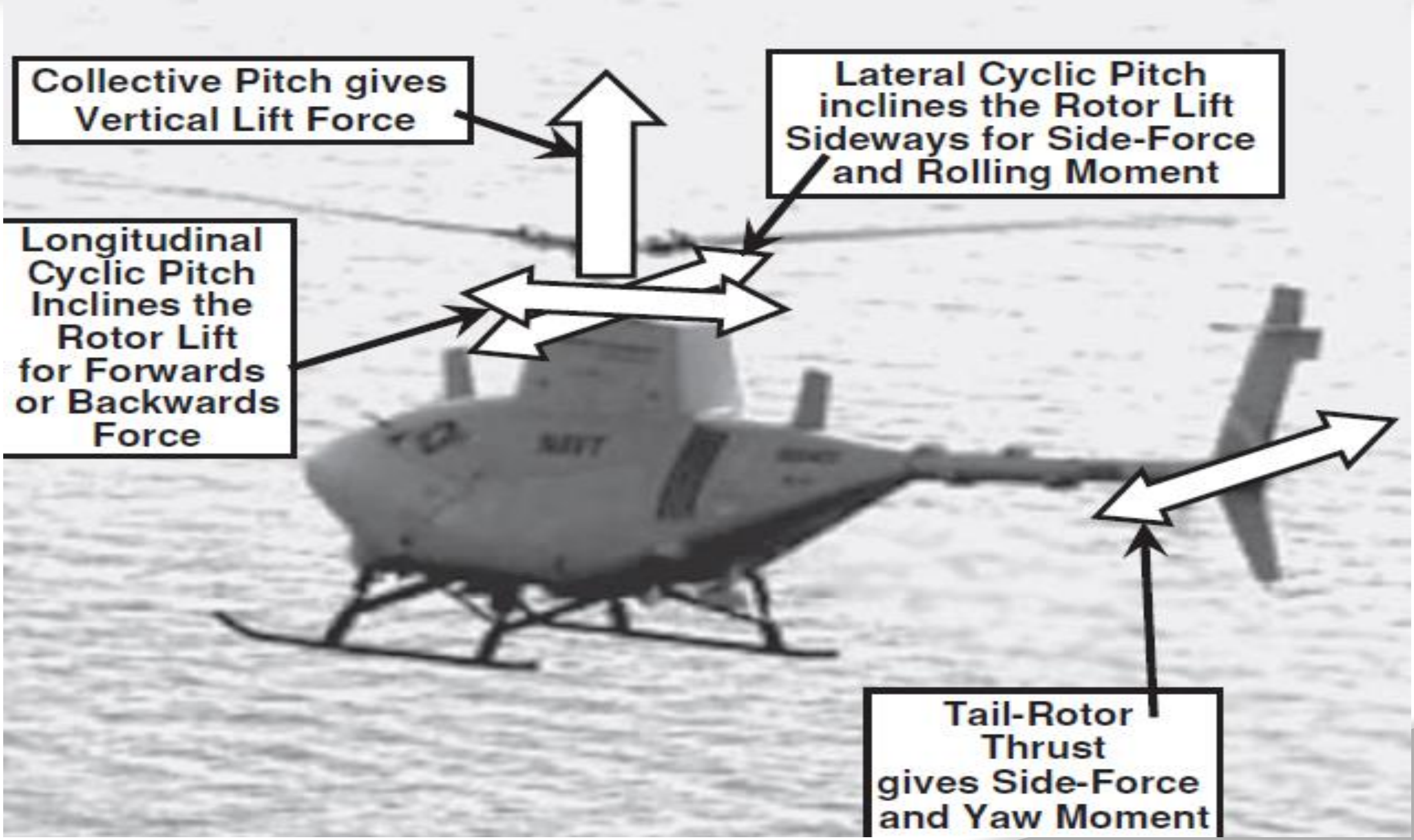
Helicopters: Single-main-rotor Helicopter

- 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

SMR helicopter controls



Collective Pitch gives Vertical Lift Force

Lateral Cyclic Pitch inclines the Rotor Lift Sideways for Side-Force and Rolling Moment

Longitudinal Cyclic Pitch Inclines the Rotor Lift for Forwards or Backwards Force

Tail-Rotor Thrust gives Side-Force and Yaw Moment

Figure 10.4. SMR helicopter controls

AFCS diagram for SMR helicopter

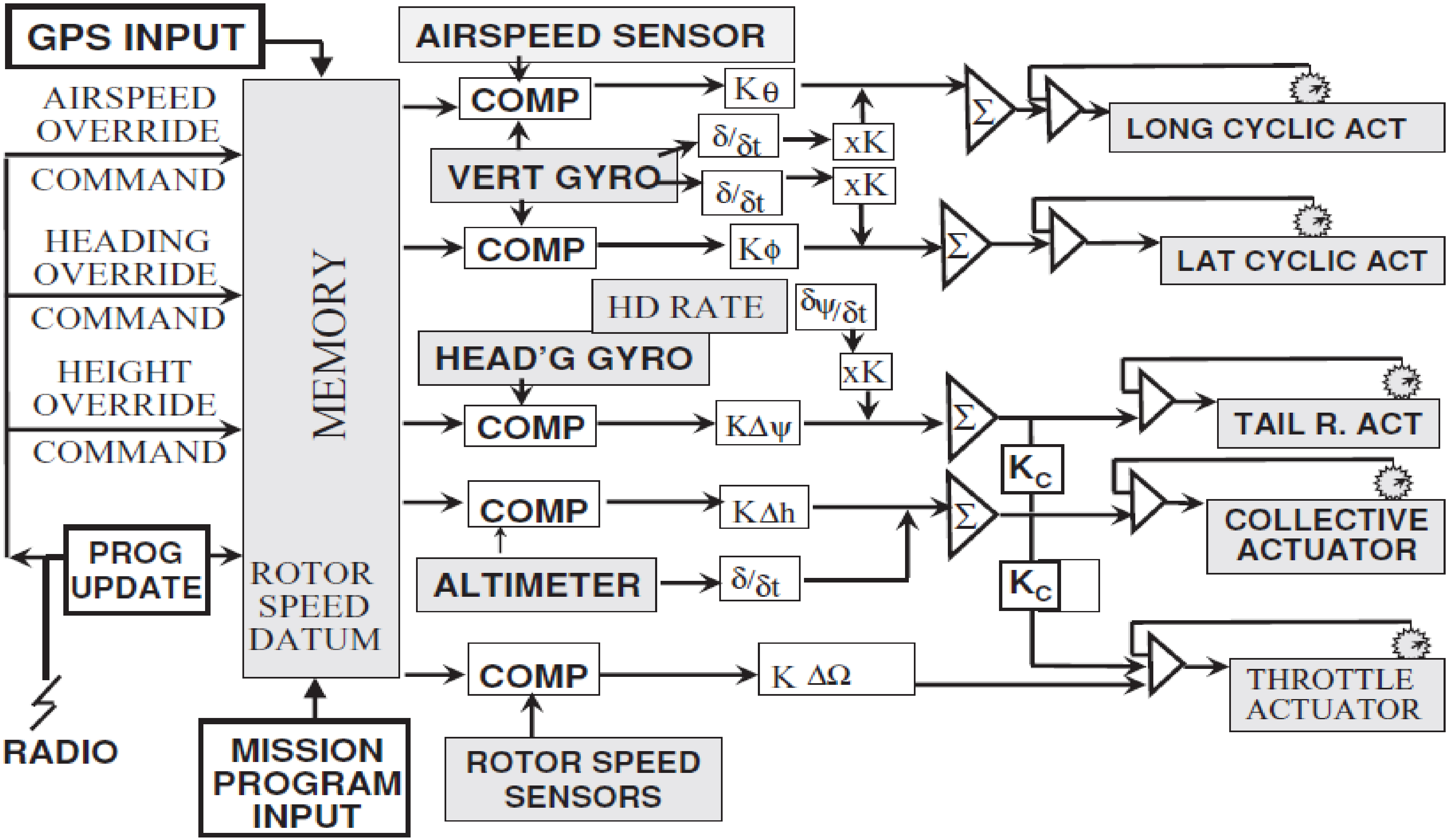


Figure 5.5. AFCS diagram for SMR helicopter

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’.

AFCS diagram for SMR helicopter

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.

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.

AFCS diagram for SMR helicopter

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.

AFCS diagram for SMR helicopter

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.

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.

Coaxial-rotor helicopter AFCS

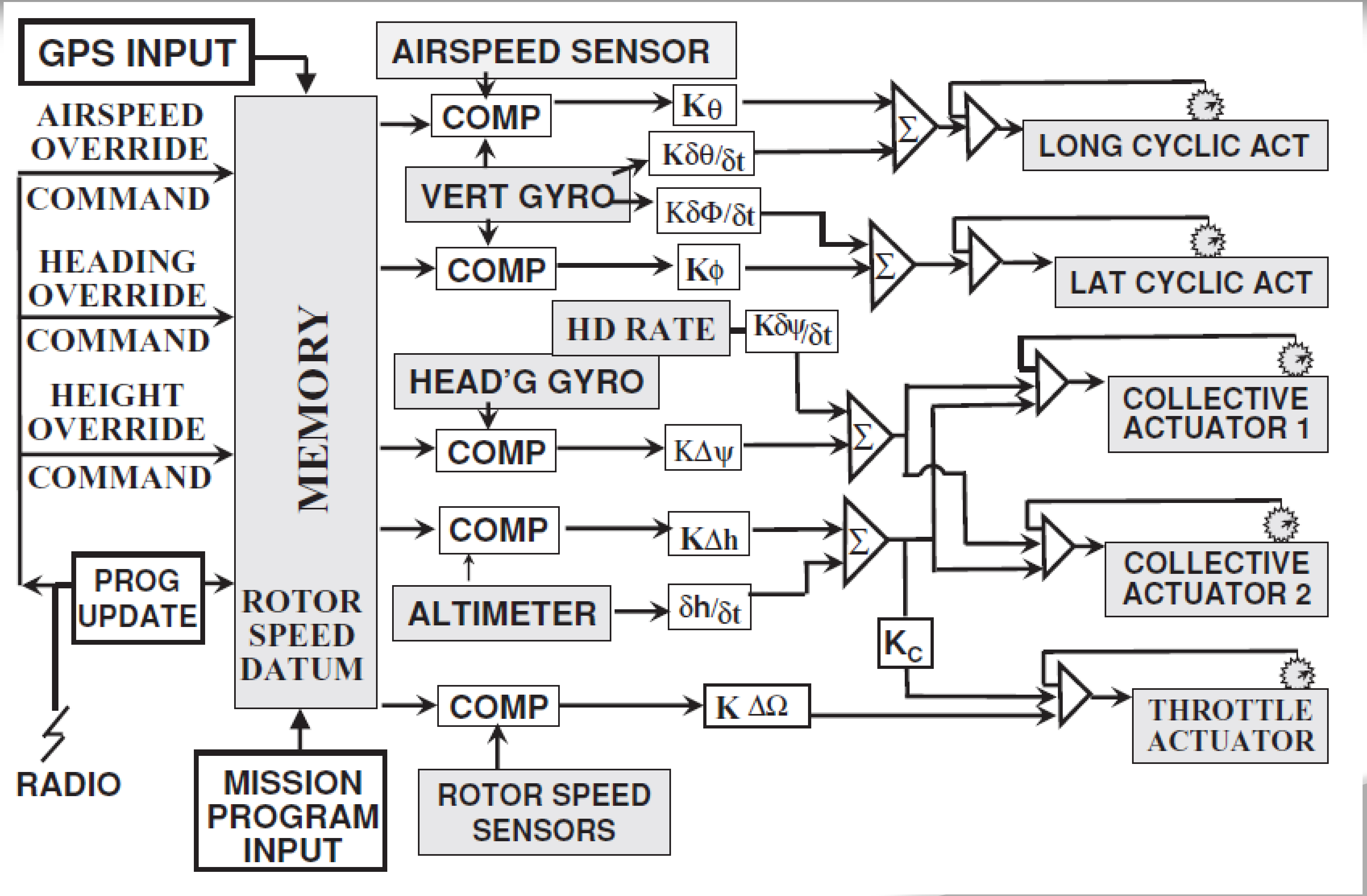


Figure 5.6. Coaxial-rotor helicopter AFCS

‘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.

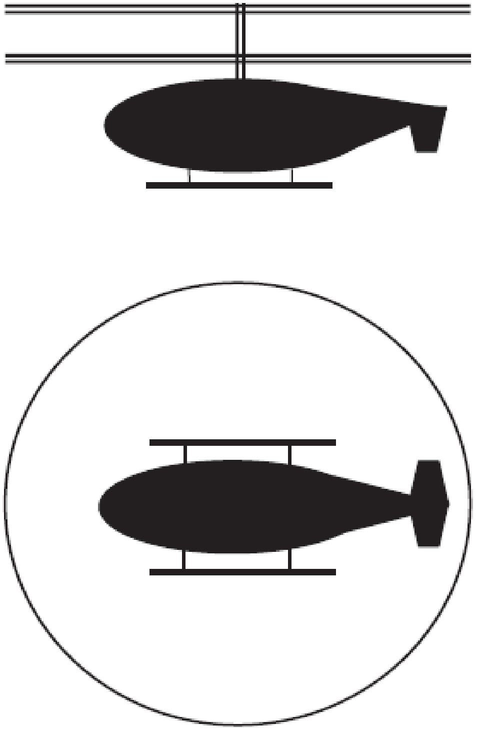


Figure 5.6. Coaxial-rotor Helicopter

Directional’ Airframe Coaxial-rotor Helicopter (CRH)

- 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. There is no resulting side-force to balance, 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. Pilots flying crewed versions of the coaxial helicopter configuration, report on its ease of control compared with a SMR helicopter and, the electronic flight control system is easier to develop.

Directional’ Airframe Coaxial-rotor Helicopter (CRH)

- 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.

Directional’ Airframe Coaxial-rotor Helicopter (CRH)

- 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.

Symmetrical Airframe Coaxial-rotor Helicopter

- Otherwise known as a plan-symmetric helicopter (PSH), this is a special case of the CRH and, 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 stabilized 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 destabilize the aircraft.

Plan-symmetric helicopter controls

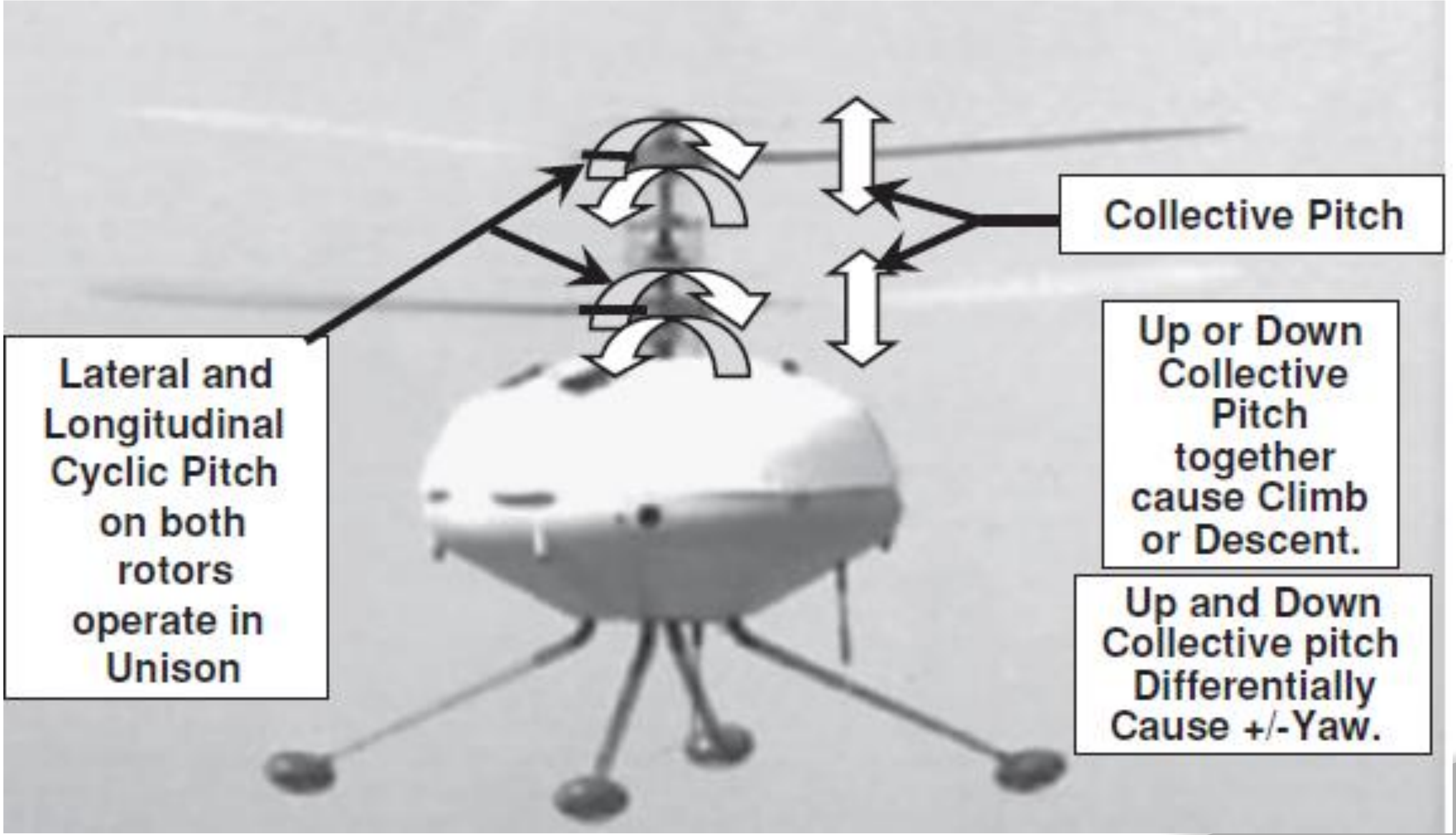


Figure 5.7. Plan-symmetric helicopter controls

Plan-symmetric helicopter controls

- 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.

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 as opposed to helicopters which normally have cyclic pitch control in both longitudinal and lateral planes.

Tilt-rotor aircraft controls

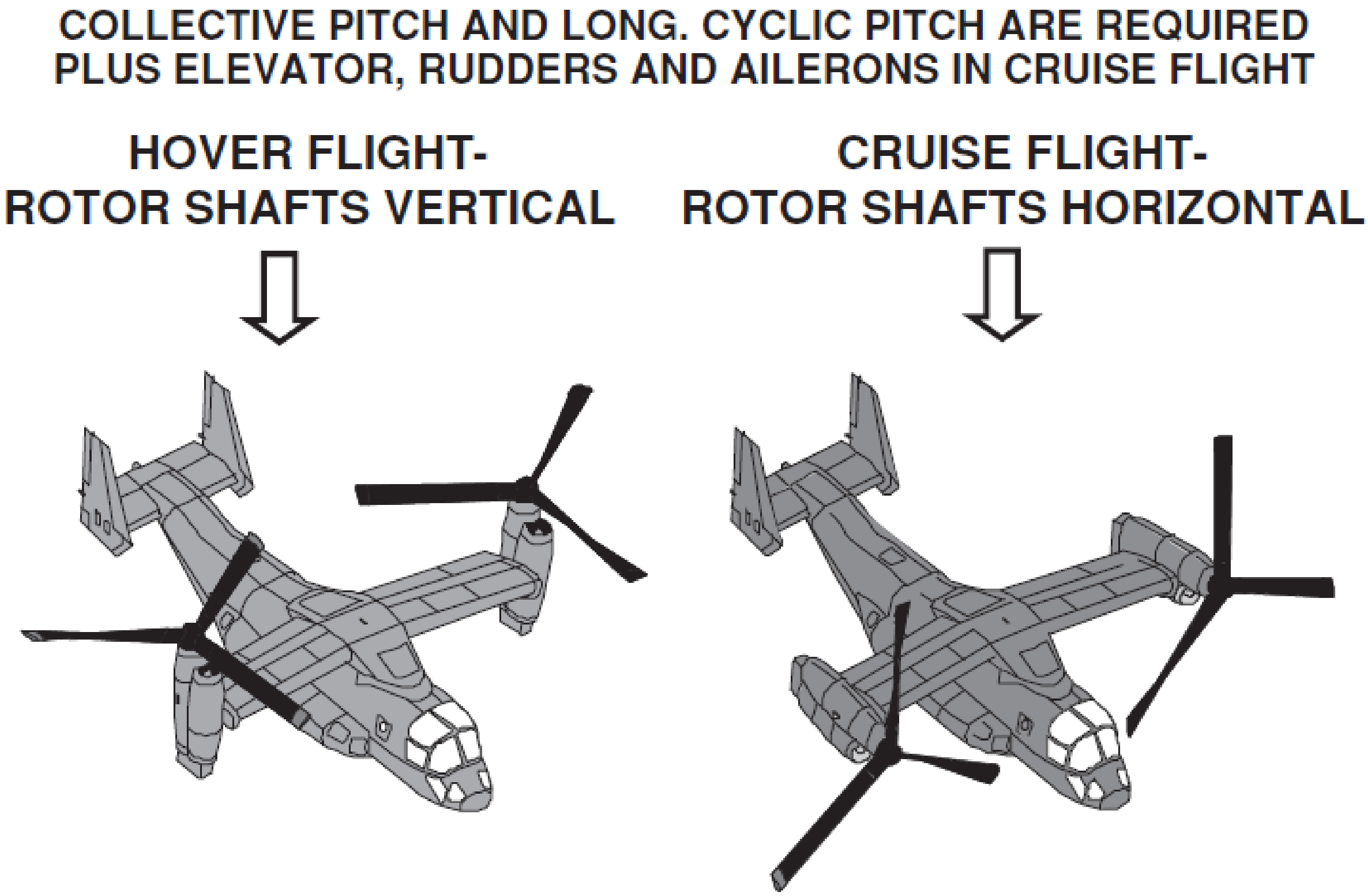
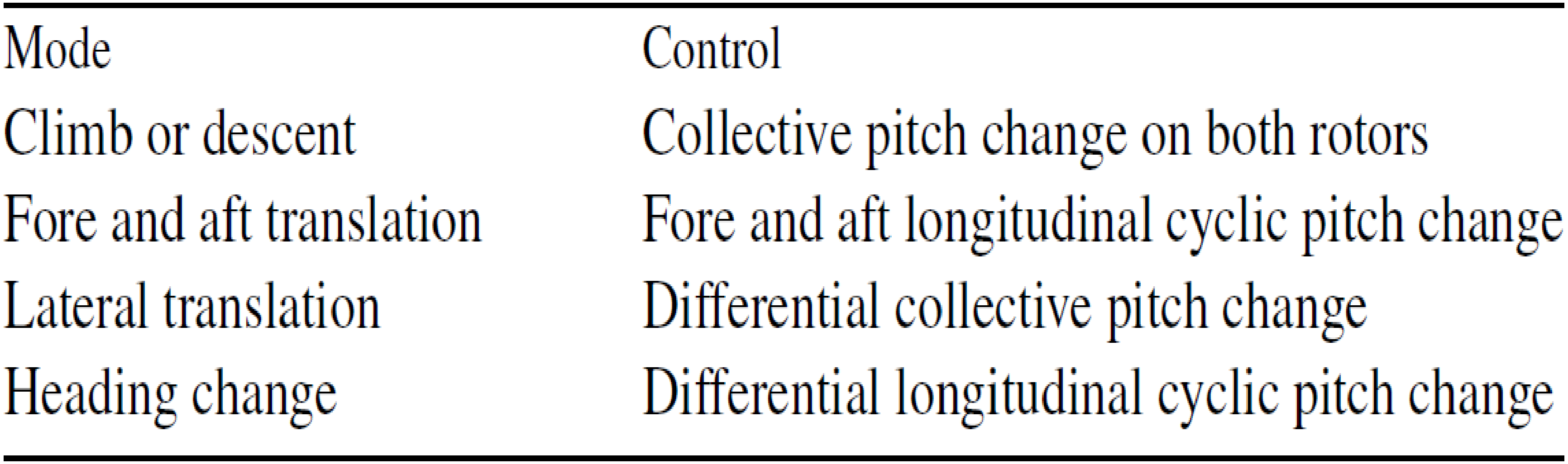


Figure 5.8. Tilt-rotor aircraft controls

Hover Flight

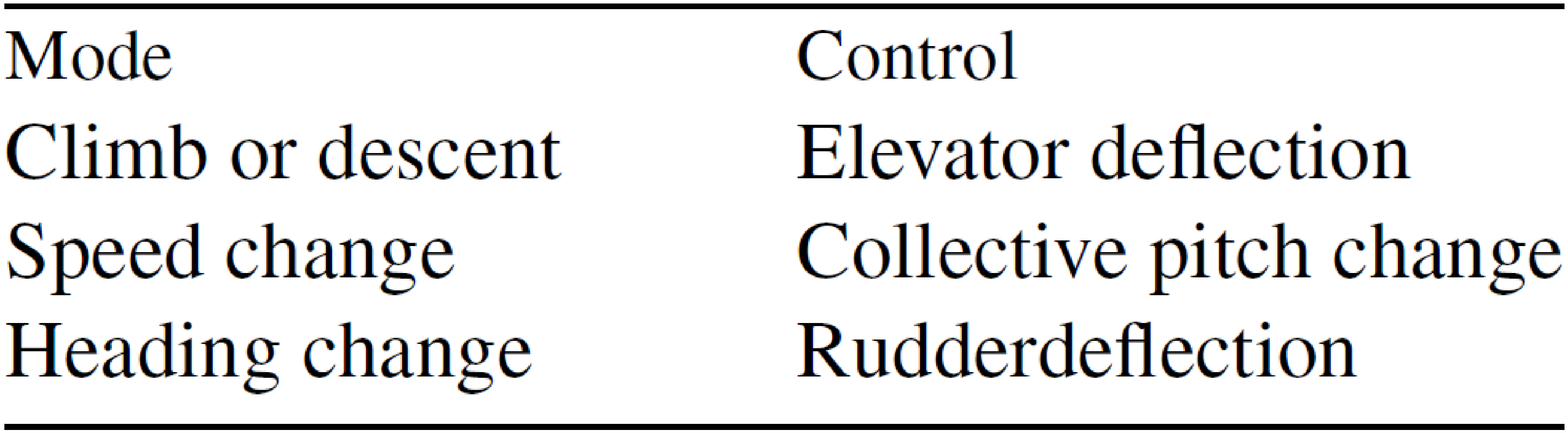
Figure 5.9. Tilt-rotor aircraft controls



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

Cruise Flight

Figure 5.10. Tilt-rotor aircraft controls



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

Tilt-rotor aircraft controls

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.

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.

- 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,

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.

Payload Control

- 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.

Sensors

- Sensors, 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.

- Qualities of accuracy, reliability, life, power supply, environmental protection and mass will be of importance to the UAV systems designer.

Height and Altitude Sensors

- Sensors for measuring tape height, that is height above ground, include those measuring distance by timing pulses of radio, laser or acoustic energy 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.

Height and Altitude Sensors

- 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.

Height and Altitude Sensors

- 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.

Airspeed Sensors

- For HTOL aircraft a standard pitot-static (PS) system 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.

Airspeed Sensors

- 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.

Hover-position-hold Sensing

- Holding station in a hover or near hover is often a requirement for a VTOL aircraft for take-off orfor 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.

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.

Autonomy

- 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.

Text Book

- Unmanned Aircraft Systems UAVs Design, Development and Deployment by Reg Austin, 2010, John Wiley & Sons Ltd.

Thank You