MINISTRY OF EDUCATION

GHANA ASSOCIATION OF SCIENCE TEACHERS

Aviation and Aerospace Engineering

for Senior High Schools

Year 3



David Kofi Oppong

Reviewed by Augustine Akuoko Kwarteng

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Ghana Education Service (GES)

(GAST)



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FOREWORD

Ghana's new Senior High School Curriculum aims to ensure that all learners achieve their potential by equipping them with 21st Century skills, knowledge, character qualities and shared Ghanaian values. This will prepare learners to live a responsible adult life, progress to further studies and enter the world of work. This is the first time that Ghana has developed a Senior High School Curriculum which focuses on national values, attempting to educate a generation of Ghanaian youth who are proud of our country and can contribute effectively to its development.

The Ministry of Education is proud to have overseen the production of these Learner Materials which can be used in class and for self-study and revision. These materials have been developed through a partnership between the Ghana Education Service, teacher unions (Ghana National Association of Teachers-GNAT, National Association of Graduate Teacher -NAGRAT and the Pre-Tertiary Teachers Association of Ghana- PRETAG) and National Subject Associations. These materials are informative and of high quality because they have been written by teachers for teachers with the expert backing of each subject association.

I believe that, if used appropriately, these materials will go a long way to transforming our Senior High Schools and developing Ghana so that we become a proud, prosperous and values-driven nation where our people are our greatest national asset.

Haruna Iddrisu MP
Minister for Education



SECTION

1

AIRCRAFT STRUCTURES

CORE CONCEPTS IN AEROSPACE ENGINEERING

AIRCRAFT STRUCTURES AND CONTROL

INTRODUCTION

This section deals with the first learning outcome of the Aircraft Structures and Control sub strand of the Core Concepts in Aerospace Engineering strand.

Welcome to the first section of the Year 3 Aviation and Aerospace Engineering subject. In this section, we'll dive into aircraft structures—looking at the materials used to build them, their unique properties and practical applications, and the different techniques used to construct the airframe. Refer to Section 1 of the Year 1 learning material for a recap of the types of aerospace vehicles and their components.

KEY IDEAS

- Aircraft fuselages usually take the form of trusses, monocoque or semi monocoque structures
- Many materials exist with properties that are favourable for aircraft construction
- UAV (drone) construction may require the use of other materials besides those used for traditional aircraft construction

AIRCRAFT MATERIALS

We will first look at the different materials available to us for the construction of aircraft parts. These materials include metals such as aluminium-, steel- and titanium alloys and non-metals such as composites and glass. Let us begin!

Aluminium Alloys

Aluminium alloys are among the most widely used materials in aircraft construction due to their excellent combination of light weight and strength. Pure aluminium is too soft for structural use, so it is alloyed with elements such as copper, magnesium, and zinc to improve its mechanical properties. These alloys are particularly useful in reducing the overall weight of the aircraft, which in turn improves fuel efficiency and performance.

In aircraft design, aluminium alloys are commonly used in the fuselage, wings, and internal support structures. Their corrosion resistance makes them ideal for external surfaces exposed to the elements. Additionally, aluminium is relatively easy to shape and machine, allowing engineers to create complex aerodynamic forms that enhance flight stability and control.

Despite their advantages, aluminium alloys do have limitations. They are not suitable for extremely high-temperature environments, such as jet engine components, and can suffer from fatigue over time. Nevertheless, their widespread availability and cost-effectiveness make them a staple in both commercial and military aircraft.



Figure 1.1: Aluminium aircraft fuselage

Steel Alloys

Steel alloys are used in aircraft construction where strength and durability are critical. Although heavier than aluminium, steel offers superior tensile strength and toughness, making it suitable for components that must withstand high loads and stress. Common alloying elements include chromium, nickel, and molybdenum, which enhance its corrosion resistance and heat tolerance.

In aviation, steel is often found in landing gear assemblies, engine mounts, and fasteners. These parts must endure repeated impacts, vibrations, and extreme conditions, and steel's robustness ensures long-term reliability. Stainless steel is favoured for its resistance to rust and its ability to maintain strength at elevated temperatures.

However, the added weight of steel means it is used selectively in aircraft design. Engineers must balance the need for strength with the importance of keeping the aircraft as light as possible. Advances in high-strength, low-alloy steels have helped reduce weight while maintaining performance, allowing steel to remain a vital material in aerospace engineering.



Figure 1.2: Landing gear with steel alloy components

Titanium Alloys

Titanium alloys are highly valued in aerospace engineering for their exceptional strength-to-weight ratio and resistance to corrosion and heat. Titanium is lighter than steel but nearly as strong, making it ideal for critical structural components. It is also biocompatible and non-magnetic, which adds to its versatility in specialised applications.



Figure 1.3: Titanium alloy components on aircraft

Aircraft components made from titanium include jet engine parts, landing gear, and airframe sections that experience high stress or temperature. Titanium's ability to withstand extreme conditions without degrading makes it especially useful in supersonic and military aircraft. Its corrosion resistance also makes it suitable for marine aircraft and those operating in humid climates.

Despite its advantages, titanium is expensive and difficult to machine, which limits its use to areas where its properties are absolutely necessary. The cost and complexity of working with titanium mean that it is often reserved for high-performance aircraft and space vehicles, where reliability and strength are paramount.

Composite Materials

Composite materials are engineered by combining two or more substances to create a material with superior properties. In aviation, the most common composites are fibre-reinforced plastics, such as carbon fibre, fibreglass, and Kevlar, embedded in a resin matrix. These materials are incredibly strong yet lightweight, making them ideal for modern aircraft design.



Figure 1.4: Composite components on aircraft

Composites are used extensively in aircraft fuselages, wings, and control surfaces. Their ability to be moulded into complex shapes allows for more aerodynamic designs, which improve fuel efficiency and performance.

Additionally, composites offer excellent resistance to fatigue and corrosion, contributing to longer service life and reduced maintenance costs.

One of the main challenges with composites is their cost and the complexity of manufacturing. They require specialised techniques and equipment, and damage can be harder to detect, and repair compared to metals. Nonetheless, their benefits have led to widespread adoption in advanced aircraft such as the Boeing 787 and Airbus A350.

Other Materials

In addition to the main structural materials, aircraft incorporate a variety of other substances for specific functions. Magnesium alloys, for example, are even lighter than aluminium and are used in non-structural components such as housings and brackets. Although they are more prone to corrosion, protective coatings can help mitigate this issue.

Rubber and plastics are used throughout the aircraft for insulation, seals, and interior fittings. These materials provide flexibility, vibration damping, and resistance to environmental factors. Glass, particularly specialised aviation glass, is used in cockpit windows and instrument panels due to its clarity and strength.

Historically, wood was used in early aircraft and is still found in some light sport and experimental planes. Modern aircraft may also use advanced ceramics and foams for insulation and fire protection. These "other materials" play a crucial role in ensuring safety, comfort, and efficiency in aviation design.



Figure 1.5: Cockpit windshields made of glass

Later in the course, when we begin building UAVs, we'll be working with some of the materials we've just discussed. However, for reasons such as affordability, ease of handling, and local availability, we may also use materials like wood and foam. These alternative options are explored next.

1. **Plastics**

   Plastics are widely used in drone construction due to their lightweight, durability, and cost-effectiveness. Thermoplastics such as ABS (Acrylonitrile Butadiene Styrene), polycarbonate, and nylon are particularly popular. These materials offer a good balance between



Figure 1.6: Plastic UAV components

strength and flexibility, making them ideal for parts that need to absorb impact or resist wear and tear.

In drones, plastics are commonly used for propeller guards, camera mounts, casings, and internal compartments. ABS is often chosen for its toughness and ease of moulding, while polycarbonate is valued for its transparency and impact resistance—perfect for protective covers and lenses. Nylon is used in gears and moving parts due to its fatigue resistance and ability to dampen vibrations.

One of the key advantages of plastics in drone design is their versatility. They can be 3D printed, injection moulded or machined to fit a wide range of applications. Their resistance to chemicals and environmental factors also makes them suitable for outdoor use. However, plastics may not be ideal for high-temperature or high-load areas, where metals or composites are preferred.

2. **Foam**

Foam materials, especially EVA (Ethylene-Vinyl Acetate) and Expanded Polypropylene (EPP), play a crucial role in drone construction, particularly for lightweight and impact-resistant designs. These foams are known for their shock absorption, vibration dampening, and low density, which help improve flight stability and protect sensitive components.

Foam is often used in drone frames, landing pads, battery insulation, and carrying cases. EVA foam, for example, is moulded into protective shapes that cushion electronics and reduce the risk of damage during crashes or hard landings. EPP foam is used in fixed-wing drones for its aerodynamic properties and ability to withstand repeated impacts without cracking.

The use of foam in drones also contributes to longer flight times due to its minimal weight. It's easy to shape and customise, making it ideal for hobbyists and professionals alike. While foam may not offer the same structural strength as metals or composites, its protective qualities and ease of use make it a valuable material in drone design.



Figure 1.7: Giant foamboard quadcopter

3. **Wood**

Wood is an unconventional but increasingly popular material in drone construction, especially among hobbyists and eco-conscious designers. Lightweight woods such as balsa, spruce, and birch are used to build drone frames that are both strong and sustainable. Wood offers a unique aesthetic and can be easily shaped using basic tools.

Wooden drones are often built for educational projects, experimental designs, or low-cost applications. Balsa wood is favoured for its feather-light weight, while plywood provides added strength and rigidity. These materials are suitable for small drones where weight and simplicity are more important than high-speed performance or advanced manoeuvrability.

One of the main benefits of using wood is its biodegradability and low environmental impact. It also allows for easy repairs and modifications. However, wood is sensitive to moisture and may not be suitable for all weather conditions. With proper sealing and design, wooden drones can be both functional and visually striking.



Figure 1.8: Wooden UAV frame

Activity 1.1 Material Match-Up for Aircraft

1. Organise yourselves into groups of 3 or 4. You'll receive a set of cards with:
   a. Names of materials used in aircraft (like aluminium, steel, foam, wood, etc.)
   b. Properties of the materials (like lightweight, strong, heat-resistant, cheap, etc.)
   c. Types of aircraft (like commercial jet, fighter jet, small UAV, glider, delivery drone)
2. Match each material to the properties that best describe it. Then, match each material to the type of aircraft it's most suitable for.
3. Discuss with members of your group why you think some materials are better for small UAVs than for large aircraft. (e.g., What makes a material good for building drones?)
4. Share your ideas with the class.

AIRFRAME STRUCTURES

Aircraft are built using different structural approaches, each designed to balance strength, weight, and performance. Here, we'll explore three key construction types – truss structure, monocoque, and semi-monocoque – and how they shape the design and function of various aircraft.

Truss Structure

The truss structure is one of the earliest and simplest forms of aircraft construction. It consists of a framework made from beams arranged in triangular shapes, which helps distribute loads evenly and maintain structural integrity. These beams are usually made from steel or aluminium tubes, and the entire frame is covered with a lightweight skin, often fabric or thin metal.

This type of construction is strong and relatively easy to build and repair, making it ideal for small aircraft and early aviation designs. The triangular arrangement of the truss helps resist bending and twisting forces during flight. Because the skin does not carry any structural load, the strength of the aircraft depends entirely on the internal framework.

However, truss structures are heavier and less aerodynamic than more modern designs. They are mostly used today in light sport aircraft, gliders, and some experimental planes. Despite their limitations, truss structures are excellent for teaching basic engineering principles and remain a valuable part of aviation history.

Examples of aircraft using this type of construction include the Wright Flyer, built in 1903; the Piper J-3 Cub and a World War I-era biplane, the Curtiss JN-4.

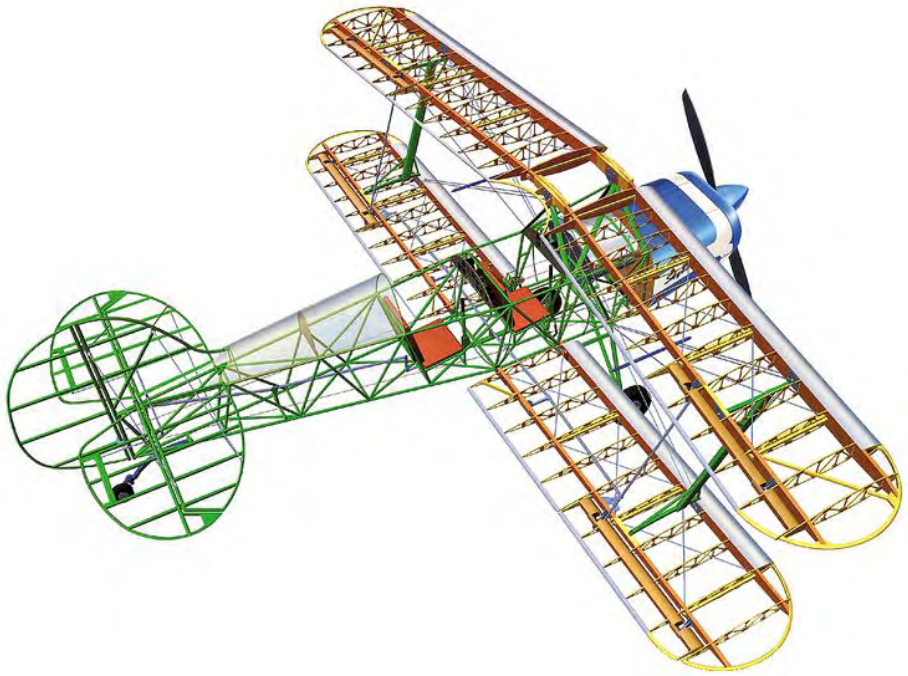


Figure 1.9: Truss airframe

Monocoque Structure

The monocoque structure is a more advanced method of aircraft construction where the outer skin of the aircraft carries most or all of the structural load. The term "monocoque" comes from French, meaning "single shell." This design eliminates the need for an internal framework, relying instead on the strength of the skin itself to maintain shape and withstand forces.

Monocoque construction is commonly used in modern aircraft fuselages and is especially popular in high-performance and lightweight designs. Materials such as aluminium alloys and composites are often used to create strong, smooth surfaces that improve aerodynamics and reduce weight. This method allows for sleek, streamlined shapes that enhance flight efficiency.

One challenge with monocoque structures is that damage to the skin can compromise the entire structure, making repairs more complex. As a result, this design is typically used in areas of the aircraft that are less likely to suffer impact or stress. Despite this, monocoque construction remains a key innovation in aircraft design, offering strength, simplicity, and aerodynamic advantages.

The De Havilland Mosquito, Luscombe 8 and Lockheed Vega are examples of aircraft having a monocoque structure.

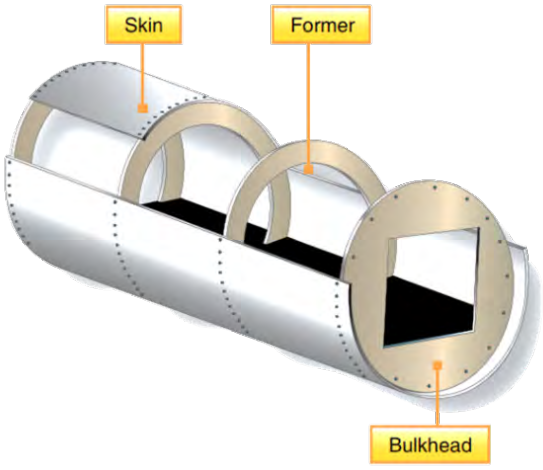


Figure 1.10: Monocoque fuselage

Semi-Monocoque Structure

The semi-monocoque structure combines the best features of both truss and monocoque designs. In this method, the aircraft has a load-bearing skin supported by an internal framework made up of longitudinal stringers and transverse bulkheads or frames. This combination allows the aircraft to handle greater loads while maintaining a lightweight and aerodynamic form.

Semi-monocoque construction is the most common method used in modern aircraft, including commercial airliners and military jets. The internal supports help distribute stress across the skin and prevent buckling, while the skin itself contributes to the overall strength. This design also makes it easier to repair damaged sections without compromising the entire structure.

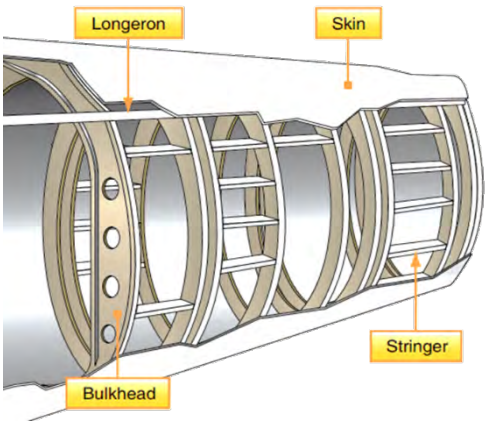


Figure 1.11: Semi monocoque fuselage

The balance of strength, weight, and durability makes semi-monocoque construction ideal for high-performance aircraft. It allows engineers to build larger, more complex airframes that can withstand the demands of flight while remaining efficient and safe. Understanding this structure is essential for anyone pursuing a career in aerospace engineering.

Several aircraft have used the semi monocoque structure, including the Boeing 737, Cessna 172 and the Supermarine Spitfire.

Activity 1.2 Build it Like an Engineer

Organise yourselves into groups of 3 or 4.

1. Create a simple model of an aircraft fuselage for a structure/construction type of your choice. You may use materials like straws, paper, cardboard, string, or tape.
   a. For a truss structure, build a frame using straws or sticks joined in triangles.
   b. For a monocoque structure, make a shell using paper or cardboard that holds its shape without an internal frame.
   c. For a semi-monocoque structure, combine a shell with internal supports like strips or frames inside.
2. Before you build, create a poster with your group depicting the type of aircraft construction you are going to build.
3. As you build, talk about what makes your structure strong, where it might be used in real aircraft and any advantages and challenges of your design.
4. Present your model and poster to the class, explaining what type of construction you chose, how it works and why it's useful in aircraft design

EXTENDED READING

4 Common Types of Airplane Fuselages
Aircraft structures and types of construction
Basic aircraft structure

REVIEW QUESTIONS

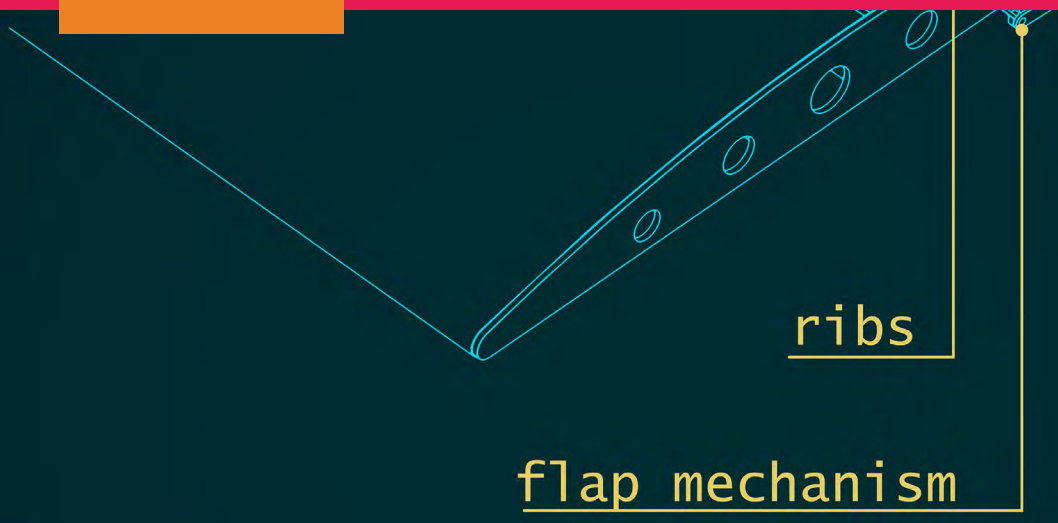
1. Compare and contrast the properties of aluminium alloys and composites. How do these properties influence their use in different parts of an aircraft?
2. You are required to design a small UAV for your school project. Choose two materials for its construction and justify your choices based on cost, weight, ease of use, and availability.

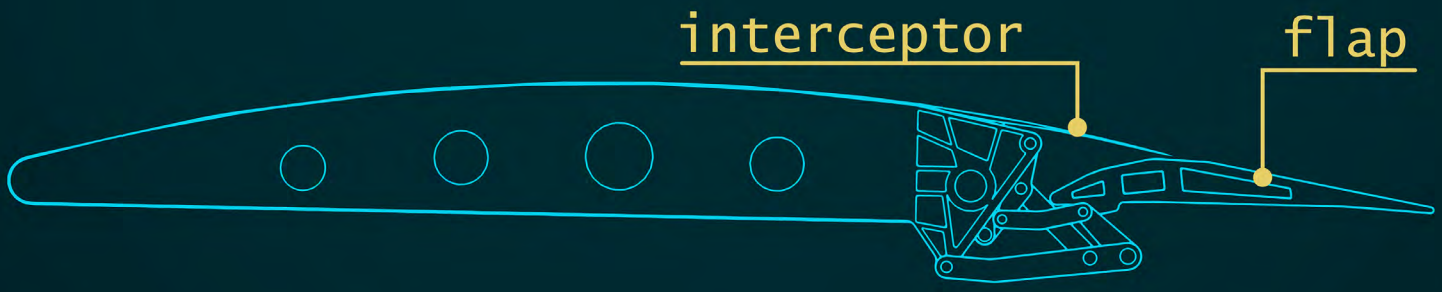


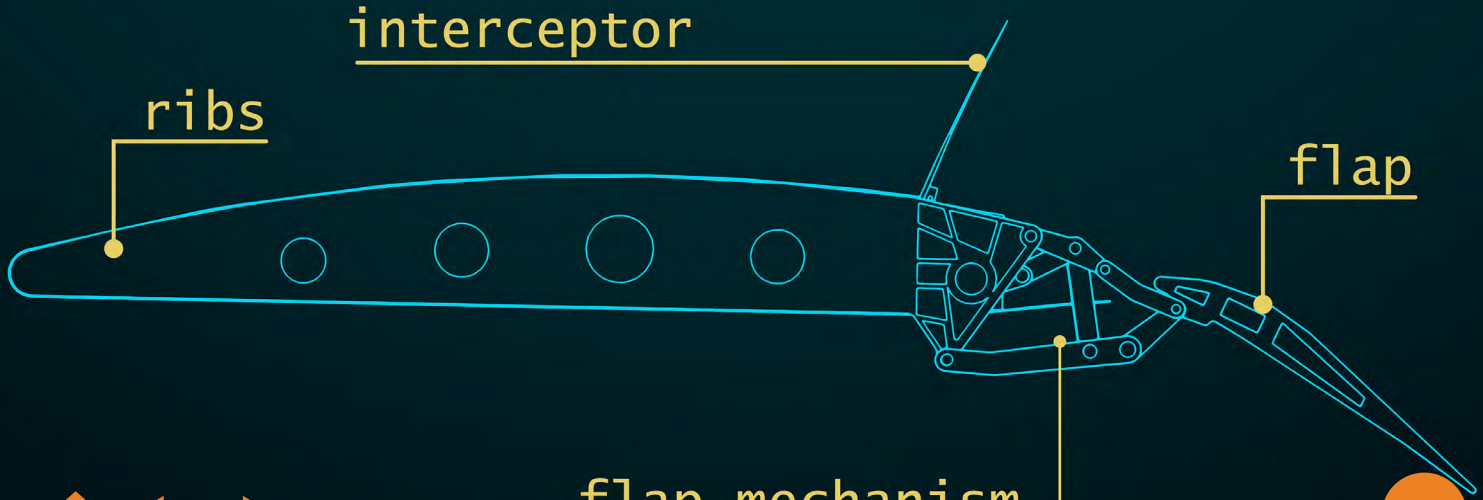
SECTION

2

STABILITY AND CONTROL







CORE CONCEPTS IN AEROSPACE ENGINEERING

AIRCRAFT STRUCTURES AND CONTROL

INTRODUCTION

This section deals with the second and third learning outcomes of the Aircraft Structures and Control sub strand of the Core Concepts in Aerospace Engineering strand.

Now that we've explored the structural designs that give aircraft their shape and strength, it's time to look at how these structures behave during flight. In Section 2, we'll focus on how aerospace vehicles are controlled and kept stable once they're airborne. You'll learn about the main control surfaces, how they affect movement, and the principles of static and dynamic stability – building your understanding of how aircraft stay balanced and responsive in the air.

KEY IDEAS

- Fixed-wing aircraft use ailerons, rudder, elevator and secondary surfaces such as flaps, slats and spoilers for control
- Flight control systems enable the pilot to change the attitude (orientation) and flight path of the aircraft
- Rotary-wing aircraft achieve control using collective, cyclic, throttle and anti-torque control inputs
- Spacecraft employ systems such as thrusters and control moment gyroscopes for control

AIRCRAFT & SPACECRAFT FLIGHT CONTROLS

As we have already learned, an aircraft is made up of many connected parts that work together as a complex machine. Once it's in the air, it's not enough just to stay flying—the aircraft must also be controlled to move safely and efficiently. This is where flight control systems come in. These systems allow the pilot to change the aircraft's direction and position by managing its movement around three main axes: pitch, roll, and yaw. In this section, we'll explore the control surfaces that make this possible, and learn how different systems – like mechanical linkages, hydraulics, and fly-by-wire electronics – help transmit

the pilot's input to the aircraft's moving parts. This will provide a deeper understanding of how aircraft and spacecraft stay balanced and respond during flight

Control Surfaces of Fixed-Wing Aircraft

To keep an aircraft stable and steer it through the air, pilots rely on control surfaces – movable parts of the wings and tail that guide the aircraft's motion. Let us touch on the primary and secondary control surfaces used in fixed-wing aircraft, how they affect movement, and why each one plays a vital role in safe and responsive flight.

Primary Control Surfaces

1. **Ailerons**

   Ailerons are located near the tips of an aircraft's wings and are responsible for controlling roll – how the aircraft tilts side to side. They work in pairs, moving in opposite directions: when one aileron goes up, the other goes down, causing the aircraft to bank in the desired direction.

   The pilot moves the control yoke or sticks left or right to operate the ailerons, causing the aircraft to roll in the corresponding direction. This rolling motion is essential for turning the aircraft, especially during manoeuvres like banking into a curve or adjusting direction mid-flight. Ailerons are used frequently during flight and are a key part of maintaining control and stability.

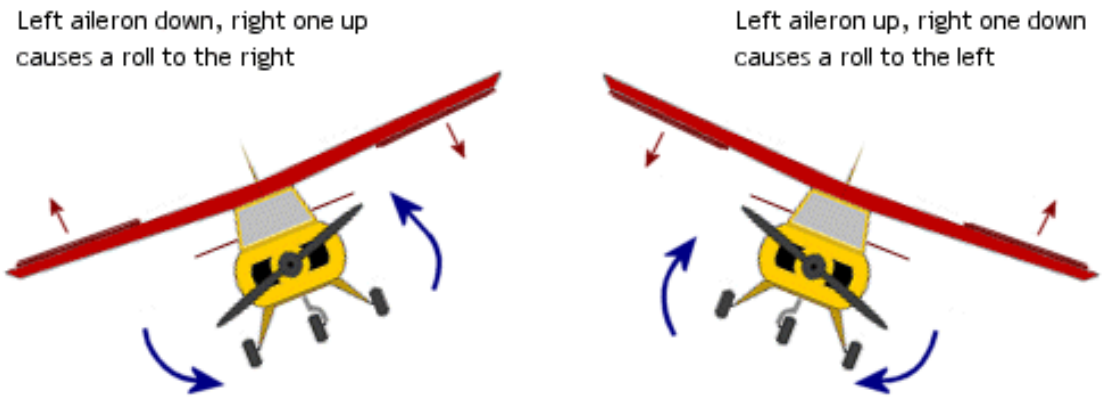


Figure 2.1: Effect of aileron movement

2. **Elevator**

   The elevator is attached to the horizontal stabiliser at the tail of the aircraft and controls pitch – how the nose moves up or down. When the elevator moves upward, the nose of the aircraft rises; when it moves downward, the nose lowers. The pilot pushes or pulls the control yoke or stick forward or backward to raise or lower the elevator.

   This control surface is crucial for climbing, descending, and maintaining level flight. Pilots use the elevator constantly to adjust altitude and keep the aircraft balanced during changes in speed or direction.

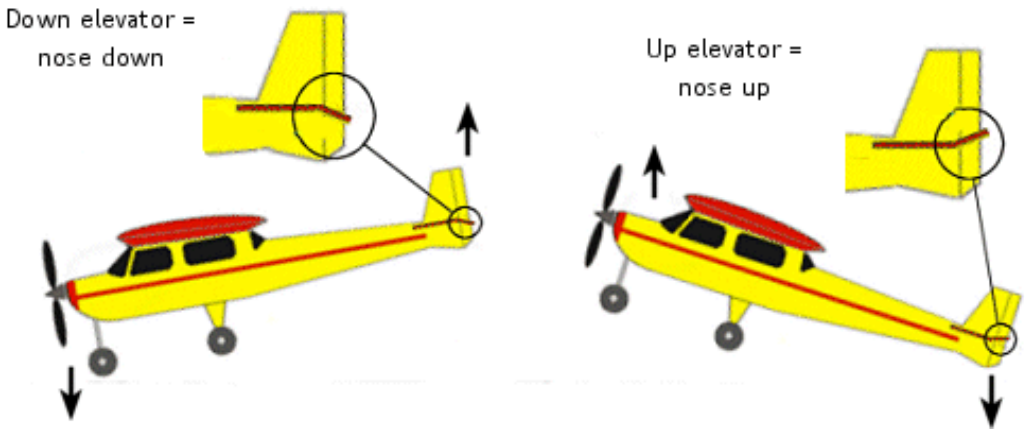


Figure 2.2: Effect of elevator movement

3. **Rudder**

The rudder is mounted on the vertical stabiliser and controls yaw—the side-to-side movement of the aircraft's nose. By turning the rudder left or right, the pilot can steer the aircraft in that direction. Presses the left or right rudder pedal to moves the rudder.

While the rudder is not the main tool for turning, it helps coordinate turns and maintain straight flight, especially in windy conditions or when correcting for uneven thrust. It also plays a key role during take-off and landing.

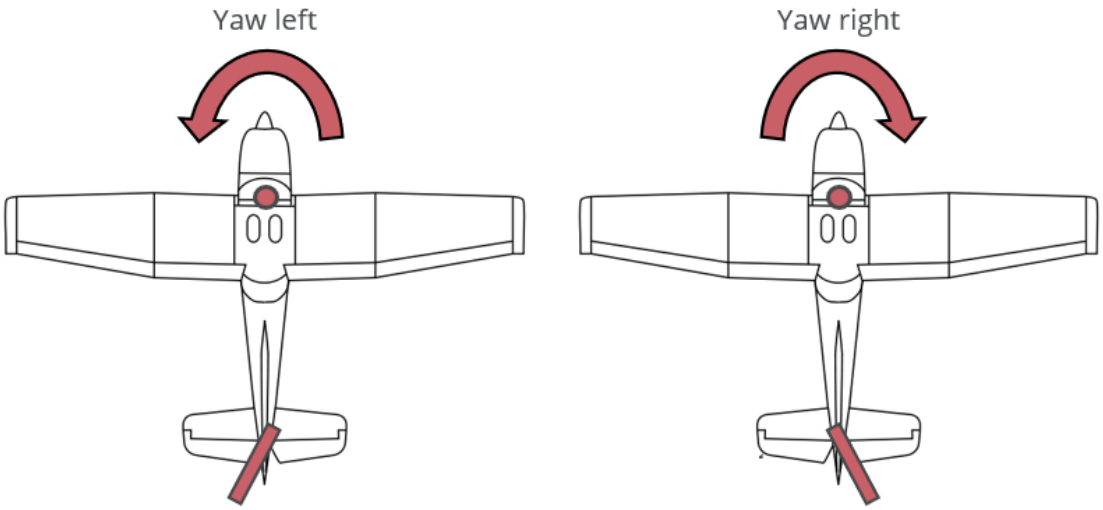


Figure 2.3: Effect of rudder movement

Secondary Control Surfaces

1. **Flaps**

Flaps are hinged surfaces located on the trailing edge of an aircraft's wings, usually closer to the fuselage. They are extended downward during take-off and landing to increase both lift and drag, allowing the aircraft to fly safely at lower speeds. This helps shorten the distance needed for take-off and landing, making flaps essential for safe operations, especially on shorter runways.

There are several types of flaps, each designed to improve performance in different ways. *Plain flaps* simply hinge downward to increase lift. *Split flaps* deflect only the lower surface, creating more drag. *Slotted flaps* allow air to flow between the flap and wing, improving lift. *Fowler flaps* slide backward and then downward, increasing both wing area and lift. Each type offers a unique balance of lift and drag, and the choice depends on the aircraft's design and intended use.

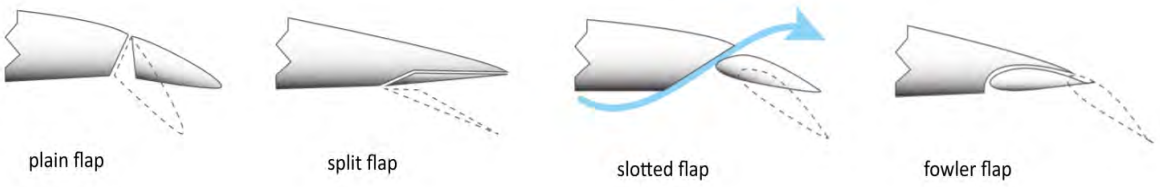


Figure 2.4: Types of flaps used on aircraft

2. Slats

Slats are located on the leading edge of the wings and are used to improve airflow over the wing at low speeds. When deployed, they create a smoother flow of air, helping the wing maintain lift and reducing the chance of stalling.

Slats are most useful during take-off, landing, or steep climbs, where maintaining lift at low speeds is critical. They work together with flaps to enhance the aircraft's performance during these phases.

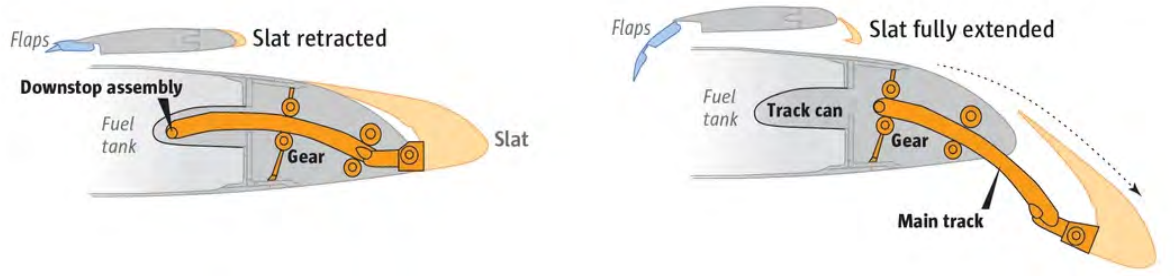


Figure 2.5: Operation of slats

3. Spoilers

Spoilers are flat panels on the top surface of the wings that can be raised to disrupt airflow and reduce lift. This helps slow the aircraft down and can also assist in descent or roll control.

Pilots often use spoilers during landing to help the aircraft settle onto the runway and reduce speed quickly. In some aircraft, spoilers are also used to help with turning by reducing lift on one wing.



Figure 2.6: Spoilers on the wing of an aircraft

4. **Trim Tabs**

Trim tabs are small adjustable surfaces attached to the trailing edge of primary control surfaces like the elevator, rudder, or ailerons. They help maintain steady flight by reducing the need for constant pilot input.

By fine-tuning the position of a control surface, trim tabs allow the aircraft to fly smoothly without the pilot having to hold the controls in place. This makes flying more comfortable and reduces fatigue during long flights.

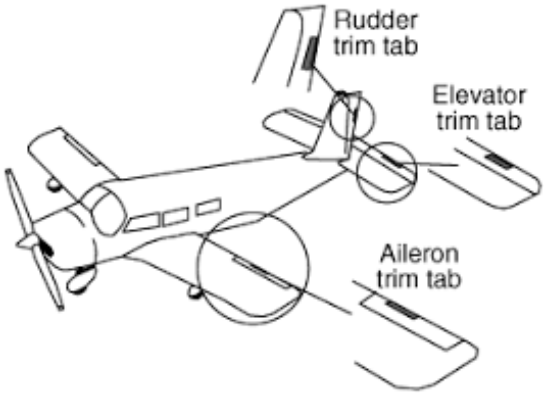


Figure 2.7: Trim tabs

Flight Control Systems of Rotary-Wing Aircraft

Unlike fixed-wing aircraft, rotary-wing aircraft such as helicopters use rotating blades and specialised control systems to manage flight. We'll now learn how these aircraft are controlled in the air, including how pilots adjust lift, direction, and stability using components like the cyclic, collective, and anti-torque pedals. These systems work together to allow precise manoeuvring and hovering, making rotary-wing flight both unique and highly versatile.

Collective Control

The collective pitch control is responsible for changing the pitch angle of all the main rotor blades simultaneously and equally. This control directly affects the lift produced by the rotor system. When the pilot raises the collective lever (usually located to the left of the pilot's seat), the pitch of the rotor blades increases, generating more lift and causing the helicopter to ascend. Lowering the collective decreases blade pitch and lift, allowing the aircraft to descend. The collective is typically linked to the engine throttle through a correlator or governor, which automatically adjusts engine power to maintain rotor RPM as blade pitch changes. This control is essential for vertical movement and is used during take-off, landing, and altitude changes.

Cyclic Control

The cyclic pitch control allows the pilot to tilt the rotor disk in a particular direction, enabling horizontal movement. It changes the pitch of each rotor blade individually as it rotates around the mast, creating an asymmetrical lift that tilts the rotor disk. This tilt causes the helicopter to move forward, backward, or sideways. The cyclic stick is typically located between the pilot's legs and operates through a complex system of linkages and the swashplate assembly, which translates the pilot's input into blade pitch changes. Mastery of the cyclic is crucial for manoeuvring the helicopter in all directions and maintaining stable flight

Throttle control

The throttle controls the engine power, which affects the speed of the rotor blades. Unlike in fixed-wing aircraft, where throttle mainly controls forward speed, in helicopters it helps

maintain the correct rotor RPM (revolutions per minute). In many modern helicopters, the throttle is automatically managed by a *governor*, which adjusts engine power as the pilot changes the collective pitch.

Anti-torque pedals

In a helicopter, the main rotor generates lift but also causes the body of the aircraft to spin in the opposite direction due to torque. To counter this, helicopters use a tail rotor that produces sideways thrust. The anti-torque pedals, located at the pilot's feet, control the pitch of the tail rotor blades. By pressing the left or right pedal, the pilot can increase or decrease the thrust from the tail rotor, allowing the helicopter to yaw. This essential for maintaining directional control, especially during hovering, take-off, and landing.

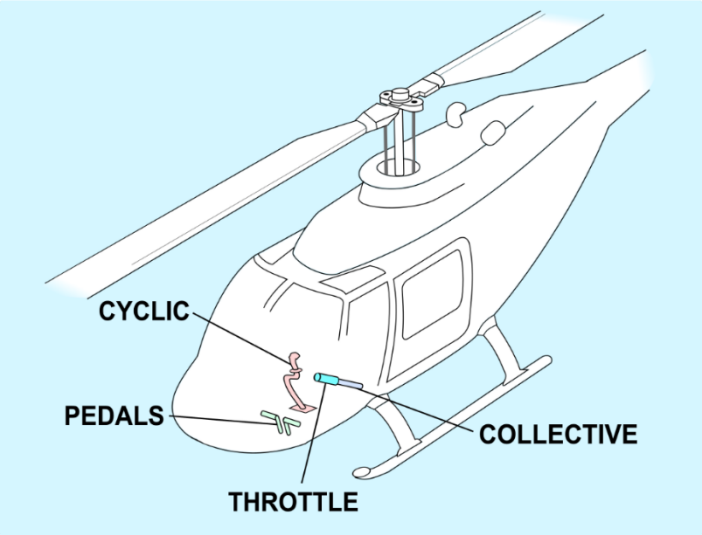


Figure 2.8: Helicopter controls

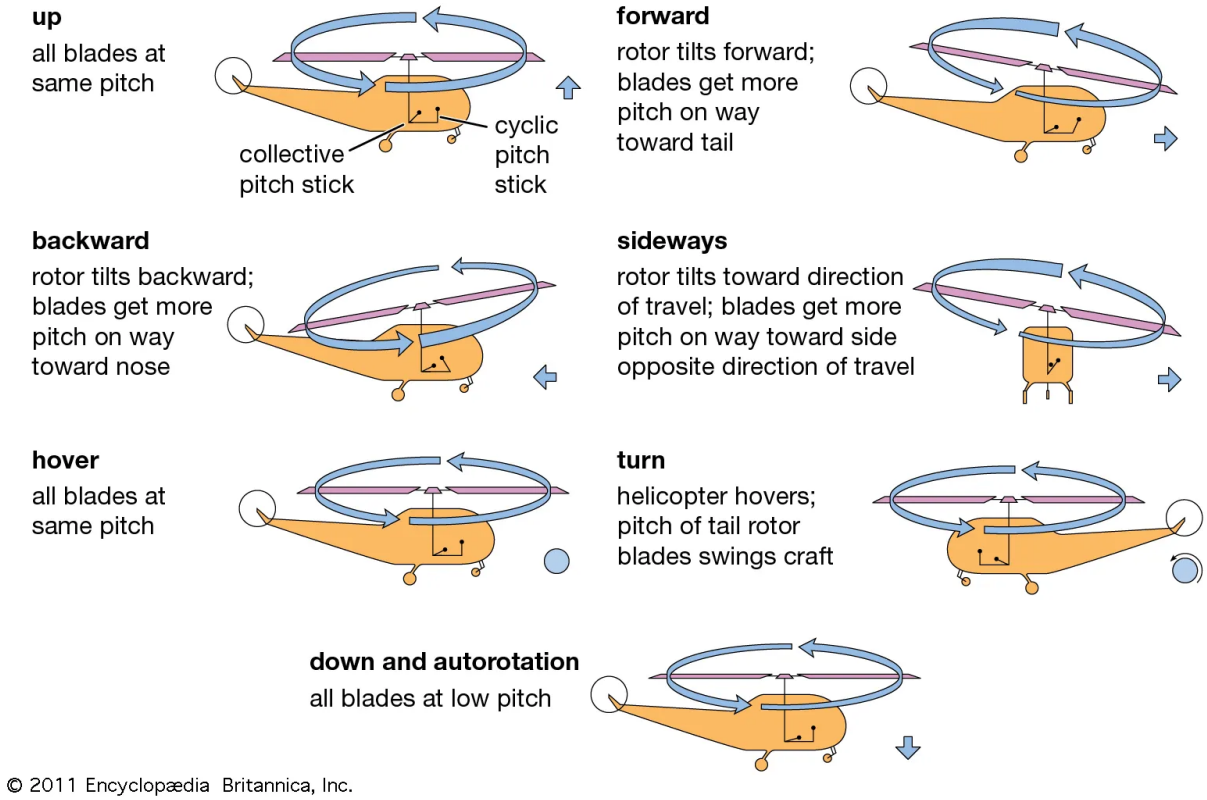


Figure 2.9: Effects of helicopter control inputs

Spacecraft Control Mechanisms

Controlling a spacecraft during flight involves unique challenges that are quite different from those faced by aircraft. Unlike aircraft, which rely on air for lift and steering, spacecraft operate in the vacuum of space where traditional control surfaces like rudders and ailerons are useless. Instead, spacecraft depend on specialised systems to manage their attitude (orientation in space) and trajectory (path of movement). These control mechanisms are vital for manoeuvring, aiming scientific instruments, maintaining communication with Earth, and successfully achieving mission goals.

Attitude Control Systems

Attitude control refers to how a spacecraft adjusts and maintains its orientation in space. There are several systems used for this:

1. Reaction Control Systems use small thrusters placed around the spacecraft to rotate or stabilise it. By firing in short bursts, these thrusters can change the spacecraft's pitch, yaw, or roll.



Figure 2.10: Reaction control system of the Apollo spacecraft

2. Reaction Wheels are spinning wheels mounted inside the spacecraft. When a wheel speeds up or slows down, it causes the spacecraft to rotate in the opposite direction due to conservation of angular momentum. They are precise and don't use fuel but can become saturated and need to be reset.

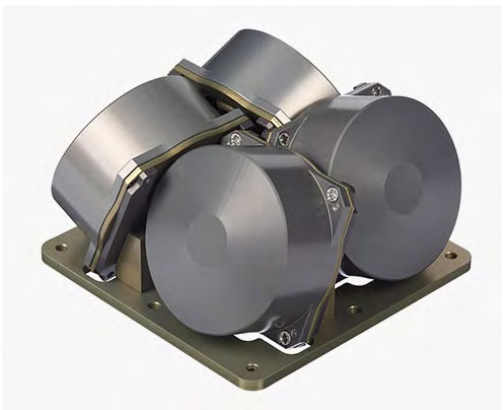


Figure 2.11: Reaction wheels of a CubeSat

3. Control Moment Gyroscopes (CMGs): Like reaction wheels but more powerful, CMGs use gimballed spinning masses to produce torque. They are ideal for large spacecraft like the International Space Station, offering strong and efficient attitude control.

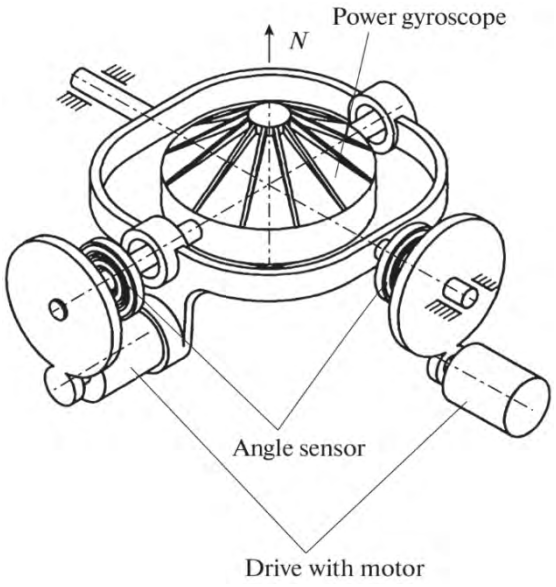


Figure 2.12: Control moment gyroscope

Thrusters for Orbital Manoeuvres

To change a spacecraft's orbit or position in space, different types of thrusters are used:

1. Chemical Thrusters: These use chemical reactions to produce thrust. They are powerful and commonly used for launch, major orbital changes, and quick manoeuvres. Examples include bipropellant and monopropellant engines.
2. Electric Propulsion Systems: These use electricity to accelerate ions and produce thrust. Though much weaker than chemical thrusters, they are highly efficient and ideal for long-duration missions. Types include ion thrusters and Hall-effect thrusters.

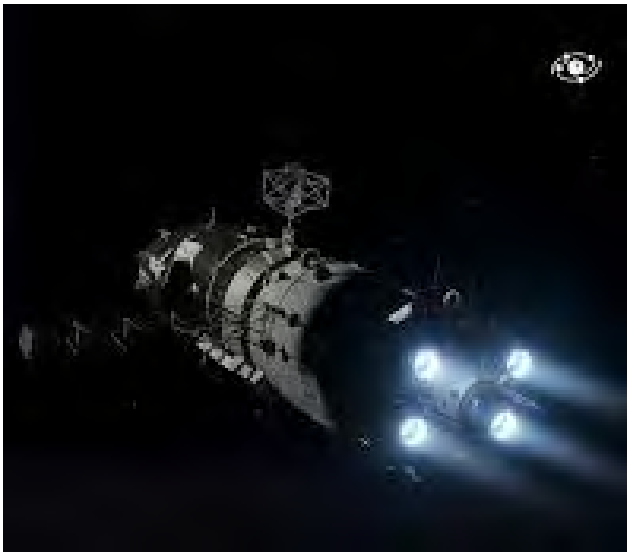


Figure 2.13: Voyager I spacecraft showing thrusters

Guidance, Navigation, and Control (GNC) Systems

GNC systems work together to ensure the spacecraft knows where it is, where it's going, and how to get there:

1. Guidance: Determines the desired path or trajectory the spacecraft should follow.
2. Navigation: Measures the spacecraft's current position, velocity, and orientation using sensors like star trackers, gyroscopes, and GPS (for near-Earth missions).
3. Control: Executes the necessary actions to stay on course, using attitude control systems and thrusters to adjust movement and orientation.

Flight Control Transmission Systems

Flight control transmission systems are the methods by which a pilot's input is transferred to the aircraft's control surfaces (like ailerons, elevators, and rudders). These systems ensure that the aircraft responds correctly to steering, climbing, and descending commands.

Mechanical Control Systems

Mechanical systems use cables, pulleys, rods, and levers to connect the pilot's controls directly to the aircraft's control surfaces. They are simple, reliable, and easy to maintain, often found in smaller or older aircraft. However, they can be heavy and require regular inspection to prevent wear and tear.

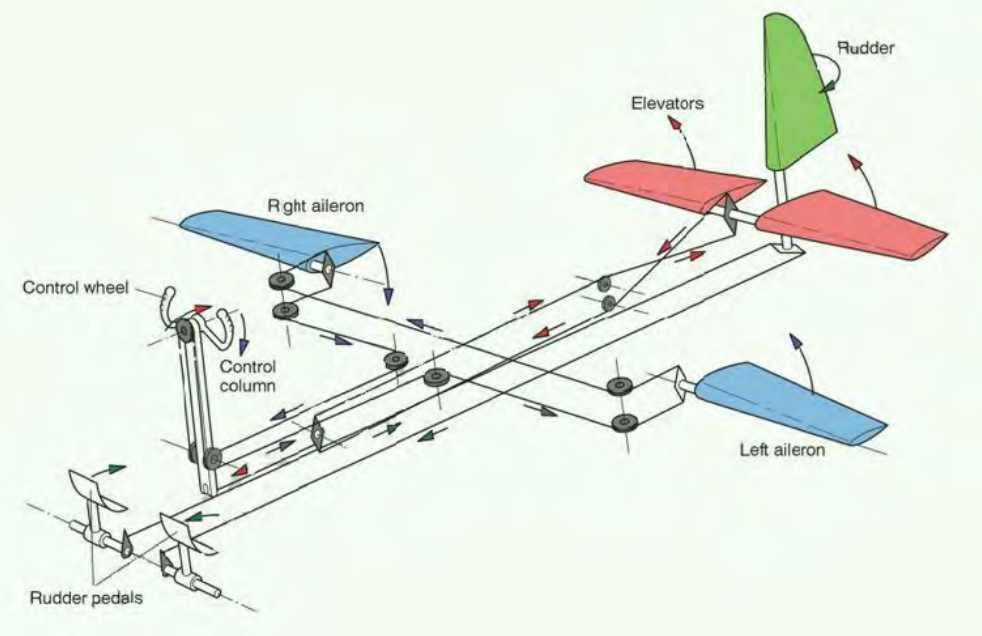


Figure 2.14: Mechanical flight control system

Hydraulic Control Systems

Hydraulic systems use pressurised fluid to move control surfaces. When the pilot moves a control, hydraulic pumps and actuators respond with powerful force, making it easier to control large or fast aircraft. These systems are common in commercial jets and military aircraft, offering smooth and responsive control, but they require careful maintenance to avoid leaks or pressure loss.

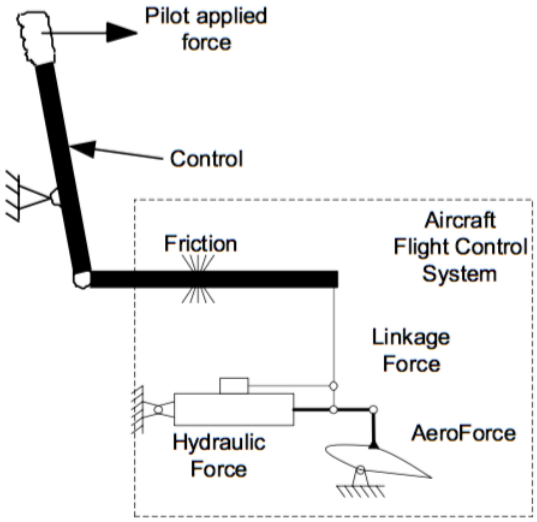


Figure2.15: Hydraulic flight control system

Fly-by-Wire Systems

Fly-by-wire systems replace mechanical and hydraulic links with electronic signals. The pilot's inputs are sent to a computer, which interprets them and commands actuators to move the control surfaces. These systems are lighter, more precise, and can include safety features like automatic stability correction. They are widely used in modern aircraft such as the Airbus A350 and Boeing 787.

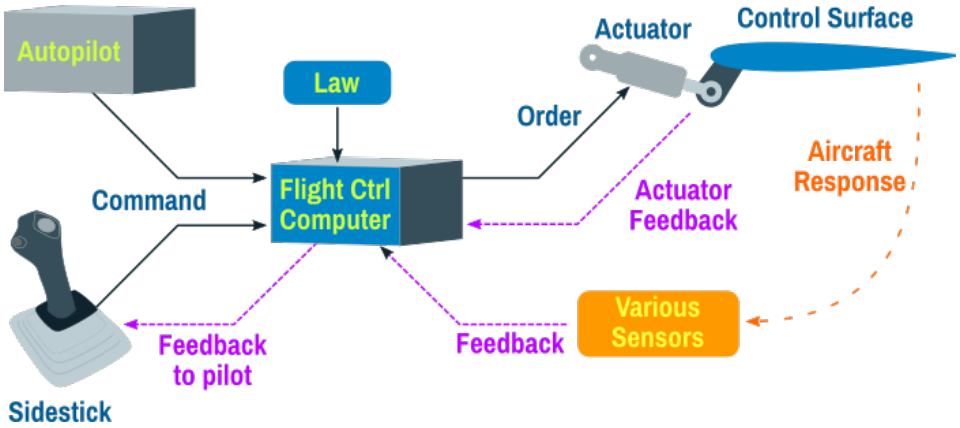


Figure 2.16: Fly-by-wire control system

Activity 2.1 Build and Explain Your Own Control System Model

Form a small group of 4 or 5, and using simple classroom materials (e.g., cardboard, string, paper clips, straws, small boxes),

1. Watch videos demonstrating the mechanisms for control inputs in fixed-wing aircrafts, rotary wing aircrafts and spacecraft. Discuss similarities or differences among their operations.
2. Build a basic model that shows how an aerospace vehicle control system of your choice works.
    a. Fixed-wing groups should show how ailerons, elevators, and rudders move.
    b. Rotary-wing groups should show collective and cyclic control.
    c. Spacecraft groups should show attitude control using thrusters or reaction wheels.
3. Prepare a short explanation and present it to the class on:
    a. What each control does.
    b. How it affects the movement of your vehicle.
    c. Why it is important for flight or space travel.

AIRCRAFT & SPACECRAFT STABILITY

Previously, we looked at how different control systems – mechanical, hydraulic, and fly-by-wire – allow pilots and onboard systems to guide aerospace vehicles during flight. However, simply having control inputs isn't enough; how well a vehicle responds also depends on how stable it is by design. In this section, we'll explore the physical principles behind stability, focusing on the role of moments and the centre of gravity. You'll discover how engineers design aircraft and spacecraft to stay balanced and recover smoothly from disturbances while flying.

Static and Dynamic Stability of Aerospace Vehicles

Stability refers to how well a vehicle can maintain or return to its intended flight path or orientation after being disturbed. This is crucial for safe and controlled operation, whether the vehicle is flying through the atmosphere or navigating in space.

Static Stability is the vehicle's initial response to a disturbance. If the vehicle begins to return to its original position or orientation immediately after being disturbed, it has positive static stability. If it remains in the new position, it has neutral static stability, and if it moves further away, it has negative static stability. This concept applies to aircraft, rockets, and satellites alike.

Dynamic Stability refers to the behaviour over time following the disturbance. A vehicle with positive dynamic stability will gradually return to its original state, often through decreasing oscillations. If the oscillations remain constant, the vehicle has neutral dynamic stability, and if they grow larger, it has negative dynamic stability. This type of stability is especially important for long-duration missions and automated flight systems.

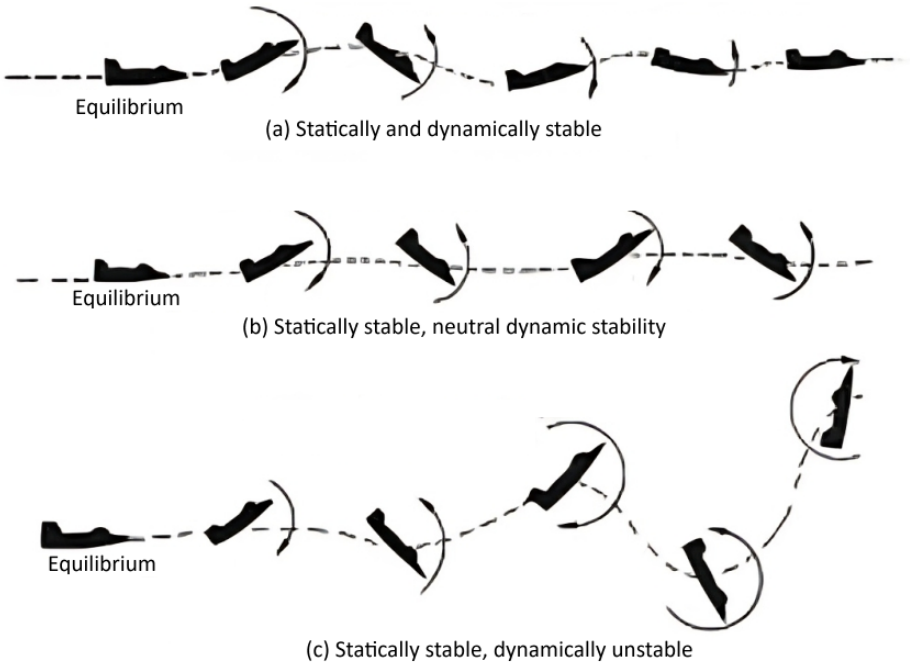


Figure 2.17: Aircraft stability

Aerospace vehicle axes

All aerospace vehicles (aircraft, spacecraft) move and rotate around three main axes:

1. Longitudinal Axis (Roll): This axis runs from the nose to the tail of the vehicle. Rotation around this axis is called roll, which tilts the wings or sides up and down. In aircraft, roll is controlled by the ailerons.
2. Lateral Axis (Pitch): This axis runs from wingtip to wingtip (or side to side). Rotation around it is called pitch, which raises or lowers the nose of the vehicle. In aircraft, pitch is controlled by the elevator.
3. Vertical Axis (Yaw): This axis runs vertically through the centre of gravity. Rotation around it is called yaw, which turns the nose left or right. In aircraft, yaw is controlled by the rudder, while helicopters use anti-torque pedals, and spacecraft use thrusters or reaction wheels.

Aircraft stability is often considered in two dimensions: longitudinal stability and lateral-directional stability.

1. **Longitudinal stability** refers to the aircraft's ability to maintain or return to steady flight along the pitch axis (nose up or down) and is affected by features such as:
    a. Centre of Gravity (CG) location: A properly positioned CG helps the vehicle naturally return to level flight. If the CG is too far forward or aft, it can reduce pitch stability.
    b. Horizontal stabiliser design: Located at the rear of most aircraft, it provides a counteracting force to balance the nose and maintain pitch control.
    c. Wing design and position: High-mounted wings or those with a slight backward sweep can improve longitudinal stability.

2. **Lateral-Directional Stability** involves the aircraft's behaviour along the roll and yaw axes (side-to-side and turning motions). It is affected by:
    a. Dihedral angle: The upward tilt of the wings helps the vehicle roll back to level after a disturbance, enhancing lateral stability.
    b. Vertical Stabiliser (Fin) design: Helps maintain directional stability by resisting unwanted yaw or side-slipping.
    c. Wing sweep and placement: Swept-back wings and high-wing configurations can improve both lateral and directional stability, especially in turbulent conditions.

Activity 2.2 Investigating Stability with Everyday Materials

You will need a small ball (e.g. a rubber ball), a flat plate, a bowl (concave surface), and an upside-down bowl (convex surface) for this activity.

Pair up with a colleague to

1. Test Static Stability
    a. Place the ball on the flat plate and gently push it. Observe how it behaves. This represents neutral static stability.
    b. Place the ball in the bowl and push it slightly. Watch how it returns to the centre. This shows positive static stability.
    c. Place the ball on the upside-down bowl and push it gently. Notice how it rolls away. This demonstrates negative static stability.
2. Discuss
    a. What does each surface represent in terms of aerospace vehicle design?
    b. Why is positive static stability important for safe flight?
3. Imagine a twig or flexible object being shaken by wind. Discuss how it might return to rest (positive dynamic stability), keep moving (neutral), or shake more violently (negative).
4. Share your findings with the class. Explain which type of stability each setup represents and why it matters in aerospace engineering.

EXTENDED READING

How the movement of the cyclic control stick affects the swashplate
Video: Aircraft Control Surfaces Explained | Ailerons, flaps, elevator, rudder and more
Video: Introduction to Spacecraft Navigation, Guidance and Control
Video: Spacecraft Gyroscopes And Reaction Wheels
Video: Reaction control system Explained

REVIEW QUESTIONS

1. Compare and contrast the flight control systems of fixed-wing aircraft, rotary-wing aircraft, and spacecraft. In your response, explain how each system is adapted to suit the vehicle's operating environment and movement capabilities.
2. Analyse how the location of the centre of gravity and the design of control surfaces influence both static and dynamic stability in aerospace vehicles. Use examples from at least two types of vehicles to support your explanation.

SECTION

3

AVIONICS



AVIONICS

COMMUNICATION, NAVIGATION AND SURVEILLANCE SYSTEMS

INTRODUCTION

This Section deals with the Communication, Navigation and Surveillance Systems sub strand of the Avionics strand.

In this section, we'll delve into the fascinating world of avionics— the electronic systems that support aircraft operations. We'll start by examining communication systems, highlighting the various technologies used and their specific applications. Next, we'll explore navigation systems, discussing the different methods available, along with their advantages and limitations. Finally, we'll look at technologies that help us detect and track aircraft, which are vital both for ground-based monitoring and for helping aircraft avoid collisions with one another.

KEY IDEAS

- Aircraft navigation employs dead reckoning or position-fixing approaches
- Radio communication technologies make it possible for aircraft to communicate with ground support staff
- Radio communication is performed at different frequencies, each possessing unique advantages and limitations
- Surveillance systems make it possible to keep track of aircraft within the airspace

AIRCRAFT COMMUNICATION SYSTEMS

(Refer to Year 1, Section 3: Introducing communication system in avionics)

Modern aircraft rely on a range of communication technologies to stay connected with air traffic control, other aircraft, and ground services. These technologies include radio systems, satellite links, and data networks, each playing a key role in ensuring safe and efficient flight operations. We will take a closer look at how these technologies work, their unique features, and the situations in which they are used.

Radio communication plays a crucial role in aviation, allowing pilots to stay in contact with air traffic controllers, other aircraft, and ground stations. Different frequency bands are used depending on the distance and purpose of the communication. Table 3.1 offers a summary of the different radio frequencies.

Table 3.1: Radio communication frequencies

Band	Frequency Range	Typical Use	Key Features
HF	3 – 30 MHz	Long-distance communication (international, oceanic)	Global coverage, affected by weather
VHF	118 – 137 MHz	Short to medium-range communication	Clear audio, line-of-sight limited
UHF	225 – 400 MHz	Military aviation	Secure, specialised use
SATCOM	1 – 2 GHz (L-band), 12 – 18 GHz (Ku-band)	Global communication	Reliable, supports voice and data

In aviation, reliable radio communication depends on three key components: antennas, transmitters, and receivers. These systems work together to ensure that aircraft can send and receive critical information during flight.

Antennas are the physical structures that radiate and capture radio waves. Aircraft are equipped with various types of antennas depending on the communication system in use. For example, VHF antennas are typically mounted on the top or bottom of the fuselage for short-range communication with control towers, while HF antennas, used for long-distance communication, may be wire-type and integrated into the aircraft's body. Satellite communication antennas are more advanced and are often enclosed in protective domes on the aircraft's upper surface.

Transmitters are responsible for generating and sending out radio signals through the antennas. They convert voice or data into electromagnetic waves that travel through the air to other aircraft or ground stations. Modern transmitters are designed to operate across multiple frequency bands and are built to withstand the demanding conditions of flight, including vibration, temperature changes, and electromagnetic interference.

Receivers perform the opposite function – they capture incoming radio signals via the antennas and convert them back into audio or data that pilots and onboard systems can understand. These receivers are highly sensitive and equipped with filters to reduce noise and interference, ensuring clear and accurate communication even in busy or challenging environments.

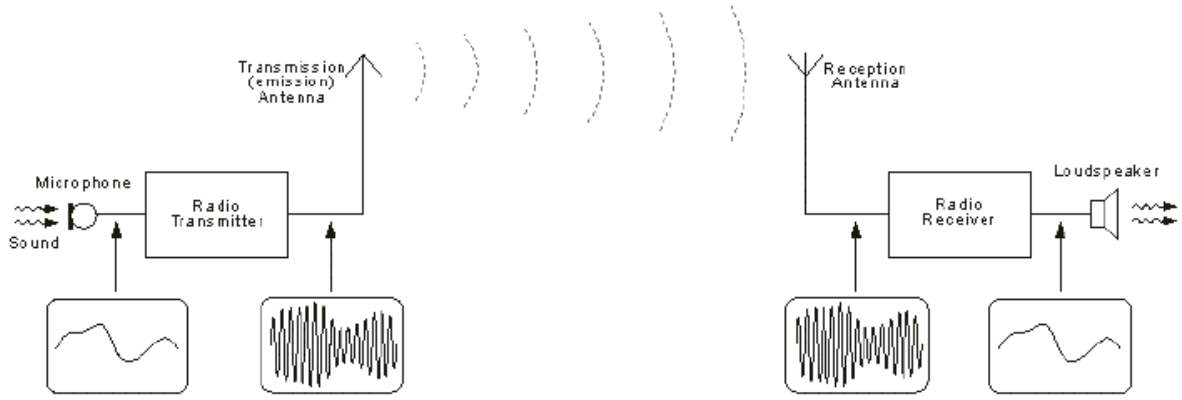


Figure 3.1: Radio communication system

Technologies for Aircraft Communications

Very High Frequency (VHF) Communication

VHF communication is the most commonly used radio system in civil aviation, operating within the 118 to 137 MHz range. It is primarily used for short to medium-range voice communication between aircraft and air traffic control (ATC), as well as between aircraft in the same vicinity. VHF signals travel in straight lines, a property known as line-of-sight propagation, which means their range is limited by the aircraft's altitude and the curvature of the Earth. At cruising altitude, VHF communication can typically reach up to 200 nautical miles.

One of the key strengths of VHF is its clear audio quality and low susceptibility to atmospheric interference, making it ideal for routine operations in controlled airspace. VHF radios are standard equipment on all commercial aircraft due to their reliability and simplicity.

In addition to voice communication, VHF is also used for data transmission, particularly through the Aircraft Communications Addressing and Reporting System (ACARS). ACARS is a digital data link system that allows aircraft to automatically send and receive messages to and from ground stations and airline operations centres. These messages can include flight plans, weather updates, maintenance reports, and other operational data. ACARS uses VHF when the aircraft is within range of ground stations, and switches to satellite or HF communication when flying over remote areas.

High Frequency (HF) Communication

HF communication operates in the 3 to 30 MHz frequency range and is used for long-distance communication, especially when aircraft are flying over oceans, polar regions, or other remote areas where VHF coverage is unavailable.

Unlike VHF, HF signals can bounce off the ionosphere, a layer of the Earth's atmosphere, allowing them to travel thousands of kilometres beyond the horizon. This makes HF ideal for transoceanic flights and communication with distant air traffic control centres.

HF radios are more complex than VHF systems and often require manual tuning and monitoring. The quality of HF communication can vary depending on atmospheric conditions, time of day, and solar activity. Despite these challenges, HF remains a critical backup and long-range communication tool in aviation.

Modern HF systems often include automatic link establishment (ALE), which helps improve connection reliability by automatically selecting the best frequency for communication. While not as clear as VHF, HF is still essential for maintaining contact in areas where no other communication infrastructure exists.

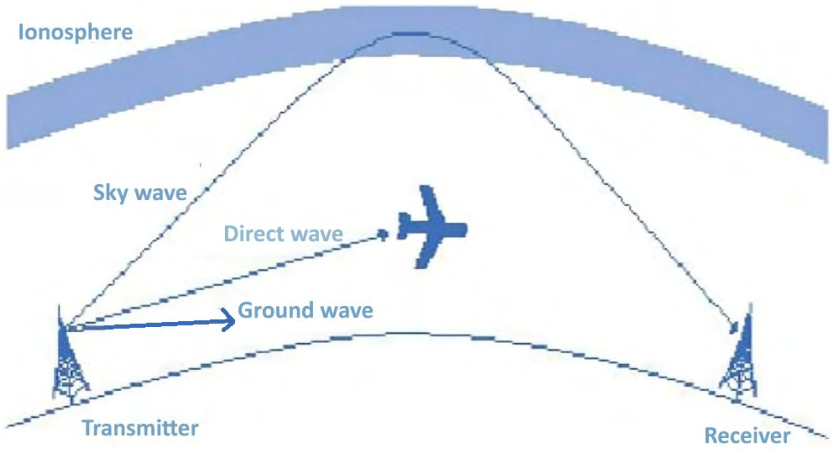


Figure 3.2: HF communication pathways

Satellite Communication (SATCOM)

SATCOM is a modern communication technology that uses satellites to provide global coverage, including over oceans, deserts, and polar regions. It operates in various frequency bands, most commonly the L-band (1–2 GHz) and Ku-band (12–18 GHz).

SATCOM allows aircraft to maintain continuous voice and data communication with ground stations and airline operations centres, regardless of location. This is especially important for long-haul international flights, where traditional VHF and HF systems may not be reliable or available.

One of the key advantages of SATCOM is its high reliability and clarity, especially for data transmission. It supports not only voice communication but also services like real-time weather updates, aircraft tracking, and passenger internet access.

SATCOM systems are more expensive and complex than VHF or HF, requiring specialised antennas and onboard equipment. However, their ability to provide seamless, high-quality communication across the globe makes them increasingly important in modern aviation.

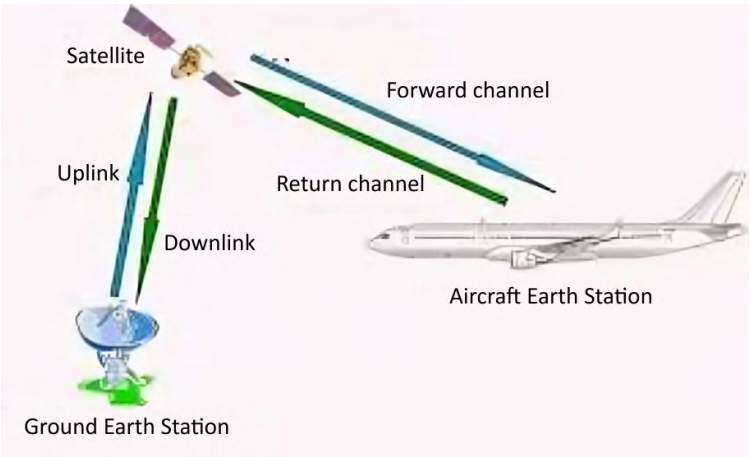


Figure 3.3: Satellite communications

Flight Deck Audio Systems

Inside an aircraft, clear communication among crew members is vital for safety and coordination. To make this possible, several systems are used to ensure that pilots, flight attendants, and other crew can talk to each other efficiently.

One of the most important tools is the intercom system, which acts like a built-in telephone network within the aircraft. It allows the pilot to speak directly with the cabin crew, whether to give instructions, share updates about the flight, or respond to any issues that arise. This system is especially useful during emergencies or when quick coordination is needed.

Supporting the intercom is the audio management system, which helps control all the sound inputs and outputs in the cockpit. Pilots wear headsets connected to this system, allowing them to adjust volume levels, switch between communication channels, and prioritise certain messages – like emergency alerts – over routine chatter. This ensures that critical information is never missed, even in noisy environments.

For communication with passengers, the aircraft is equipped with a Passenger Address (PA) system. This system lets the crew make announcements throughout the cabin, such as safety instructions before take-off, updates during the flight, or information about landing procedures. The PA system uses microphones and speakers placed throughout the aircraft to make sure everyone on board can hear clearly.

Activity 3.1 Matching Communication Technologies to Flight Scenarios

Pair up with a colleague to complete this activity.

Each flight scenario below describes a different type of aircraft operation. Think about which communication technology would be most suitable for each scenario: VHF, HF, or SATCOM. Then, write down your choice and explain briefly to your pair why that technology is appropriate for the scenario.

Scenario A: A passenger aircraft flying from Kumasi to Accra, staying within Ghanaian airspace.

Scenario B: A cargo aircraft flying from Ghana to Brazil, crossing the Atlantic Ocean.

Scenario C: A military aircraft operating in a remote desert region with no nearby ground stations.

Scenario D: A commercial jet cruising at high altitude over the Indian Ocean.

Scenario E: An aircraft taxiing and preparing for take-off at Kotoka International Airport.

AIRCRAFT NAVIGATION SYSTEMS

(Refer to Year 1, Section 3: Avionics Navigation Systems)

Navigation systems help pilots determine the aircraft's position, direction, and route during flight. These systems are essential for guiding aircraft safely from one location to another, whether flying across a city or between continents. Here, we will explore the technologies that make modern navigation possible, from ground-based aids to satellite systems.

Navigation by Dead Reckoning

Dead reckoning is one of the oldest methods of navigation, and it's still used today – especially as part of more advanced systems. It involves calculating the aircraft's current position based on a previously known position, along with estimates of speed, time, direction, and wind conditions. It does not rely on external signals or landmarks, which makes it useful in areas where other navigation aids are unavailable.

Although dead reckoning can be affected by errors in measurement or changing flight conditions, it forms the foundation of more sophisticated systems like Inertial Navigation Systems and Doppler Navigation Systems. These systems improve accuracy by using onboard sensors and instruments to continuously update the aircraft's position without needing input from ground stations or satellites.

Here's a simple example to illustrate the principle of dead reckoning.

If an aircraft leaves one point and travels on a heading 030^0 at a speed of 50 knots, after 30 minutes, it would have covered a distance of 50 * (30 / 60) or 25 nautical miles. This translates to a displacement of 25 * cos (30) or 21.65 nautical miles north and 25 * sin (30) or 12.5 nautical miles east of the starting point.

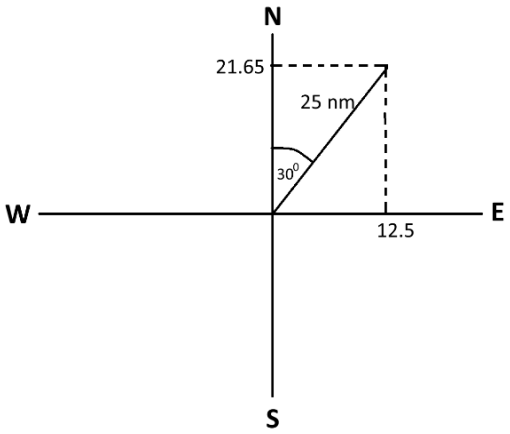


Figure 3.4: Dead reckoning calculation

Inertial Navigation Systems

An Inertial Navigation System (INS) is a self-contained navigation system that determines an aircraft's position, speed, and direction by measuring its movements. It uses accelerometers to detect changes in speed and gyroscopes to measure changes in orientation. Starting from

a known position, the system continuously calculates the aircraft's current location by tracking how far and in what direction it has moved.

There are two main types of INS used in aviation:

1. *Stable Platform Systems:* In this older design, the sensors are mounted on a platform that remains level and fixed in orientation using gimbals. This allows the system to measure movement relative to a stable reference frame. While accurate, these systems are mechanically complex and heavier.
2. *Strapdown Systems:* In this more modern design, the sensors are fixed directly to the aircraft's body (i.e., "strapped down"). The system uses fast digital processing to interpret the aircraft's movements in real time. Strapdown systems are lighter, more compact, and more reliable due to having fewer moving parts, though they require more computational power.

INS is highly valued in aviation because it does not rely on external signals, making it resistant to jamming or signal loss. However, it is prone to drift – small errors that accumulate over time. To maintain accuracy, INS is often integrated with other systems like GPS, which can correct these errors and provide long-term precision.

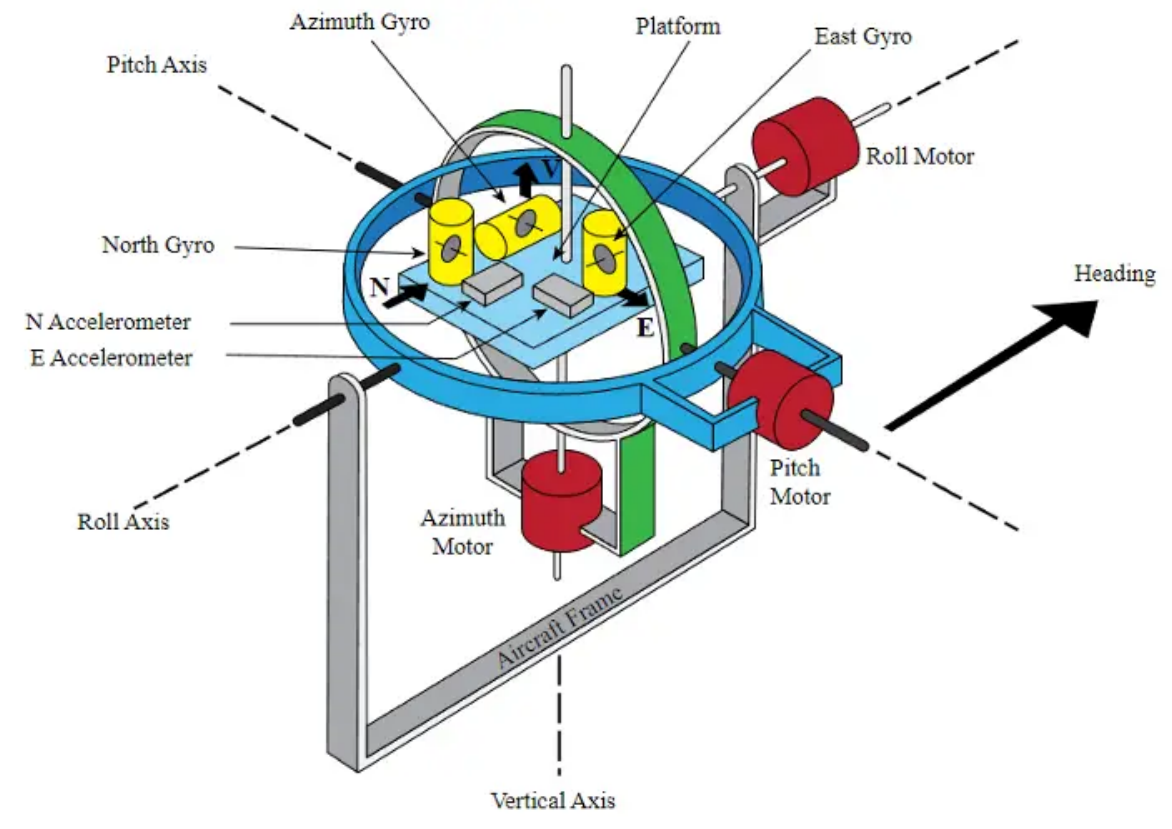


Figure 3.5: Stable platform INS

Doppler Navigation Systems

Doppler Navigation Systems use the Doppler effect – the change in frequency of a wave as the source moves relative to an observer – to estimate an aircraft's velocity and position. These systems send radio waves toward the ground and measure the frequency shift of the

waves reflected. By analysing these shifts, the system can determine the aircraft's speed and direction of movement over the Earth's surface. The Doppler frequency shift, Δf, can be calculated using the equation:

$$\triangle f = \frac{v \cdot f}{c}$$

where, v is the aircraft velocity, f is the frequency of transmission, and c is the speed of wave (electromagnetic) propagation.

Doppler systems are particularly useful in environments where GPS or ground-based navigation aids are unavailable, such as over oceans or in remote regions. Like INS, Doppler navigation is self-contained and does not depend on external signals. However, it can be affected by terrain features and changes in altitude, which may influence the accuracy of the reflected signals.



Figure 3.6: Doppler navigation system showing beams

Navigation by Position-Fixing

Position-fixing navigation systems help aircraft determine their exact location by using signals from external sources. Unlike dead reckoning, which estimates position based on movement, these systems rely on radio signals from ground stations or satellites to calculate the aircraft's position more accurately. They are essential for safe and precise navigation, especially in busy or unfamiliar airspace. We will explore four key position-fixing systems used in aviation: VOR, ADF, DME, and GNSS.

VOR (VHF Omnidirectional Range)

VOR is a widely used ground-based navigation system that operates in the VHF band (108–117.95 MHz). It transmits two signals: one is constant in all directions, and the other rotates. The aircraft's receiver compares these signals to determine the radial, or angle, from the station. This allows pilots to know their direction relative to the VOR station and follow specific flight paths known as airways.

VOR stations are strategically placed across countries and continents, forming a network that supports enroute navigation and instrument approaches. VOR is known for its accuracy and reliability, though its range is limited by line-of-sight, meaning it works best when the aircraft is at higher altitudes and within visual range of the station.

Modern aircraft often use VOR receivers integrated with cockpit displays, allowing pilots to follow courses with precision.

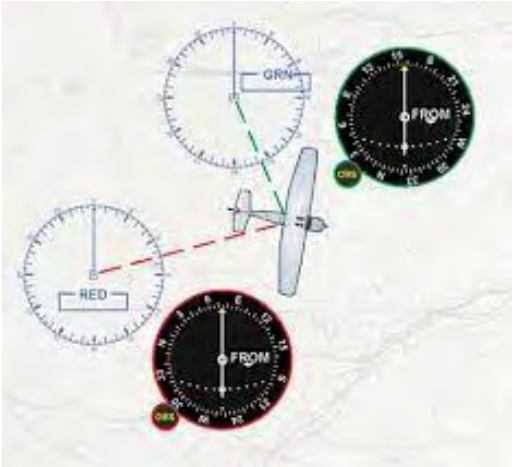


Figure 3.7: VOR navigation

ADF (Automatic Direction Finder)

ADF is a navigation system that uses signals from Non-Directional Beacons (NDBs), which operate in the low and medium frequency bands (190–535 kHz). Unlike VOR, NDBs transmit signals in all directions without encoding directional information. The aircraft's ADF receiver detects the signal and points toward the beacon, allowing the pilot to determine the bearing to or from the station.

ADF is particularly useful for approach procedures, especially in areas with limited infrastructure or where terrain makes other systems impractical. It is also used in training environments to teach basic navigation principles.

However, ADF is less accurate than VOR and more susceptible to interference from weather, terrain, and electrical sources. Its use has declined in favour of more precise systems, but it still serves as a backup and is used in some regions where newer technologies are not yet fully deployed.

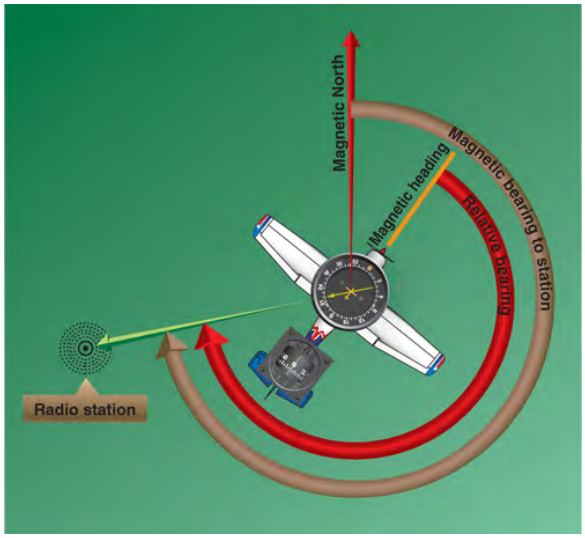


Figure 3.8: ADF navigation

DME (Distance Measuring Equipment)

DME is a system that provides the slant range distance between an aircraft and a ground station. It works by sending a signal from the aircraft to the station, which responds with a signal that allows the aircraft to calculate the distance based on the time delay between transmission and reception.

DME is often paired with VOR stations, forming a VOR/DME system that gives both direction and distance information. This combination allows pilots to fix their position more precisely and follow published routes and procedures.

DME is highly accurate and reliable, especially at cruising altitudes. It is used for enroute navigation, holding patterns, and instrument approaches. Like VOR, DME is a line-of-sight system and requires a network of ground stations.



Figure 3.9: DME system

GNSS (Global Navigation Satellite System)

GNSS refers to satellite-based navigation systems that provide global coverage and highly accurate positioning. The most widely used GNSS in aviation is GPS (Global Positioning System), though other systems like Russia's GLONASS, Europe's Galileo, and China's BeiDou are also becoming more integrated.

GNSS works by receiving signals from multiple satellites orbiting the Earth. By calculating the time it takes for each signal to reach the aircraft, the system determines the aircraft's three-dimensional position (latitude, longitude, and altitude).

GNSS is used for enroute navigation, area navigation (RNAV), and precision approaches, including Required Navigation Performance (RNP) procedures. It offers unmatched flexibility and accuracy, and it does not rely on ground infrastructure, making it ideal for remote and oceanic operations.

Despite its advantages, GNSS can be affected by signal jamming, spoofing, or interference, so it is often used alongside traditional systems like VOR and DME for redundancy and safety.

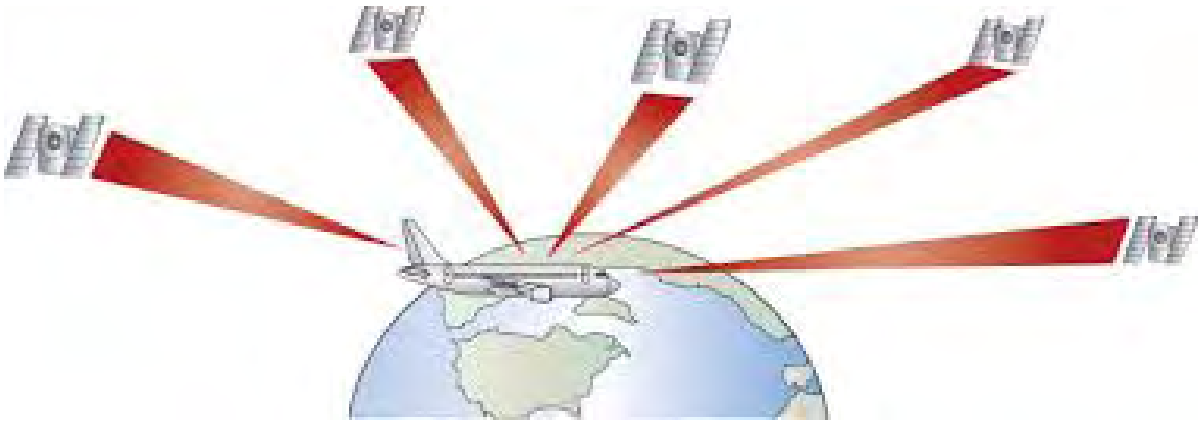


Figure 3.10: GNSS navigation

Instrument Landing System (ILS)

The Instrument Landing System (ILS) is a precision navigation aid used to guide aircraft safely during the final approach and landing, especially in poor visibility conditions such as fog, rain, or at night. It provides pilots with both lateral (side-to-side) and vertical (up-and-down) guidance to align the aircraft with the runway.

ILS works by transmitting radio signals from ground-based equipment located near the runway. It consists of two main components:

1. *Localiser:* This part of the system provides horizontal guidance, helping the pilot stay aligned with the centreline of the runway. It transmits signals from an antenna placed at the far end of the runway.
2. *Glide Slope:* This component provides vertical guidance, helping the pilot maintain the correct descent angle toward the runway. The glide slope antenna is located beside the runway, near the touchdown zone.

In addition to these, marker beacons or distance measuring equipment may be used to inform the pilot of their distance from the runway threshold.

ILS is classified into categories (CAT I, II, III) based on the level of precision and the minimum visibility required for landing. For example, CAT I allows landings with visibility as low as 550 metres, while CAT III can support landings in near-zero visibility.

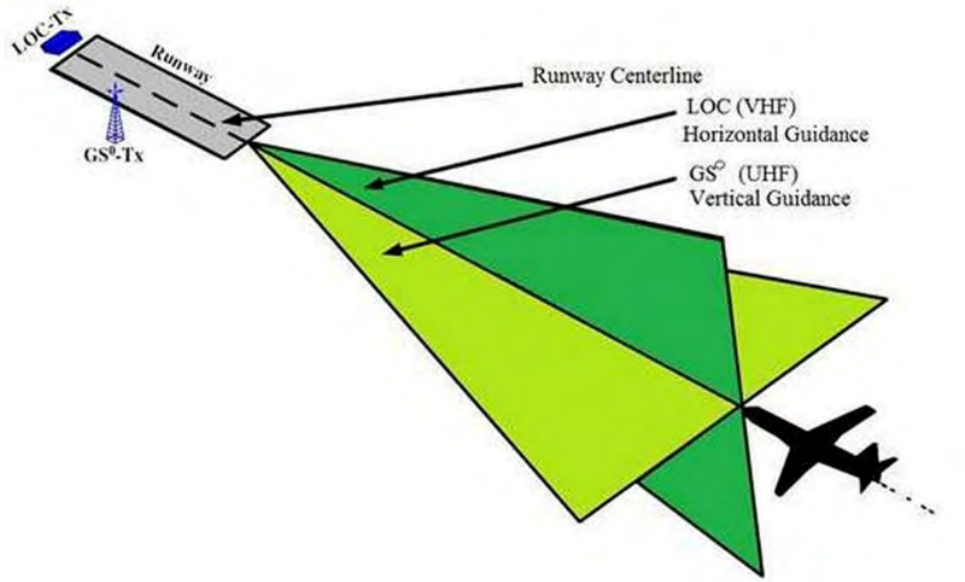


Figure 3.11: Instrument landing system

Area Navigation (RNAV)

RNAV, short for Area Navigation, is a modern navigation method that allows aircraft to fly directly between any two points in space, rather than having to follow ground-based navigation aids like VOR or NDB stations. This system uses onboard computers and sensors – often in combination with satellite navigation (GNSS) – to calculate the aircraft's position and guide it along a chosen route.

RNAV improves flight efficiency by allowing more flexible routing, which helps reduce fuel consumption, flight time, and congestion in busy airspace. It also supports precision approaches to airports, even those without traditional navigation aids.

RNAV is a key part of Performance-Based Navigation (PBN), which sets standards for accuracy and reliability in modern air traffic management. It is widely used in both commercial and military aviation and is essential for navigating in regions with limited ground infrastructure.

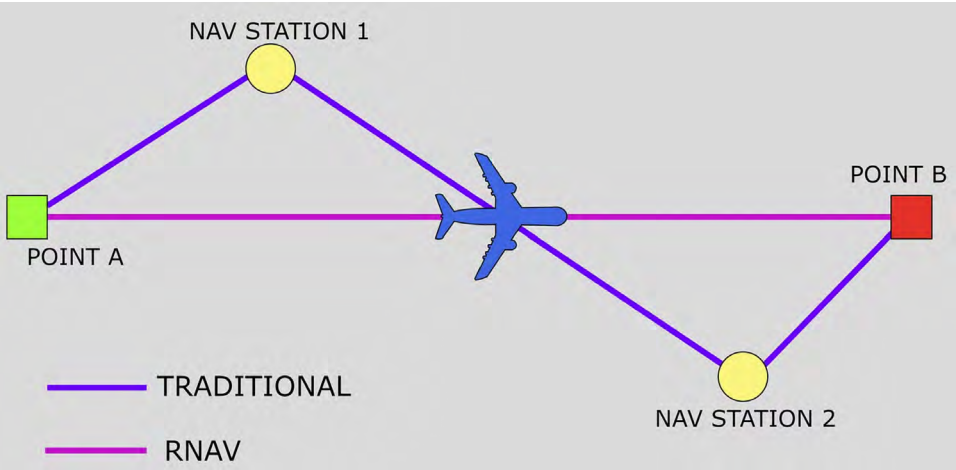


Figure 3.12: Area navigation

Activity 3.2 Choosing the Right Navigation System

Organise yourselves into groups of 4 or 5 to complete this activity.

1. Each flight scenario below describes a different type of aircraft operation with unique navigation needs.

   Scenario A: A commercial aircraft flying from Accra to Kumasi, staying within Ghanaian airspace.

   Scenario B: A cargo aircraft flying from Ghana to Brazil, crossing the Atlantic Ocean

   Scenario C: A military aircraft operating in a remote desert region with no nearby ground stations.

   Scenario D: A small aircraft approaching an airport equipped only with an NDB.

   Scenario E: A passenger jet flying over the Indian Ocean, far from any ground-based navigation aids.
2. Think about which navigation system or systems (INS, Doppler, VOR, ADF, DME, GNSS) would be most suitable for each scenario.
3. Write down your choice(s) for each scenario and explain briefly to the whole class why that system is appropriate.
4. Solve these two sample calculations:

   a. An aircraft departs Kotoka International Airport in Accra at 9:00 am, intending to fly northeast on a heading of 045°. The airspeed is 45 knots, and a steady wind is blowing from the west (eastward) at 10 knots.

      i. Using vector analysis or diagrams, estimate the aircraft's ground speed and actual flight path.

      ii. Explain how the wind affects the aircraft's actual direction of travel compared to its intended heading.

      iii. Based on your analysis, suggest how the pilot might adjust the heading to maintain the intended course. Justify your recommendation.

   b. If the one-dimensional position of an aircraft relative to a point, in metres, is given by three onboard systems as 300, 304 and 302, and the equipment have certainties of 0.7, 0.8 and 0.9, respectively, estimate the current position of the aircraft.

AIRCRAFT SURVEILLANCE SYSTEMS

(Refer to Year 1, Section 3: Introduction to the various aerospace surveillance systems)

Surveillance systems are essential for monitoring aircraft positions and movements in the airspace. These systems help air traffic controllers track aircraft, ensure safe separation, and manage traffic flow efficiently. Surveillance technologies can be ground-based or aircraft-based, and they vary in how they detect and report aircraft positions. In this sub-section, we'll explore key surveillance systems used in aviation today, including radar-based and satellite-based technologies.

1. **Primary Surveillance Radar (PSR)**

   Primary Surveillance Radar is one of the earliest and most fundamental technologies used in air traffic control. It works by sending out pulses of radio waves from a ground-based antenna. When these waves hit an object – such as an aircraft – they bounce back to the radar station. By measuring the time it takes for the signal to return and the direction it came from, the system can determine the range and bearing of the aircraft.

   PSR does not require any equipment on the aircraft, which means it can detect non-cooperative targets – aircraft that are not transmitting any signals. This makes it especially useful for detecting unidentified or malfunctioning aircraft, or those without transponders.

   However, PSR has limitations. It cannot provide information about the aircraft's altitude or identity, and its accuracy decreases with distance. It can also be affected by weather, terrain, and clutter from ground objects.

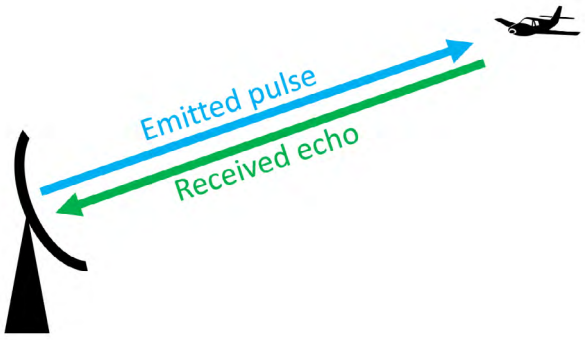


Figure 3.13: Primary surveillance radar

2. **Secondary Surveillance Radar (SSR)**

   Secondary Surveillance Radar is a more advanced system that works in cooperation with equipment on board the aircraft. When the SSR ground station sends out an interrogation signal, the aircraft's transponder responds with a coded reply. This reply can include the aircraft's identity (Mode A) and altitude (Mode C). More advanced transponders using Mode S can also exchange additional data, such as flight number and intent.

   SSR provides more detailed and accurate information than PSR and is widely used in controlled airspace. It allows air traffic controllers to identify and track aircraft more precisely, improving safety and efficiency.

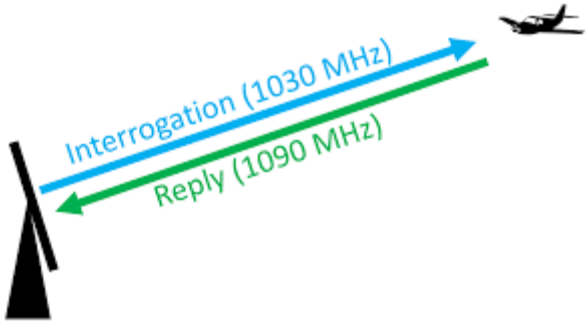


Figure 3.14: Secondary surveillance radar

However, SSR depends on the aircraft having a working transponder. If the transponder is turned off or fails, the aircraft becomes invisible to SSR. For this reason, SSR is often used alongside PSR to ensure full coverage.

3. **Combined PSR/SSR Systems**

Many radar installations use a combination of PSR and SSR to take advantage of the strengths of both systems. PSR detects all aircraft in the area, regardless of whether they are transmitting signals, while SSR provides detailed information about cooperative aircraft.

This combination is especially useful in busy terminal areas and major airports, where both identification and detection of all aircraft are critical. The PSR ensures that no aircraft goes undetected, while the SSR provides the data needed for efficient traffic management.

Combined systems improve situational awareness, reduce the risk of mid-air collisions, and support redundancy in case one system fails.



Figure 3.15: PSR/SSR antenna system

4. **TCAS (Traffic Collision Avoidance System)**

TCAS is an onboard safety system designed to prevent mid-air collisions between aircraft. It monitors the airspace around the aircraft by listening for transponder signals from nearby aircraft. If another aircraft comes too close, TCAS issues a Traffic Advisory (TA) to alert the pilot. If the situation becomes more critical, it gives a Resolution Advisory (RA), instructing the pilot to climb or descend to avoid a collision.

TCAS operates independently of air traffic control and provides real-time, automated alerts. It is especially useful in busy airspace or when aircraft are flying at similar altitudes.

However, TCAS only works if nearby aircraft are equipped with compatible transponders. It also does not consider terrain or weather, so pilots must still use their judgment and follow ATC instructions. Despite these limitations, TCAS has significantly improved flight safety and is mandatory on many commercial aircraft.

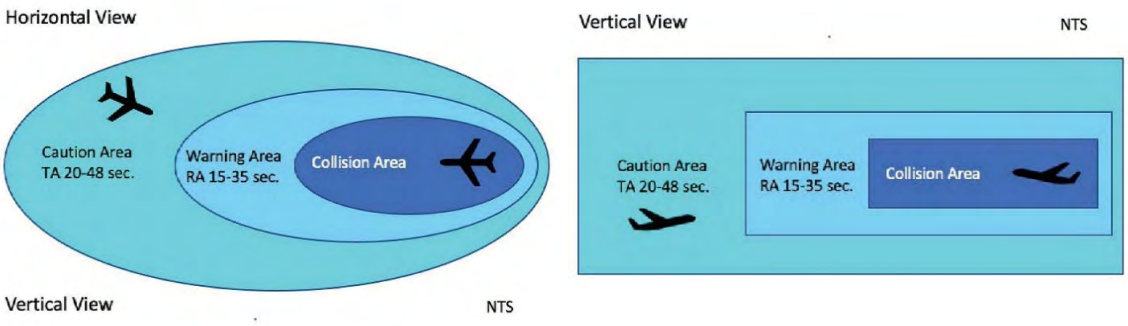


Figure 3.16: TCAS protection volume

5. **ADS-B (Automatic Dependent Surveillance–Broadcast)**

ADS-B is a modern surveillance system that uses satellite navigation and onboard transmitters to broadcast an aircraft's position, speed, altitude, and other data. This information is sent automatically and continuously to ground stations and other aircraft equipped with ADS-B receivers.

ADS-B is called "automatic" because it requires no pilot input, "dependent" because it relies on GNSS for positioning, and "broadcast" because it sends out information to anyone listening. It supports both air traffic control and air-to-air awareness, making it a powerful tool for improving safety and efficiency.

ADS-B offers high accuracy, low cost, and global coverage, especially in areas where radar is unavailable, such as over oceans or remote regions. However, it requires aircraft to be equipped with ADS-B transmitters, and like all satellite-based systems, it can be affected by jamming or interference.

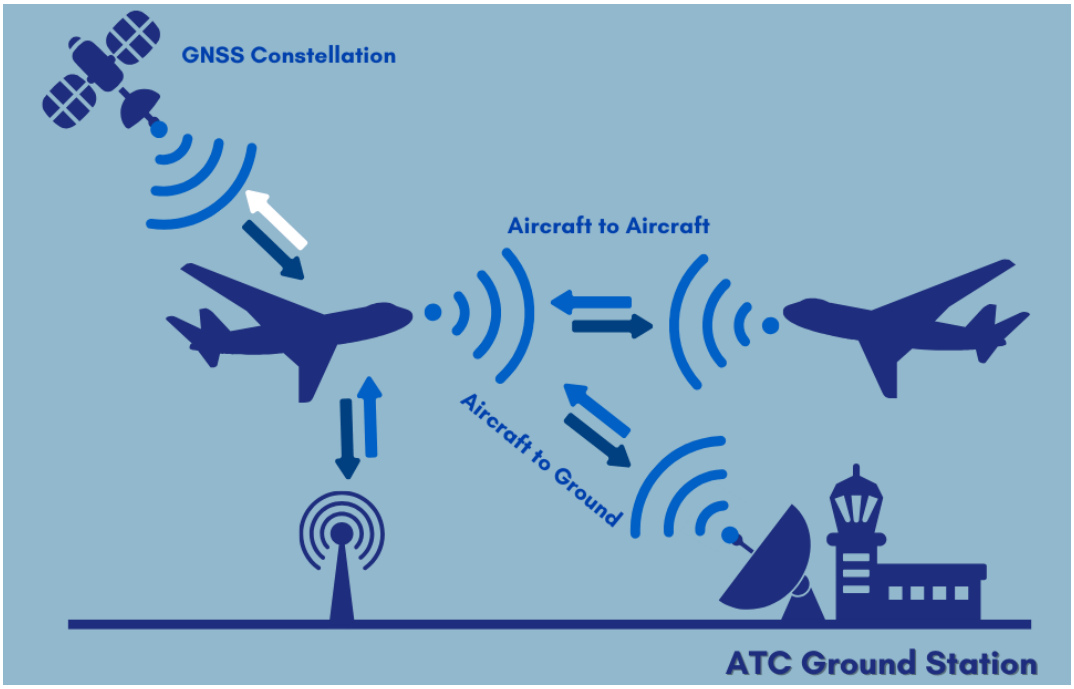


Figure 3.17: ADS-B architecture

Activity 3.3 Matching Surveillance Systems to Airspace Scenarios

Work with a colleague to complete this activity.

Each scenario below describes a different situation involving aircraft and airspace conditions.

Scenario A: An aircraft is flying near a busy international airport with full radar coverage.

Scenario B: A small aircraft without a transponder enters controlled airspace unexpectedly.

Scenario C: Two commercial jets are flying close together at cruising altitude over a remote region.

Scenario D: An aircraft is flying over the ocean, far from any ground-based radar stations.

Scenario E: A military aircraft is operating in a region where signal jamming is a concern.

1. Identify the most suitable surveillance system or systems (Primary Surveillance Radar, Secondary Surveillance Radar, Traffic Collision Avoidance System, Automatic Dependent Surveillance Broadcast) for each scenario.
2. Write down your choice(s) and explain briefly to your pair why that system is appropriate for the scenario.
3. As a pair, calculate the distance of an aeroplane from a radar tower, given a signal return time of 3 milliseconds and the speed of light equal to 3 x 108 m/s. What real-world factors, like weather or equipment issues or aircraft size/shape, could affect the accuracy of this distance measurement? Compare your calculation and error factors with a classmate, resolving any differences to reach a consensus.

EXTENDED READING

Aircraft Communication Systems
Aircraft communication systems presentation
How do commercial aircraft navigate
Aircraft Navigation Systems Explained: From VOR To GPS
Primary surveillance radar
Surveillance technologies

REVIEW QUESTIONS

1. You are tasked with selecting appropriate communication technologies for three different aircraft operations:
   - Aircraft A is flying a short domestic route within range of ground stations.
   - Aircraft B is flying across the Atlantic Ocean, far from any ground-based communication infrastructure.
   - Aircraft C is a military aircraft operating in a remote region with high risk of signal interference.

   For each aircraft,

   a. Choose the most suitable communication technology or combination of technologies from the following: VHF, HF, SATCOM, ACARS.

   b. Justify your choices by comparing the advantages and limitations of each technology in relation to the scenario.

2. You are required to plan a flight for three different aircraft:
   - Aircraft A is flying a short domestic route between two cities with full ground-based navigation coverage.
   - Aircraft B is flying across the Atlantic Ocean with no access to ground-based stations.
   - Aircraft C is a military aircraft operating in a remote desert region with limited infrastructure.

   For each aircraft,

   a. Select the most appropriate navigation system(s) from the following: VOR, ADF, DME, INS, Doppler, GNSS, RNAV, ILS.

   b. Justify your choices by comparing the merits and limitations of the selected systems in relation to the flight scenario.

3. Imagine you are designing a surveillance strategy for a new international airport located near a coastline, with both domestic and international flights, including military operations. The airport must be able to detect all aircraft types, including those without transponders, and support safe separation in both controlled and uncontrolled airspace.

   a. Propose a combination of surveillance systems that would meet these requirements.

   b. Justify your choices by comparing the capabilities, limitations, and ideal use cases of each system.

   c. Explain how these systems would work together to ensure complete coverage and safety.

SECTION

4

AIRCRAFT MAINTENANCE



AVIATION INDUSTRY

AIRCRAFT MAINTENANCE

INTRODUCTION

This section covers the Aircraft Maintenance sub strand of the Aviation Industry strand.

Aircraft maintenance plays a vital role in keeping aviation safe, reliable, and efficient. It involves a wide range of activities designed to ensure that an aircraft remains in excellent working condition throughout its service life. In this section, you'll explore the basic principles, procedures, and systems that help maintain an aircraft's airworthiness. It includes regular checks, inspections, identifying faults and carrying out repairs to help prevent problems before they occur. It also ensures that aircraft meet strict safety regulations and operate smoothly during flights.

KEY IDEAS

- Aircraft maintenance tasks may be routine, planned or unscheduled
- It is essential to use the right tool for each maintenance task
- Maintenance logs provide a legal and historical record of all work done on an aircraft
- The safety of the maintenance engineer is paramount, and they must put on personal protective equipment (PPEs) appropriate for the task

AIRCRAFT MAINTENANCE

(Refer to Year 1, Section 4, Introduction to aviation careers, their roles and learning pathways)

We first explore different types of maintenance tasks and how each supports smooth flight operations. We will then look at common tools and equipment used in aircraft servicing, with a focus on their functions and safe use. In the end, you will be able to categorise maintenance tasks and recognise essential tools used in aircraft maintenance.

Aircraft maintenance is essential for keeping planes and helicopters safe, reliable, and ready to fly. It involves checking, repairing, and servicing different parts of the aircraft to make sure everything works as it should. Maintenance helps prevent accidents, keeps flights running on time, and ensures the aircraft meets strict safety rules. Without regular maintenance, even the most advanced aircraft could become unsafe to operate.



Figure 4.1: The role of aircraft maintenance

Types of Aircraft Maintenance Tasks

Aircraft maintenance is carried out in different ways depending on the situation, the aircraft's condition, and its flight schedule.

Routine Maintenance

Routine maintenance, also known as line maintenance, includes the regular checks and servicing tasks carried out while the aircraft is in active use. These tasks are essential for ensuring the aircraft is safe and ready for flight without causing delays to its schedule. Routine maintenance is typically performed at the airport and can be broken down into several key types:

1. **Pre-flight Inspections**

   Pre-flight inspections are carried out before every flight. Technicians and flight crew check the aircraft's exterior and interior to ensure everything is in proper working order. This includes examining the fuselage, wings, landing gear, and control surfaces for visible damage, checking fluid levels, and confirming that instruments and lights are functioning correctly. These inspections are crucial for identifying any issues that could affect the safety of the flight.

2. **Post-flight Inspections**

   After landing, post-flight inspections are performed to assess the aircraft's condition following its journey. These checks help detect any wear, damage, or faults that may have occurred during the flight. Technicians look for signs of overheating, leaks, or unusual vibrations, and they may also review flight data recorded during the trip. Post-flight inspections ensure that any problems are addressed before the aircraft is used again.

3. **Service or Transit Checks**

   Service checks, also known as transit checks, are quick inspections and servicing tasks carried out between flights while the aircraft is on the ground. These checks include topping up fluids, inspecting tyres and brakes, and ensuring that emergency equipment is in place. Transit checks are designed to be fast and efficient, allowing the aircraft to stay on schedule while maintaining safety standards.

4. **Overnight Inspections**

   Overnight inspections are more detailed checks performed when the aircraft is not scheduled to fly until the next day. These inspections allow technicians to take more time examining systems, reviewing maintenance logs, and performing minor repairs or adjustments. Overnight inspections help prepare the aircraft for the next day's operations and are often used to catch issues that may not be visible during quicker checks.



Figure 4.2: Pre-flight inspection

Planned Maintenance

Planned maintenance refers to maintenance activities that are scheduled in advance to keep aircraft in safe and efficient working condition. These tasks are not triggered by faults or failures but are carried out at regular intervals or based on specific conditions. Planned maintenance can be divided into three main types:

1. **Periodic Maintenance**

   Periodic maintenance is performed at set intervals – such as every few weeks, months, or after a certain number of flight hours or landings. These intervals are determined by the aircraft manufacturer or aviation authorities. The goal is to inspect and service key systems before wear and tear becomes a problem. Examples include:

   a. checking engine performance
   b. inspecting control surfaces and landing gear
   c. testing avionics and electrical systems

2. **Preventive Maintenance**

   Preventive maintenance focuses on replacing or servicing parts before they fail. It's based on the known lifespan of components and systems. By replacing parts early, technicians reduce the risk of unexpected breakdowns and improve overall reliability. Examples include:

   a. replacing filters, seals, and fluids
   b. lubricating moving parts
   c. servicing batteries and sensors

This type of maintenance helps avoid costly repairs and keeps the aircraft operating smoothly.

3. **Predictive Maintenance**

Predictive maintenance, **also called condition-based maintenance, uses** real-time data from sensors and monitoring systems to determine when maintenance is needed. Instead of relying on fixed schedules, technicians assess the actual condition of parts and systems. Examples include:

a. monitoring engine vibration or temperature
b. analysing wear patterns in brakes or tyres
c. using software to track system performance

This approach allows for more accurate and efficient maintenance, reducing downtime and improving safety.



Figure 4.3: Planned maintenance

Unscheduled or Emergency Maintenance

Unscheduled maintenance happens when something goes wrong unexpectedly. This could be due to a system failure, damage during flight, or a warning signal from the cockpit. It's also called corrective or emergency maintenance. Examples include:

1. Fixing a hydraulic leak
2. Replacing a faulty sensor
3. Repairing damage from a bird strike



Figure 4.4: Emergency maintenance

Basic Aircraft Maintenance Tools

To keep aircraft safe and airworthy, maintenance engineers rely on a wide range of specialised tools. Each tool is designed for a specific job, from routine inspections to complex, high-precision adjustments. A thorough understanding of how to use these tools safely and effectively is essential for anyone working in aviation maintenance. The tools we will cover are commonly used during routine and preventive maintenance on both aeroplanes and helicopters.

Torque Wrench

A torque wrench is a precision tool used to apply a specific amount of rotational force, or torque, to a fastener, such as a bolt or nut. In aircraft maintenance, where over-tightening or under-tightening can lead to catastrophic failure, a torque wrench is indispensable. Fasteners on an aircraft have specific torque requirements defined in the maintenance manual, which must be followed precisely.

There are several types of torque wrenches, including click-type, beam-type, and digital. The most common in aircraft maintenance is the click-type, which "clicks" when the pre-set torque value is reached. This audible and tactile signal prevents the user from applying excessive force. The use of a torque wrench ensures that all fasteners are tightened to the correct tension, preventing them from loosening during flight due to vibration and stress.



Figure 4.5: Torque wrench

Multimeter

An aircraft's electrical systems are complex and vital for its operation. A multimeter is a versatile electronic measuring instrument that combines several measurement functions in one unit. It is essential for troubleshooting and verifying the functionality of an aircraft's electrical and electronic systems.

A typical multimeter can measure voltage (volts), current (amps), and resistance (ohms). AMEs use it to check the continuity of wires, diagnose faulty components, measure battery voltage, and ensure that circuits are receiving the correct power. The digital multimeter (DMM) is the standard in modern maintenance, providing accurate, easy-to-read measurements. Its ability to perform multiple tests makes it a cornerstone tool for any electrical task, from checking navigation lights to diagnosing issues with the avionic systems.



Figure 4.6: A digital multimeter

Safety Wire Pliers

Safety wire is a critical component in aircraft maintenance used to secure fasteners, preventing them from loosening due to vibration. Safety wire pliers, also known as twisting pliers, are specifically designed to facilitate this process. The pliers have a locking mechanism that grips the wire, and a central spindle that, when pulled, twists the two ends of the wire together.



Figure 4.7: Safety wire pliers

The correct application of safety wire is a skill that requires practice. The wire must be twisted tightly but not so much that it weakens or breaks. The purpose is to ensure that if a fastener tries to rotate and loosen, the wire will be put into tension, stopping the rotation. This simple but effective method is used on a vast number of components, particularly in the engine bay and on landing gear, where vibration is most pronounced.

Borescope

A borescope is a type of inspection camera used to visually inspect areas that are otherwise inaccessible without extensive disassembly. In aircraft maintenance, the borescope is an invaluable tool for engine inspection. By inserting the flexible probe into small openings, such as spark plug ports or inspection ports, an AME can examine the internal components of an engine, including turbine blades and combustion chambers.

This non-destructive inspection method allows for the early detection of issues like cracks, corrosion, and foreign object damage (FOD). Borescope inspections are a standard part of routine maintenance checks and are crucial for determining the health of an engine, potentially saving thousands of cedis in repair costs and preventing in-flight failures. Modern borescopes often have high-resolution cameras, LED lighting, and the ability to record images and videos for detailed analysis.



Figure 4.8: Borescope

Spanners

A spanner is a tool used to provide grip and mechanical advantage in applying torque to turn objects, usually rotary fasteners such as nuts and bolts. In aircraft maintenance, a comprehensive set of spanners is a fundamental requirement. They come in various types, including open-ended, ring, and combination spanners, each suited for different applications.

Open-ended spanners are useful for reaching fasteners in tight spaces, while ring spanners provide a better grip and are less likely to slip, reducing the risk of damaging the fastener head. Combination spanners, which have an open end and a ring end of the same size, are particularly versatile. Due to the high precision required, aerospace spanners are often made from high-strength alloys and are calibrated to specific tolerances.



Figure 4.9: A spanner

Screwdrivers

A screwdriver is a tool used for turning screws. While seemingly simple, screwdrivers in aircraft maintenance are a diverse and essential category of tools. They are used for a multitude of tasks, from removing access panels and covers to working on delicate electronic components.

Screwdrivers come in many different head types, including flathead, Phillips, Torx, and Pozidriv, each designed to fit a specific screw head. It is vital to use the correct type and size of screwdriver for each screw to prevent 'cam-out' (slipping out of the head) which can damage the screw and the component it is securing. Aircraft screwdrivers are often made with non-magnetic materials for use near compasses and other sensitive instruments, and many features ergonomic handles for comfort and precision during extended use.



Figure 4.10: Screwdriver set

Ground Support Equipment

Ground support equipment (GSE) includes all the specialised tools and machinery used to keep aircraft running smoothly on the ground. This equipment allows ground crews and technicians to safely and efficiently service, inspect, maintain, and move aircraft. GSE is essential for a wide range of tasks, including starting engines, refuelling, towing, and providing stable access for inspections and repairs.

1. **Aircraft Handling Equipment**

   Aircraft handling equipment is used on the ground to move and position aircraft safely. This includes tow tractors and tow bars, which are used to push or pull an aircraft away from the gate or into a hangar. Other examples are ground power units (GPUs), which provide electrical power to the aircraft while its engines are switched off, and air start units (ASUs), which deliver a blast of compressed air to start the engines. These tools are essential for ground crews to manage aircraft movements efficiently and safely around the airport without using the aircraft's own power.

2. **Servicing and Power Equipment**

   Servicing and power equipment are vital for keeping an aircraft operational between flights. This category includes a variety of tools that handle the aircraft's essential fluids and power needs. Fuel trucks are used to refuel the aircraft, while de-icing vehicles spray a special fluid to remove ice and snow from the wings and fuselage. Other equipment includes potable water trucks and lavatory service carts, which replenish the aircraft's water supply and empty waste tanks. Ground power units (GPUs) and air conditioning units (ACUs) also fall into this category, providing power and climate control to the cabin while the aircraft is on the ground.

3. **Maintenance Access and Safety Equipment**

Maintenance access and safety equipment are used to provide maintenance engineers with safe and stable platforms to work on all parts of the aircraft. This includes a variety of platforms, stairs, and stands that allow engineers to reach high areas like the tail fin or the engines. Wheel chocks are essential safety tools, placed against the aircraft's wheels to prevent it from moving while parked. Landing gear pins and safety locks are also used to secure components during maintenance. These tools are crucial for preventing accidents and ensuring that all maintenance tasks can be performed effectively and without risk to the personnel or the aircraft.



Figure 4.11: Ground support equipment

Personal Protective Equipment

Personal Protective Equipment (PPEs) is essential for aircraft maintenance engineers. It protects them from the numerous hazards present in their work environment. The aviation maintenance industry involves exposure to a wide range of risks, including loud noises, chemicals, heavy machinery, and working at heights. Proper use of PPEs is not just a recommendation; it is a mandatory safety protocol designed to prevent injuries and ensure the well-being of all personnel.

1. **Head Protection**

Working in and around aircraft exposes engineers to the risk of head injuries from falling objects or bumping into components. Hard hats or safety helmets are worn in designated areas, such as during engine installation or when working beneath a raised aircraft, to protect against impacts.

2. **Eye and Face Protection**

Eyes are particularly vulnerable to hazards like flying debris, chemical splashes from hydraulic fluid or fuel, and bright light from welding. Safety glasses or goggles with side shields are the most common form of eye protection. For more intensive tasks like grinding or welding, a full-face shield or welding helmet is used to protect the entire face.

3. **Hearing Protection**

Aircraft engines, power tools, and ground support equipment generate high levels of noise that can cause permanent hearing damage. Maintenance engineers must use hearing protection whenever they are in noisy environments. This can include earplugs, which are inserted into the ear canal, or earmuffs, which cover the entire ear. In some cases, both are used for maximum protection.

4. **Hand Protection**

   The hands are constantly in contact with tools, machinery, and various substances. Protective gloves are essential for preventing cuts, abrasions, burns, and chemical exposure.

5. **Foot Protection**

   The hangar and workshop floors present several hazards, including heavy objects, sharp debris, and slippery surfaces. Safety boots or shoes with reinforced steel or composite toes protect against crushing injuries. They also often have slip-resistant soles to prevent falls and puncture-resistant soles to protect against sharp objects.

6. **Respiratory Protection**

   Maintenance engineers can be exposed to airborne contaminants such as paint fumes, dust, and vapours from cleaning solvents. Respirators are used to filter these particles and gases from the air before they are inhaled. The type of respirator used depends on the specific hazard, ranging from simple dust masks for non-toxic particles to full-face respirators with specialised filters for chemical vapours.

7. **High-Visibility Clothing**

   When working on the airfield or around moving ground support equipment, it is crucial for personnel to be easily seen. High-visibility vests or jackets, often in fluorescent yellow or orange with reflective strips, ensure that they are visible to vehicle operators and pilots, especially in low-light conditions.



Figure 4.12: Personal protective equipment

Table 4.1 is a summary of PPEs used by aircraft maintenance engineers. It is crucial to inspect all PPEs for damage before each use and replace any items that are worn or broken. PPE must also fit properly to be effective.

Table 4.1: Personal protective equipment

PPE Category	Purpose	Typical Equipment
Head Protection	Protects against impact from falling objects or bumping head	Hard hats, safety helmets
Eye & Face Protection	Guards against flying debris, chemical splashes, and intense light	Safety glasses, goggles, face shields
Hearing Protection	Prevents hearing damage from loud noises	Earplugs, earmuffs
Hand Protection	Protects from cuts, abrasions, burns, and chemical exposure	General-purpose gloves, chemical-resistant gloves, heat-resistant gloves
Foot Protection	Shields feet from heavy objects, sharp debris, and slips	Steel-toe boots, slip-resistant shoes
Respiratory Protection	Prevents inhalation of airborne contaminants	Dust masks, respirators with filters
Body Protection	Ensures visibility and protects against the elements	High-visibility vests/jackets, overalls

Activity 4.1 The Maintenance Blunder

Organise yourselves into small groups of 3 or 4.

Carefully read the story below, which describes a maintenance task.

Kwame, a new engineer, is tasked with inspecting the landing gear of a small aircraft. He walks onto the tarmac without his safety vest. He grabs a torque wrench to check a bolt but uses a spanner instead because the torque wrench's handle is a little greasy. He notices a loose wire and, without checking the maintenance manual, uses a bit of tape to secure it. He uses his bare hands to clean a hydraulic fluid spill and then, because he's in a rush, climbs up a nearby ladder that isn't properly secured to get a better look at a component. He completes the inspection and reports that everything is fine.

1. Identify all the mistakes Kwame made. Think about:
    a. What PPE did he fail to use?
    b. What tools did he use incorrectly or fail to use?
    c. What safety procedures did he ignore?
2. For each mistake you identify, explain what the potential consequences could be.

3. Rewrite the story, describing how Kwame *should* have performed the maintenance task safely and correctly. Make sure to include the proper use of tools and PPE, and a focus on safety.
4. Share your group's findings and rewritten scenario with the rest of the class.

AIRCRAFT MAINTENANCE STANDARDS

Building on our foundational knowledge of maintenance types, tools, and safety practices, we now dive into the practical side of aircraft maintenance. We'll learn how to perform simple maintenance tasks according to industry standards and how to properly document all the work we do. We'll also explore the role of Maintenance, Repair, and Overhaul (MRO) organisations and the critical importance of following approved procedures and regulatory guidelines.

Aircraft maintenance is a highly disciplined field governed by strict rules and standards, which are the backbone of aviation safety. It's important to know what these standards are, why they are so important, and which organisations are responsible for them.

Aircraft maintenance standards are critical for several reasons:

1. *Safety:* The primary goal is to prevent accidents and incidents. These standards dictate precise procedures for inspections, repairs, and part replacements to catch potential problems before they become a danger in the air.
2. *Uniformity:* Standards ensure that maintenance work is performed in the same way, everywhere in the world. This means an aircraft maintained in one country can be trusted to fly safely in another.
3. *Reliability:* By following a strict maintenance schedule, aircraft are kept in excellent condition, which reduces the chance of unexpected malfunctions or delays.
4. *Economic Sense:* While maintenance can be costly, adhering to standards helps save money in the long run by preventing major failures and extending the life of the aircraft.

Aircraft maintenance standards are set by international and national authorities. They work together to ensure a consistent approach to aviation safety globally.

1. The *International Civil Aviation Organisation (ICAO)* sets the global standards and recommended practices for aviation safety. Almost every country, including Ghana, is a member of ICAO and agrees to follow its guidelines. ICAO's standards cover everything from pilot licensing to aircraft design and, most importantly, aircraft airworthiness and maintenance.
2. *Ghana Civil Aviation Authority (GCAA)* is responsible for enforcing the standards set by ICAO within Ghana. It creates and implements specific regulations, licenses, and monitors maintenance organisations and certified engineers. The GCAA ensures that all aircraft operating in Ghana meet both international and national safety requirements, making it the primary guardian of aviation safety in our country.

3. *Federal Aviation Administration (FAA)* and *European Union Aviation Safety Agency (EASA)* are the major aviation authorities for the USA and Europe, respectively. Although their rules are primarily for their own regions, their influence is global. Because many of the world's aircraft are manufactured in the USA (e.g., Boeing) or Europe (e.g., Airbus), their standards for design and maintenance are followed by airlines and maintenance crews all over the world. The GCAA often works with bodies like the FAA and EASA to ensure that standards are consistent for aircraft coming from these regions.
4. *Aircraft Manufacturers*, including companies like Boeing, Airbus, and Embraer also play a key role. When they design an aircraft, they develop a detailed set of maintenance instructions and schedules. These are published in a maintenance manual. This manual tells engineers exactly how often and in what way to inspect and repair every part of the aircraft. Regulatory authorities like the GCAA approve these manuals, making them a mandatory set of standards that must be followed to keep the aircraft safe.

Maintenance Procedures and Documentation

In aircraft maintenance, strict processes must be followed and each step meticulously recorded. This process involves two key components: maintenance procedures and documentation.

Maintenance Procedures

Maintenance procedures are the step-by-step instructions for performing any task on an aircraft, from a simple inspection to a complex engine overhaul. These procedures are detailed in the aircraft's maintenance manual, which is created by the manufacturer and approved by regulatory bodies like the GCAA.

Following these procedures is mandatory. They specify the exact tools to use, the torque values for every bolt, and the safety precautions to take. This ensures that every task is performed correctly, consistently, and safely, regardless of who is doing the work. Deviating from these approved procedures is a serious offence that can compromise the safety and airworthiness of the aircraft.

Documentation

Documentation is the official record of all maintenance activities. Every task performed on an aircraft, no matter how small, must be recorded in the aircraft's logbook and other official forms. This documentation includes:

1. Who performed the task (the certified engineer's name and licence number).
2. What was done (a clear description of the work).
3. When it was done (the date and time).
4. Why it was done (e.g., routine inspection, repair of a fault).
5. Which maintenance manual reference was followed.

This documentation serves as a complete history of the aircraft and is vital for traceability, allowing future engineers to see exactly what has been done to the aircraft. Regulatory authorities, also use these records during audits to ensure all maintenance standards have been met.

Maintenance, Repair, and Overhaul (MRO) Organisations

Airlines often focus on their primary business of flying passengers and cargo. The complex and highly specialised work of heavy maintenance, repairs, and overhauls is often outsourced to dedicated organisations known as Maintenance, Repair, and Overhaul (MRO) organisations, also referred to as Aircraft Maintenance Organisations (AMOs).

MROs are essentially large, certified workshops for aircraft. They are approved by the regulatory agencies and have the expertise, equipment, and facilities to perform major maintenance tasks that airlines might not have the resources to handle themselves. Their services can range from routine inspections and scheduled maintenance checks to complex engine overhauls, major structural repairs, and even aircraft modifications.

Performing basic maintenance tasks

We now focus on how to perform a basic maintenance job, like checking tyre pressure, inspecting fluid levels, or doing a pre-flight visual inspection. We will emphasise the correct procedures, the use of checklists, and the importance of referring to maintenance manuals or Standard Operating Procedures (SOPs).

Preparing for the task

Here are some key steps involved in preparing for a basic maintenance task:

1. Identify and wear the required Personal Protective Equipment

   Safety always comes first. It is necessary to identify and put on the correct Personal Protective Equipment (PPE) for the specific task. A risk assessment should guide this choice, but common PPE includes safety boots, gloves to protect hands from chemicals or abrasions, and safety glasses to shield the eyes from debris. For tasks in noisy environments, ear protection is also mandatory.

2. Gather the appropriate tools for the task

   Using the correct tool for the job is non-negotiable in aircraft maintenance. Before starting, consult the maintenance manual or task card to identify all the tools required. This is not just about having the right spanner; it's about having the right size and type, such as a torque wrench set to a specific value. Having all the tools ready prevents delays and ensures the task can be completed without improvised shortcuts that could lead to errors.

3. Review of the applicable procedure

   Never assume you know the procedure. Even for a simple task like checking tyre pressure, the aircraft's maintenance manual contains the official, step-by-step procedure. An engineer must review this procedure to understand the sequence of steps, the required torque settings, and any specific safety warnings. This practice ensures that the work is done in accordance with the manufacturers and regulatory standards, guaranteeing the aircraft's airworthiness.

4. Ensure the aircraft is secured and safe to approach

   Before approaching the aircraft, it's vital to ensure it is in a safe condition for maintenance. This involves several critical steps:

a. Chock the wheels: Place chocks on both sides of the wheels to prevent the aircraft from moving.
b. Confirm the master switches are off: All electrical power should be off to prevent accidental activation of systems.
c. Install safety locks and pins: If working on landing gear or control surfaces, ensure all safety pins and locks are installed to prevent unexpected movement.
d. Check for hot surfaces: Be aware of any hot areas, especially around engines that have just been shut down.

Components of a Basic Maintenance Log Entry

Accurate and complete documentation is a fundamental pillar of aircraft maintenance. Every time a maintenance task is performed, a detailed record is created in the aircraft's logbook. This log entry serves as a legal and historical record of the aircraft's condition and maintenance history. Here are the essential components of a basic maintenance log entry:

1. *Date and Time:* The exact date and time the maintenance task was started and completed. This is crucial for tracking compliance with scheduled maintenance intervals.
2. *Aircraft Identification:* The registration number (e.g., 9G-ABC) and the aircraft's serial number. This ensures that the maintenance entry is correctly linked to the specific aircraft.
3. *Task Description:* A clear, concise description of the maintenance task performed. This should be a factual account of the work, such as "Replaced main landing gear tyre" or "Carried out a pre-flight visual inspection."
4. *Maintenance Manual Reference:* The specific chapter, section, and page of the approved maintenance manual that was followed. This proves that the work was done in accordance with the manufacturers and regulatory standards.
5. *Certified Personnel Information:* The name and signature of the certified Aircraft Maintenance Engineer (AME) who performed the work. This is a legal certification that the work was completed correctly and the aircraft is airworthy.

When making a maintenance log entry, it is essential to be clear and accurate. Use precise language, avoid slang or vague descriptions, and only use approved abbreviations. Always double-check entries for errors before submitting them and remember to note the reasons for any maintenance tasks that were not completed.

Activity 4.2 Maintenance Role-Play

Find a partner to work with.

Here is a sample checklist for a main landing gear tyre inspection:

Step 1: Preparation & Safety

[ ] Confirmed aircraft wheels are chocked.

[ ] Ensured brakes and wheels are cool to the touch.

[ ] Put on required PPE (safety gloves and safety glasses).

Step 2: Tyre Pressure Check

[ ] Located the tyre valve stem.

[ ] Removed the valve cap.

[ ] Used a calibrated tyre pressure gauge to check the pressure.

[ ] Confirmed the pressure reading is within the specified limits (e.g., 205-215 psi).

[ ] Replaced the valve cap securely.

Step 3: Visual Inspection - Tread

[ ] Inspected the entire circumference of the tyre tread for uneven wear.

[ ] Checked for any signs of cuts, punctures, or embedded foreign objects (e.g., stones, metal).

[ ] Looked for any flat spots, which could indicate heavy braking.

[ ] Confirmed that the tread wear has not reached the base of any groove.

Step 4: Visual Inspection - Sidewall

[ ] Inspected the inner and outer sidewalls for any bulges, cracks, or cuts.

[ ] Checked for signs of weather-checking or deterioration of the rubber.

[ ] Looked for any signs of slipping on the wheel rim.

Step 5: Visual Inspection - Wheel Rim and Brakes

[ ] Visually checked the wheel rim for any cracks, dents, or signs of overheating.

[ ] Inspected the brake unit for any signs of fluid leaks.

Step 6: Completion

[ ] All checks completed and no defects found.

[ ] If a defect was found, it was noted and reported for further action.

[ ] Logbook entry prepared and signed off.

1. Take turns acting as the lead technician and the assistant: one person reads each step of the checklist out loud while the other person demonstrates how that step would be performed.
2. Switch roles once you have completed the entire checklist.
3. Join with another pair to form a group of four. Discuss the regulations that govern aircraft maintenance, including personnel certification.
4. Your group will be given a case study of an aviation incident due to improper maintenance practices for discussion.

EXTENDED READING

Aircraft maintenance

Aircraft Maintenance 101

REVIEW QUESTIONS

1. An aircraft suffers a minor hydraulic system malfunction during a flight. The pilot manages to land safely, and an initial visual inspection by a ground crew member notes a small leak near the landing gear. As a senior aircraft maintenance engineer assigned to lead the maintenance team, synthesise your knowledge of maintenance procedures, documentation, and the roles of MROs to outline the complete process you would follow.
2. Develop a training plan for a new, inexperienced maintenance apprentice starting their first day. The plan must integrate the correct use of a specific tool (e.g., a torque wrench) with the appropriate safety protocols and documentation practices. Explain how this integrated approach not only ensures the apprentice's safety but also contributes to the overall airworthiness of the aircraft and compliance with GCAA regulations.

SECTION

5

UAV DESIGN



UNMANNED AERIAL VEHICLES (UAVS)

DESIGN AND FABRICATION OF UAVS

INTRODUCTION

This section deals with the first two learning outcomes of the Design and Fabrication of UAVs sub strand of the Unmanned Aerial Vehicles (UAVs) strand.

In this section we will explore the principles of aircraft conceptual design. This process begins with clearly defining the problem that the new aircraft needs to solve. From there, we'll establish a list of specific requirements and develop several potential design concepts. After carefully assessing these options, we'll select the "best" concept and perform the necessary calculations to determine the aircraft's size and specifications. This information is crucial for the next step, where we'll build the aircraft model.

KEY IDEAS

- It is possible to determine the physical characteristics of a UAV through the use of empirical data and mathematical equations
- Several design concepts may provide a solution to a problem. The "best" one must be selected using a structured approach
- The first step in any UAV design endeavour is a proper definition of the problem to be solved
- Writing clear, complete and verifiable requirements properly defines the scope of the design problem

DEVELOPMENT OF UAV CONCEPTS

We will focus on the process of designing a UAV. We'll start by defining the specific problem our design needs to solve and then create a list of requirements it must meet. Next, we'll explore different design concepts that satisfy those requirements and learn how to select the best one.

Defining the UAV Design Problem

Before we can design anything, we first need to clearly define the problem we are trying to solve. A well-defined problem is the foundation of a successful design, ensuring the final aircraft does exactly what is needed.

This process involves some key considerations:

Mission Requirements

The first step is to understand the UAV's purpose or mission. What is the aircraft's job? Is it a delivery drone, a surveillance vehicle, or a search and rescue drone? The mission requirements dictate everything else in the design. For example, a surveillance UAV will need to carry cameras and stay airborne for a long time, while a delivery drone must be able to carry a specific weight and navigate complex urban environments.

Operational Environment

Next, we must consider the operational environment – where and how the UAV will be used. This includes factors like:

1. *Climate:* Will it operate in hot deserts, cold arctic regions, or in tropical rain?
2. *Terrain:* Will it fly over mountains, open water, or a city with tall buildings?
3. *Airspace:* Will it operate in controlled airspace, requiring specific communication and navigation systems, or in open, unrestricted areas?

Understanding the environment helps determine the materials, power source, and control systems needed to ensure the UAV can operate safely and reliably.

Performance Objectives

Once the mission and environment are clear, we can set the performance objectives. These are measurable goals that the UAV must achieve. They often include:

1. *Payload Capacity:* How much weight can the UAV carry? This is crucial for cameras, sensors, or packages.
2. *Range:* How far can it fly from its base or operator?
3. *Endurance:* How long can it stay in the air on a single charge or tank of fuel?
4. *Speed:* How fast does it need to fly to complete its mission in time?
5. *Manoeuvrability:* How quickly can it change direction or altitude?

Constraints

Finally, every design project has constraints – limitations that must be respected. These might include:

1. *Budget:* How much money is available for design, materials, and manufacturing?
2. *Time:* How quickly does the UAV need to be ready?
3. *Size and Weight:* Are there physical limitations on its dimensions or total weight? This is particularly important for drones that must fit into a small launch vehicle or be carried by a single person.
4. *Regulations:* Are there legal limitations set by aviation authorities (like the GCAA in Ghana) that the design must comply with?

An example problem statement:

Design a small, lightweight UAV system to be used for monitoring crop health over a 5-acre farm. The UAV must be able to capture high-resolution imagery of the crops, operate for at least 15 minutes on a single battery charge, and withstand typical weather conditions in a farming community. The UAV system must be affordable, easy to operate, and comply with all relevant aviation regulations.

Note

We will use this problem throughout this section.

Developing requirements

Once the UAV design problem has been clearly defined, the next critical step is to translate that problem into a list of specific, detailed requirements. Requirements are precise statements that describe what the UAV must be able to do, how well it must perform, and what limitations it must meet. They act as a blueprint for the design process and a checklist for success, ensuring that the final product directly addresses the original problem. Good requirements have several important characteristics that make them effective.

1. **Clarity**

   Requirements must be clear and unambiguous. Each statement should have a single, precise meaning that cannot be misunderstood. Vague terms like "long flight time" or "easy to use," do not provide precise information. Instead, a clear requirement would be "The UAV shall have an endurance of at least 60 minutes" or "The UAV's control system shall be operable by a single person with less than one hour of training." Clear requirements prevent misunderstandings and provide a solid benchmark for the design.

2. **Completeness**

   The set of requirements must be complete, covering all aspects of the design problem. This means addressing every part of the mission, operational environment, performance objectives, and constraints. A complete set of requirements would not just list the payload capacity but also specify the required flight speed, the materials to be used, and the budget. Leaving out a key requirement could lead to a design that works but fails in a critical area.

3. **Verifiability**

   A requirement must be verifiable, meaning it can be proven to be met through testing, inspection, or analysis. If a requirement cannot be verified, it is impossible to know if the design is successful. For example, the requirement "The UAV shall have a maximum speed of 50 km/h" is verifiable with a speedometer during a flight test. However, a requirement like "The UAV shall be reliable" is not verifiable on its own and would need to be broken down into measurable sub-requirements, such as "The UAV shall have a Mean Time Between Failures (MTBF) of 100 flight hours."

4. **Consistency**

   Requirements must be consistent with each other. They should not contradict one another. For example, a requirement for "a heavy payload of 20 kg" combined with "an endurance of 5 hours on a small battery" would be inconsistent and physically impossible to achieve with current technology. Inconsistencies like this must be identified and resolved early in the design process, usually by adjusting the requirements or rethinking the design approach.

5. **Feasibility**

   Finally, all requirements must be feasible – they must be realistic and achievable within the given constraints of budget, time, and technology. It is easy to create a list of amazing features, but if the technology doesn't exist or the budget is too small to build it, the requirements will not be very useful.

A sample set of requirements from the problem we defined earlier are:

1. The UAV shall capture imagery with a minimum resolution of 12 megapixels.
2. The UAV shall have a minimum flight endurance of 15 minutes on a single battery charge.
3. The UAV shall be capable of operating in wind speeds up to 15 km/h and light rain conditions.
4. The UAV shall be capable of monitoring a 5-acre farm in a single flight.
5. The UAV system shall be operable by a single user with minimal training.
6. The UAV shall comply with all applicable aviation regulations for small, unmanned aircraft systems as specified by the GCAA.
7. The total cost of the UAV system (including the UAV, ground control station, and necessary accessories) shall not exceed GHS 20,000.
8. The UAV shall have a maximum take-off weight of 5 kg to ensure portability and ease of handling.

Developing Evaluation Criteria

After defining the design problem and translating it into a set of clear requirements, the next step in the design process is to develop a robust method for evaluating different design options. This is done by creating evaluation criteria. These criteria are a set of rules and metrics that allow a design team to objectively compare and select the best possible concept. Without a clear and fair way to evaluate concepts, the selection process can become subjective and lead to a poor final design. A well-structured evaluation system ensures that the chosen design is the one that best meets all the project's needs and requirements.

1. **Identify Key Performance Parameters (KPPs)**

   The first step is to identify the most critical aspects of the design that will determine its success. These are known as Key Performance Parameters (KPPs). KPPs are directly derived from the design requirements. They are the non-negotiable factors that the

design must excel at. For our problem, these parameters might include flight endurance, payload capacity, range, speed, stability, image resolution, and data transmission rate.

2. **Define Metrics and Measurement Methods**

   For each KPP, a clear metric and a method for measuring it must be defined. A metric is a specific, quantifiable way to measure performance. For example, the KPP of "endurance" could be measured with the metric "flight time in minutes." The measurement method might be "simulation data from a flight model" or "data from a prototype test flight." This ensures that every design is judged using the same standards.

3. **Establish Target Values and Thresholds**

   Next, you must set specific performance benchmarks for each metric. A target value is the ideal performance goal (e.g., "target endurance of 60 minutes"). A threshold value is the minimum acceptable performance (e.g., "minimum endurance of 45 minutes"). Any design that does not meet the threshold is automatically eliminated. This helps narrow down the choices and focus on realistic concepts.

4. **Assign Weights to the Criteria**

   Not all criteria are equally important. To reflect this, each criterion is assigned a weight (usually a percentage). For example, for a delivery drone, payload capacity might be more important than top speed, so it would receive a higher weight. This ensures that the final decision prioritises the most critical aspects of the mission.

5. **Develop a Scoring System**

   A scoring system is then created to assign a numerical score to each design based on its performance against the weighted criteria. For each metric, a score is given (e.g., from 1 to 5), which is then multiplied by its weight. The total score for a design is the sum of all its weighted scores. The concept with the highest total score is considered the "best."

6. **Consider Qualitative Factors**

   Finally, while the numerical scoring system is vital for objectivity, it's also important to consider qualitative factors. These are aspects that are difficult to measure numerically but are still important, such as the aesthetics of the design, the ease of maintenance, or the potential for future upgrades. These factors can be discussed and used as tiebreakers if two concepts have very similar scores.

Table 5.1 provides a structured framework for evaluating different UAV designs based on our design problem. It uses key criteria to help us make a more objective and informed decision.

Table 5.1: Evaluation criteria

Criterion	Description	Weight	Metric	Target Value	Threshold Value	Scoring
Image Quality	Ability to capture clear and detailed images of crops for health assessment.	0.2	Image Resolution	12 Megapixels	8 Megapixels	1: <8 MP, Unusable. 2: 8-9 MP, Poor. 3: 10-11 MP, Acceptable. 4: 12-13 MP, Good. 5: >13 MP, Excellent
Flight Endurance	Duration of flight on a single battery charge.	0.2	Flight Time	15 minutes	12 minutes	1: <12 min, Unacceptable. 2: 12-13 min, Poor. 3: 14 min, Acceptable. 4: 15-16 min, Good. 5: >16 min, Excellent
Ease of Use	How easy the system is to operate, deploy, and maintain.	0.3	Training Time, Deployment Time	Training: <4 hours, Deployment: <10 min	Training: <8 hours, Deployment: <15 min	1: Complex, requires extensive training. 2: Difficult, long setup. 3: Moderate, some training. 4: Easy to use, quick setup. 5: Very intuitive, minimal setup

Cost	Total cost of the system.	0.3	Total System Cost	GHS 20,000	GHS 25,000	1: >GHS 30,000, Unaffordable. 2: GHS 25,000-30,000, Expensive. 3: GHS 20,000-25,000, Moderate. 4: GHS 15,000-20,000, Good. 5: <GHS 15,000, Excellent

Developing and Evaluating Design Concepts

Once we have a clear design problem and a set of evaluation criteria, the next step is to get creative and develop several different design ideas, or "candidate concepts." It's important not to settle on the first idea that comes to mind. Instead, think of a variety of approaches to solve the problem.

This stage is all about brainstorming and exploring different possibilities. For a UAV, this might mean considering various airframe configurations. For example, a mission might be accomplished by a fixed-wing aircraft that looks like a small aeroplane, a multi-rotor drone with four or more propellers (like a quadcopter), or a hybrid design that can take off vertically and fly horizontally. Each concept will have different strengths and weaknesses – one might have great endurance, while another might be better at carrying a heavy load. You should sketch out these ideas, noting their key features and how they might address the mission requirements.

After developing several distinct concepts, we proceed to evaluate them using the criteria we established earlier. This is where the scoring system comes into play. For each concept, we assess its performance against every criterion and assign it a score. Then, we multiply each score by the criterion's weight. The final step is to total the scores for each concept and determine the "best" design as the one with the highest score. This is the one that best meets all the requirements and is the most promising candidate to move forward with.

Table 5.2 presents candidate concepts for our design problem.

Table 5.2: Design concepts

Feature/Criteria	**Concepts**		
	Quadcopter with Gimbal-Stabilised Camera	**Fixed-Wing UAV with Automated Flight Path**	**Hybrid VTOL UAV**
Image Quality	Resolution: 12 MP - 20 MP	Resolution: 12 MP - 20 MP	Resolution: 12 MP - 20 MP
Flight Endurance	Typically, about 20 minutes	Typically, about 50 minutes	Typically, about 35 minutes
Ease of Use	Training: 2 hours, Setup: 5 minutes	Training: 8 hours, Setup: 15 minutes	Training: 10 hours, Setup: 20 minutes
Cost	GHS 17,000	GHS 22,000	GHS 29,000

Based on this information, we can score each concept, with reference to Table 5.1, to select one as the desired candidate for further development. This is shown in Table 5.3.

Table 5.3: Decision matrix

Feature/ Criteria	**Weight**	**Concept 1** - Quadcopter with Gimbal-Stabilised Camera		**Concept 2** - Fixed-Wing UAV with Automated Flight Path		**Concept 3** - Hybrid VTOL UAV	
		Score	Weighted score	Score	Weighted score	Score	Weighted score
Image Quality	0.2	5	1	5	1	5	1
Flight Endurance	0.2	5	1	5	1	5	1
Ease of Use	0.3	5	1.5	3	0.9	2	0.6
Cost	0.3	4	1.2	3	0.9	2	0.6
Total			4.7		3.8		3.2

With reference to Table 5.3, we select the first concept: *Quadcopter with gimbal-stabilised camera*, for further development because it has the highest weighted score.

Activity 5.1 The Community Helper UAV

As a team of young aerospace engineers, identify a problem in the community that UAVs can help to solve. E.g. A UAV to inspect the condition of rooftops to check for damage after a storm.

1. For the problem you chose, create a list of clear and measurable requirements.
2. Brainstorm at least two different design concepts that could solve the problem. Sketch them out and write a brief description of each, highlighting its key features (e.g., "Concept 1: A quadcopter with a high-resolution camera" or "Concept 2: A fixed-wing drone with a long-range battery").
3. Develop a set of evaluation criteria and use it to select the best concept.
4. Prepare a short presentation for the class. Explain the problem you chose, show your design concepts, and use your decision matrix to justify why you selected your final design.

UAV DESIGN ESTIMATES

We turn our focus now to carrying out simple calculations that will help size a selected UAV concept. We will consider how to size fixed-wing and multirotor UAVs.

Sizing Fixed-Wing UAVs

The stall speed is usually given as part of the requirements. Say for this discussion that it is specified as 40 km/h or 11.11 m/s; Let us also say that we decide to use electric motors and propellers for propulsion.

There is a design parameter known as Wing loading. It is the ratio of the aircraft weight to the area of its wing. It helps us to determine the size of the wing. But before we can do this, we need to select a suitable aerofoil for the wing section.

There are numerous aerofoils we can select, as we learned in the Second Year. (Refer to Year 2, Section 1 and 2, Introduction to Aerodynamics). Perhaps the most common are the NACA four-digit, five-digit and six-digit aerofoils. Others include the Clark series and Eppler series aerofoils. Some aerofoils are symmetrical while others are cambered. We usually use cambered aerofoils for the wing and symmetrical ones for the horizontal and vertical stabilisers. We also consider the maximum thickness of the aerofoil in the case where we want to store for example, fuel or stow the landing gear in the wing.

Each aerofoil has a maximum coefficient of lift for a given flow condition (Reynolds number) which occurs at the critical angle of attack. Most of the UAVs we will build operate at low speeds (lower Reynolds numbers). The website at http://airfoiltools.com/ is very useful for finding the maximum coefficient of lift.; it has a catalogue of a great number of aerofoils we can select from.

Say we select the NACA 63-415 aerofoil for our design. It has a maximum lift coefficient of about 1.5 at 15 degrees angle of attack. Recall that the formula for finding the lift coefficient is:

$$c_L = \frac{L}{\frac{1}{2} \times \rho \times v^2 \times S}$$

where L is the lift, ρ is the density of air, V is the freestream velocity of the aircraft and S is the wing area.

Just before stall, the lift generated by the wing equals the aircraft's weight. Replacing L with the weight, W, V with the stall speed, V_{stall} and C_L with $C_{L,max}$ and rearranging the equation, we find that the wing loading,

$$\left(\frac{W}{S}\right) = \frac{1}{2} \times \rho \times V_{stall}^2 \times C_{\max} \qquad \text{(Equation 1)}$$

GCAA mandates that our aircraft flies below 400 ft (122 m) above ground level. Let us approximate this to 400 ft (122 m) above sea level. The air density at this altitude is approximately 1.2 kg/m^3 (this value can be obtained by interpolating between 100 m and 200 m on the International Standard Atmosphere table).

Substituting the values into Equation 1, we obtain the wing loading for our design,

$$\left(\frac{W}{S}\right) = \frac{1}{2} \times 1.2 \times 11.11^2 \times 1.5 = 111.089\ N/m^2$$

This is the maximum wing loading that meets our stall speed requirement. Any value smaller than this implies a smaller stall speed, which is preferable.

Knowing our design weight (let's take it to be 5 kg) we can find the wing area now:

$$S = \frac{W}{\left(\frac{W}{S}\right)} = \frac{5 \times 9.81}{111.089} = 0.442 m^2$$

Another design parameter that will help us select the propulsion system components is the thrust-to-weight ratio or power-to-weight ratio. Thrust-to-weight ratio is normally used for jet engine designs whiles the latter for propeller-driven designs.

The following equation can help us estimate the power-to-weight ratio for our design, knowing the wing loading.

$$\frac{W}{P} = \frac{\eta_P}{\frac{a V_{\max}^3}{\left(\frac{W}{S}\right)} + \frac{b}{V_{\max}}\left(\frac{W}{S}\right)} \qquad \text{(Equation 2)}$$

In Equation 2, η_P is the propeller efficiency, V_{max} is the maximum aircraft velocity, equal to about 1.2 – 1.3 times the cruise speed (which is usually part of the requirements), P is the power at sea level (useful for selecting a gas engine) and *a* and *b* are defined as follows:

$$a = \frac{1}{2} \times \rho_0 \times C_{D_0}$$

where ρ_0 is the air density at sea level and C_{D_0} is the aircraft zero-lift drag coefficient.

$$b = \frac{2K}{\rho\sigma}$$

where $K = \frac{1}{\pi \times e \times AR}$, e being the Oswald efficiency factor, usually between 0.7 and 0.95 and AR, the wing aspect ratio, which must be decided (higher aspect ratio wings make for good performance at high altitudes).

ρ is the air density at the altitude where the maximum speed is specified, and $\sigma = \frac{\rho}{\rho_0}$

We will use the following values in our calculation of the power loading:

Parameter	Value
V_{max}	70 km/h or 19.44 m/s
η_P	0.8
C_{D_0}	0.01
ρ_0	1.225 kg/m^3
e	0.9
AR	6
ρ	1.2 kg/m^3

With these values,

$$a = \frac{1}{2} \times 1.225 \times 0.01 = 0.006125$$

$$K = \frac{1}{3.142 \times 0.9 \times 6} = 0.0589$$

$$\sigma = \frac{1.2}{1.225} = 0.9796$$

$$b = \frac{2 \times 0.0589}{1.2 \times 0.9796} = 0.1$$

and

$$\left(\frac{W}{P}\right) = \frac{0.8}{\frac{0.006125 \times 19.44^3}{111.089} + \frac{0.1 \times 111.089}{19.44}} = 0.82 \ N/W$$

We multiply this value by the maximum velocity to get the thrust loading,

$$\left(\frac{w}{T}\right) = 0.82 \times 19.44 = 15.941$$

With this value, and knowing the design weight, we can select a motor-propeller combination that provides a thrust of

$$T = \frac{W}{\left(\frac{W}{T}\right)} = \frac{5 \times 9.81}{15.941} = 3.08\ N$$

Usually, manufacturers will quote the thrust value in kg; so our target thrust is $\frac{3.08}{9.81} = 0.314\ kg$ or 314 grams. If this value is too high, we can use more than one propulsion system, say two motors, etc.

A quick search on https://hobbyking.com/, an online shop for drone parts leads us to the *PROPDRIVE v2 2826 1000KV Brushless Outrunner Motor*. This motor provides 670 grams of static thrust when combined with an 20 x 15 (cm) propeller and powered by a 3S Lithium-polymer battery (11.1 V). At full throttle, it consumes a current of 10 A. Since the thrust provided by a propeller generally decreases with forward speed, we decide to use this motor; the extra thrust becomes a plus.

If our aircraft must fly for 15 minutes or 0.25 hours, we need to select a battery pack that has a capacity of about $10 \times 0.25 = 2.5\ Ah$ or 2500 mAh. Let us add on an extra 500 mAh to cater for start-up, etc. This means we need to find a 3S Lithium polymer battery that has a capacity of at least 3000 mAh. (You can add up the extra in the time. For instance, you could have used 20 minutes instead of 15 for the calculation.) Another battery parameter you might come across is the C-rating. A higher C-rating means that the battery can charge/discharge faster and is generally preferrable.

Looking again on Hobbyking (there are many other places where we might find drone parts including Horizon Hobby – https://www.horizonhobby.com/, Banggood – https://www.banggood.com/ and AliExpress – https://aliexpress.com/), we select the *Turnigy 3300mAh 3S 30C Lipo Pack w/XT-60*. It is of moderate price, and its capacity meets our specifications. It weighs approximately 300 grams and comes with the XT-60 connector.

To complete the power system design, we select an electronic speed controller (ESC) for the motor: the *Turnigy Plush-32 20A (2~4S) Brushless Speed Controller w/BEC* (it is always good to choose an ESC with a higher amperage rating than the motor) and a propeller: the *Durafly Rare Bear Reno Racer 680mm Replacement 8x5 Propeller*. The propeller available has a smaller pitch and so will produce slightly lower thrust than the 8x6. But this is ok, since we do not require all its thrust for our design, anyway.

We selected a value of 6 for aspect ratio. With this value, and knowing the wing area, we can determine the wingspan. This is the length of the wing from tip to tip.

$$b = \sqrt{AR \times S} = \sqrt{6 \times 0.442} = 1.63\ m$$

If we have decided to use a rectangular wing for our design, we can find the chord length,

$$c = \frac{S}{b} = \frac{0.442}{1.63} = 0.271\ m \approx 28\ cm$$

We now turn to sizing the tail of the aircraft. The horizontal/vertical tail volume coefficient relates the tail surfaces to the wing.

$$\bar{V}_H = \frac{l_h}{c} \times \frac{S_H}{S}$$

and

$$\bar{V}_V = \frac{l_v}{b} \times \frac{S_V}{S}$$

where S_H is the area of the horizontal tail and S_V is the area of the vertical tail, and the distances l_h and l_v are as shown in Figure 5.1 and Figure 5.2.

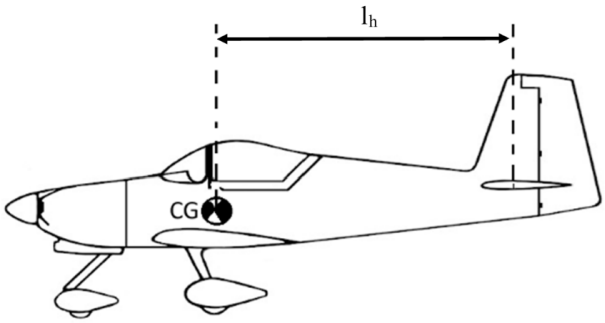


Figure 5.1: Horizontal tail arm

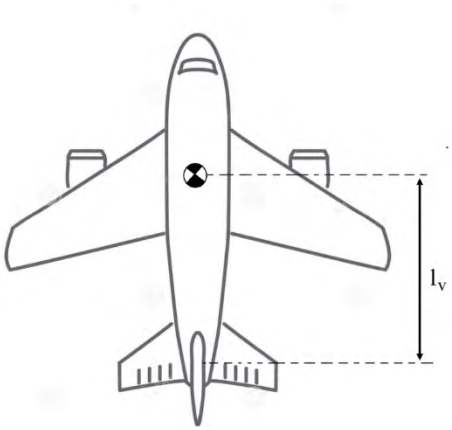


Figure 5.2: Vertical tail arm

The value of l usually depends on the length of the fuselage, and here, we will take $l_v = l_h = l$. We usually design the centre of gravity of the aircraft to be at the position of the wing along the fuselage. Depending on how we plan to distribute the weight of the aircraft components, for example, we might like to mount the motor and propeller at the front and put the payload midway along the fuselage. Our portability requirements might also dictate a maximum fuselage length. Suitable values of the horizontal tail volume coefficient for general aviation aircraft lie somewhat between 0.5 and 0.7, whiles, for the vertical tail, a range of 0.03 to 0.07 is common. We will adopt these values for our design.

Let us take $l = 0.5\ m, \bar{V}_H = 0.6$ and $\bar{V}_V = 0.04$; then,

$$S_H = 0.6 \times \frac{0.271}{0.5} \times 0.442 = 0.144\ m^2$$

$$S_V = 0.04 \times \frac{1.63}{0.5} \times 0.442 = 0.058\ m^2$$

Using $AR = 4$ for the horizontal tail and 5 for the vertical tail, and assuming rectangular surfaces, the chord and span for the same are presented in ***Table 5.4***.

Table 5.4: Tail size

Parameter	Horizontal tail	Vertical tail
Span, *b*	0.76 m or 76 cm	0.54 m or 54 cm
Chord, *c*	0.18 m or 18 cm	0.107 m or 10.7 cm

To complete the design, we select the wheels, again from our online stores, picking one whose diameter provides adequate ground clearance for the propeller.

It is worth mentioning here that the design process is iterative, and if at any time we are unsatisfied with any parameter or unable to find a component that meets our specifications on the market, we can adjust the relevant value and perform the calculations again.

Let us now turn to multirotors.

Sizing Multirotor UAVs

Recall from our first-year lessons about UAVs that multirotors use several motor-propeller units to provide both lift and thrust. They have the capability to hover as well as transition in all directions.

In selecting the propulsion system components for a multirotor, we must satisfy both hover and forward (backward, sideward) flight requirements. In hover, the total thrust generated by the rotors must equal the weight of the aircraft. In forward flight, the UAV tilts at an angle to the horizontal, and the thrust generated by the rotors must support the weight and provide the force that propels it forward. We will therefore use the results from the forward flight analysis to select the propulsion system components.

Let us design a quadcopter (multirotor with four motors) as an alternative to the fixed wing we designed earlier. With reference to Figure 5.3, the following equation applies:

$$F_{drag} = W \cdot \tan\theta \qquad (3)$$

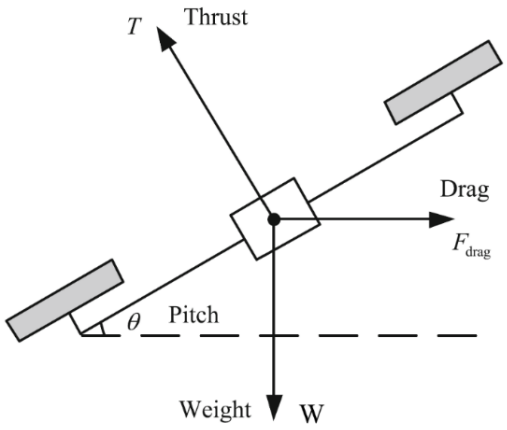


Figure 5.3: Multirotor UAV in forward flight

To move at a constant speed, the forward force must balance the drag. The drag force can be found using the following equation:

$$F_{drag} = \frac{1}{2} \times \rho \times V^2 \times S \times C_D$$

where ρ is the air density, V is the forward velocity of the UAV, C_D is the drag coefficient and S is a reference area, which we will take equal to the area of the drone when viewed from above. The drag coefficient will vary depending on the pitch angle, but for design, we will use the maximum value.

We evaluate the drag equation for flight at 400 ft (122m) where the density is about 1.2 kg/m^3 with a maximum velocity of 70 km/h (19.44 m/s) and take and C_D equal to 0.05. We must now estimate the area, S. Say, that due to portability requirements, we are limited to a maximum linear dimension of 0.6 m. Let us take S to be the area of the square with sides equal to this value. Hence, $S = 0.6 \times 0.6 = 0.36\ m^2$. Substituting these into the drag equation, we get:

$$F_{drag} = \frac{1}{2} \times 1.2 \times 19.44^2 \times 0.36 \times 0.05 = 4.08\ N$$

Knowing the design weight, 5 kg or 49.05 N, we can find θ, using Equation 3:

$$\theta = \tan^{-1}\left(\frac{4.08}{49.05}\right) = 4.75^0$$

The total thrust we need to generate can be determined using, again, with reference to Figure 5.3 as:

$$T = \frac{W}{\cos\theta} = \frac{49.05}{\cos(4.75)} = 49.22\ N$$

We could have used Pythagoras' theorem to obtain the same result:

$$T = \sqrt{F_{drag}^2 + W^2} = \sqrt{4.08^2 + 49.05^2} = 49.22\ N$$

Since we have four rotors, each must generate a thrust of $\frac{49.22}{4} = 12.3\ N$ or $\frac{12.3}{9.81} = 1.25\ kg$.

We head again to our online store, Hobbyking to find a motor-propeller combination to meet our specification. We find that the *PROPDRIVE v2 2836 2200KV Brushless Outrunner Motor* generates static thrust of 1.428 kg when combined with a 15 × 14 cm propeller and running on a 3S Lithium polymer battery (11.1 V), drawing 35 A of current.

We can estimate the battery capacity required, just like we did for the fixed wing case. Here there are four motors, each drawing 35 A of current. That makes $35 \times 4 = 140\ A$. If we want to run for 15 minutes (0.25 hours), we need a battery with a capacity of at least $140 \times 0.25 = 35\ Ah$ or 35000 *mAh*.

We found the highest capacity available for a 3S LiPo battery on Hobbyking to be 8000 mAh; it's the *Turnigy Rapid 8000mAh 3S2P 140C Hardcase LiPo Battery Pack w/XT90*. It weighs about 500 grams. If we combine four of these in parallel, we will obtain a capacity of 32000 mAh for a total weight of about 2 kg. 32000 mAh will afford us $\frac{32}{140} \approx 0.23$ hours, close to 14 minutes of flight time. This is ok for us. You may have realised now, that the power requirements for a multirotor UAV are higher than that required for a fixed-wing UAV with the same performance.

Let us now design the frame of the quadcopter. We can use either a plus (+) or X-configuration for our quadcopter. ***Figure 5.4*** illustrates this.

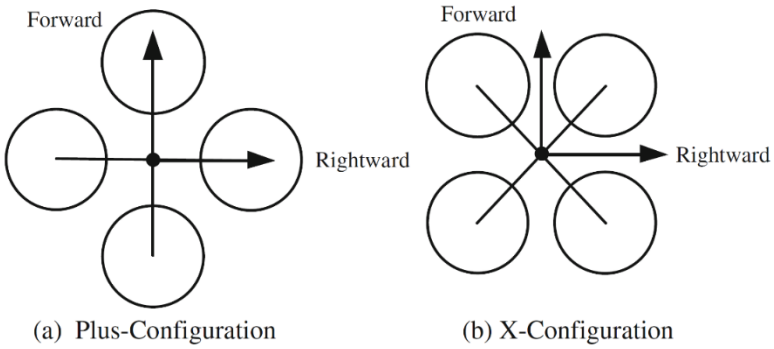


Figure 5.4: Plus and X quadcopter configurations

The geometry of a multicopter is generally defined, with reference to ***Figure 5.5*** by,

$$R = \frac{r_{max}}{\sin\frac{\theta}{2}} = \frac{r_{max}}{\sin\frac{180^0}{n}} \qquad (4)$$

where n is the number of arms the multicopter has and θ is the angle between the arms.

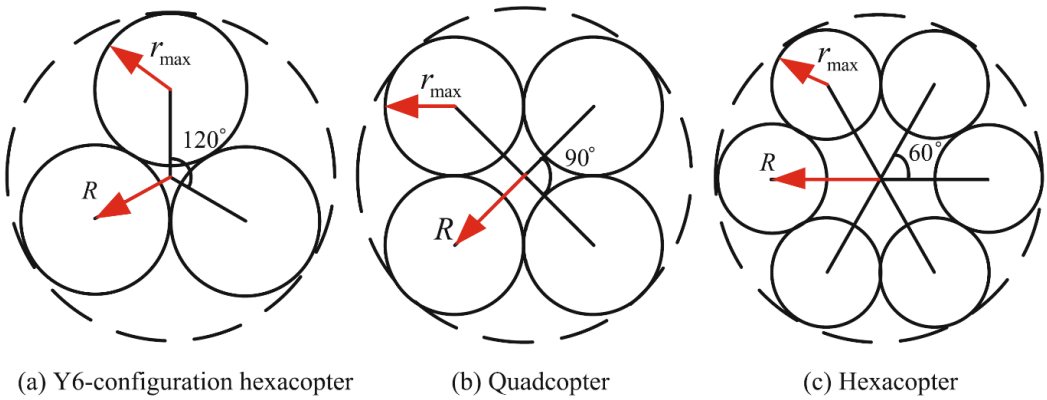


Figure 5.5: Multicopter arm length

So, for our quadcopter which has $r_{max} = \frac{6}{2} = 3$ inches or 0.0762 m and $\theta = 90^0$ or n = 4, we have

$$R = \frac{0.0762}{\sin\left(\frac{180}{4}\right)} = 0.108\ m\ or\ 10.8\ cm$$

For a quadcopter, adjacent motors rotate in opposite directions. Hence, we will need two clockwise (CW) and two counterclockwise (CCW) propellers.

Activity 5.2 Sizing Your Community Helper UAV

Work together with your team from the last activity.

Following from your selection of the "best" Community Helper UAV concept from *Activity 5.1*, it is time to calculate some of its physical characteristics. Proceed depending on your choice of either a fixed-wing or multirotor UAV concept.

1. For a fixed-wing concept
    a. Specify the design stall speed and look up the maximum C_L value of your selected aerofoil. Use this information to compute the wing loading and hence, the wing area
    b. Compute the power loading at maximum velocity. [Assume a propeller with efficiency, 0.8; use a zero-lift coefficient value of 0.01and Oswald efficiency factor of 0.9]
    c. Determine the wingspan
    d. Assume a value for the tail moment arms within your size restrictions. Using values of 0.6 and 0.04 for the horizontal and vertical tail volume ratios, determine the area of the horizontal and vertical tails.
2. For a multirotor concept
    a. Using a drag coefficient of 0.05 and reference area of 0.3 m^2, estimate the total drag force on the UAV
    b. Determine the total thrust required by the UAV
    c. Research motor-propeller combinations to meet the thrust requirement
    d. Determine the radius of the circle that passes through the centre of all rotors
3. (For all groups) Share your calculations with the entire class.

EXTENDED READING

Blog posts: Steps for drone design
Drone battery Wh (Watt Hours) [A full guide]
How to design an aircraft: Wing Loading

REVIEW QUESTIONS

1. A design team is developing a crop-monitoring UAV. They have selected a battery with 400 Watt-hours (Wh) of energy, and their preliminary calculations suggest the UAV will consume 120 Watts (W) of power.
   a. Calculate the UAV's flight time in minutes. Show your work.
   b. If their requirement is for an endurance of at least 45 minutes, will this design meet the requirement? Explain your answer.
2. You have been tasked with designing a UAV to deliver a small, high-value package from a central warehouse to a hospital 15 km away within 20 minutes. Due to the hospital's location, the UAV must be able to land in a small, congested area.
   a. Analyse the strengths and weaknesses of two different design concepts – a fixed-wing drone and a multi-rotor drone – against the key performance parameters of speed and landing area.
   b. Based on your analysis, which concept would you recommend for this specific mission, and why? Your justification should show a clear understanding of the trade-offs between the two designs.

SECTION

6

BUILDING UAVS



UNMANNED AERIAL VEHICLES (UAVS)

DESIGN AND FABRICATION OF UAVS

INTRODUCTION

This section deals with the first indicator of the third learning outcome of the Design and Fabrication of UAVs sub strand of the Unmanned Aerial Vehicles (UAVs) strand.

In this section, we will explore aspects related to the construction of a conceptual UAV design. We shall begin by reviewing safety regulations applicable within the laboratory environment. Next, we will examine the various materials available for building the UAV, followed by an overview of the tools and equipment in the lab that will assist us during the construction process. Finally, we will identify the supplies required to assemble our models.

KEY IDEAS

- Fasteners are used to secure several parts of a UAV together
- Finishes are applied to improve the appearance of a UAV
- It is essential to observe safety rules while building UAVs in the lab
- Different tools are required for UAV construction depending on the type of materials used and the nature of the part to be produced

UAV CONSTRUCTION

We will focus on constructing the UAV we designed in the previous section. Let us first remind ourselves of some safety practices as most of our activities will be carried out in the laboratory.

Safety Practices While Building UAVs

Building UAVs allows us to apply what we've learned to real-world projects. However, working in the lab comes with risks, especially when using tools, electricity, and chemicals. To keep everyone safe and make sure the work goes smoothly, it's important to follow safety rules.

Here is a recap of key safety practices:

General Laboratory Safety

It is important to wear appropriate personal protective equipment (PPE) before beginning any lab work. This includes safety goggles to protect the eyes, lab coats to shield clothing, and closed-toe shoes to safeguard the feet. A clean and organised workspace also helps prevent accidents and makes tools and materials easier to locate. It is important to know the location of emergency equipment such as fire extinguishers, first aid kits, and emergency exits. Eating or drinking in the lab is strictly prohibited to avoid contamination and accidental ingestion of harmful substances. Any accidents or unsafe conditions should be reported to the instructor or lab supervisor immediately.

Electrical Safety

When working with electrical components such as wires, batteries, and circuits, inspect all items for damage before use. Frayed wires or loose connections can pose serious risks. Insulated tools should be used to prevent electric shocks. Power sources must be turned off before connecting or disconnecting any electrical parts. Avoid overloading sockets and keep liquids away from electrical equipment to prevent short circuits and electrocution.

Mechanical Safety

UAV assembly often involves cutting, drilling, and shaping materials. These tasks require careful handling of sharp tools and fast-moving machinery. Ensure that all materials are securely fastened before working on them. Loose clothing, jewellery, or accessories should not be worn, as they can get caught in moving parts. Tools must be used only for their intended purposes, and manufacturer instructions should be followed closely.

Chemical Safety

Some UAV building processes involve the use of adhesives, solvents, or cleaning agents. Before using any chemical, read the labels and safety data sheets to understand the risks and proper handling procedures. Chemicals must be used in well-ventilated areas or under fume hoods to prevent inhalation of harmful fumes. Protective gloves and goggles are necessary to shield the skin and eyes. Chemicals should be stored in clearly labelled containers and kept away from heat sources. Disposal of chemical waste must follow school or local environmental guidelines to ensure safety and sustainability.



Figure 6.1: Personal protective equipment

Laboratory Tools/Equipment/Supplies for UAV Construction

Constructing our UAV will involve working with a range of materials and systems, including wood, plastics, metals, composites, foam board and electronics, among others. Each material requires specific tools and safety practices. This section outlines the essential equipment and supplies we will use successfully build and assemble UAVs.

Working with Wood

Wood is commonly used for structural frames and support components. We will use hand saws or coping saws for cutting, files and sandpaper for smoothing, and clamps to hold pieces in place. Wood glue and fasteners such as screws or nails are used for joining parts. A sturdy workbench with a vice is helpful for securing materials during construction.



Figure 6.2: A handsaw in use

Working with Plastics

Plastics are lightweight and ideal for body panels or protective covers. Tools such as utility knives, plastic cutters, and rotary tools are used for shaping. Heat guns may be needed to bend certain plastics. Adhesives like epoxy or plastic cement help in assembly. Safety goggles are essential when cutting or heating plastic.

In addition to these tools, 3D printers are increasingly used to create custom plastic parts for UAVs. These printers allow the digital design of components and production to high precision using materials like PLA or ABS filament. 3D printing is especially useful for making propeller mounts, camera holders, or lightweight structural pieces. It is essential to follow safety guidelines when handling heated elements and moving parts.



Figure 6.3: A 3D printer

Foam board is ideal for wings and lightweight structures. It can be cut with craft knives or hot wire cutters. Cutting mats and rulers help maintain precision. Foam-safe adhesives or glue guns are used for joining parts. Gentle handling is important to avoid damaging the material.

Working with Metals

Metals like aluminium are used for strong, lightweight frames. We use hacksaws or rotary tools for cutting, and files or sanders for finishing edges. Drills are needed for making holes, and rivet guns or screwdrivers for fastening. Gloves and eye protection are necessary due to sharp edges and sparks.



Figure 6.4: A hand drill

Working with Composites

Composites such as carbon fibre and fibreglass offer strength and low weight. Cutting tools include diamond-coated blades and rotary cutters. Resin and hardener are applied with brushes or rollers. Students must wear gloves and masks to avoid exposure to dust and chemicals, and work in well-ventilated areas.



Figure 6.5: Carbon fibre kit

Working with Electronics

Electronics are the heart of UAV control systems. We will use soldering irons for connecting wires and components, multimeters for testing circuits, and wire strippers for preparing connections. Breadboards and microcontrollers (like Arduino or Raspberry Pi) are used for prototyping. Batteries, motors, ESCs (Electronic Speed Controllers), and sensors (e.g., GPS, gyroscopes) are essential components. Proper storage and handling of electronic parts are important to prevent damage from static electricity or moisture.



Figure 6.6: Multi-functional wire stripper

Fasteners

Fasteners help hold parts of the UAV together securely, whether it's the frame, wings, electronics, or other structural elements. Choosing the right fastener depends on the materials being used and the type of connection needed – temporary or permanent. Below are common types of fasteners we may use for our designs.

Screws

Screws are widely used for joining wood, plastic, and metal parts. They come in various sizes and head types, such as flat-head or Phillips-head. Screws create strong, removable joints and are easy to install using a screwdriver or drill. We will use them to attach panels, mount motors, or secure electronic components.



Figure 6.7: Types of screws

Bolts and Nuts

Bolts and nuts are used together to create strong, secure connections, especially in metal and composite structures. A bolt passes through a hole in the material, and a nut is tightened on the other side. Washers may be added to distribute pressure and prevent damage. They are ideal for parts that may need to be disassembled or adjusted later.



Figure 6.8: Bolts and nuts

Rivets

Rivets are permanent fasteners commonly used in metal and composite work. They consist of a pin and a head that is deformed during installation to hold materials together. Rivets are lightweight and strong, making them suitable for UAV frames and structural joints. Installing rivets requires a rivet gun and careful alignment of the parts.



Figure 6.9: Types of rivets

Zip Ties

Zip ties, also known as cable ties, are plastic fasteners used to bundle wires or temporarily hold parts together. They are quick to apply and useful for organising electronic components or securing lightweight materials. While not suitable for structural connections, zip ties are excellent for managing cables and keeping the workspace tidy.



Figure 6.10: Zip ties

Velcro Straps

Velcro straps provide adjustable, reusable fastening. They are ideal for securing batteries, payloads, or removable panels. Velcro allows for quick access and repositioning, which is helpful during testing and modification. These straps are especially useful because they provide flexibility and ease of use.



Figure 6.11: Velcro strap

Finishes

Once the UAV has been assembled, applying a finish helps protect the materials, improve appearance, and sometimes enhance performance. Finishes can prevent damage from moisture, sunlight, and wear, while also allowing personalisation of the model. We will look at three common types of finishes: paint, varnish, sticker paper and vinyl wraps.

Paint

Paint is one of the most popular finishes for UAVs. It adds colour and style, making the drone easier to identify and more visually appealing. More importantly, paint can protect surfaces – especially wood, foam board, and plastic – from moisture and UV damage. Spray paints are commonly used because they provide a smooth, even coat and dry quickly. Apply paint in thin layers and allow each coat to dry before adding another. Painting should be done in a well-ventilated area or outdoors, and safety masks should be worn to avoid inhaling fumes.



Figure 6.12: Spray paint

Varnish

Varnish is a clear protective coating often used on wooden parts of a UAV. It enhances the natural look of the wood while providing a layer of protection against moisture and scratches. Varnish can be applied with a brush and usually requires several coats for a durable finish. Each coat must be allowed to dry fully before the next is added. Like paint, varnish should be used in a ventilated space, and gloves and masks worn during application.



Figure 6.13: Varnish

Sticker Paper

Sticker paper is a fun and creative way to decorate UAVs. It allows for the addition of logos, labels, or custom designs without using paint. Sticker paper can be printed with a design and then cut to shape before being applied to the drone's surface. It works well on smooth materials like plastic, foam board, and metal. While sticker paper doesn't offer much protection, it's useful for identification and branding, especially in competitions or group projects.



Figure 6.14: Sticker paper

Vinyl wraps

Vinyl wraps are thin, adhesive-backed sheets used to enhance appearance and protect the UAV surfaces. They come in various colours, patterns, and textures, allowing for creative customisation and easy identification of drones. Vinyl wraps offer protection against scratches, moisture, and UV rays, and are especially useful on foam board, plastic, and metal surfaces. They are removable and replaceable, making them ideal for projects that may require updates or repairs.



Figure 6.15: Vinyl wraps

Activity 6.1 Constructing a UAV Wing

Organise yourself into a small group of 3 or 4 members to construct a basic UAV designed in the previous section, using the materials provided. Follow the steps below carefully and observe all safety guidelines.

Materials provided

1. Fuselage & Tail Construction
    a. Lightweight wood or balsa sheets (for fuselage sides, tail surfaces)
    b. Plastic/plywood sheets (for mounting hardware or reinforcements)
    c. Lightweight screws, bolts, and nuts
2. Wings
    a. Wooden strips for wing ribs
    b. Foam board for wing surface
    c. Carbon fibre rods for wing spars
    d. Epoxy or wood glue
    e. Craft knives, saws, and sandpaper
    f. Rulers, cutting mats, clamps
    g. Safety goggles and gloves
3. Propulsion System
    a. Brushless DC motor(s) (appropriate size for UAV)
    b. Electronic Speed Controller (ESC)
    c. Propellers (matched to the motor size and thrust needs)
    d. Propeller adapters/mounts
4. Power System
    a. Rechargeable LiPo battery (common for UAVs)
    b. Battery charger and balance charger board
    c. Battery straps/holders
5. Control System
    a. Radio transmitter and receiver (TX/RX)
    b. Flight controller board (e.g., Pixhawk, Arduino-based, or similar student-friendly controller)
    c. Servos (for control surfaces if fixed-wing)
    d. Wiring, connectors, and heat-shrink tubing
6. Assembly & Reinforcement
    a. Hot glue gun and glue sticks

   b. Fiberglass tape or reinforced packing tape (for strengthening joints)
   c. Zip ties and Velcro (for securing electronics and wiring)
7. Testing & Field Gear
   a. Measuring scale (to check weight)
   b. Multimeter (for checking electrical connections and battery voltage)
   c. Portable tool kit (screwdrivers, pliers, wire cutters, soldering iron + solder)
8. Safety & Documentation
   a. Fireproof LiPo battery storage bag
   b. First aid kit (workshop safety requirement)
   c. Build logs or notebooks (test results, and reflections)

Safety guidelines

1. Always wear safety goggles when cutting or sanding materials.
2. Use gloves when handling epoxy or carbon fibre.
3. Cut on a mat and away from your body.
4. Work in a well-ventilated area when using adhesives.

Build Steps

1. **Planning & Preparation**
   a. Layout the design previously selected (including payload, endurance, mission profile).
   b. Sketch the UAV layout: fuselage, wings, tail, propulsion, electronics placement.
   c. Gather all materials, tools, and safety equipment (safety goggles, gloves, cutting mats, etc.).
2. **Wing Construction**
   a. Refer to your sketch of the UAV showing the wing design, the placement of ribs, spars, and foam board covering.
   b. Cut the wooden strips into rib shapes using saws or craft knives. Sand the edges smooth and ensure all ribs are uniform in size.
   c. Position the carbon fibre rods along the length of the wing where the spars will go. Use epoxy to bond them to the ribs. Clamp the assembly and allow it to dry.
   d. Cut the foam board to match the wing shape. Carefully glue it over the rib and spar structure, pressing gently to avoid warping.
   e. Inspect the wing for alignment and strength. Make any necessary adjustments.
3. **Fuselage Construction**
   a. Cut balsa wood or lightweight plywood into fuselage sides.

b. Assemble using epoxy/glue with internal formers or light frames.
c. Reinforce with carbon fibre rods or strips if needed.
d. Add a mounting plate for the motor and battery.
e. Sand smooth and ensure correct alignment.

4. **Tail Assembly**
   a. Cut balsa or foam board for the horizontal stabilizer and vertical fin.
   b. Shape with sandpaper to reduce drag.
   c. Attach small servos to control rudder and elevator.
   d. Glue securely to fuselage tail section.
5. **Landing Gear (if required)**
   a. Simple gear: carbon rods or lightweight aluminium wire with small wheels.
   b. Fixed gear or skids can be attached depending on UAV mission.
6. **Propulsion System**
   a. Mount the brushless DC motor to the fuselage nose (or rear, depending on design).
   b. Attach propeller and adapter.
   c. Connect the motor to the Electronic Speed Controller (ESC).
   d. Route wiring neatly inside the fuselage.
7. **Power System**
   a. Install the LiPo battery inside the fuselage with Velcro straps or a battery bay.
   b. Connect to ESC (ensure polarity is correct).
   c. Add a fireproof LiPo bag for safe storage/charging when not in use.
8. **Control System**
   a. Install receiver (RX) in fuselage and connect to servos + ESC.
   b. Mount the flight controller board (e.g., Pixhawk or Arduino-based).
   c. Calibrate control surfaces:
      i. Rudder (yaw)
      ii. Elevator (pitch)
      iii. Ailerons (roll, if included in wing build)
   d. Secure all wiring with zip ties or tape.
9. **Wing-to-Fuselage Integration**
   a. Mount completed wing assembly to fuselage with glue, screws, or elastic bands (depending on design).
   b. Check dihedral angle and ensure wings are straight.

c. Connect servo wires (for ailerons/flaps if included).

10. **Finishing & Safety Checks**
    a. Check the centre of gravity (CG) by balancing the UAV.
    b. Inspect glue joints and reinforcements.
    c. Perform an electronics test: motor throttle, servo response, radio link.
    d. Review safety practices: goggles, gloves, propeller safety, and battery handling.
    e. Clean your workspace and store tools properly.

EXTENDED READING

Photogrammetry Drone: Airframe
Foam Board Cutting Tips and Laminations
Drone With Self-made Wooden Frame
The Ultimate Guide to Building a Quadcopter From Scratch
DIY Drone Building: An overview
Step-by-Step Guide: How to Build a Drone for Beginners

REVIEW QUESTIONS

1. Imagine your team has been selected to design and build a UAV for a national student competition in Ghana. The UAV must be lightweight, durable, and capable of flying in both dry and humid conditions. Your team must choose appropriate materials for the wings, frame, and propeller mounts.

   Develop a materials selection plan that includes:

   a. The materials you would choose for each part and why

   b. How environmental factors (e.g., humidity, temperature) might affect your choices

   c. A comparison of at least two alternative materials for each part

   d. A justification of your final selections based on performance, cost, and ease of use in a school lab setting

2. Your team has been provided with the following materials to construct the wing of a UAV:

   a. Wood for the ribs

   b. Carbon fibre rods for the spars

   c. Foam board for the wing surface

      Using this setup, develop a construction plan that includes:

      i. The tools and supplies your team will need to shape, assemble, and finish the wing.

      ii. The safety practices that must be followed during each stage of the construction.

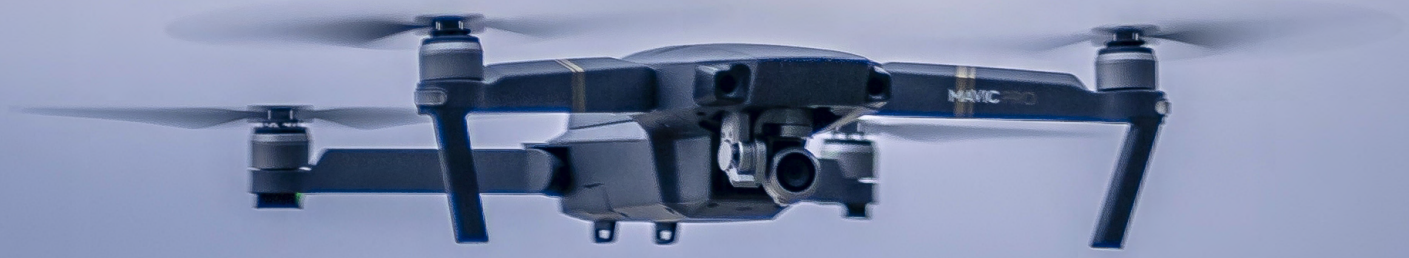
      iii. An explanation of how the choice of tools and safety measures supports both the quality of the build and the well-being of the team.

      iv. A reflection on how you would modify your plan if one of the materials were unavailable or replaced with an alternative.

SECTION

7

FLYING UAVS



UNMANNED AERIAL VEHICLES (UAVS)

DESIGN AND FABRICATION OF UAVS

INTRODUCTION

This section deals with the second indicator of the third learning outcome of the Design and Fabrication of UAVs sub strand of the Unmanned Aerial Vehicles (UAVs) strand.

This final section focuses on flying the UAV models constructed in the previous section. We will begin by flying UAVs using simulation software, which provides a safe and controlled environment to practise flight skills and build confidence. These simulations will prepare us for operating the actual models during the final parts of the section.

KEY IDEAS

- Flying a UAV in a simulation environment allows practice of manoeuvres in order to gain confidence before real-world flights
- GCAA has laid down rules to guide the flight of UAVs in Ghana
- It is important to be mindful of safety when flying UAVS

UAV SIMULATION FLIGHTS

(Refer to Year 2, Section 6, Integrating Simulators to enhance UAV Operations Safety and Year 3, Section 2, Aircraft & Spacecraft Flight Controls)

We will focus on gaining hands-on experience flying UAVs in a simulation environment. Several flight simulators are available for use, including RealFlight, FlightGear, PicaSim, Reflex XTR[2], and many others. These tools allow the practise of flight control, navigation, and safety procedures in a virtual setting before transitioning to real-world UAV operations.

We will follow the steps listed next to setup and fly in the simulation environment.

1. Plug in the USB flight controller or joystick. Most simulators will automatically detect it. If needed, install drivers or calibration software.
2. Open the simulator settings and map the controller inputs (throttle, yaw, pitch, roll) to match the UAV controls. Test each input to ensure it responds correctly.
3. Choose a UAV model within the simulator that closely resembles the one you built in the previous class sessions.

4. Choose a basic flight environment (e.g., open field or training ground) with minimal obstacles.
5. Before flying, check that all controls are working, the model is stable, and the simulation settings (e.g., wind, gravity) are appropriate for training.
6. Take turns flying the UAV in simulation. Start with basic manoeuvres like take-off, hovering, and landing before progressing to more complex tasks.
7. After each session, discuss what went well, what was challenging, and how you can improve. Log your flight hours and progress.

Activity 7.1 Take-off in a Simulator

Work with a colleague to set up a UAV flight simulation environment and practise the take-off manoeuvre.

1. Open the flight simulation software on your computer.
2. Plug in the flight controller or joystick. Go to the settings and ensure the throttle, yaw, pitch, and roll controls are correctly mapped and responsive.
3. Choose a UAV model that most closely resembles the one you have built and a simple flight environment, such as an open field.
4. Perform the take-off manoeuvre
    i. Begin with the UAV on the ground in a stable position.
    ii. Slowly increase the throttle to lift the UAV off the ground.
    iii. Use gentle pitch and roll inputs to maintain balance.
    iv. Once airborne, stabilise the UAV at a safe altitude and hover for a few seconds.
    v. Reduce throttle slightly to maintain altitude and avoid climbing too fast.
5. After completing the take-off, discuss with your partner what went well and what was challenging. Write down your observations and any adjustments you would make next time.

REAL-WORLD UAV FLIGHTS

(Refer to Year 2, Section 6, GCAA UAV regulations and Year 3, Section 2, Aircraft & Spacecraft Flight Controls)

We turn our focus now to flying the UAV models we have constructed. We will begin with a recap of the GCAA regulations on UAV operations, which we covered in Year 2. This review will ensure that we are well-prepared to conduct real-world flights responsibly and in compliance with national guidelines.

GCAA prohibits flights in icy conditions or during the night unless special permission is granted. Drones must always be flown within visual line of sight. The GCAA also restricts flights in certain areas – drones must not be flown within 10 kilometres of airports or helipads, above 400 feet, or within 30 metres of buildings and vehicles without express permission. Flying over crowds or in congested urban, suburban, or rural areas is also forbidden.

The following safety practices are useful when flying our UAVs:

1. Perform a thorough inspection of the aircraft before launching the UAV. This includes checking for physical damage, ensuring all components like propellers and wires are secure, and verifying that the battery is fully charged and properly connected. Software and firmware should be up to date, and if the UAV uses GPS, a strong signal lock must be confirmed before take-off to ensure accurate navigation.
2. Choose the right environment for flight. UAVs should be flown in open spaces, far from buildings, trees, and power lines. Weather conditions must be favourable – no strong winds, rain, or poor visibility. Respect no-fly zones such as areas near airports or military installations to avoid legal and safety issues.
3. During flight, it is essential to maintain visual contact with the UAV. Pilots should keep a safe distance from people and obstacles, especially during take-off and landing.
4. One student should operate the UAV at a time, under the supervision of an instructor. Avoid distractions like mobile phones during flight operations. This will reduce the risk of errors or accidents during UAV handling.
5. After each flight, power down the UAV safely by disconnecting the battery before handling it. Review flight data to reinforce your learning and identify areas for improvement. Properly clean and stow the UAVs to ensure they remain in good condition for future use.

   Flying UAVs successfully requires more than just technical assembly – it involves smart piloting habits and understanding of the equipment. One useful practice is learning to use accessory channels on the remote controller. These extra switches, knobs, or buttons can be programmed for specific functions like activating lights, deploying payloads, switching flight modes, or triggering emergency failsafe actions.

   Maintaining orientation is another key skill. It is easy to lose track of which direction the UAV is facing, especially when it's far away. To help with this, use colour-coded propellers or LED lights on the front and rear of the drone. Practice slow, deliberate movements and begin with the UAV facing away from you until you're confident with directional control.

   Launching fixed-wing drones requires a different approach than multirotors. The most common method is a hand launch, where the pilot gently throws the drone into the wind while the motor is running at full throttle. Alternatively, a runway launch can be used if space allows, or a catapult launcher for larger or heavier models. Check wind direction, ensure a firm grip, and coordinate timing with motor activation to achieve a smooth launch.

Activity 7.2 UAV Regulations and safety

1. Organise yourself into groups of 4 or 5 members,
2. Discuss the GCAA regulations that govern the flight of UAVs in Ghana.
3. In your group discuss the safety practices that must be observed while flying UAVs.

Activity 7.3 UAV Flight Practice

Organise yourselves into groups of 4 or 5. If the UAV you have built is not deemed safe you will be provided with a UAV for this activity.

Perform a pre-flight inspection of your UAV and complete a basic flight exercise under supervision.

Part 1: Pre-Flight Checks

1. Inspect Your UAV
    a. Check that all propellers are secure and undamaged.
    b. Look for loose wires or broken parts.
    c. Make sure the frame is stable and intact.
2. Power System
    a. Ensure the battery is fully charged.
    b. Connect the battery securely and check for proper voltage.
3. Remote Controller Setup
    a. Turn on the remote controller.
    b. Test all stick movements and accessory switches (e.g., knobs or buttons).
    c. Confirm that flight mode switches are working.
4. GPS & Compass
    a. Wait for a strong GPS signal.
    b. Calibrate the compass if needed.
5. Control Surface Check (Fixed-Wing Only): Move the sticks and confirm that the control surfaces respond correctly.

Part 2: Practice flight

1. Launch Your UAV
    a. Multirotor: Place it on a flat surface and gently increase throttle to lift off.
    b. Fixed-Wing: Face into the wind and perform a hand launch with full throttle.
2. Maintain Orientation

   a. Keep the UAV facing away from you.
   b. Use coloured propellers or lights to help track direction.
3. Perform Basic Manoeuvres
   a. Practice hovering (for multirotors).
   b. Fly forward, turn left and right, and adjust altitude.
   c. Use accessory switches to activate any programmed functions.
4. Land Safely
   a. Reduce throttle slowly and guide the UAV to a smooth landing.
   b. Power off the UAV and disconnect the battery.

After the Flight,

1. Discuss what went well and what was challenging.
2. Record your observations in your flight log.
3. Clean and store your UAV properly.

EXTENDED READING

How to Fly a Drone: the ultimate guide
How to Fly a Drone
Flying a 3D Printed Fixed Wing Drone

REVIEW QUESTIONS

1. Compare and contrast the challenges faced during UAV simulation flights and real-world UAV flights. Based on your experience, explain how simulation helps to prepare for actual flight operations.
2. Design a basic flight plan for a real-world UAV mission using knowledge from simulation training. Include pre-flight checks, launch method, flight manoeuvres, and landing strategy. Justify your choices based on safety and control.

REFERENCES

1. Aircraft structures for engineering students, 6th Edition by T. H. G. Megson
2. Pilot's handbook of aeronautical knowledge, FAA
3. Helicopter flying handbook by FAA
4. Pilot's Handbook of Aeronautical Knowledge by FAA
5. Aircraft Communications and Navigation Systems, 2nd Edition by Mike Tooley and David Wyatt
6. El-Sheimy, N., Youssef, A. *Inertial sensors technologies for navigation applications: state of the art and future trends.* Satell Navig 1, 2 (2020). https://doi.org/10.1186/s43020-019-0001-5
7. Smith, M., Moser, D., Strohmeier, M., Lenders, V., & Martinovic, I. (2018). *Undermining privacy in the aircraft communications addressing and reporting system (ACARS).* Proceedings on Privacy Enhancing Technologies, 2018(3), 105-122.
8. Aviation Maintenance Technician Handbook – General (FAA-H-8083-30B), FAA

   Equipment Maintenance Log Best Practices
9. Aircraft design: A conceptual approach, 6th Edition, by Daniel P. Raymer
10. Aircraft design: A Systems Engineering Approach, 1st Edition, by Mohammad H. Sadraey
11. Introduction to multicopter design and control by Quan Quan
12. Shigley's Mechanical Engineering Design, 10th Edition, by Richard G. Budynas and J. Keith Nisbett
13. Ghana Civil Aviation (Remotely Piloted Aircraft Systems) Directives, 2018
14. The FlightGear Manual for FlightGear, version 2024.1.1, March 2025

GLOSSARY

- **3D Printer**: A machine that creates three-dimensional objects by building them layer by layer from a digital design, usually using plastic material.
- **Air Traffic Control (ATC)** – A service that manages aircraft movements on the ground and in the air to ensure safe and orderly flight operations.
- **Altitude**: The height of the UAV above the ground or sea level, usually measured in meters.
- **Asymmetrical Lift** – A condition where lift is unevenly distributed across the rotor or wing surfaces, often causing the vehicle to tilt or roll to one side.
- **Bearing** – The direction or angle from the radar station to the aircraft, measured clockwise from north.
- **Composite** – A material made by combining two or more different substances to create one with improved strength, lightness, or durability—commonly used in aircraft for parts like wings and fuselages.
- **C-rating** – A measure of how quickly a battery can safely discharge its energy. A higher C-rating means a battery can provide more power in a shorter amount of time, which is important for things like rapid acceleration
- **Endurance** – The total time an aircraft can stay in the air on a single charge or tank of fuel.
- **Enroute Navigation** – The process of guiding an aircraft between departure and arrival points, typically at cruising altitude and outside terminal areas.
- **Filament**: The plastic material used by a 3D printer to create objects. Common types include PLA and ABS.
- **Flight Plan**: A planned route or set of actions for a UAV flight, including take-off, manoeuvres, and landing.
- **Flight Simulator**: A computer-based system that mimics real UAV flight conditions, allowing flight practice without using a physical drone.
- **Frayed Wire**: A wire with its outer covering damaged or worn out, exposing the metal strands inside. It can be dangerous and should not be used.
- **Fume Hood**: A special cabinet with ventilation that safely removes harmful fumes and vapours when working with chemicals.
- **Governor** – A device in helicopters that automatically adjusts engine power to maintain a constant rotor speed when the pilot changes the collective pitch
- **Holding Pattern** – A circular or oval flight path flown by an aircraft while waiting for clearance to land or proceed, often used during delays or congestion.
- **Instrument Approach** – A procedure that allows aircraft to land using navigation instruments, especially in poor visibility, guided by systems like ILS or RNAV.
- **Interference** – Unwanted signals or noise that disrupt or weaken radio communication or navigation systems.
- **Ionosphere** – A layer of the Earth's atmosphere that reflects certain radio waves, allowing long-distance communication such as HF radio.

- **Joystick**: A control stick on the remote controller used to move the UAV in different directions like up, down, left, or right.
- **Line-of-Sight**: The ability to see your UAV directly with your eyes while flying, without any obstacles blocking your view.
- **Mission** – The specific purpose or task an aircraft is designed to perform, such as surveillance, delivery, or search and rescue.
- **Monocoque** – A type of aircraft construction where the outer skin carries all the structural loads, like a shell, without needing an internal frame.
- **Payload** – The useful cargo an aircraft carries, which can include cameras, sensors, or packages, but does not include the aircraft's own weight or fuel.
- **Pitch Angle of a rotor blades** – The angle between a rotor blade and its plane of rotation. Changing the pitch angle controls how much lift each blade produces, which is essential for vertical movement in helicopters.
- **Pre-Flight Inspection**: A safety check done before flying to make sure the UAV is in good condition and ready for flight.
- **Prototype**: A first or early version of a product or model used to test ideas and make improvements before final production.
- **Range** – The maximum distance an aircraft can fly from its take-off point to its landing point without needing to refuel or recharge.
- **RNAV (Area Navigation)** – A navigation method that allows aircraft to fly directly between any two points using onboard systems, without relying on ground-based aids.
- **Semi-monocoque** – A construction method that uses both a load-bearing skin and internal supports (like frames and stringers) to share the structural load—common in modern aircraft.
- **Standard operating procedures** – a set of detailed, step-by-step instructions for how to perform routine tasks
- **Stress** – The force or pressure applied to a material or structure, which can cause it to bend, stretch, or break depending on its strength.
- **Tarmac** – another name for the airport's paved surfaces where aircraft are parked, serviced, loaded, and unloaded.
- **Transponder** – An electronic device on an aircraft that automatically responds to signals from radar, providing information such as identity and altitude.
- **Truss** – A framework made of connected beams arranged in triangles, used to build strong and lightweight aircraft structures.
- **UV (Ultraviolet)**: A type of light from the sun or artificial sources that can affect materials by causing fading, damage, or drying.

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