1

First Flights

The first controlled flight of a heavier-than-air airplane, 17 December 1903. (Source: *W. Wright, O. Wright, and J. Daniels, 1903, US Library of Congress*.)

"Wilbur, having used his turn in the unsuccessful attempt on the 14th, the right to the first trial now belonged to me. After running the motor a few minutes to heat it up, I released the wire that held the machine to the track, and the machine started forward in the wind. Wilbur ran at the side of the machine, holding the wing to balance it on the track. Unlike the start on the 14th, made in a calm, the machine, facing a 27-mile wind, started very slowly. Wilbur was able to stay with it till it lifted from the track after a forty-foot run. One of the Life Saving men snapped the camera for us, taking a picture just as the machine had reached the end of the track and had risen to a height

Introduction to Aerospace Engineering with a Flight Test Perspective, First Edition. Stephen Corda.

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of about two feet.[1] The slow forward speed of the machine over the ground is clearly shown in the picture by Wilbur's attitude. He stayed along beside the machine without any effort.

The course of the flight up and down was exceedingly erratic, partly due to the irregularity of the air, and partly to lack of experience in handling this machine. The control of the front rudder was difficult on account of its being balanced too near the center. This gave it a tendency to turn itself when started; so that it turned too far on one side and then too far on the other. As a result the machine would rise suddenly to about ten feet, and then as suddenly dart for the ground. A sudden dart when a little over a hundred feet from the end of the track, or a little over 120 ft from the point at which it rose into the air, ended the flight. As the velocity of the wind was over 35 ft per second and the speed of the machine over the ground against this wind ten feet per second, the speed of the machine relative to the air was over 45 ft per second, and the length of the flight was equivalent to a flight of 540 feet made in calm air. This flight lasted only 12 seconds, but it was nevertheless the first in the history of the world in which a machine carrying a man had raised itself by its own power into the air in full flight, had sailed forward without reduction of speed and had finally landed at a point as high as that from which it started."

Orville Wright writing about the first successful flight of a heavier-than-air flying machine from Kill Devil Hills, North Carolina, on 17 December, 1903[2]

1.1 Introduction

The history of aerospace engineering is full of firsts, such as the first balloon flight, the first airplane flight, the first helicopter flight, the first artificial satellite flight, the first manned spacecraft flight, and many others. In this first chapter, these many firsts are discussed in the context of the aerospace engineering involved in making these historic events happen. The first flight of a new vehicle design is a significant achievement and milestone. It is usually the culmination of years of hard work by many people, including engineers, technicians, managers, pilots, and other support personnel. First flights often represent firsts in the application of new aerospace engineering concepts or theories that are being validated by the actual flight.

As an aerospace engineer, you have the opportunity to contribute to the first flight of a new aircraft, a new spacecraft, or a new technology. Aerospace engineers are involved in all facets of the design, analysis, research, development, and testing of aerospace vehicles. This encompasses many different aerospace engineering discipline specialties, including aerodynamics, propulsion, performance, stability, control, structures, systems, and others. Several of these fundamental disciplines of aerospace engineering are introduced in this text. The aerospace engineer tests the vehicle, on the ground and in flight, to verify that it can perform as predicted and to improve its operating

[1] John Thomas Daniels, Jr. (1873–1948) snapped the iconic photograph of the Wright brothers' historic first flight. Daniels was a member of the Kill Devil Hills, North Carolina, Life Saving Station, which relied on volunteers to respond to the frequent shipwrecks in this barrier island area. The Wright's *Flyer* made four flights on 17 December 1903, three of which were photographed. After the fourth and final flight, a gust of wind caught the airplane and Daniels grabbed a wing strut, attempting to hold the airplane down. He was caught between the biplane wings when the *Flyer* flipped over in the wind. Although the *Flyer I* was destroyed, Daniels was unhurt, and he would later recount that he had "survived the first airplane crash".

[2] Orville Wright, *How We Made the First Flight* (1986) Federal Aviation Administration, Office of Public Affairs, Aviation Education Program, US Department of Transportation.

characteristics. Flight testing is usually the final test to be performed on the complete vehicle or system.

In many areas of engineering and technology, there is sometimes a perception that there is "nothing left to be done", or that "there is nothing left to be invented". The impressive successes of our aerospace past may appear, to some, to dim the prospects for future innovations. Aerospace engineers have indeed designed, built, and flown some of the most innovative, complex, and amazing machines known to humanity. However, there is still ample room for creativity and innovation in the design of aerospace vehicles, and opportunities for technological breakthroughs to make the skies and stars far more accessible. By the end of this textbook, you will have greatly increased your knowledge of aerospace engineering, but you will also be humbled by how much more there is to be discovered.

1.1.1 Organization of the Book

Aerospace engineering encompasses the fields of aeronautical and astronautical engineering. As a broad generalization, the aeronautical field tends to deal with vehicles that fly through the sensible atmosphere, that is, *aircraft*. Astronautics deals with vehicles that operate in the airless space environment, that is, *spacecraft*. Aerospace engineering is, in many ways, a merging of these two fields, and includes aircraft, spacecraft, and other vehicles that operate in both the air and space environments. In the coming sections, we get more precise with the definitions of the various types of aerospace vehicles, such as aircraft and spacecraft.

The material in the text is organized in an academic building-block fashion as shown in Figure 1.1. In Chapter 1, we start by defining and discussing some of the many different types of aircraft and spacecraft. Many first flights of these different types of aerospace vehicles are described, providing insights and perspectives into the development and evolution of aerospace engineering. The terms *aircraft* and *spacecraft* are clearly defined, along with definitions of the various parts, components, and assemblies that make up various examples of these types of vehicles. The reader also makes a literary "first flight" in a modern, supersonic jet airplane, which introduces many of the areas to be discussed in the coming chapters.

In Chapter 2, several *introductory concepts* in aerospace engineering and flight test are discussed. This chapter gives the reader some of the basic concepts and terminology, in aerospace

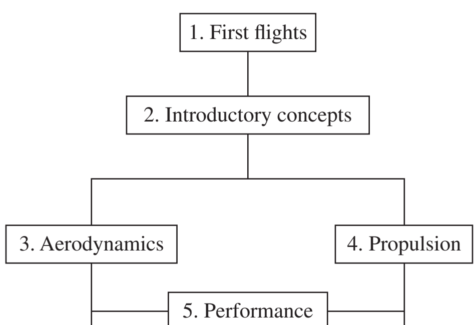

Figure 1.1 Academic building blocks followed in the text.

engineering and flight test, from which to learn the material in the subsequent chapters. Some basic mathematical ideas, definitions, and concepts are reviewed, which starts to fill our engineering toolbox with the basic tools required to analyze and design aerospace vehicles. Basic aerospace engineering concepts, relating to the flight of aerospace vehicles, are introduced, including aircraft axis systems, free-body diagrams, the regimes of flight, and the flight envelope. Basic flight test concepts are introduced, including the different types of flight test, the flight test process, the players involved, and the use of flight test techniques.

The fundamental disciplines of *aerodynamics* and *propulsion* are discussed in Chapters 3 and 4, respectively. The study of aerodynamics, in Chapter 3, provides the theories and tools required to analyze the flow of air over aerospace vehicles, the flow that produces aerodynamic forces such as lift and drag. We discover how and why these aerodynamic forces are created, and how this affects the design of aerodynamic surfaces such as airfoils and wings. In studying propulsion in Chapter 4, we learn about the devices that generate the thrust force to propel aerospace vehicles both in the atmosphere and in space. We develop a deeper understanding of how thrust is produced, regardless of the type of machinery that is used.

The study of *performance*, in Chapter 5, builds upon an understanding of aerodynamics and propulsion, as shown graphically in Figure 1.1. Performance deals with the linear motion of the vehicle caused by the aerodynamic forces (lift and drag) and propulsive force (thrust) acting upon it. Performance seeks to determine how fast, how high, how far, and how long a vehicle can fly.

In Chapter 6, the study of *stability and control* also builds upon the fundamental disciplines of aerodynamics and propulsion. Stability and control deals with the angular motion of the vehicle caused by the aerodynamic and propulsive moments acting on it. We investigate the vehicle's stability when disturbed from its equilibrium condition and seek to understand the impacts of various vehicle configurations and geometries. We also look at the means by which the vehicle can be controlled throughout its flight regime.

Many examples of ground and flight testing are integrated throughout the text, in sections entitled *Ground Test Techniques* and *Flight Test Techniques*. The flight test techniques are described in a unique manner, by placing the reader "in the cockpit" of different aircraft as the test pilot or flight test engineer. The reader obtains an intimate knowledge of the engineering concepts, test techniques, and in-flight data collection by "flying" the flight test techniques. A collateral benefit of this approach is that the reader is familiarized with several different types of real aircraft.

1.1.2 FTT: Your Familiarization Flight

This is the first of many flight test techniques (FTTs) that are "flown" in the text. The FTT is a precise and standardized method, used to efficiently collect data during flight test, research, and evaluation of aerospace vehicles. The FTT process is discussed in more detail in a later section of this chapter.

This first FTT introduces you to aerospace engineering in an exciting way, by taking a flight in a supersonic jet aircraft. A flight test engineer (FTE) often flies a *familiarization flight* in an aircraft prior to performing test flights, especially if this is an aircraft that is new to the FTE. As the name implies, this flight serves to *familiarize* the FTE with the aircraft and the flight environment. The areas of familiarization usually include the aircraft's performance, flying qualities, cockpit environment, avionics, or other special test equipment and instrumentation. The present FTT provides a general description of a familiarization flight, but the primary objective is to introduce you to a wide range of aerospace engineering and test concepts that are explored in later chapters. Your familiarization flight will raise many technical questions about aerospace engineering and flight test, and this provides motivation to seek answers in the chapters to come.

Figure 1.2 McDonnell Douglas F/A-18B *Hornet* supersonic fighter. (Source: *Courtesy of the author*.)

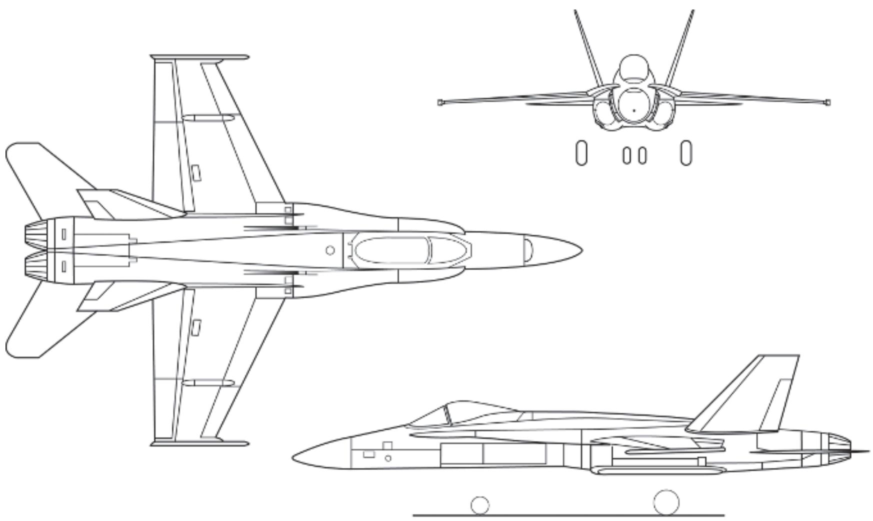

Figure 1.3 Three-view drawing of the McDonnell Douglas F/A-18A *Hornet* (single-seat version shown). (Source: *NASA*.)

For your familiarization flight, you will be flying the McDonnell Douglas (now Boeing) F/A-18B *Hornet* supersonic jet aircraft, shown in Figure 1.2. The F/A-18B is a two-seat, twin-engine, supersonic fighter jet aircraft, designed for launching from and landing on an aircraft carrier. Almost all aerospace vehicles are designated with letters and numbers, which we will decipher in a later section. A three-view drawing of the F/A-18A is shown in Figure 1.3. You will get very familiar

Table 1.1 Selected specifications of the McDonnell Douglas F/A-18B *Hornet*.

Item	Specification
Primary function	All-weather, supersonic fighter/attack jet aircraft
Manufacturer	McDonnell Douglas Aircraft, St Louis, Missouri
First flight	18 November 1978
Crew	1 pilot + 1 instructor pilot or flight test engineer
Powerplant	2 × F404-GE-400 afterburning turbofan engine
Thrust, MIL (ea. engine)	10,700 lb (47,600 N), military power
Thrust, MAX (ea. engine)	17,700 lb (78,700 N), maximum afterburner
Empty weight	~25,000 lb (11,300 kg)
Maximum takeoff weight	51,900 lb (23,500 kg)
Length	56 ft (17.1 m)
Height	15 ft 4 in (4.67 m)
Wingspan	37 ft 6 in (11.4 m)
Wing area	400 ft^2 (37.2 m^2)
Airfoil, wing root	NACA 65A005 modified
Airfoil, wingtip	NACA 65A003.5 modified
Maximum speed	1190 mph (1915 km/h), Mach 1.7+
Service ceiling	>50,000 ft (>15,240 m)
Load factor limits	+7.5 g, −3.0 g

with these types of drawings of aerospace vehicles, where typically side, top, and front views of the vehicle are depicted. Selected specifications of the F-18 *Hornet* are given in Table 1.1. The chapters to come will help you understand all of the technical details in these specifications, such as what defines a "low bypass turbofan jet engine with an afterburner" or why wing area, maximum weights, or load factor limits are important.

Before you can go flying in an F-18, you need to be properly dressed. You don an olive-green flight suit, black flight boots, and an anti-G suit, an outer garment that fits snuggly over the lower half of your body. Inflatable bladders, sewn into the anti-G suit, inflate with pressurized air to prevent blood from pooling in your lower extremities, keeping the blood in your head, so that you do not lose consciousness when the aircraft is maneuvering at high load factors or g's. You slip your arms into a parachute harness that buckles around your chest and both legs. You are wearing the harness for the parachute, but not the actual parachute, as you will buckle this harness into your ejection seat, which contains your emergency parachute in the headrest.

With your flight helmet, oxygen mask, and kneeboard, a small clipboard-type writing surface, in your helmet bag, you walk out to the airport ramp, where the jet is parked. As you walk up to the aircraft, you note its general configuration. The aircraft has a slender fuselage with a low-mounted, thin wing, aft-mounted horizontal tail, twin vertical tails, and tricycle landing gear, comprising two main wheels, extending from either side of the fuselage, and a fuselage nosewheel. You observe that the landing gear looks quite sturdy, designed for harsh aircraft carrier landings. The jet is powered by twin engines, with semicircular air inlets on each side of the fuselage and side-by-side exhaust nozzles at the aft end of the fuselage. The two aviators sit in a tandem configuration, beneath a long "bubble" canopy that is hinged behind the aft cockpit. Your test pilot will be seated in the front cockpit and you will be in the aft cockpit.

You approach the aircraft from its left side, next to the cockpit, as shown in Figure 1.4. Before you climb into the cockpit, you perform a walk-around of the jet to learn a little more about it. Underneath the left wing, near the fuselage, you look into the left engine inlet, which is a semicircular

Figure 1.4 F/A-18B *Hornet* walk-around, left wing. (Source: *Courtesy of NASA/Lauren Hughes*.)

opening. This inlet feeds air to the turbofan jet engine. Later, we will learn about why the inlet is shaped in this way and how the air mass flow, which is ingested through the inlet, is related to the production of thrust. Looking underneath the fuselage, you see a large cylindrical fuel tank with pointed ends, hung underneath the centerline of the fuselage. Of course, you know that the fuel quantity carried aboard the aircraft dictates how far and how long the aircraft can fly. We will see that the range and endurance is a function of more than just the fuel quantity; it is also a function of key parameters related to the aerodynamics and propulsion of the vehicle. We will also learn about how to obtain range and endurance through flight testing.

You move towards the leading edge of the left wing. You observe that the wing is thin, with a somewhat sharp leading edge, and that the wing leading edge is swept backward. There is a large hinged flap surface at the inboard wing trailing edge. We will explore the aerodynamics of three-dimensional wings and their two-dimensional cross-sectional shapes, known as airfoils. We will learn why airfoils and wings are shaped differently for flight at different speeds, including why wings are swept back. We will discuss how hinged flaps increase the lift of a wing. Fundamentally, we will discuss how a wing produces aerodynamic lift, and will discuss the many ways of quantifying the lift and drag of an aircraft, through analysis, ground test, or flight test.

Now you are at the rear of the aircraft, looking at the two engine nozzles, as shown in Figure 1.5. The nozzles have interlocking metal petals that can expand and contract to change the nozzle exit area. We will examine how the flow properties change with area in subsonic and supersonic nozzle flows. We will learn how to calculate the velocity, pressure, and temperature of the gas flowing through the nozzle. You look down the afterburner of the jet engine, which appears to be an almost empty duct. We will discuss the various components of the jet engine, including the afterburner, and will explain their functions. The jet engine is an amazing engineering achievement. We will explore its beginnings, and the engineers who invented it. We also learn about how engines are tested in the ground and flight environments.

Coming around the right, aft end of the airplane, as shown in Figure 1.6, you look at the horizontal and vertical tail surfaces. We will learn why these surfaces are critical to the stability and control of the aircraft. We will see that the locations and sizes of these surfaces are important parameters in defining the aircraft's stability in flight, and will also learn about the control forces associated with

Figure 1.5 F/A-18B *Hornet* walk-around, engine nozzles. (Source: *Courtesy of NASA/Lauren Hughes*.)

Figure 1.6 F/A-18B *Hornet* walk-around, aft, right empennage, and right wing flaps. (Source: *Courtesy of NASA/Lauren Hughes*.)

deflection of these surfaces in an air stream. We will discuss several different flight test techniques used to quantify an aircraft's stability. Near the nose of the airplane, you notice several L-shaped tubes mounted on the lower side of the fuselage. We will learn about these Pitot tubes, which are used to measure the F-18's airspeed, and will investigate how they work in subsonic and supersonic flight. We will also see that flight testing is required to calibrate these probes to obtain accurate airspeed information. You come to the aircraft nose, which has a pointed shape. We will explore the aerodynamics of two and three-dimensional bodies, such as this nose shape. We will also touch on the interesting phenomena that occur when these types of pointed shapes are at high angles of attack.

Returning to the left side of the fuselage, with your walk-around complete, you meet up with your test pilot. It is time to get into the airplane and go flying. The pilot climbs the ladder into the front cockpit and you follow, making your way into the back cockpit. You buckle your lap belt, plug in your G-suit hose, and connect the ejection seat shoulder belts to your harness. Next, you don your flight helmet, connect your oxygen mask hose, plug in your communications cable, and slip on your flying gloves. You strap your kneeboard on your right thigh so that you will be able to take some notes during your flight. Now that you are strapped in and have connected all of your gear, you have a chance to relax and look around. There is a center control stick, two rudder pedals at your feet, and two throttle levers by your left side. The instrument panel in front of you has three square display screens, surrounded by buttons, and an array of other circular, analog instruments (Figure 1.7).

You hear the test pilot in your helmet earphones, asking if you can hear him and if you are ready for engine start. You reply affirmatively, and a few seconds later, you hear the whir of the engines coming alive. After engine start, the canopy lowers, and the pilot performs various checks, including checks of the flight control system. After these checks, the pilot taxis the jet to the end of the runway. The pilot performs the pre-takeoff checks, then tells you to arm your ejection seat, and asks if you are ready for takeoff. You say you are ready to go. The pilot contacts the control tower and requests a takeoff clearance with an unrestricted climb. The tower grants both requests, and the pilot taxis the jet to the centerline of the runway.

The pilot pushes the throttles forward into full afterburner and the jet accelerates forward. In what seems like a very short distance, the F-18 is airborne. We will learn how to calculate the takeoff

Figure 1.7 F/A-18B *Hornet* front cockpit. (Source: *NASA*.)

distance and define the parameters that affect this calculation. We will also learn how to measure the takeoff distance in flight test. The pilot keeps the jet low to the ground, continuing to gain airspeed, and then pulls the jet up to what seems like a near vertical climb. You feel pushed down heavily into your seat. Looking at the g-meter, you see that you are pulling about 4 g's, making you feel four times heavier than your normal weight. We will see how the load factor affects the turn radius of this type of pull-up maneuver and we will calculate the radius of this vertical turn. We will discuss climb performance and define how to calculate the rate and angle of climb. We will also investigate climb performance from an energy perspective, where we account for kinetic and potential energies of the vehicle. We will make energy plots that define the performance capabilities of the aircraft, and we will discuss the flight test techniques used to quantify climb performance.

Looking at the altitude indication, you see that the numbers are increasing rapidly. At an altitude of about 14,000 ft (4270 m), the pilot rolls and pulls out of the vertical climb, so that you are upside down, and then rolls the aircraft upright to wings-level flight. Reducing the engine power, the pilot stabilizes the aircraft at a constant airspeed and altitude to let you catch your breath for a moment. Looking at the cockpit instruments, you see that you are at an airspeed of about 220 knots (253 mph, 407 km/h) and a Mach number of 0.6. We will discover that there are many different kinds of airspeeds and look at the reason for these different definitions. We will learn about Mach number, how it is defined, what it physically means, and why it is so important in high-speed aerodynamics. We will see that in this steady-state flight condition, there are four forces acting on the aircraft, which are in balance, and we will learn that this steady-state trim condition is an important starting point for most of the flight test techniques.

The pilot climbs the F-18 higher, leveling off at an altitude of 30,000 ft (9140 m). The airspeed indicates 350 knots (403 mph, 643.7 km/h), the outside air temperature (OAT) is a frigid −48°F (412°R, 228.7 K), and the Mach number reads about 0.6. We will learn about how the atmosphere changes, from sea level to high altitudes, and how this affects the calculations of aircraft performance. We will develop models of the atmosphere that will be used in our analyses. The pilot advances the throttles into full afterburner, and the F-18 accelerates in level flight. You watch the Mach indicator, waiting for it to indicate that you have broken the sound barrier and are flying at supersonic speed. We will discuss what is meant by the "sound barrier" and how it was "broken" for the first time. Looking out at the wing, you see something that looks like blurry light-and-dark lines or bands, dancing on the wing surface. You glance at the airspeed indication and it shows 530 knots (609.9 mph, 981.6 km/h). These are shock waves forming on the wing as the jet reaches transonic speeds. We will explain why these form on the wing and at what flight speeds. We will discuss the implications of these shock waves on the aerodynamics of the aircraft. We will learn that there are techniques to visualize these flow structures in flight.

The jet continues the level acceleration, and the Mach meter is indicating about Mach 0.96, when it jumps to Mach 1.1. We will explain the aerodynamic cause of this jump in the Mach indication. You have been on the ground and heard the sonic boom of a jet flying overhead at supersonic speed, yet you heard no sonic boom as your F-18 went supersonic. We will learn about sonic booms and some of the research that has been conducted to understand them. The F-18 continues to accelerate, reaching about Mach 1.3 in level flight. You are now flying at supersonic speed, traveling a distance of about one mile every four seconds. We will learn about high-speed supersonic flow and how it is fundamentally different from low-speed, subsonic flow. We will delve into discussions about even higher speed hypersonic flow, where the Mach number is greater than about five, and the flow physics is distinctly different.

The pilot pulls the throttles back, and the F-18 decelerates to subsonic speed. The pilot asks if you are ready to do some maneuvering. Of course, you say that you are more than ready. First, the pilot does some high-g, level turns, so that you can acclimatize to higher g-loadings. You successively fly level turns at 2g, then 4g, then 6g. With each successive turn, the high load factors push you down further into your seat. We will learn about level turn performance capabilities, the important parameters involved, and the associated flight test techniques. We will also learn about the flight envelope of the aircraft, as related to the airspeed and load factors that are within the aircraft's capabilities.

Now, the pilot asks if you want to fly, so you grab hold of the control stick and get a "feel" for the F-18. We will discuss why the handling qualities of an aircraft are important and how they are evaluated. The pilot tells you to do some rolls, so you push the stick full over to the left and the jet rolls around the horizon in a blur. We will discuss the aircraft stability in all three of its axes, and determine what characteristics determine whether its motion is stable or unstable about these axes. The pilot tells you to pull back the throttles to slow the jet down so that you can do some low-speed flight. You pull the control stick back, raising the nose of the aircraft, and increasing the angle-of-attack. You continue slowly pulling the nose up and, at an angle-of-attack of about 20°, the aircraft starts to gently rock from side-to-side. Pulling back a little more and the wing rock increases and the nose wanders a bit from side to side. At about 25° angle-of-attack, you cannot pull the stick back any further. Looking at the altimeter, you see that you are descending at a high rate. The pilot tells you to recover by returning the control stick to its center or neutral position. After you do this, the nose attitude decreases rapidly and the aircraft is back flying in level flight. We will learn about the aerodynamics associated with high angle-of-attack flight and stall. We will also discuss the aerodynamics and issues involved with aircraft spins. The various ground and flight test techniques to learn about stalls and spins will be covered.

It is time to head back to the airport. The pilot takes the flight controls, rolls the F-18 inverted, and then pulls down in a maneuver called a split-S. As the aircraft is coming through the vertical, you have a great view of the ground below, as shown in Figure 1.8. While this is a fun maneuver to lose altitude quickly, we will see that it can also be used to obtain aerodynamic data about the aircraft. The pilot enters the landing pattern, lowers the landing gear, and slows for the landing approach. Similar to takeoff performance, we will discuss the important parameters, associated with landing performance, and determine how to calculate the landing distance. We will see how the type of runway surface and other factors affects this distance. The F-18 touches down and rolls

Figure 1.8 F-18 familiarization flight, view from the aft cockpit, on the backside of a split-S. (Source: *Courtesy of NASA/Jim Ross.)*

to a stop on the runway. You have had a successful familiarization flight during which we have identified many areas to be discussed and explored in the chapters ahead.

1.2 Aircraft

In the broadest sense, the term "aircraft" refers to all types of vehicles that fly within our Earth's sensible atmosphere. The Federal Aviation Administration (FAA), in its Federal Aviation Regulations [6], defines an *aircraft* as "a device that is used or intended to be used for flight in the air". Aircraft support their weight with the force derived from either static or dynamic sources. For example, a lighter-than-air balloon supports its weight with static buoyancy, while a heavier-than-air airplane generates aerodynamic lift, which balances its weight, due to the dynamic reaction of air flowing over its wings.

1.2.1 Classification of Aircraft

There are many different types of aircraft, and a wide variety of ways that one could classify these different types. We could classify the different types of aircraft based on their geometric configuration, the type of propulsion, the mission or function, or other factors. Perhaps, a reasonable first distinction that we can make is between aircraft that are lighter-than-air and those that are heavier-than-air. A classification of aircraft, based on this starting point, is shown in Figure 1.9.

Lighter-than-air aircraft include airships and balloons. We can further subdivide heavier-than-aircraft into *powered* and *unpowered* aircraft, that is, aircraft with and without one or more propulsive devices or engines. Unpowered, heavier-than-air aircraft include gliders or sailplanes. Powered, heavier-than-air aircraft can be subdivided into *airplanes*, *rotorcraft*, and *ornithopters*, where the distinction between these different types of aircraft is based on their type of lift production. Airplanes have a *fixed wing*, which produces lift due to the air flowing over it. Rotorcraft encompass all heavier-than-air aircraft that generate lift from rotating wings or spinning *rotor blades*. Rotorcraft can be further divided into *autogyro* and *helicopter*. The autogyro has unpowered, free-spinning rotor blades, which require forward motion for lift production, whereas the helicopter has powered rotors that can produce lift even without forward speed. Ornithopters use *flapping wings* to generate both lift and thrust, similar to a bird. Many early would-be inventors

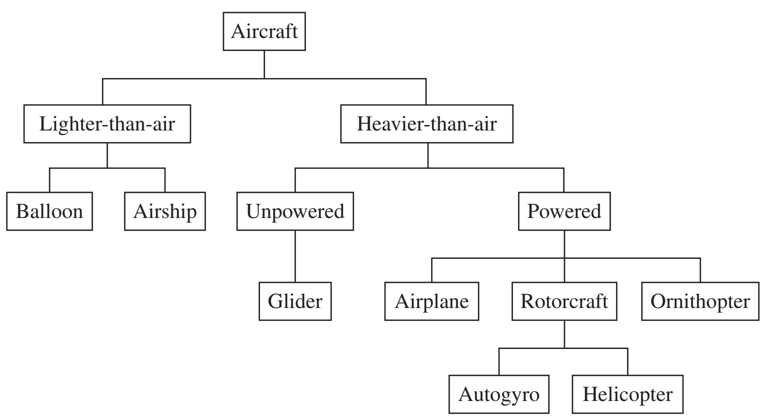

Figure 1.9 Classification of different types of aircraft.

of the first heavier-than-air airplane attempted to fly this type of flapping wing machine, but without success. We generally follow the classifications given in Figure 1.9 to describe aircraft in the following sections. We start our discussion of aircraft with the fixed-wing airplane.

1.2.2 The Airplane

Since most of us have grown up in a time where airplanes are commonplace, it is difficult to imagine that we do not know what an airplane is “supposed to look like”. However, if we were living in the late 1800s, prior to the first successful flight of a heavier-than-air machine, we would probably be influenced by nature, and think that airplane flight should mimic bird flight. Some of the early aviation enthusiasts took this to the extreme, attempting to construct flyable ornithopters. Other early aviation pioneers made careful observations of bird flight, trying to understand nature’s secrets about flight. There are now many variants on what an airplane looks like, but there are several common fundamental engineering aspects to heavier-than-air flight that have made it successful. We will see examples of this in the design and successful flight of the first airplane.

1.2.2.1 The First Airplane

At the beginning of this chapter, the iconic photograph of the first controlled, sustained flight of a heavier-than-air, powered airplane was presented. This first flight was the culmination of years of hard work by two brothers from Dayton, Ohio: Orville (1871–1948) and Wilbur (1867–1912) Wright. The brothers followed a logical and systematic approach in the design, construction, and flight test of their powered airplane. They critically reviewed much of the existing technical information and data relevant to aeronautical theory and aircraft design. In several important areas, the Wright brothers determined that the state-of-the-art information and data was not adequate or was incorrect, so they performed their own, independent analyses and tests to obtain what they needed. An example of this is the designs of the airfoil shapes for their wings and propellers, which were based on data that they collected using a wind tunnel of their own design. They also developed their own aircraft internal combustion engine, with the help of expert machinist, Charlie Taylor. The Wright brothers’ determination to ensure that their airplane design was based on sound technical data was fundamental to their success.

The Wright brothers were also methodical and systematic in their approach to flying and flight testing. Between 1900 and 1903, they performed extensive flight testing with gliders of their own design. Starting first with unmanned, kite-like gliders (Figure 1.10), they systematically progressed to manned glider flights (Figure 1.11). The Wright brothers designed, built, and flew their first manned glider at Kitty Hawk, North Carolina, in 1900 with disappointing results. They test flew another glider design in 1901, but this second manned glider also flew poorly. It was not until their third glider design in 1903 that the Wright brothers were satisfied with how the glider flew. These glider design iterations systematically improved the performance and flying qualities of their unpowered airplanes and these lessons learned were incorporated into their 1903 powered airplane design.

The glider flying had another very important purpose, in addition to collecting flight data to improve their designs. By flying these many glider flights, the Wright brothers were learning *how to fly*. They gained extensive piloting experience in how to *control* their aircraft in the new three-dimensional world of flying. They understood that not only must a successful heavier-than-air vehicle lift its own weight, but it must also be *controllable*. They designed their aircraft to be controllable by the pilot in all three axes, with independent control effectors in pitch, roll, and yaw.

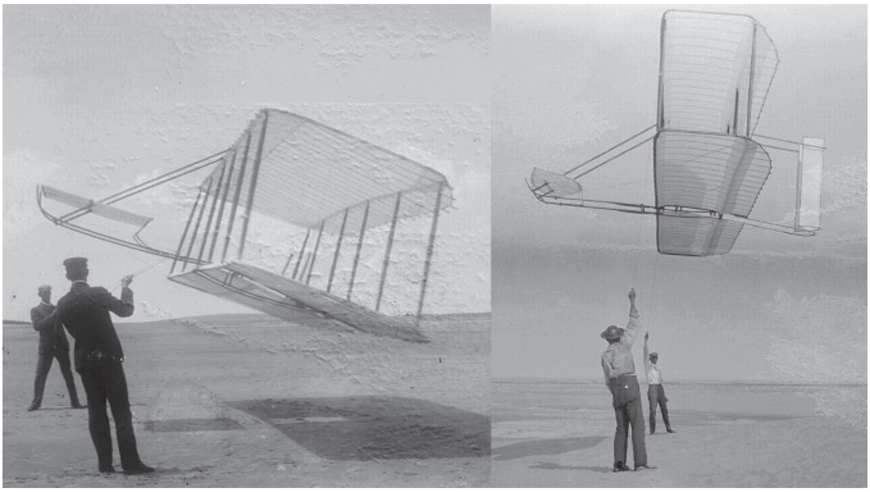

Figure 1.10 Unmanned, kite-like gliders from 1901 (left) and 1902 (right). (Source: *Wright Brothers, 1901 and 1902, US Library of Congress, PD-old-100*.)

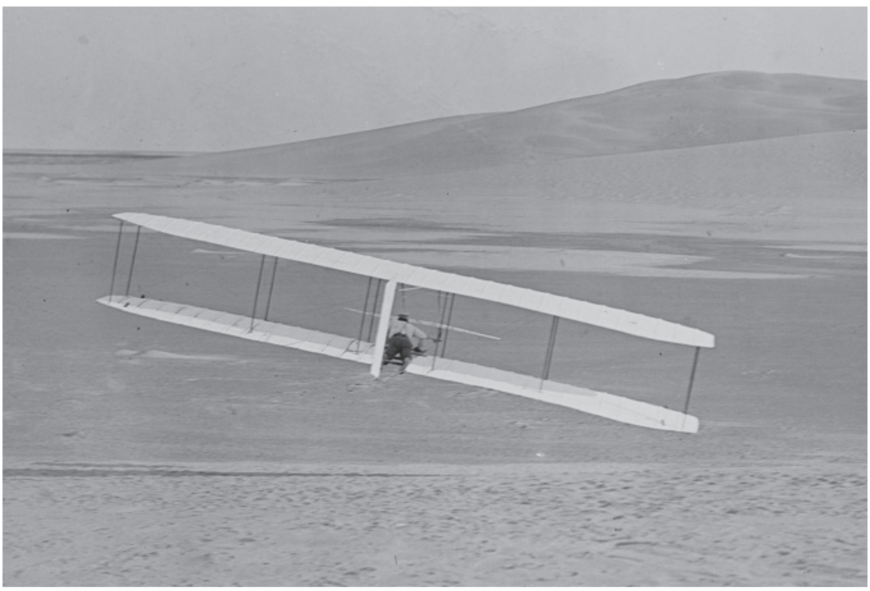

Figure 1.11 Flight of a Wright brothers manned glider, October 24, 1902. Note the single vertical rudder on this glider. (Source: *O. Wright, 1902, US Library of Congress, PD-old-100*.)

Their airplane design had an elevator for pitch control, a rudder for yaw control, and for roll control, they used a scheme of *warping* or twisting of the wings.

The Wright brothers spent a considerable amount of time observing the flight of birds, and in particular the flights of buzzards. Their observations of bird flight gave them valuable insights into how to control a flying vehicle. They observed that as the birds soared and turned, the shape of their wings changed. Realizing that this wing twisting or warping was critical to the roll control of the maneuvering birds, the Wright brothers incorporated the wing warping concept into their airplane designs, and finally into the design of the first successful heavier-than-air airplane.

It is interesting to read the Wright brothers' description of their invention of a heavier-than-air flying machine in their original patent, as shown below. Note, that they make particular mention of the stability and control aspects of their airplane.

> Be it known that we, Orville Wright and Wilbur Wright, citizens of the United States, residing in the city of Dayton, county of Montgomery, and State of Ohio, have invented certain new and useful Improvements in Flying-Machines, of which the following is a specification. Our invention relates to that class of flying machines in which the weight is sustained by the reactions resulting when one or more aeroplanes are moved through the air edge-wise at a small angle of incidence, either by the application of mechanical power or by the utilization of the force of gravity. The objects of our invention are to provide means for maintaining or restoring the equilibrium or lateral balance of the apparatus, to provide means for guiding the machine both vertically and horizontally, and to provide a structure combining lightness, strength, convenience of construction, and certain other advantages which will hereinafter appear.
>
> US patent 821,393, "Flying-Machine"
> Application filed March 23, 1903
> Patent granted May 22, 1906

The Wright brothers' successful, first powered airplane, the *Flyer I*, was a canard[3] configuration biplane, with a forward-mounted, all-moving horizontal, biplane elevator and an aft-mounted, vertical, twin rudder. (The all-moving nature of the elevator is clearly seen in the photograph of the *Flyer I*'s first flight, shown at the beginning of the chapter.). The airplane structure was a spruce and ash wooden framework, covered with finely woven muslin cotton fabric. The wing bracing wires were 15-gauge bicycle spoke wire. The airplane had a single, four-cylinder, gasoline-fueled piston engine, capable of producing about 12 horsepower (8.9 kW). Less than half a gallon of gasoline fuel was carried onboard the airplane. There was no engine throttle, the pilot could only open or close the fuel line that supplied the engine. The engine drove two contra-rotating, pusher propellers through a chain-drive transmission system. The propellers rotated at an average speed of about 350 revolutions per minute (rpm). The 170 lb (77 kg) engine was mounted on the right wing. To counterbalance the engine weight, the pilot was placed on the left wing. Since the typical pilot weight of about 145 lb (66 kg) was less than the engine weight, the right wing was about 4″ (10 cm) longer than the left.

Unusual by today's standards, the pilot lay prone on his stomach, with his hips in a padded wooden cradle, facing towards the front-mounted elevator. The wing-warping roll control and rudder-deflection yaw control were interconnected, such that sliding of the hip cradle sideways caused the wings to warp and the rudders to deflect. A wooden lever in the pilot's left hand controlled the aircraft pitch by changing both the angle of the elevator and the camber or shape of the elevator airfoil section. If the pilot pulled back on the lever, the elevator angle and camber were increased, thereby increasing its lift. If the pilot pushed the lever forward, the elevator angle and camber were decreased, resulting in less elevator lift. (Airfoil camber is discussed in Chapter 3.)

---

[3] The word *canard* is literally translated from French as "duck". It is speculated that the aeronautical usage came from the French public's comparison of a 1906 airplane, designed and flown by Brazilian aviation pioneer Alberto Santos-Dumont, to a duck. This 1906 airplane, named the *No. 14-bis*, was a biplane with a forward-mounted elevator. Santos-Dumont first flew the *No. 14-bis* on 13 September 1906, but this powered hop was only 23 feet (7 m) in distance. He is credited with flying the first public flight of a heavier-than-air airplane in Europe, when he flew the *No. 14-bis* on 23 October 1906, traveling a distance of about 200 feet (61 m).

Table 1.2 Selected specifications of the 1903 Wright *Flyer I*.

Item	Specification
Primary function	First heavier-than-air flying machine
Manufacturer	Orville and Wilbur Wright, Dayton, Ohio
First flight	17 December 1903
Crew	One pilot
Powerplant	In-line, 4-cylinder, water-cooled piston engine
Engine power	12 hp (8.9 kW) at 1020 rpm
Fuel capacity	0.2 gal (0.65 l) of gasoline
Propellers	Two 2-bladed, 8 ft (2.4 m) diameter
Empty weight	605 lb (274 kg)
Gross weight	750 lb (341 kg)
Length	21 ft 1 in (6.43 m)
Height	9 ft 4 in (2.8 m)
Wingspan	40 ft 4 in (12.3 m)
Wing area	510 ft^2 (47.4 m^2) (upper and lower wings)
Wing loading	1.47 lb/ft^2 (7.18 kg_f/m^2)
Maximum speed	30 mph (48.3 km/h)
Stall speed	22 mph (35 km/h)
Ceiling	30 ft (9.0 m)

The *Flyer I* used a 60 ft (18.3 m) launch rail for takeoff. The aircraft was restrained, sitting on the rail, until the pilot was ready for takeoff. He then released the restraining rope and the aircraft started its takeoff roll along the rail, riding on two modified bicycle wheel hubs. The aircraft had wooden skids for landing on the sandy ground. The *Flyer I* had a maximum airspeed of about 30 mph (48 km/h) and a maximum altitude of about 30 ft (9.0 m). Selected specifications of the Wright *Flyer I* are given in Table 1.2.

After winning a coin toss, Wilbur Wright attempted the first flight of the *Flyer I* on 14 December 1903. The launch rail was placed on an incline, giving the aircraft a downhill, gravity-assisted takeoff roll. Taking off in a light wind, Wilbur pulled the *Flyer I* off the launch rail, but almost immediately stalled the aircraft, causing it to return to earth in about three seconds. This "powered hop", with a gravity-assisted takeoff, could not be considered a first, controlled flight of a heavier-than-air airplane. The aircraft sustained some minor damage, which took three days to repair.

On 17 December 1903, it was Orville's turn to attempt the first flight. Since the winds were blowing at more than 20 mph (32.2 km/h), the launch rail was placed on level ground and pointed into the wind. At 10:35 am, Orville Wright made the first controlled, powered flight in a heavier-than-air airplane, with the flight lasting about 12 seconds, landing 120 ft (37 m) from the point of takeoff. The Wright brothers made four flights that day, with the final flight lasting almost a full minute. A summary of the initial flights of the *Flyer I* on 14 and 17 December 1903 is given in Table 1.3. After the successful flights of 17 December, the Wright brothers sent a telegram to their father, telling him about their accomplishment (Figure 1.12). Soon after the fourth landing, a gust of wind picked up the *Flyer I* and it tumbled end-over-end across the rough and sandy terrain. The *Flyer I* was destroyed and never flew again. Quite fittingly, a part of the *Flyer I* would soar again, when a piece of its wing fabric and a piece of wood from one of its propellers were carried inside a spacesuit pocket of Neil Armstrong when he stepped onto the surface of the moon on 20 July 1969.

Table 1.3 Wright brothers' flights of 14 and 17 December 1903.

Flight No.	Date	Flight Time	Ground Distance	Pilot
1	14 Dec	3 sec	112 ft (34.1 m)	Wilbur
2	17 Dec	12 sec	120 ft (36.6 m)	Orville
3	17 Dec	13 sec	175 ft (53.3 m)	Wilbur
4	17 Dec	15 sec	200 ft (61.0 m)	Orville
5	17 Dec	59 sec	852 ft (260 m)	Wilbur

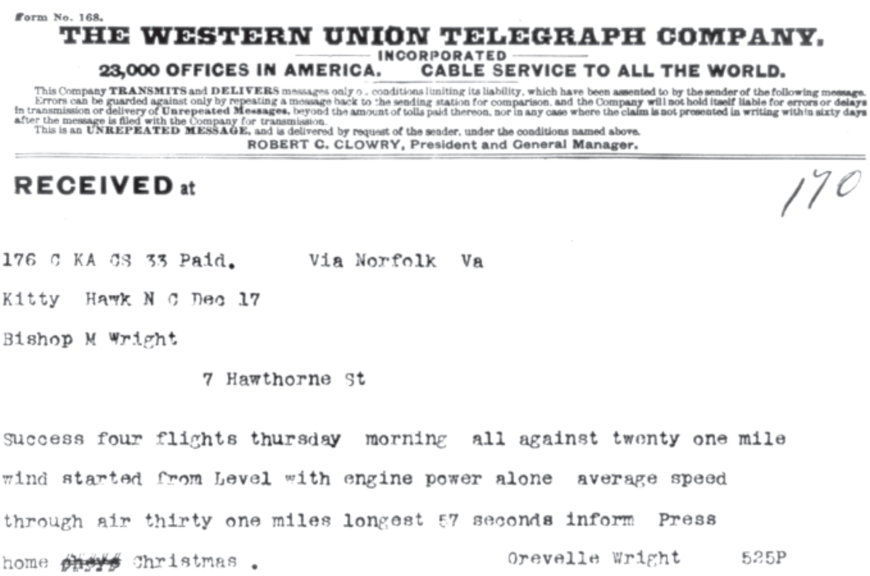
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Figure 1.12 Telegram from Orville Wright on 17 December 1903 after a successful day of flying. The stated speed through the air of 31 mph is the sum of the ground speed and wind speed. (Source: *PD-old-100*.)

1.2.2.2 Parts of an Airplane

In this section, the major parts of a fixed-wing airplane are described. There are many different aircraft configurations, as discussed in the next section. For our present purpose, we reference a somewhat standard aircraft configuration, with a single fuselage, a single wing attached to the fuselage, podded engines mounted underneath the wings, and horizontal and vertical tail surfaces mounted to the fuselage, aft of the wing, as shown in Figure 1.13. This configuration is in wide use today for commercial, military, and general aviation applications. The following discussion is generally applicable to other aircraft configurations, discussed in the next section. The major components of an airplane are the *fuselage*, *main wing*, *empennage*, *engines*, and *landing gear*. The fuselage contains the cockpit, passenger, and cargo compartments. The main wing extends from either side of the fuselage and often has integral fuel tanks within it. The *empennage*[4] is the tail area of the airplane, comprising the horizontal and vertical *stabilizers* and the associated moving control surfaces: the *elevators* and *rudders*, respectively. If the airplane is a powered airplane, there is one or

[4] The word *empennage* comes from the French *empenner*, to feather an arrow, where *empennage* refers to the feathers of an arrow.

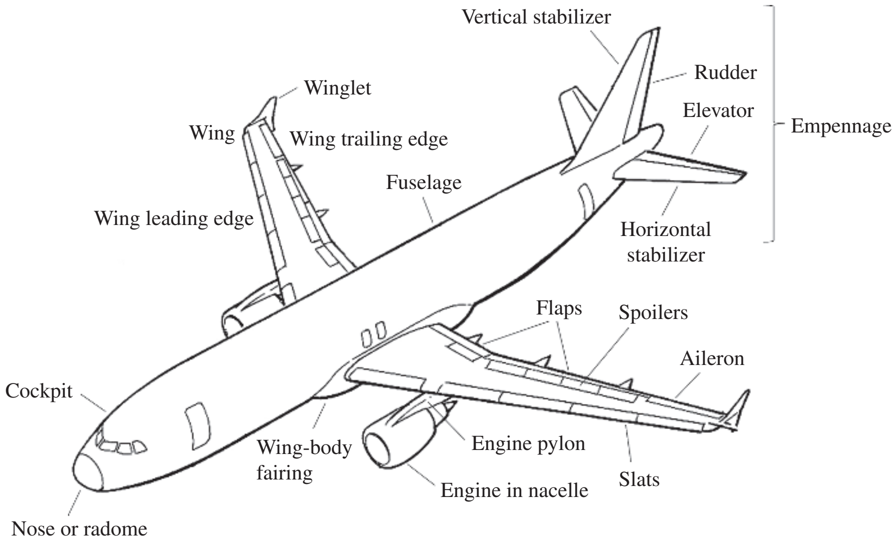

Figure 1.13 Parts of the conventional configuration airplane.

more wing or fuselage-mounted engines. The powerplant may be a reciprocating-engine–propeller combination or a jet engine. The engines may be *podded*, with the engine pods or *nacelles* mounted above or below the wings or on the sides of the fuselage. The engines may be *buried* in the fuselage, with an inlet or intake opening towards the front of the fuselage and exhaust openings at the aft end. The landing gear is composed of wheels with tires attached to struts, extending from the fuselage, wings, or engine pods. Often, the landing gear configuration consists of two main gear assemblies under the wings and a nose gear at the front of the fuselage, although other configurations are possible.

The elevators and the rudder on the empennage, and the ailerons on the wings comprise the primary flight control system. Each of these control system surfaces provides an incremental aerodynamic force that creates a moment to rotate the aircraft about its center of gravity (CG) in the desired direction. As shown in Figure 1.14, these control surfaces enable rotation of the airplane in three dimensions, where the elevator, ailerons, and rudder provide pitch, roll, and yaw rotations, respectively. Elevators are flap-like devices located at the trailing edges of the horizontal stabilizers. Some aircraft, typically military fighter aircraft, have all-moving horizontal stabilizers, called *stabilators* or *stabs*, instead of a combination of stabilizers and elevators.

The ailerons on the left and right wings deflect in opposite directions; that is, when the right aileron deflects upward, the left aileron deflects downward and vice versa. The downward deflected aileron results in additional lift on one side of the wing, while the upward deflected aileron results in decreased lift on the other side of the wing, creating the rolling moment. The additional lift produced by the downward deflected aileron also results in additional drag. This additional drag produces a yawing moment in a direction opposite or *adverse* to the desired direction of roll, and therefore is called *adverse yaw*. To counter this adverse yaw, the rudder is deflected to produce an opposing yawing moment, resulting in what is termed a *coordinated turn*.

High-speed aircraft also have secondary or auxiliary flight controls, which include devices on the wings called flaps, slats, and spoilers. Flaps are high-lift devices, located at the inboard wing trailing edge sections. When deflected or lowered, the flaps provide increased lift at lower airspeeds, enabling steeper landing approach glide paths without an increase in the approach airspeed. Slats,

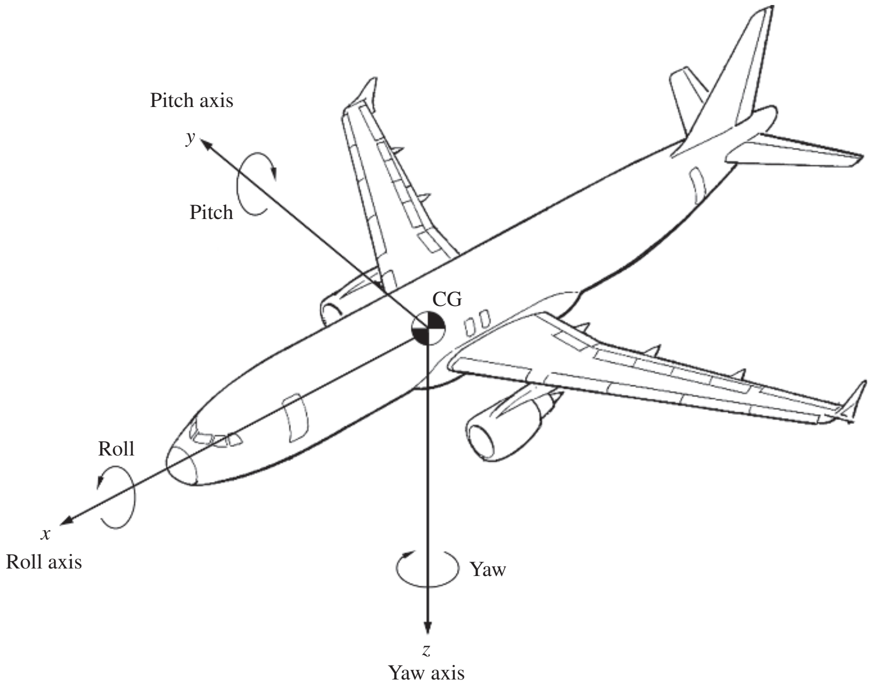

Figure 1.14 Airplane axes and rotations.

which are extended from the wing leading edge, are also high-lift devices that increase the wing lift at low speeds. There are several different types of wing flaps and slats, of varying mechanical complexity and aerodynamic effectiveness, which are discussed in Chapter 3. Spoilers, which extend upward from the wing upper surface, reduce or "spoil" the lift, to assist the airplane in slowing down and descending. They are also deployed after landing, to "dump" the wing lift and transfer the airplane's weight from the wings to the landing gear, which improves braking. Spoilers can also be used as a means of airplane roll control, when deployed differentially (extending from one wing and not the other).

1.2.2.3 Airplane Configurations

Airplanes come in all shapes and sizes. Usually, the configuration of an airplane is driven, or at least strongly influenced, by its mission requirements. For example, a commercial airliner has a large fuselage cabin area due to the requirement to transport passengers. A military fighter jet may have a highly swept wing to allow it to fly supersonically (we will see why this is so in Chapter 3.). A utility airplane that must be able to take off and land on snow might have skis for landing gear. These are a few examples of the types of aircraft configurations that may be driven by the mission requirements. It may be possible to satisfy the mission requirements with a variety of design solutions, limited only by the imagination and creativity of the airplane designer, and influenced by advancements in technology. A listing of possible airplane configurations for different components is given in Table 1.4. This listing is not meant to be exhaustive, but rather to illustrate the many possibilities in airplane designs. We briefly discuss several of these configuration options, citing real airplane design examples along the way, to better appreciate the possibilities.

Table 1.4 Sampling of possible airplane configurations.

Area	Possible airplane configurations
Fuselage type	Single fuselage, twin fuselage, twin boom
Number of wings	Monoplane, biplane, triplane
Wing location	Low-wing, mid-wing, high-wing
Wing type	Straight, aft-swept, forward-swept
Horizontal tail	Aft-mounted, forward-mounted (canard), tailless
Vertical tail	Single or twin vertical fin
Propulsion	Reciprocating piston, gas turbine (jet), rocket
Number of engines	Single or multi-engine
Engine(s) location	Above or below wing, fuselage side-mounted, internal
Landing gear type	Wheel, skid, float, ski
Landing gear	Tricycle, tail wheel, bicycle

Figure 1.15 North American F-82 *Twin Mustang* twin fuselage airplane. Note that there is a pilot in each fuselage cockpit. (Source: *US Air Force*.)

It is quite common for airplanes to have a single fuselage, whereas twin fuselage airplane designs are somewhat rare. A twin fuselage aircraft may offer some advantages for some applications. The twin fuselage airplane may have reduced design and development time and costs, if an existing single-fuselage airplane can be used as a baseline. This was the case for the North American F-82 *Twin Mustang*, developed near the end of World War II (see photo in Figure 1.15, drawing in Figure 1.16). Based on the single-fuselage XP-51 Mustang (see Figure 3.72), the F-82 was designed as a very long range fighter escort aircraft, with a nominal range of over 2000 miles (3200 km). The F-82 twin fuselages were from the single-fuselage P-51, which was stretched by 57″ (1.45 m), allowing for the installation of additional fuel tanks. Both cockpits were retained from the single-fuselage airplanes, so that a pilot in either cockpit could fly the airplane, which was advantageous for very long duration flights. The F-82 saw combat during the Korean War,

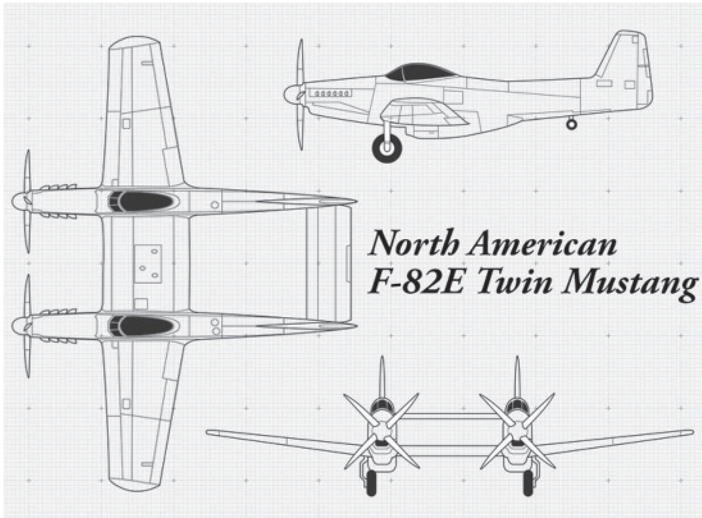

Figure 1.16 Multiple-view drawing of North American F-82 *Twin Mustang*. (Source: *NASA*.)

being the first fighter to shoot down a North Korean aircraft. The F-82 *Twin Mustang* still holds the record for the longest, non-stop flight by a propeller-driven fighter airplane, when it flew from Hawaii to New York, a distance of 5051 miles (8128 km), in 14 hours 32 minutes on 27 February 1947.

The twin fuselage configuration has found an application for airplanes that carry a large, centerline payload, such as the Virgin Galactic *White Knight Two*, which carries the *Spaceship Two* (see photo in Figure 1.17, drawing in Figure 1.18). The twin-fuselage *White Knight Two* is the first stage of a two-stage space launch system, with the *Spaceship Two* being the second stage. Only the right fuselage of the *White Knight Two* is configured to carry pilots and passengers, but, conceivably, the left fuselage could be designed to do so also. All three fuselages, the two *White Knight Two* and single *Spaceship Two* fuselages, are similar in design. This is an interesting design philosophy, whereby the *White Knight Two* is configured to be flown like the *Spaceship Two*, with a similar cockpit arrangement, equipment, and pilot sight picture. This allows for training and proficiency flying in the *White Knight Two* airplane which simulates, at least, the glide, approach, and landing phases of the *Spaceship Two*.

Similar to the twin fuselage configuration, an airplane may have twin longitudinal *booms* that extend from the main wing to the tail. The twin boom configuration may be advantageous for powerplant integration or for ease of access to aft fuselage cargo doors. The twin booms also provide additional volume for carrying fuel or equipment. The Cessna 337 *Skymaster* is an example of a twin-boom, twin-engine airplane that has been used as a general aviation and military utility aircraft (see photo in Figure 1.19, drawing in Figure 1.20). The twin booms allow both engines to be mounted on the fuselage centerline, with one in a *puller* or *tractor* configuration (forward-mounted engine) and the other in a *pusher* configuration (aft-mounted engine). An advantage of having both engines along the airplane centerline, versus mounted on either side of the fuselage, is that lateral-directional control is not degraded in the event of an engine failure, i.e. there is no yawing tendency with the power loss of one engine.

An airplane with tailwheel landing gear, also sometimes called *conventional landing gear*, is the Extra 300 airplane (see photo in Figure 1.21, drawing in Figure 1.22). The Extra 300 is a two-place,

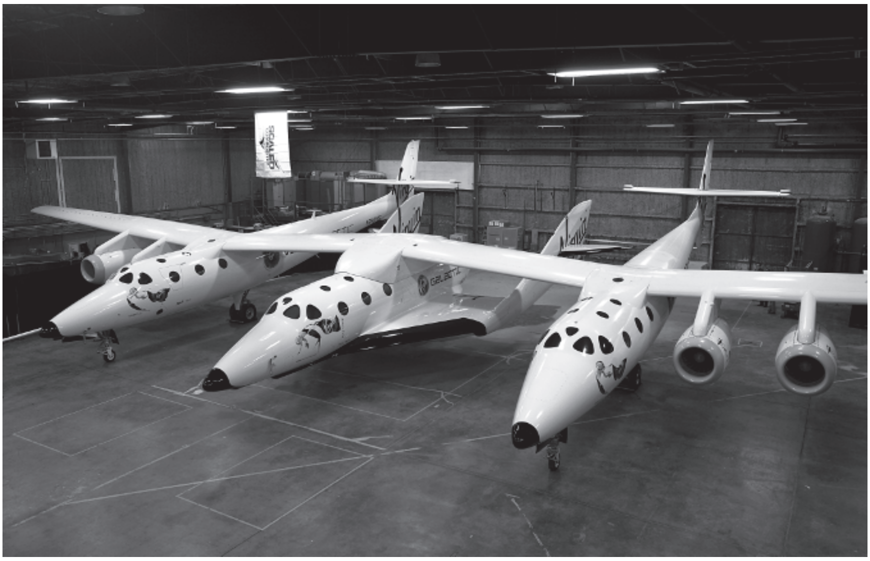

Figure 1.17 Virgin Galactic *White Knight Two* and *Spaceship Two*. (Source: © *Virgin Galactic/Mark Greenberg, "SS2 and VMS Eve" https://en.wikipedia.org/wiki/File:SS2_and_VMS_Eve.jpg, CC-BY-SA-3.0. License at https://creativecommons.org/licenses/by-sa/3.0/legalcode*.)

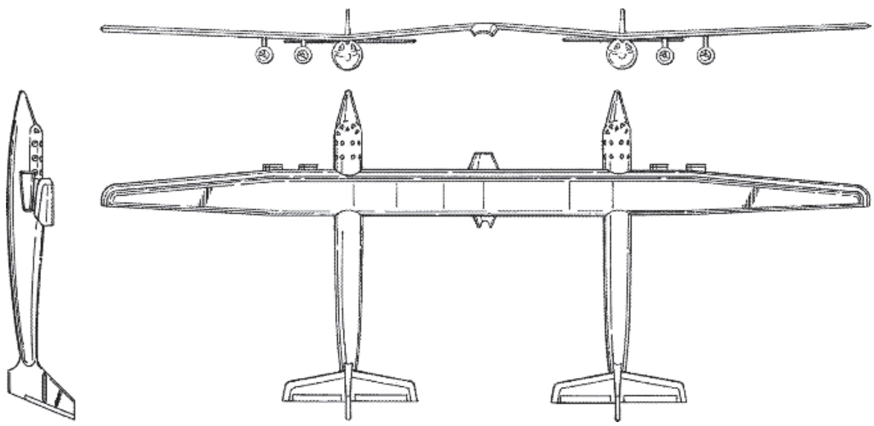

Figure 1.18 Three-view drawing of the Virgin Galactic *White Knight Two* (*Spaceship Two* not attached). (Source: *US Design Patent D612,719 S1, US Patent and Trademark Office, July 25, 2008*.)

single engine, high-performance, aerobatic, general aviation airplane with an all-composite, carbon fiber main wing. The tailwheel configuration is needed to provide ground clearance for the large-diameter propeller at the front of the airplane. The wing is attached to the middle of the fuselage, hence, it is termed a *mid-wing* configuration. The North American *Twin Mustang* is a *low-wing* monoplane and the Cessna *Skymaster* is a *high-wing* monoplane, where the main wing is attached to the bottom and top of the fuselage, respectively.

An example of a forward-swept wing configuration is the Grumman X-29 experimental, supersonic research aircraft (see photo in Figure 1.23, drawing in Figure 1.24). The X-29

Figure 1.19 Cessna 337 *Skymaster* twin-engine airplane with twin booms. (Source: © *User: Kogo, "Cessna Skymaster O-2" https://en.wikipedia.org/wiki/File:Cessna_Skymaster_O-2_5.jpg, GFDL 1.2. License at https://commons.wikimedia.org/wiki/Commons:GNU_Free_Documentation_License,_version_1.2.*)

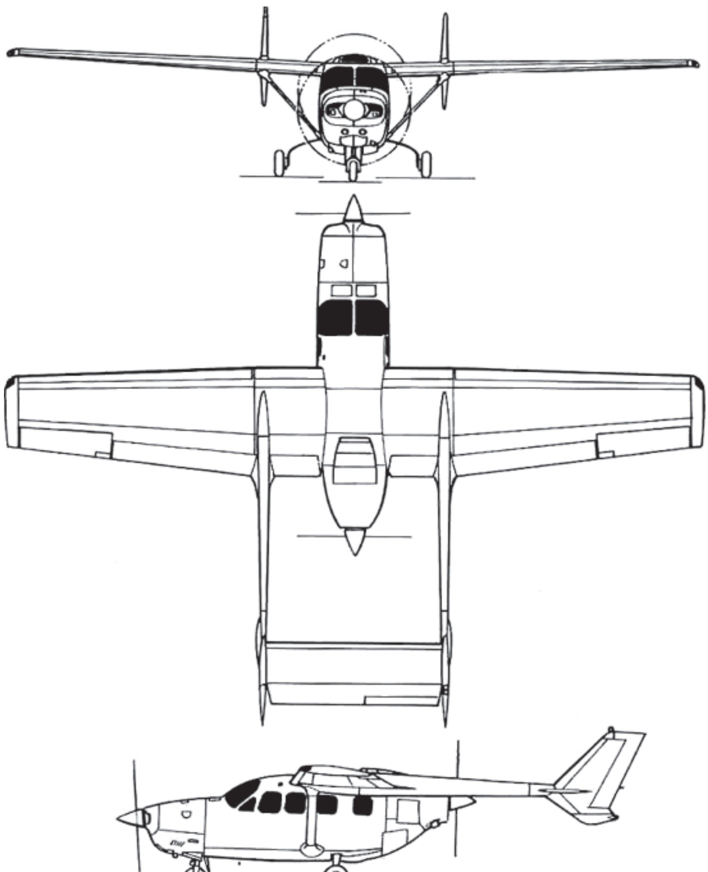

Figure 1.20 Three-view drawing of the Cessna *Skymaster*. (Source: *Courtesy of Richard Ferriere, with permission*.)

Figure 1.21 Extra 300 single-engine, mid-wing, tailwheel airplane. (Source: *Courtesy of the author*.)

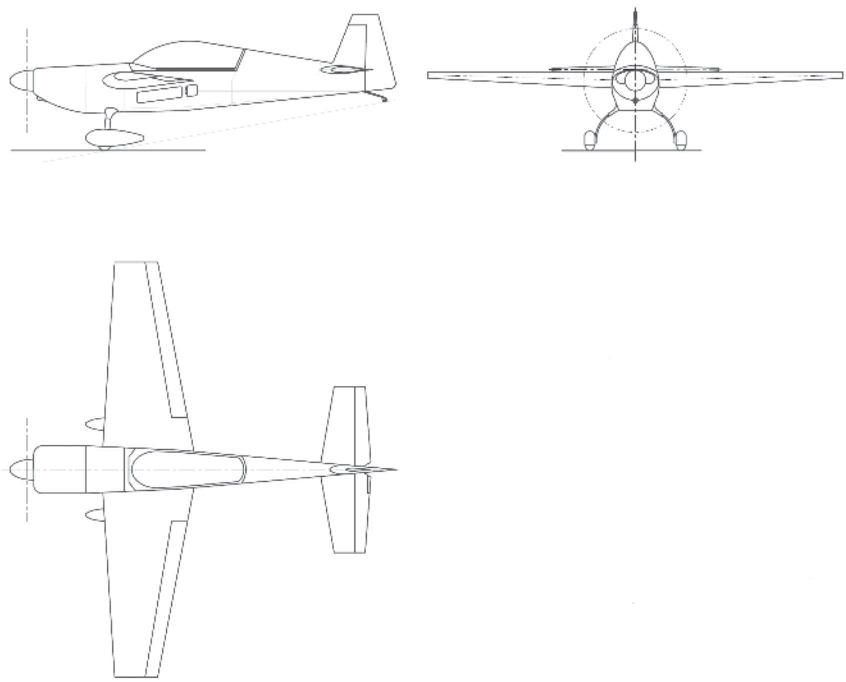

Figure 1.22 Three-view drawing of Extra 300. (Source: *Courtesy of Extra Aircraft, Germany, with permission*.)

investigated forward-swept wing maneuverability and other advanced technologies. Two X-29 aircraft were built, with test flights conducted by NASA and the US Air Force. The single-seat X-29 had a forward-swept main wing and trapezoidal-shaped canard surfaces forward of the wing. Forward-swept wings are susceptible to divergent aeroelastic twisting, so the X-29 wing was fabricated with advanced composite materials, which could provide the required structural stiffness with low weight. The forward-swept wing X-29 was inherently unstable, requiring a

Figure 1.23 Grumman X-29 forward-swept wing research aircraft. (Source: *NASA*.)

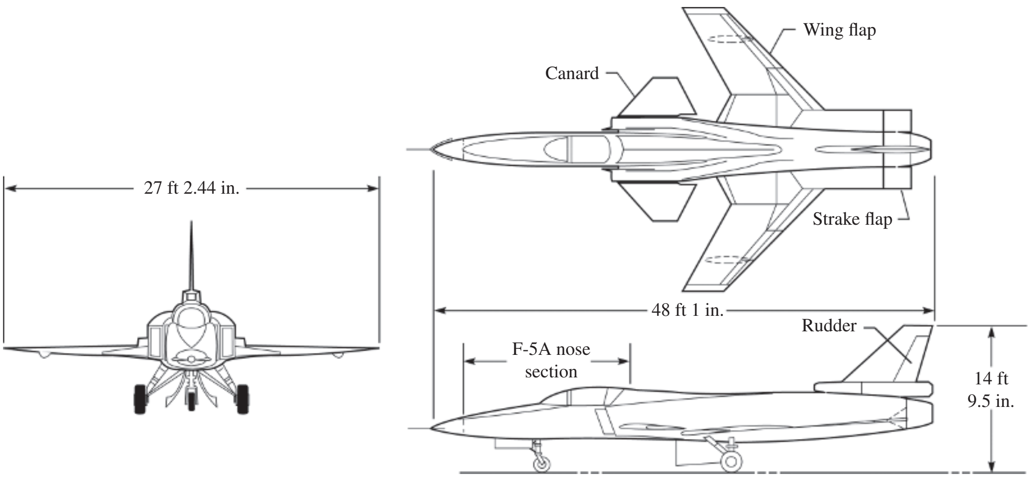

Figure 1.24 Three-view drawing of the Grumman X-29 forward-swept wing aircraft. (Source: *NASA*.)

state-of-the-art "fly-by-wire" flight control system, where the aircraft was constantly flown and stabilized by computers. A single General Electric F404 turbofan jet engine powered the X-29, enabling a top speed of Mach 1.8 at 33,000 ft (10,000 m). The first flight of the X-29 was on 14 December 1984. The two X-29 aircraft completed 422 research test flights over a period from 1984 to 1991.

Most of the airplane configurations that we have discussed so far are single-wing or *monoplane* configurations. An example of an airplane with two main wings, a *biplane*, is the Russian Antonov An-2 *Colt* (see photo in Figure 1.25, drawing in Figure 1.26). The two wings need not have the same dimensions. In fact, a biplane's wings can differ in size, airfoil shape, wing sweep, or other characteristics. The An-2 is a large, rugged, single-engine aircraft designed to perform a variety of utility

Figure 1.25 Antonov An-2 *Colt* single-engine, biplane with ski landing gear. (Source: © *Sergey Ryabtsev, "Randonezh Antonov An-2R" https://en.wikipedia.org/wiki/File:Antonov_An-2R_on_ski_Ryabtsev.jpg, GFDL-1.2, License at https://commons.wikimedia.org/wiki/Commons:GNU_Free_Documentation_License,_version_1.2.*)

tasks such as cargo hauling, crop dusting, water bombing (for fighting forest fires), parachute drop, glider towing, or military troop or civilian passenger transport. Designed by the Antonov Design Bureau, Kiev, Ukraine in 1946, the An-2 was produced for the next 45 years. Because of its sturdy construction, relatively simple systems, low speed capabilities, and large payload capacity, the An-2 has become a popular "bush" plane for flying people and cargo in and out of remote, unimproved areas. Known as a short takeoff and landing, or STOL, airplane, the An-2 can takeoff in less than about 600 ft (180 m) and, due to its extremely low stall speed of less than 30 mph (48 km/h), it needs only about 700 ft (210 m) to land. The An-2 shown in Figure 1.25 has conventional landing gear, but with skis for operation on snow-covered terrain replacing the tires.

All of the airplane configurations that we have discussed so far have distinct fuselage, wing, and tail components. The *flying wing* is a *tailless* airplane configuration, where the fuselage and wing are blended together. The flying wing concept is not new. Flying wing prototype aircraft were built and flown as early as the 1940s. Several flying wing designs were also built and flown in the early 20th century. The Northrop B-2 *Spirit* "stealth bomber" is a modern example of a flying wing airplane (see photo in Figure 1.27, drawing in Figure 1.28). Its two jet engines are "buried" in the blended wing-fuselage to mask their heat signature, enhancing its stealth capability. While there are significant aerodynamic advantages, especially in terms of reduced drag, for a tailless flying wing configuration, the stability and control issues require some special considerations. The advent of "fly-by-wire" flight control technology has made these design issues much easier to manage. We discuss the interesting stability and control considerations of flying wings further in Chapter 6.

1.2.3 Rotorcraft: the Helicopter

Thus far, we have discussed only *fixed-wing* aircraft. We now discuss *rotary-wing* aircraft or *rotorcraft*, where the lift-producing surfaces are rotating. The rotating wings, more properly called *rotor blades*, are attached to the *rotor hub* at the top of a *rotor mast* above the aircraft. The rotor

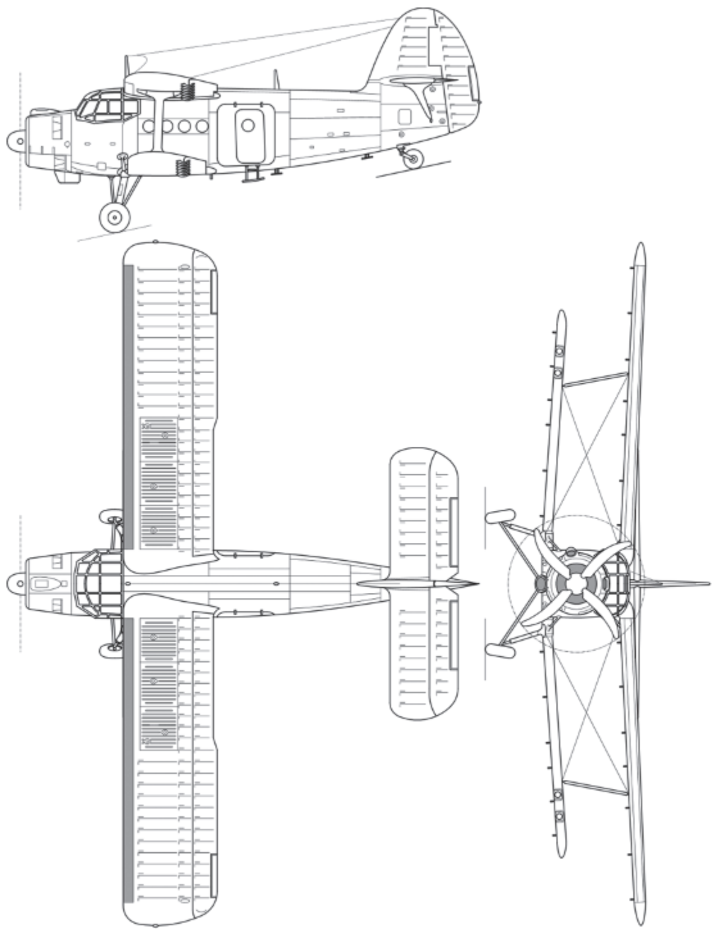

Figure 1.26 Multiple-view drawing of the Antonov An-2 *Colt*. (Source: *Kaboldy, "Antonov An-2 3-View" https://en.wikipedia.org/wiki/File:Antonov_An-2_3view.svg, CC-BY-SA-3.0, https://creativecommons.org/licenses/by-sa/3.0/legalcode.*)

blades, hub, and mast collectively are simply called the *rotor*. Rotorcraft include helicopters and autogyros. Helicopters are heavier-than-air flying machines that can take off and land vertically, translate in any direction, including backwards, and remain stationary in the air or *hover*. They have engine-driven rotor blades that produce both lift and thrust. The lift produced does not depend on the forward speed, so the helicopter can take off and land with zero forward velocity. The rotor can still produce lift if the engine is not running, as long as there is forward speed to keep the rotor blades spinning or auto-rotating. In this manner, the helicopter can glide like a fixed-wing airplane.

Two models of helicopters are shown in Figure 1.29, the Sikorsky UH-60 *Black Hawk* helicopter and the Bell OH-58 *Kiowa* light helicopter. The UH-60 is a twin-engine, single-rotor, 4-bladed military helicopter, designed for utility and transport operations. It carries a crew of two, and up to 11 passengers. The rotor of the UH-60 has a diameter of 53 ft 8 in (16.36 m). The UH-60 has a cruise speed of about 170 mph (294 km/h) and can climb to a maximum altitude of about 20,000 ft (6100 m). A three-view drawing of the UH-60 is shown in Figure 1.30. The Bell OH-58 *Kiowa* is a single-rotor, 2-bladed, military helicopter, designed for light utility and transport. The *Kiowa* is

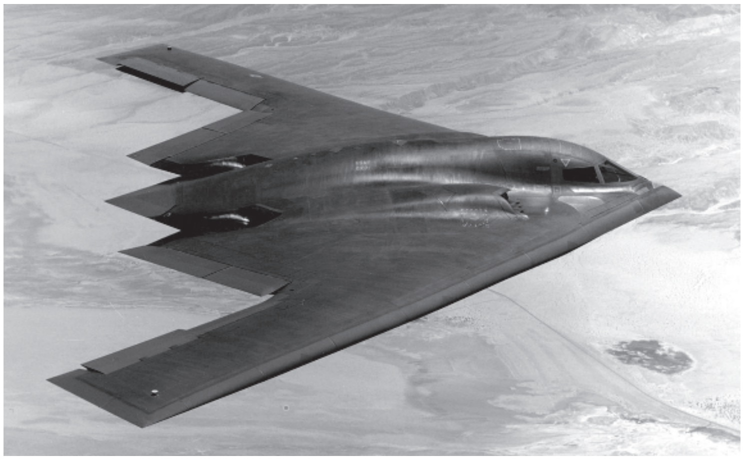

Figure 1.27 Northrop Grumman B-2 *Spirit* flying wing airplane. (Source: *US Air Force*.)

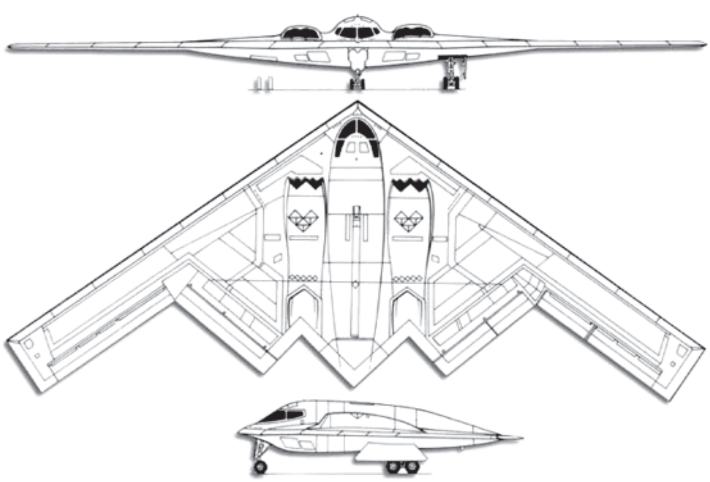

Figure 1.28 Three-view drawing of the Northrop Grumman B-2 *Spirit*. (Source: *PD-USGov-Military*.)

the military version of the popular Model 206A *Jet Ranger* civilian helicopter. The OH-58 carries a crew of one or two pilots with the civilian version capable of carrying up to four passengers. The rotor diameter of the OH-58 is 35 ft (10.7 m). The OH-58 has a cruise speed of 127 mph (204 km/h) and a maximum ceiling of about 15,000 ft (4600 m).

Autogyros, also known as gyrocopters or gyroplanes, have unpowered, free-spinning rotor blades that require forward motion to produce lift. Thrust is provided by an independent engine–propeller combination mounted in the fuselage as in a fixed-wing airplane. A short, fixed wing attached to the fuselage may also generate lift. The autogyro has many attributes of a helicopter, but since it requires forward motion to generate lift, it cannot take off and land vertically, fly backwards, or hover in still air. For completeness, we make the distinction between helicopters and autogyros, but our discussion focuses on the helicopter, as it is the predominant rotorcraft in use today.

Figure 1.29 Two models of helicopters, the twin-engine, Sikorsky UH-60 *Black Hawk* medium-lift helicopter and the single-engine Bell OH-58 *Kiowa* light helicopter. (Source: *NASA*.)

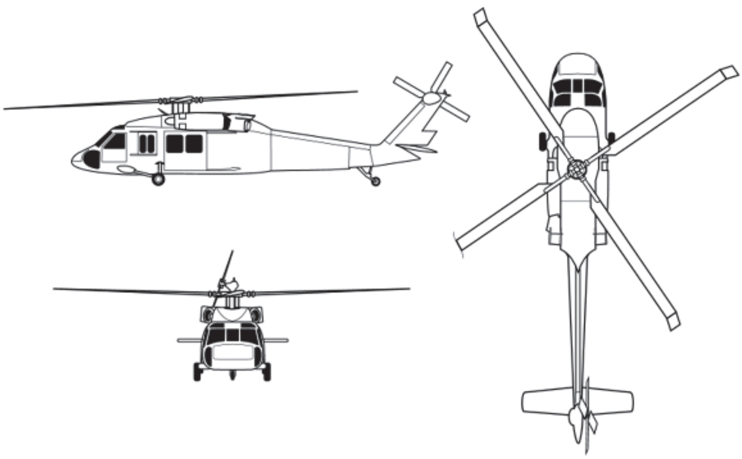

Figure 1.30 Three-view drawing of the Sikorsky UH-60 *Black Hawk* helicopter. (Source: © *User: Fox 52, "UH-60 Orthographical Image" https://en.wikipedia.org/wiki/File:UH-60_orthographical_image.svg, CC-BY-SA-4.0. License at https://creativecommons.org/licenses/by-sa/4.0/legalcode.*)

1.2.3.1 The First Rotorcraft

Early inspiration for the design of rotorcraft may have come from nature. There are several examples of rotating winged seeds in nature that glide through the air as a means of dispersion. These flying seeds or *samaras* (a fruit with a wing) have been the interest of past aeronautical enthusiasts or inventors and current aeronautical engineers. In 1808, aeronautical pioneer, Sir George Cayley (1773–1857) wrote about the sycamore seed, as follows.

> I was much struck with the beautiful contrivance of the chat of the sycamore tree. It is an oval seed furnished with one thin wing, which one would at first imagine would not impede its fall but only guide the seed downward, like the feathers of an arrow. But it is so formed and balanced that it no sooner is blown from the tree than it instantly creates a rotative motion preserving the seed for the centre, and the … wing keeps it nearly horizontal, meeting the air in a very small angle like the bird's wing.

The aerodynamics of this natural rotating wing has been studied extensively, including through the application of modern computational techniques, attempting to unlock the secrets of another example of nature's optimization of flight.

The notion of a flying, rotating wing dates back to an ancient Chinese rotating toy, which was essentially a feather acting as a propeller, attached to the end of a stick. By applying rotation to the stick between the palms of one's hands and releasing the toy, the rotating feather propeller would generate lift, making the toy fly for a short time. In 1483, Leonardo da Vinci conceived of a human-carrying rotorcraft he called an "aerial screw". The da Vinci aerial screw concept did not address several critical issues in the design of a practical rotorcraft, which would not be solved for many centuries.

One of these issues was the development of a propulsion system, to rotate the blades with sufficient power and yet light enough in weight to lift the rotorcraft into the air. This propulsion issue was shared by the designers of heavier-than-air fixed-wing airplanes and would not be solved until the early 20th century, with the advent of the internal combustion engine. Another issue, unique to rotary-wing aircraft, had to do with the reaction torque developed by a rotating wing. The torque imparted by the engine to the rotor blade shaft also results in a reaction torque, which tends to want to rotate the vehicle in the opposite direction of the blade motion. This reaction-torque must be countered by some means, so that the vehicle does not rotate when the rotor blades are spinning. Other issues to be solved included the high vibration environment due to the large, spinning rotor, which can lead to mechanical failure and structural metal fatigue. Many of these issues are still being actively worked on today to improve helicopter designs.

During the early 20th century, there were many attempts at building and flying a vehicle capable of vertical flight. On 13 November 1907, about four years after the Wright brothers' first successful flight of a heavier-than-air fixed-wing airplane, a French bicycle maker, Paul Cornu (1881–1944), flew a helicopter of his own design to a vertical height of 1 ft (30 cm) and hovered for 20 seconds, making this the first free flight of a heavier-than-air rotorcraft. Cornu's helicopter had two 20 ft (6.1 m) diameter rotors with large low aspect ratio blades mounted on spinning spoked wheels, as shown in Figure 1.31. The opposite rotation of the rotors, located at opposite ends of the vehicle, served to counter the reaction-torque. A 24 horsepower, gasoline-fueled internal combustion

Figure 1.31 Paul Cornu's rotorcraft. (Source: *PD-USGov*.)

engine, powered the rotors. In the several flights of the Cornu helicopter, it achieved a maximum vertical height of only about 6 ft (1.8 m), never rising above the region of aerodynamic ground effect, where there is increased lift and decreased drag. (Aerodynamic ground effect is discussed in Chapter 3.)

The first practical helicopter design is perhaps the experimental Vought Sikorsky VS-300 helicopter, designed by helicopter pioneer Igor Sikorsky. The first flight of the VS-300 was on 14 September 1939 in Stratford, Connecticut, piloted by Igor Sikorsky himself. While the first flight of the VS-300 was only a few vertical inches in the air and lasted only 10 seconds, this experimental helicopter prototype, and subsequent variants, would set rotorcraft speed and endurance records (Figure 1.32). The VS-30 had a three-bladed, 28 ft (8.5 m) diameter main rotor, powered by a 75 hp Lycoming engine, and weighed 1325 lb (601 kg). For the first time, the reaction-torque of the main rotor was countered using an anti-torque tail rotor, an additional spinning rotor mounted vertically at the end of the fuselage (Figure 1.33). The single main rotor coupled with an anti-torque tail rotor configuration became the predominant helicopter configuration, the predecessor of the modern-day helicopter.

1.2.3.2 The Helicopter

The major components of a typical, modern helicopter with a single main rotor and anti-torque tail rotor are shown in Figure 1.34. Most, if not all, of the major components are attached to or contained within the structural airframe, including the cockpit, passenger or cargo cabin, engine, fuel tanks, transmission, and landing gear. The landing gear may be skids, fixed or retractable wheels, or amphibious floats. The powerplant may be an internal combustion engine or a turboshaft engine. There may be a single engine or dual engines for additional power and redundancy. The main rotor, comprising the blades, hub, and mast, and the tail rotor are connected to the engine through the transmission, where gearboxes reduce the engine's rotational speed, allowing them to rotate at the required lower speed.

Helicopter main rotor systems are usually of a single or dual rotor configuration. As we have discussed, the single rotor configuration requires an anti-torque mechanism, such as a tail rotor. In a dual rotor system, the rotors spin in opposite directions, which cancels the rotor torque.

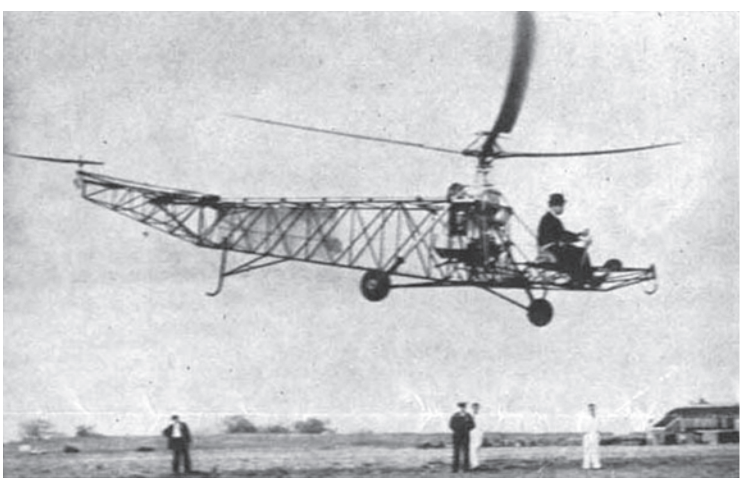

Figure 1.32 The VS-300 helicopter, piloted by its designer, Igor Sikorsky. (Source: *PD-USGov*.)

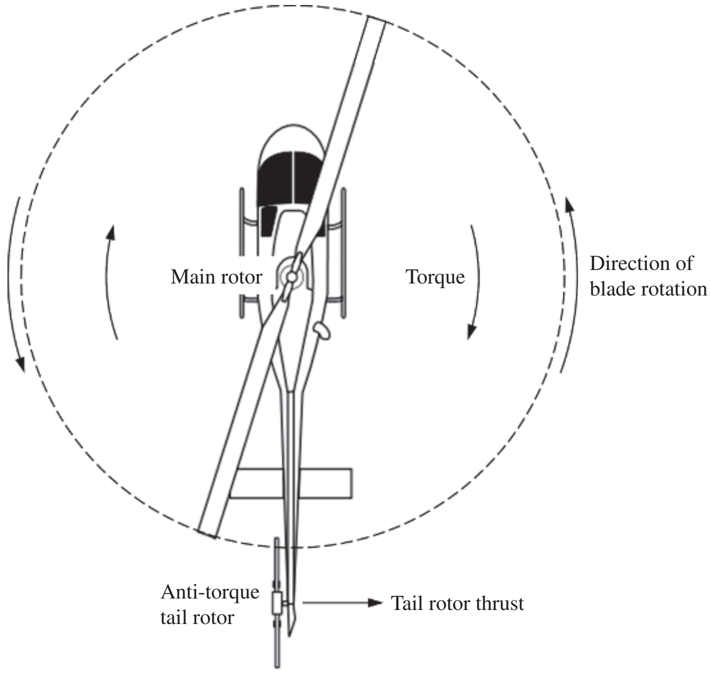

Figure 1.33 Helicopter with a single main rotor and anti-torque tail rotor.

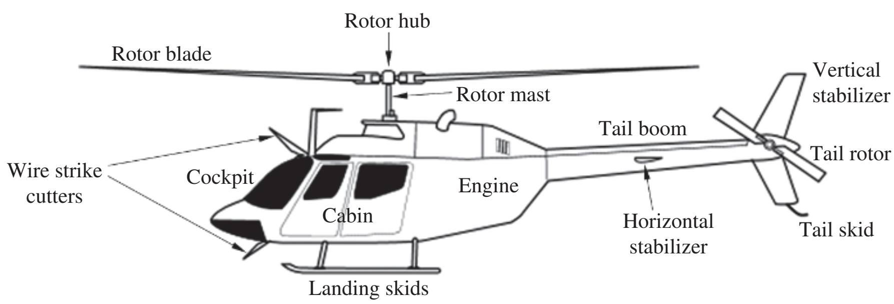

Figure 1.34 Components of the modern helicopter.

The Boeing CH-47 *Chinook*, shown in Figure 1.35, is an example of a twin engine, heavy-lift helicopter with dual tandem rotors.

The main rotor blades are attached to the top of the rotor mast at the rotor hub. A rotor system, whether single or dual, is classified as a *fully articulated*, *semi-rigid*, or *rigid* rotor system, based on the method of attachment of the blades to the hub and the way that the blades move relative to the rotor plane of rotation. Of the three rotor systems, a fully articulated rotor system has the most degrees of freedom for blade movement. With this system, each rotor blade can move independently in three directions relative to the plane of rotation: up or down, called *blade flap*, and fore or aft, called *blade lead or lag*, respectively, and in rotation about the blade spanwise axis, that is, a rotation that changes the blade pitch angle, called *blade feathering*. The blades are attached to the hub using three independent mechanical hinges, appropriately called the flapping hinge, the lead/lag hinge,

Figure 1.35 Boeing CH-47 *Chinook* twin engine, dual tandem rotor heavy-lift helicopter. (Source: *NASA*.)

and the feathering hinge. Fully articulated rotor systems are used on helicopters with more than two main rotor blades.

Blade flapping and lead/lag motion is needed to balance the unequal lift being produced across the rotor disk. In forward flight, the rotation of the blades results in an increase in lift for the rotor blade that is advancing into the relative wind and a decrease in lift for the retreating blade. Blade feathering controls the amount of lift that is produced by changing the blade pitch or angle-of-attack. Increasing or decreasing the blade pitch increases or decreases the lift, respectively.

With the semi-rigid rotor system, the rotor blades have two degrees of motion relative to the rotor plane of motion, flapping and feathering. The rotor blades are rigidly attached to the rotor hub, but the hub attachment to the mast is such that it can have a see-saw or teetering motion relative to the plane of rotation. This teetering motion allows the rotor blades to flap, but since the blades are rigidly attached to the hub, the blades on either side of the hub flap as a unit. This means that for a typical two-blade semi-rigid rotor system, when the blade on one side goes down, the blade on the opposite side goes up. Blade feathering is the same as in the fully articulated system, using a feathering hinge. Semi-rigid rotor systems are usually found on helicopters with two main rotor blades.

In the rigid rotor system, the rotor blades are rigidly attached to the hub and the hub is rigidly attached to the mast, such that the blades have a single degree of motion relative to the rotor plane of motion, that of feathering. Mechanically, the rigid system is much simpler than the other systems, since there are no flapping and lead/lag hinges and mechanisms. Any aerodynamically induced flapping and lead/lag motions of the blades must be absorbed by the blades and hub, making the structural design of these components more complex. A rigid rotor system may also have higher vibration characteristics than the other types of systems.

Returning to the single main rotor configuration, let us investigate other types of anti-torque devices. In addition to the conventional tail rotor, other types of anti-torque devices may be used, such as a Fenestron or NOTAR® system. The Fenestron design, also called a fantail, is essentially a tail rotor with multiple blades shrouded within a circular duct. While a conventional tail rotor may have two to five rotor blades, a fantail may have as many as 8–13 blades. The fantail blades are also shorter in length or span, and spin at a higher rotational speed than conventional tail rotor blades. The shrouded fantail acts like a ducted fan, which is more aerodynamically efficient than an exposed tail rotor. Vibration and noise are also reduced with the fantail. The shrouding has some safety advantages, protecting the rotor from striking foreign objects in flight, such as trees or power lines, and reducing risk to personnel on the ground. A disadvantage of the fantail is the added weight due to the structure around the rotor.

NOTAR® is an acronym for NO TAil Rotor. The NOTAR® system is based on a combination of an aerodynamic phenomenon, known as the Coanda effect, and direct jet thrust. A fan, located at the forward end of the tail boom, produces a low pressure, high volume flow of ambient air that is expelled through two longitudinal slots on the right side of the tail boom. These horizontal air jets create a low pressure area that causes the downwash flow from the main rotor to curve around the circular cross-section of the boom. This circulation control around the boom, created by the air jets, is known as the Coanda effect. The accelerated flow around the right side of the tail boom results in an aerodynamic lift force in a direction that counteracts the main rotor torque. In hovering flight, this circulation control system provides up to 60% of the required anti-torque. Additional anti-torque is provided by a rotating, direct jet thruster that is fed by the fan air in the boom. Vertical stabilizers provide additional directional control in forward flight. Advantages of the NOTAR® system include the elimination of tail rotor mechanisms and transmissions, and the safety benefit of not having a tail rotor with regards to tail strike.

Several desirable features of rotary-wing and fixed-wing aircraft are brought together in the *tilt-rotor* aircraft, such as the Boeing V-22 *Osprey* (Figure 1.36). The tilt-rotor aircraft combines the rotorcraft capabilities of vertical takeoff, hover, and landing with the benefits of a fixed-wing aircraft, such as improved speed, range, and fuel efficiency, as compared with a pure rotorcraft. The tilt-rotor has two counter-rotating main rotors or propellers that are mounted on engine nacelles at the ends of a short wing. The nacelles can be rotated in flight between horizontal and vertical

Figure 1.36 Boeing V-22 *Osprey* tilt-rotor aircraft. (Source: *US Air Force*.)

positions. With the nacelles in their vertical position, the tilt-rotor can operate like a helicopter with two counter-rotating main rotors. With the nacelles in the horizontal position, the tilt-rotor flies like a fixed-wing, twin-engine airplane with two large propellers. As can be seen in Figure 1.36, the 38 ft (11.6 m) diameter, rotating blades are a compromise between a helicopter and an airplane. With a cruising speed of about 240 knots (444 km/h), a maximum altitude of about 25,000 ft (7600 m), and a capability to takeoff vertically at a weight of about 53,000 pounds (24,040 kg), the V-22 tilt-rotor combines the benefits of rotary and fixed-wing aircraft.

1.2.4 Lighter-Than-Air Aircraft: Balloon and Airship

As the name implies, lighter-than-air vehicles are aircraft that utilize gases that are less dense than atmospheric air. The gas may be less dense because it is heated, as in a hot air balloon, or because it has an inherently lower density than air, such as helium or hydrogen in a gas balloon or airship. Lighter-than-air aircraft obtain their lift primarily from buoyancy, rather than from aerodynamic lift. We discuss two types of lighter-than-air aircraft, the *balloon* and the *airship*. The distinction between a balloon and an airship has to do with the ability to propel and steer the vehicle. A balloon does not have a propulsion system, while the airship has a means of propulsion, and is steerable.

Buoyancy is based on Archimedes' principle, which states that an object, submerged in a fluid, is acted upon by a buoyant force with a magnitude equal to the weight of the fluid displaced by the object, and in a direction that is opposite to the weight of the object. The fluid can be a liquid or a gas, so Archimedes' principle is applicable to a ship or submarine in the ocean or a balloon or airship in the air. Assuming that the fluid is air, the buoyancy force, F_b, can be written as

$$F_b = W_a = m_a g = \rho_a \mathcal{V} g \tag{1.1}$$

where W_a, m_a, and ρ_a are the weight, mass, and density, respectively, of the air displaced by the object of volume, $\mathcal{V}$, and g is the acceleration due to gravity. Now imagine that we have a hollow object, with a volume $\mathcal{V}$, which we can fill with a substance of density, ρ_g. The weight of the substance in the object is given by

$$W_g = \rho_g \mathcal{V} g \tag{1.2}$$

(For simplicity, we ignore the weight of the hollow object that contains the substance of density ρ_g.)

If we fill the object with a substance that has the same density as air, $\rho_g = \rho_a$, the weight of the object equals the buoyancy force, and the object remains stationary in the air, as shown in Figure 1.37a. If we fill the object with a substance that has a density greater than air, $\rho_g > \rho_a$, the object's weight is greater than the buoyancy force and the object sinks. If we fill the object with a substance that has a density less than air, $\rho_g < \rho_a$, the object's weight is less than the buoyancy force and the object rises. As common sense would dictate, if we fill the hollow object with lead, it sinks, and if we fill it with helium or hydrogen, the object rises. We could also fill the object with air, at a higher temperature than the external, ambient air, so that the air inside the object is at a lower density. This then is the fundamental physics behind the buoyancy of the balloon and airship.

1.2.4.1 The First Balloon

Balloons are perhaps the earliest form of manned flying vehicles. The first recorded, manned flight of a *hot air balloon* occurred on November 21, 1783 in Paris, France. The balloon, with aeronauts Jean Francis Pilatre de Rozier and the Marquis d'Arlandes onboard (a person who operates or

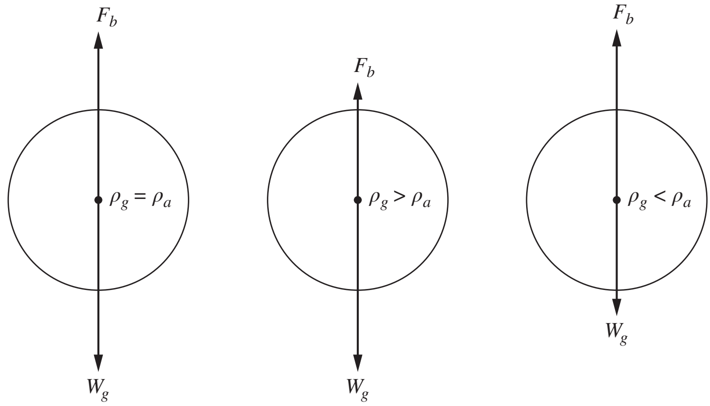

Figure 1.37 Buoyancy, (a) stationary, $\rho_g = \rho_a$, (b) sinking, $\rho_g > \rho_a$, and (c) rising, $\rho_g < \rho_a$.

travels in a balloon or airship is called an *aeronaut*), flew for about 25 minutes over the city of Paris, rising to an altitude of about 3000 ft (914 m) and covering a distance of about 5 miles (8.1 km). This was the first free flight by mankind in an aerial vehicle. The balloon was built by Joseph and Etienne Montgolfier of France, who were to play a major role in the future development of balloon flight. A firebox, suspended underneath an opening at the bottom of the balloon, held a fire that filled the balloon with hot air. The balloon aeronauts stood on a platform, encircling the bottom of the balloon, from which they could add fuel to and tend the fire in the firebox.

With a background in paper manufacturing, the Montgolfier brothers were supposedly inspired by seeing scraps of paper, in their paper mill, being lifted aloft by smoke from a fire. Based on these observations, they believed that the smoke was a new, undiscovered gas that was less dense than air, which they dubbed “Montgolfier gas”. They believed that a thicker smoke contained more of this “Montgolfier gas”, so they sometimes burned unusual materials, such as rotted meat and shoes, to produce as thick a smoke as possible for their balloons. They did not realize that the smoke was simply heated air and was therefore less dense than unheated air. The brothers used a trial-and-error method, rather than one based on an understanding of the physics, in developing their balloons.

An aspect of the Montgolfier brothers’ balloon development, which was insightful and may have contributed to their success, was their incremental design and flight test approach. They started with the flight of a smaller scale, 10 m (32.8 ft) diameter, unmanned hot air balloon that was tethered to the ground, and built up to flights of larger, manned balloons. The Montgolfier brothers’ flight test approach was also admirable from a risk reduction standpoint. Prior to risking a balloon flight with people onboard, they flew a balloon carrying three farm animals, a sheep (aptly named Montauciel, French for “climb to the heavens”), a duck, and a rooster, to assess the effects of balloon flight on living creatures. There was logic to their selection of these three particular animals. The sheep was thought to have a physiology that was similar to a human being, thus it was selected to assess the physiological effects of altitude. Since the duck was capable of flight at the balloon altitudes, it was used to assess any non-physiological effects of balloon flight. The rooster was a non-flight capable bird, so it was used to assess altitude effects in comparison with the duck. On 9 September 1783, the sheep, duck, and rooster made history as the first living creatures to fly in a balloon. Their balloon flight lasted about 8 minutes, ascending to an altitude of about 1500 ft (460 m) and landing safely about 2 miles (3.2 km) from their launch point.

The next incremental step was the flight of a 75 ft (22.9 m) tall, 55 ft (16.8 m) diameter, tethered balloon with a man onboard. On October 15, 1783, Etienne Montgolfier was the first person to ascend in a tethered balloon followed, later that day, by Jean Francis Pilatre de Rozier, who rode the tethered balloon to a height of about 80 ft (24.4 m), the length of the tethered line attached to the balloon. Just a little over a month later, the first free flight of a balloon was completed by de Rozier and the Marquis d'Arlandes in a Montgolfier balloon.

Ten days after the first manned hot air balloon flight, aeronauts Jacques Alexander Charles and Nicholas Louis Robert flew the first manned flight of a *gas balloon* on 1 December 1783, also in Paris, France. Charles and Robert ascended to an altitude of about 1800 ft (550 m), covered a distance of about 25 miles (40.2 km), and were airborne for about 2 hours. The rubber-coated, silk balloon was filled with flammable hydrogen gas, an attractive choice from a buoyancy standpoint, but a poor choice from a flight safety perspective. Hydrogen gas would be used in balloons (and airships) well into the 20th century – with many instances of catastrophic events due to its high flammability – until being replaced by helium gas. In fact, de Rozier, of hot air balloon fame, died when his hydrogen gas balloon exploded while attempting to cross the English Channel in 1785. De Rozier's balloon was a hybrid gas-and-hot air balloon, essentially a hot air balloon with an internal hydrogen gas chamber. Sadly, in addition to being one of the first persons to fly, de Rozier was also the first air crash fatality. The first manned balloon flight in the USA was in a hydrogen gas balloon, piloted by the Frenchman Jean-Pierre Blanchard on 9 January 1793. Blanchard's balloon lifted off from Philadelphia, Pennsylvania, climbed to an altitude of about 5800 ft (1770 m) and landed in New Jersey.

In addition to opening up a new era in flight, balloons also found military applications. Tethered balloons were used as military observation platforms by the French in the late 18th century and by the armies during the US Civil War. Balloons were also used for artillery spotting in World War I.

1.2.4.2 The Balloon

The two types of balloons that we have been discussing, the hot air balloon and the gas balloon, are different based on the source of the lighter-than-air substance that provides the buoyancy. As its name implies, the hot air balloon is filled with air at a higher temperature, hence, a lower density, than the external, ambient air. The gas balloon is filled with an unheated gas, with a lower density than air, such as hydrogen, helium, or ammonia.

Balloons do not have a means of propulsion, so they literally drift with the wind. By adjusting the balloon's buoyancy, the balloon pilot can cause the balloon to rise or sink, moving the balloon vertically into different wind currents and thereby having some, albeit limited, control of horizontal motion. Both types of balloons have a fabric *envelope* that is filled with the lifting gas, a *basket* or *payload* suspended underneath the envelope, and a means of adjusting the buoyancy in flight. The basket is used to carry people, while the payload could be any type of equipment or instrumentation that is carried aloft.

The major components of a conventional, modern hot air balloon are shown in Figure 1.38. The envelope of the modern hot air balloon is constructed of lightweight, synthetic fabric panels that are sewn together in banana peel shaped vertical rows, called gores. The fabric is structurally reinforced with horizontal and vertical load tapes. In a conventional hot air balloon, the envelope has a teardrop shape, but it can have a variety of other shapes. Hot air can be vented from the envelope, either through a deflation port located at the top of the envelope or through other vents in the side of the envelope. Venting of hot air is one means of buoyancy control for the balloon pilot. The envelope side vents can also be used to turn the balloon about its vertical axis, providing some control of the basket position relative to the direction of motion, which may be useful to the

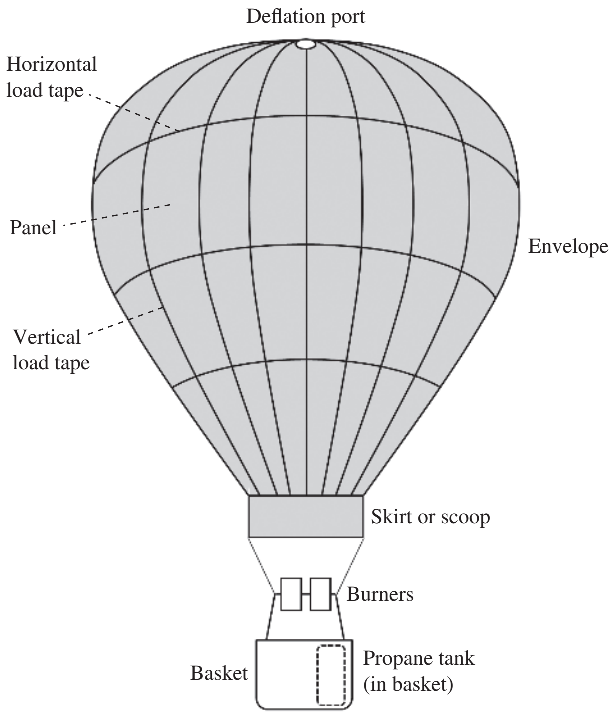

Figure 1.38 The hot air balloon.

pilot in landing the balloon. The burners, mounted beneath the envelope, are used to heat the air inside the envelope. Unlike the first manned balloon flight, which used damp straw, old rags, and rotting meat as fuel for their firebox, modern balloons use liquid propane, which is stored in tanks inside the basket. The opening at the bottom of the envelope, called the skirt or scoop, is coated with a fire resistant material to prevent the burner flames from igniting the envelope. By controlling the firing of the burner, the balloon pilot can control the temperature of the hot air in the envelope and hence the buoyancy of the balloon. The basket or gondola is suspended beneath the envelope using stainless steel or Kevlar composite cables. The basket is commonly made of wicker, metal, or fabric, covering a metal frame. Flight instruments and avionics, such as an altimeter, variometer or rate-of-climb indicator, radio, and transponder, are mounted in the basket. In the example problem below, we gain an appreciation for the size of a hot air balloon required to carry a reasonable weight, which includes the weight of the envelope, heating system, basket, aeronauts, and hot air inside the envelope.

The early hot air balloons had the obvious disadvantages of literally carrying a fire aloft and needing to carry the heavy load of firewood or other combustibles to fuel the fire. In fact, the first hot air balloon flight by de Rozier and d'Arlandes was cut short due to their concern that the balloon was starting to catch fire. Once balloon designers figured out how to adequately seal balloons to prevent the leakage of the buoyant gas, the gas balloon soon became preferred over the hot air balloon. However, the burners of modern-day hot air balloons are much more efficient and safer, making hot air balloons the current preference for sport ballooning.

The major components of a typical gas balloon are shown in Figure 1.39. Similar to a hot air balloon, the gas balloon has an envelope that is inflated with the buoyant gas. The gas balloon envelope is typically spherical in shape and made of a thin, gas-tight synthetic material. Typical

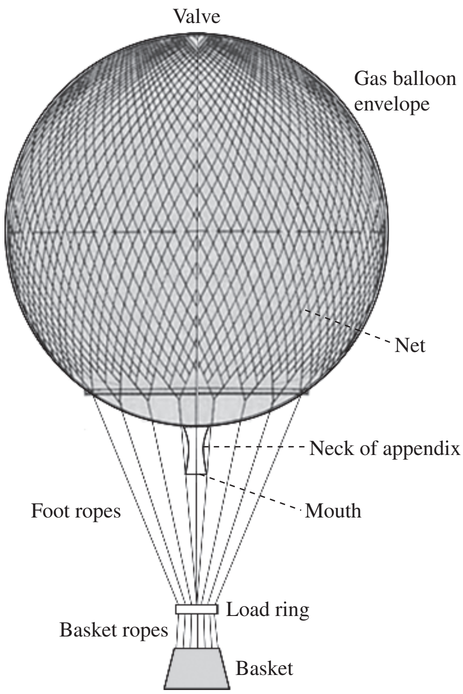

Figure 1.39 Major components of the gas balloon.

lifting gases include helium, hydrogen, and ammonia. A net surrounds the gas envelope and is connected via ropes to the load ring, from which the gondola or basket is suspended. The net serves to spread the load of the payload evenly over the surface of the envelope. A valve is located at the top of the envelope, which can be opened by the pilot, allowing gas to escape, to control the rate of ascent. In addition to this vent valve, the ascent and descent of gas balloons are controlled by throwing ballast bags, filled with sand or water, overboard. A tube at the bottom of the envelope, called the appendix, is used to fill the balloon and serves as an outlet to relieve the buildup of gas pressure inside the envelope due to temperature increases. There is also a rip panel on the envelope, which can be opened to rapidly deflate the balloon on the ground, in a high wind condition, or in an emergency situation. The basket or gondola is similar to that used for hot air balloons.

Gas balloons are used for sport ballooning, but less so than hot air balloons, due to their increased complexity and the high cost of the lifting gas. The maximum altitude capability of gas balloons is much greater than hot air balloons. Gas balloons can ascend to near-space altitudes of over 120,000 ft (37 km), above 99.5% of the earth's atmosphere. For this reason, high-altitude gas balloons are used extensively for scientific research.

Scientific gas balloons are used for a myriad of research and observation purposes, including studies of the weather, the upper atmosphere, and deep space. The envelope volume of the gas balloon expands significantly as it ascends and the external, ambient air pressure decreases. When fully expanded, these specialized gas balloons can be as large as 400 ft (120 m) in height and 460 ft (140 m) in diameter, with a volume of 40 million ft^3 (1.1 million m^3). The gas envelope skin of these massive balloons is made of a thin polyethylene film, with a thickness of only 0.8 mil (one mil is one thousandth of an inch) or 20 microns. With a maximum payload capability of about 8000 pounds (3629 kg), a scientific balloon can reach an altitude of 120,000 ft (37 km). They are also used as a means of lifting a test object, such as a parachute or vehicle, to an altitude where it can be released to study aerodynamics, flight dynamics, or other characteristics.

Unlike the gas balloons that expand as they ascend, the *superpressure gas balloon* is designed to maintain a constant volume at all altitudes. The gas envelope of a superpressure balloon is constructed of a high-strength polyester film that can bear the high loads as the gas pressure changes. Superpressure balloons can stay aloft for months, making ideal long endurance, high altitude scientific platforms.

The hybrid balloon combines features of the hot air and gas balloons. The hybrid balloon generates its buoyancy from a combination of heated gas from a burner and the carriage of an unheated, lighter-than-air gas such as helium or hydrogen. De Rozier attempted to cross the English Channel in a hybrid hot air–hydrogen gas balloon. Since de Rozier's time, hybrid balloons have been used for several long distance flights, including a solo, around-the-world flight by Steve Fossett in 2002. Fossett's circumnavigation in a hot air–helium hybrid balloon took over 14 days.

1.2.4.3 The Airship

An airship is distinguished from a balloon by both its ability to propel itself through the air, typically using internal combustion engines driving propellers, and also its ability to be steered. Early airships were called dirigible balloons, after the French *dirigible*, meaning "capable of being directed or steerable". Developed in the early 20th century, airships were the first powered aircraft that had flight controls for steering.

Similar to a balloon, an airship obtains its lift from a buoyant gas that is contained within a gas envelope. The buoyant gas used in airships is the same as that used in gas balloons, with the inert helium being used in most modern airships. Early airships were filled with hydrogen gas, with the same disastrous results as experienced with hydrogen-filled balloons. Typically, an airship's envelope has an axisymmetric, streamlined shape that contains the buoyant gas in separate gas bags or cells. Airships can be classified as rigid or non-rigid, based on the construction of the envelope, as shown in Figure 1.40.

The rigid airship has an envelope comprising a structural frame with a fabric outer covering. In early airships, the structural frame was made of wood, covered by cotton cloth fabric, similar to the construction of early airplane airframes. Modern airships use a metal, typically aluminum, framework and synthetic materials for the covering. The rigid structure maintains the shape of the airship and carries the structural loads of the vehicle. The gas bags or cells are mounted inside the rigid envelope. While the gas bags or cells are filled with a pressurized, buoyant gas, the rigid envelope is typically a non-pressurized structure.

A non-rigid airship, also called a *blimp*, is somewhat similar to a gas balloon in that the internal pressure of the buoyant gas maintains the shape of the envelope. Gas bags inside the envelope are filled with the buoyant gas, while other gas bags called *ballonets* are filled with air at sea level pressure. The combination of these gas bags is used to maintain the shape of the non-rigid airship hull. To compensate for the change in size of the buoyant gas bags, due to changes in pressure with altitude, air is forced into or out of the ballonets. Air is pumped into the ballonets using auxiliary blowers and is released from the ballonets using vents.

A third type of airship, the semi-rigid airship, is a combination of the rigid and non-rigid designs. Its envelope shape is maintained by the internal gas bags, but there is also a supporting structure, such as a "backbone" keel, much like a ship.

All of these airship types usually have a gondola beneath the envelope structure, where the aircrew, passengers, and cargo are carried. On larger, rigid airships, passenger and cargo compartments can be located inside the rigid envelope structure. This is not possible for non-rigid airships. Larger

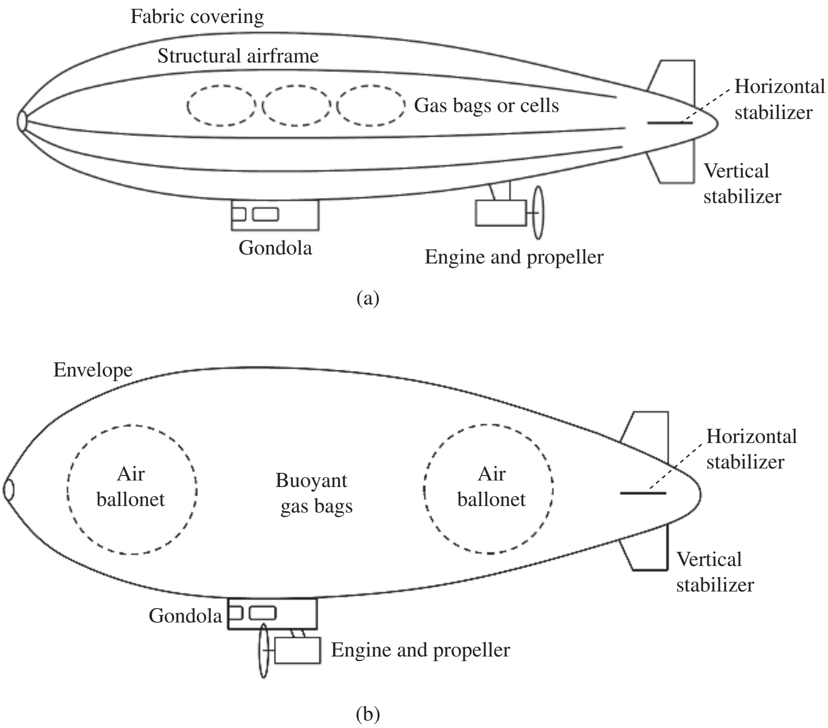

Figure 1.40 Components of airships, (a) rigid airship and (b) non-rigid airship.

airships typically may have multiple *power cars* or *engine cars* – separate nacelles where the internal combustion engine and propeller are installed. These engine cars may be mounted from the gondola structure or from other locations on the envelope. The propeller mounting may be of the *pusher* (facing aft) or *tractor* (facing forward) configuration. The multiple engines allow for the application of asymmetric thrust, which is used to help steer the airship. Movable, horizontal and vertical, control surfaces, located at the tail of the airship, are also used for steering and to control the attitude of the airship. To descend, the airship can vent gas and to climb, it can drop ballast. Longitudinal trimming of the airship can be accomplished through weight shifting, by pumping water or gas fore and aft inside the vehicle.

Takeoff, landing, and general ground handling of an airship requires unique facilities and a large ground crew. An airship can take off or ascend much like a balloon, but it can also use its engines to assist in the lift-off. The landing is made by slowly descending towards a ground crew, dropping ropes for them to grab, and being anchored to the ground. A mooring mast may also be used, where the nose or bow of the airship is attached or moored to the mast. As might be imagined, a large number of people are required in the ground crew for ground handling of the airship. The process is more difficult in gusty or high wind conditions.

Perhaps the most famous rigid airships were those built in the early 20th century by the German Zeppelin Company. One of the most famous Zeppelin passenger airships was the LZ-129 *Hindenburg* (LZ stood for Luftschiff Zeppelin, German for “Airship Zeppelin” and “129” is the airship designation number). The *Hindenburg* was 803.8 ft (245.0 m) in length and 135.1 ft (41.2 m) in diameter. The giant airship contained over 7 million ft^3 (200,000 m^3) of hydrogen gas. Powered by four Daimler-Benz 16-cylinder diesel engines, the *Hindenburg* had a cruise speed of 76 mph (125 km/h) and a typical cruise altitude of only 650 ft (198 m). The *Hindenburg* had a flight crew of 39 men, an additional dozen chefs and stewards, and a doctor on board. Luxury accommodation for 72 passengers included private cabins, promenade observation areas, a dining room, a lounge with a grand baby piano, and a smoking room, which was kept at a higher than ambient pressure to prevent any leaking hydrogen gas from entering. For the passengers, flying in a Zeppelin passenger airship was much like taking a voyage on a luxury cruise ship. These large passenger airships were the first commercial airliners, able to cross long distances, including routinely flying across the Atlantic Ocean.

Even though these Zeppelins were filled with highly flammable hydrogen gas, they had a very good safety record and flew all over the world carrying passengers and cargo for almost a decade. However, on 6 May 1937, the *Hindenburg* caught fire while attempting to dock at the Naval Air Station in Lakehurst, New Jersey, reducing the huge airship to a skeleton and ashes in less than a minute. Although never definitively proven, the leading theory for the cause of the fire was the ignition of leaking hydrogen gas by a static electric spark. This high profile disaster, along with a series of other airship accidents, contributed to the decline and ultimate demise of the airship as a viable means of commercial air travel. Replacing the flammable hydrogen gas with helium made the airship safer for flight, but the advancements in fixed-wing airplanes soon made the airship obsolete.

Airships are still used today, but mostly for applications where flying "low and slow" is desired, such as aerial advertising, tourism, remote sensing, and aerial observation. There has been renewed interest in using airships as long duration, very high altitude, scientific and commercial platforms, similar to high altitude balloons. An advantage of the airship is its ability to maintain a constant location over a point on the earth, similar to a stationary satellite. Scientific applications of airships include astronomical or weather observations. Commercial uses include acting as telecommunications platforms.

An example of a modern airship is the Zeppelin NT, shown in Figure 1.41. The Zeppelin NT is a semi-rigid, helium-filled airship with a gas volume of 290,450 ft^3 (8255 m^3). With a length of 246 ft (75 m) and a diameter of 46 ft (14.2 m), the Zeppelin NT has a gross weight of about 23,500 lb (10,700 kg). It carries a crew of 2 and 12 passengers at speeds up to 77 mph (125 km/h) and altitudes up to about 8500 ft (2600 m). The airship is powered by four 200 hp (149 kW) Lycoming IO-360, air-cooled, piston engines.

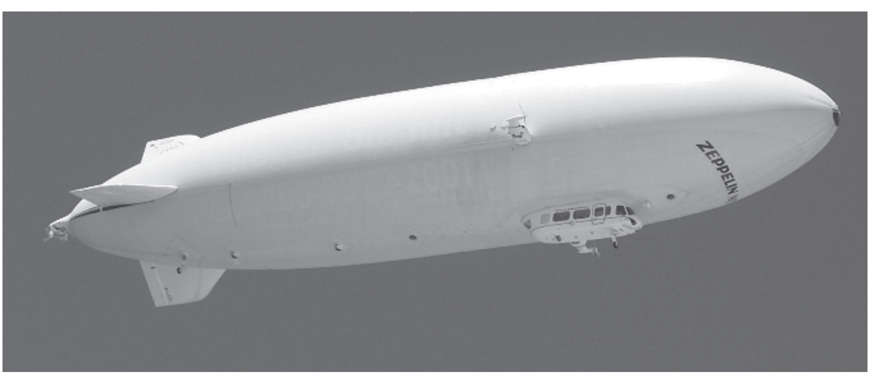

Figure 1.41 A modern airship, the Zeppelin NT, 2010. (Source: *User: Stefan-Xp, "Zeppelin NT" https://commons.wikimedia.org/wiki/File:Zeppelin_NT.jpg, CC-BY-SA-3.0. License at https://creativecommons.org/licenses/by-sa/3.0/legalcode.*)

Another related aircraft, the *hybrid airship*, combines elements of the lighter-than-air airship and the heavier-than-air, fixed-wing airplane. The hybrid airship obtains its lift from a combination of aerostatic (buoyant) lift and aerodynamic lift. By virtue of its more aerodynamic shape and higher cruise airspeeds, as compared with a conventional airship, the aerodynamic lift of a hybrid airship can approach 50% of the total lift.

1.2.5 The Unmanned Aerial Vehicle

As the name implies, an *unmanned aerial vehicle* (UAV) is an aircraft without a pilot inside the vehicle. As such, any of the aircraft types shown in Figure 1.9 can be a UAV. The UAV may be flown remotely by a pilot on the ground or may operate autonomously, independent of real-time human intervention. A UAV that is flown remotely by a pilot is also sometimes referred to as a remotely piloted aircraft. For autonomous operation, a set of instructions or a flight plan may be programmed into computers onboard the UAV, or these instructions may be transmitted to the UAV via a communications or data link from the ground. This includes the capability to perform autonomous takeoffs and landings. The autonomous landing of a UAV on an aircraft carrier has even been demonstrated. The *unmanned aircraft system*, or UAS, refers to the complete system involved with the UAV operation, including the flight vehicle, ground control station, instrumentation, telemetry, communication, navigation equipment, and other support equipment.

Since it does not carry a human pilot, a major advantage of a UAV is its ability to fly into hostile environments, such as military combat, a forest fire, or a hurricane, without the potential for loss of human life. UAVs can also be used to reach remote areas that are otherwise inaccessible, such as during disaster relief. Unmanned aerial vehicles have seen an amazing proliferation in recent years, finding applications in a wide range of applications, including military, scientific, and commercial uses. Military UAVs perform reconnaissance, surveillance, and combat missions. A military UAV that carries weapons is designated as an unmanned combat air vehicle (UCAV). Equipped with the appropriate sensors and instruments, scientific applications of UAVs include earth remote sensing, meteorological sensing, geophysical mapping, and archaeological surveying, just to name a few. Some of the commercial applications of UAVs include oil, gas, and mineral exploration, aerial surveying of crops, livestock monitoring, wildlife mapping, pipeline and power line inspection, forest fire detection, motion picture filming, and potentially in the near future, parcel delivery.

UAVs come in all shapes and sizes, ranging from vehicles with conventional airplane configurations and weights to biologically inspired *micro air vehicles* that are the size and weight of insects. The General Atomics *Predator* UAV, shown in Figure 1.42, has a length of 36 ft (11 m), wingspan of 86 ft (26 m), and maximum weight of about 7000 lb (3200 kg). The much larger Northrop Grumman RQ-4 *Global Hawk* UAV, shown in Figure 1.43, has a length of 44 ft (13.5 m), wingspan of 116 ft (35.4 m), and maximum weight of about 25,600 lb (12,600 kg).

Both the *Predator* and the *Global Hawk* can be classified as *long endurance* UAVs with the ability to fly at very high altitudes for a very long time. The *Predator* can fly at over 50,000 ft (15,000 m) for over 30 hours, and the *Global Hawk* can fly at over 60,000 ft (18,000 m) for over 30 hours. Long endurance capability is another advantage of the UAV in performing surveillance, reconnaissance, and remote sensing. While the *Predator* is turboprop powered and the *Global Hawk* has a turbofan jet engine, other UAV propulsion system options, such as solar power, may enable *ultra-long endurance* UAVs to stay aloft for days, weeks, or longer. Some development work has been performed on the design of UAVs that could stay aloft for such long periods of time that they would act as airborne communication or earth-sensing "satellites".

Contrast the size, weight, shape, and capabilities of the UAVs such as the *Predator* and *Global Hawk* with the *micro air vehicle* (Figure 1.44), which can be the size and weight of an insect.

Figure 1.42 The unmanned aerial vehicle, the General Atomics MQ-9 *Predator* UAV. (Source: *NASA*.)

Figure 1.43 A large, jet engine-powered UAV, the Northrop Grumman RQ-4 *Global Hawk*. (Source: *NASA*.)

While some micro air vehicles have conventional airplane configurations, many are *biologically inspired* designs, based on insects, birds, or other small flying creatures. They often mimic the flight characteristics of the living creature being copied, such as using flapping wings to generate lift and thrust. The extremely small size of micro air vehicles make them ideal for applications where it is

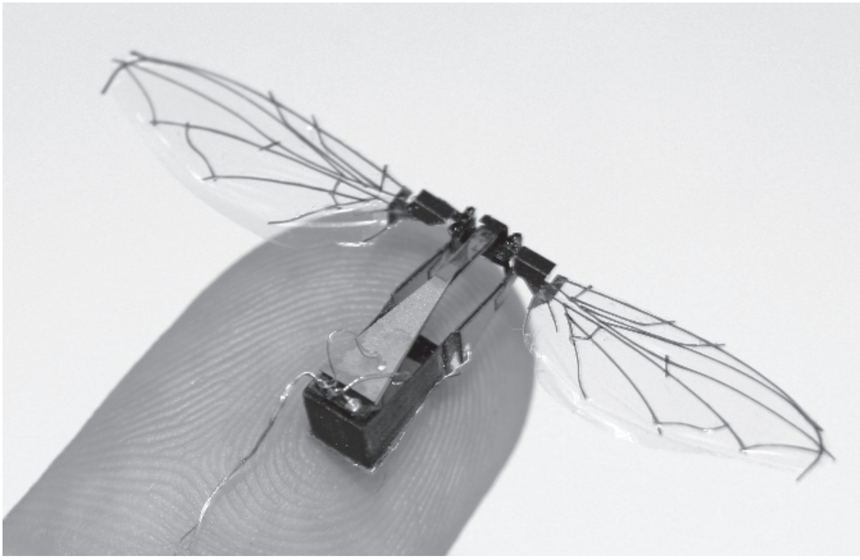

Figure 1.44 A biologically inspired micro air vehicle. (Source: *Air Force Research Laboratory, US Air Force*.)

desirable for the vehicle to be unnoticed, such as for clandestine surveillance, or where they need to operate in a very confined space, such as search and rescue in the rubble of a building that has collapsed. However, due to their small size, the integration of desired systems and components, to provide power, navigation, control, and sensing, is quite a challenge.

1.3 Spacecraft

Spacecraft are vehicles that are designed to operate in space, where there is no sensible atmosphere, including in Earth orbit and in the vacuum of space. Spacecraft are, in many ways, fundamentally different from aircraft. Since aircraft operate in the sensible atmosphere, their design is usually dominated by aerodynamic considerations, such as maximizing lift and minimizing drag. Spacecraft that operate solely in airless space do not typically have these aerodynamic design constraints. In fact, they may appear to be completely non-aerodynamic, that is, there may be components and parts that protrude from the spacecraft in every direction. However, spacecraft that need to return from space through the atmosphere require similar aerodynamic designs considerations to fixed-wing airplanes. Spacecraft must operate in the harsh environment of the vacuum of space, where there are extremes in temperature, space radiation, and possible impacts from micrometeorites.

Similar to aircraft, spacecraft come in a wide variety of shapes and sizes. In this section, we discuss several different types of spacecraft, classified primarily based on their function or mission. In keeping with the general theme of this chapter, we look at several unmanned and manned spacecraft that were "firsts", including the first artificial satellite and the first manned spacecraft. In addition, we discuss a unique type of "one-person spacecraft", the spacesuits worn be astronauts. All spacecraft require some kind of launch vehicle or launch system to get them into space. At the end of this section, the rocket booster is discussed, still the only feasible launch system that we currently have to get spacecraft into space. Other non-rocket-based launch systems are mentioned, which may provide space access in the future.

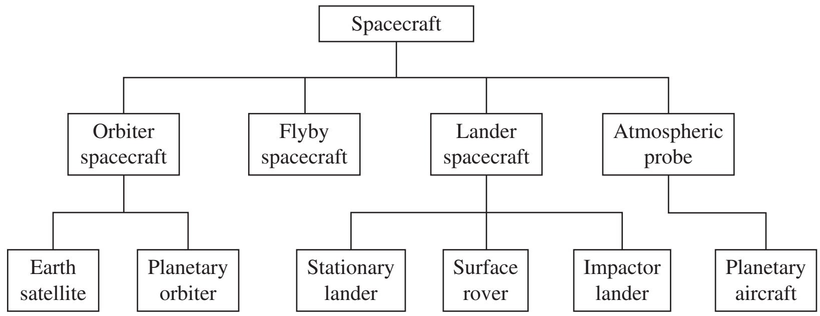

Figure 1.45 Classification of different types of spacecraft.

1.3.1 Classification of Spacecraft

Spacecraft can be classified in a variety of ways, based on geometric configuration, type of propulsion, mission, or other factors. Figure 1.45 shows one such classification of spacecraft types, based primarily on the mission or function of the vehicle. Using this scheme, the spacecraft are classified as an *orbiter*, *flyby spacecraft*, *lander*, or *atmospheric probe*. Brief descriptions of these different types of spacecraft are given below.

1.3.1.1 Orbiter Spacecraft

Orbiter spacecraft are launched and placed into orbit around the earth or another planet. Earth orbiter spacecraft, also called artificial satellites, have a variety of missions and functions, including those involving communications, navigation, meteorology, reconnaissance, and scientific research. Spacecraft that are sent to orbit another planet are typically used for scientific research. These planetary orbiter spacecraft may serve as a communications or data relay platform for a lander that is sent to the planet's surface. We discuss several orbiter spacecraft, including different types of unmanned, artificial earth satellites and manned orbiting vehicles in later sections.

1.3.1.2 Flyby Spacecraft

Unlike orbiting spacecraft, flyby spacecraft follow a trajectory that is not a closed orbit around a planet. They may be sent on interplanetary journeys that take many years. As their name implies, this type of spacecraft is designed to fly by a planet or other celestial object of scientific interest, collecting data with their array of sensors and instruments. Some flyby trajectories can be cleverly designed to bring the spacecraft in close proximity to a series of planets.

Four of the most successful flyby spacecraft are the *Pioneer 10* and *11* and *Voyager 1* and *2* spacecraft, all launched in the 1970s. These spacecraft were sent on trajectories to fly by the solar system's outer planets and then continue, beyond our solar system. *Pioneer 10* was the first spacecraft to fly by the gas giant planet, Jupiter. *Pioneer 11* was the second spacecraft to visit Jupiter and the first to fly by the ringed, gas giant, Saturn. *Voyager 1* completed flybys of Jupiter and Saturn and then, in 2012, became the first manmade object to leave our solar system. It also discovered the first volcanic activity on another world, the active volcanoes on the Jupiter moon, Io. In addition to flybys of Jupiter and Saturn, *Voyager 2* was the first spacecraft to fly by Uranus and Neptune. A more detailed discussion of the *Pioneer 10* flyby spacecraft is given in a later section.

1.3.1.3 Lander Spacecraft

Lander spacecraft are designed to land on the surface of another planet or other celestial body. The landing may be a "soft" landing, where the spacecraft survives and is able to perform other functions on the surface, or it may be a high velocity impact, where the spacecraft obtains data during its descent, but is not designed to survive the impact. At the time of writing, lander spacecraft have successfully impacted or soft landed on the Moon, Mercury, Mars, Venus, Saturn's moon Titan, and a few asteroids and comets.

The first type of lander spacecraft that was flown into space was the *impactor* lander. This is, perhaps, the simplest type of lander spacecraft, since it does not have the design complexity to soft land on a surface. Data is collected about the planet or celestial body, including the atmosphere, if present, as the impactor descends to the surface. The Russian impactor spacecraft, *Luna 2*, was the first manmade object to "land" on another celestial body, impacting the Moon on 14 September 1959. With an estimated impact speed of 3.3 km/s (7382 mph), the vehicle was certainly destroyed upon impact. *Luna 2* was the second in a series of lunar explorer spacecraft sent to the Moon by Russia. The first intended Russian impactor lander, *Luna 1*, was unsuccessful, due to an error in its trajectory, causing it to miss hitting the Moon by about 6000 km (3700 miles).

As shown in Figure 1.46, the 390 kg (860 lb) *Luna 2* spacecraft was spherical in shape with protruding antennas. Sensors and instrumentation on board the spacecraft included radiation detectors, micrometeorite detectors, and a magnetometer to detect the Moon's magnetic field. Data from these sensors confirmed that the Moon does not have a radiation belt or any significant magnetic field. On its way to the Moon, *Luna 2* released an amount of sodium gas into space, which created a

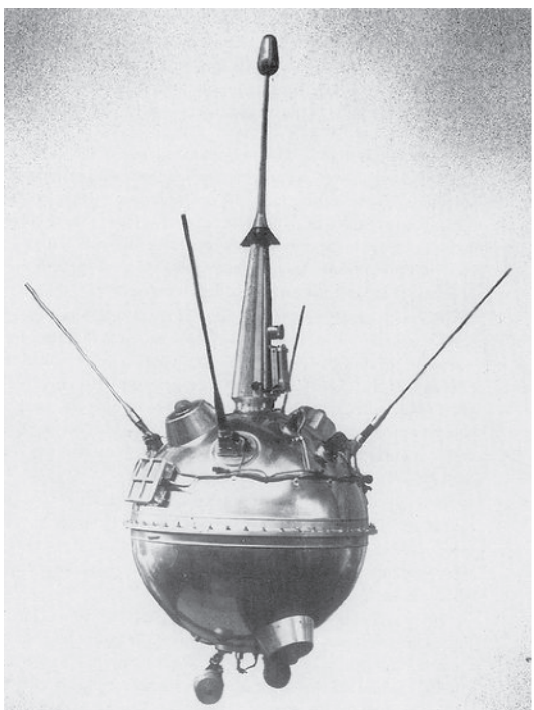

Figure 1.46 An impactor spacecraft, Soviet *Luna 2*, the first manmade object to land on another celestial body, the Moon, 1959. (Source: *NASA*.)

comet-like, bright orange gas trail that was visible from Earth. The purpose of this gas release was to study the behavior of a gas in outer space.

A variation of the impactor lander is the *penetrator* spacecraft, which is designed to survive the tremendous forces of the impact and penetrate into the surface. It then makes measurements that are telemetered back to Earth, typically by relaying the data to a “mothership” spacecraft in orbit.

The *stationary lander* and the *surface rover* make soft landings on a planet or other body. The stationary lander remains at its landing spot, while the surface rover is able to move about the surface. The rover has the advantage of being able to move about the surface, allowing it to explore a larger area than the stationary lander, but this comes at a higher risk of damage in navigating the terrain and surface obstacles. Both the stationary lander and the surface rover may have semi-autonomous functions, such as unfolding solar arrays or antennas, but they are often sent commands by controllers on Earth. The movement of a surface rover on another planet is precisely choreographed by controllers on Earth to ensure the safety and success of the vehicle’s movements. We discuss the *Curiosity* Mars surface rover in a later section.

If there is sufficient atmosphere to produce significant frictional heating, shielding may be required to protect the lander spacecraft from high heating during its entry and descent. The landing must be soft enough so that the spacecraft is undamaged and able to perform its mission on the surface, typically scientific data collection. Parachutes, rockets, or both, may be used to decelerate the lander during its descent. Rockets may be fired, right before touchdown, to reduce the landing impact velocity. Touchdown of the spacecraft may be on mechanical landing gear or inflatable cushions or bags, to absorb the final landing loads. For landing on bodies with very low gravity, a harpoon-type device may fire an anchor cable into the surface to hold the spacecraft onto the surface.

This was the scheme used for the European Space Agency (ESA) *Philae*, a small robotic lander that made the first soft landing on the surface of a comet, *67P/Churyumov–Gerasimenko*, on 12 November 2014 (Figure 1.47). The *Philae* lander had anchoring harpoons on its belly that would fire downward into the comet, when the spacecraft touched down on the gravity-less comet. The

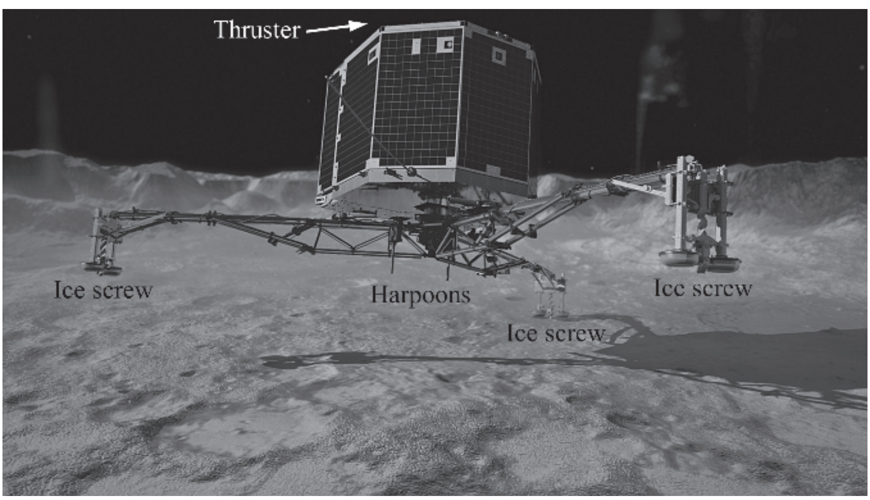

Figure 1.47 Depiction of *Philae* landing on Comet *67P Churyumov–Gerasimenko*. (Source: *Adapted from DLR German Aerospace Center, “Rosetta’s Philae Touchdown” https://en.wikipedia.org/wiki/File:Rosetta%27s_Philae_touchdown.jpg, CC-BY-SA-3.0. License at https://creativecommons.org/licenses/by-sa/3.0/legalcode.*)

lander would then fire a thruster, on top of the spacecraft, gently pushing it onto the surface, while ice screws were drilled into the surface from its three landing footpads. Unfortunately, the landing impact was softer than planned, so that the anchoring harpoons did not fire. Without the anchors in place, the *Philae* lander bounced off the comet surface a few times, but luckily settled down to a permanent landing without being damaged.

The first spacecraft to soft land on another celestial body was the Russian *Luna 9*, which landed on the Moon on 3 February 1966. This was followed by the United States *Surveyor 1*, which soft landed on the Moon four months later, on 2 June 1966. Both landers answered a question that was in debate prior to a spacecraft actually landing on the Moon: would a spacecraft sink deeply into the dust on the surface of the Moon, perhaps even burying the lander? This was a question that was of some concern for future plans to land people on the Moon. The lunar surface supported the weight of the landers, definitively putting this issue to rest. Both *Luna 9* and *Surveyor 1* were stationary landers, and both used retrorockets to reduce their rate of descent for a soft landing. One of the major objectives achieved by *Surveyor 1* was the validation of the technologies required to soft land on the moon, paving the way for manned landers.

The Lunar Excursion Module (LEM) and the Lunar Roving Vehicle (LRV) were manned lander spacecraft that landed on the moon during the *Apollo* program (Figure 1.48). The LEM was a stationary lander that carried two astronauts from Moon orbit to the lunar surface. It was a two-stage spacecraft, with a descent stage and an ascent stage. The ascent stage returned the astronauts to rendezvous in lunar orbit with the *Apollo* Command Module spacecraft. There were six successful landings of the LEM on the moon between 1969 and 1972. The LRV was a surface rover that was carried to the lunar surface by the LEM. It was an open-frame, electrically powered, four-wheeled, car-like vehicle with side-by-side seating for two astronauts. The LRV was used on the moon for the last three *Apollo* missions.

Figure 1.48 *Apollo 16* Lunar Excursion Module and Lunar Roving Vehicle on the moon, 1972. (Source: *NASA*.)

1.3.1.4 Atmospheric Probe

Some spacecraft carry smaller, specially instrumented atmospheric probe spacecraft that are released to enter the atmosphere of another planet. These atmospheric probes are used to collect scientific data about the planet and its atmosphere as they descend. Entering the atmosphere at hypersonic speeds, they typically encounter large aerodynamic forces and high heating. Deceleration and thermal protection may be required using an aeroshell, a rigid shell structure that detaches from the beneath the probe. High drag devices, such as parachutes, may also be deployed to decelerate the probe and allow more time for data collection during its descent. Data from the probe is typically telemetered to the orbiter "mothership" spacecraft, where it is relayed back to Earth. Often, atmospheric probes are not designed to survive to landing on the planet surface, burning up in their fiery descent.

The *Pioneer 13* spacecraft, also known as the *Pioneer Venus Multiprobe*, carried four atmospheric probes to the planet Venus in the late 1970s. The probes were spherically shaped, pressure vessels with aeroshells. One probe was 1.5 m (4.9 ft) in diameter and the other three were smaller, at 0.8 m (2.6 ft) in diameter (Figure 1.49). The aeroshell of the large probe detached to provide thermal protection, and a parachute was used to decelerate the probe. The smaller probes did not have parachutes and their aeroshells remained attached. The probes were not designed to survive to landing on Venus, but amazingly, one of the small probes continued to transmit signals for over an hour after impacting the surface. The main spacecraft body or *bus* (to be discussed in the next section) was also used as an atmospheric probe, even though it did not have a heat shield or parachute.

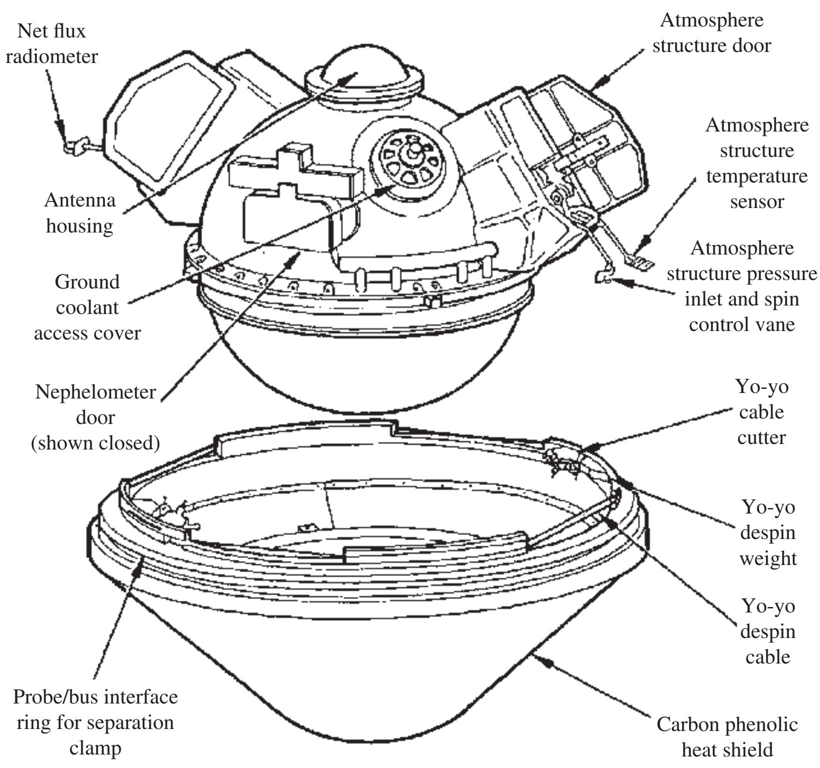

Figure 1.49 Diagram of *Pioneer 13* small probe. (Source: *NASA*.)

When the 2.5 m (8.2 ft) diameter, 290 kg (639 lb) cylindrical spacecraft was no longer able to stay in orbit around Venus, it entered the atmosphere and transmitted scientific data until it burned up at an altitude of about 110 km (68.4 miles).

1.3.1.5 Planetary Aircraft

Another type of atmospheric spacecraft is the planetary aircraft. This concept involves the deployment of an unmanned aircraft in the atmosphere of a planet, where it flies in the atmosphere and makes scientific measurements and observations, similar to an airborne science-type aircraft on Earth. An advantage of the planetary aircraft is that it can explore a larger area than other types of lander spacecraft. It may even be possible for the planetary aircraft to land and take off on the planet, giving it the capability to explore several different landing sites. While many of these concepts involve unmanned aerial vehicles, an ultimate possibility might be manned planetary aircraft, allowing astronauts to travel about and explore a planet from the air and cover large distances over the planet surface. A wide variety of planetary aircraft have been proposed, including gliders, powered-airplanes, rotorcraft, airships, and balloons. Propulsion concepts for these aircraft have included rocket power and a combustion, electric battery, or solar-powered engine-propeller combination.

Aircraft flight on another planet involves some unique design challenges. First, the aircraft must be packaged to fit within the volume constraints of the rocket booster that is launched from Earth, which usually involves folding of the aircraft's structural components. Upon arriving at the planet of interest, the aircraft must be deployed and unfolded in the planetary atmosphere. The aircraft may also need to be capable of transitioning from a near-vertical, free-fall type deployment to horizontal flight. Other complexities include autonomous operation of the aircraft flight control and navigation systems, propulsion, sensors, telemetry, and other systems. The atmospheres of other planets are dramatically different, in terms of density, pressure, temperature, composition, and other factors, than Earth's atmosphere. This must be taken into consideration in the aerodynamic design of the aircraft and its flying qualities. For instance, since the atmosphere of Mars is much less dense than on Earth, flight near the surface of Mars corresponds to flight at over 100,000 ft (30 km) on Earth.

The rocket pioneer, Wernher von Braun, proposed one of the earliest concepts of using large manned gliders to land on Mars. In the 1970s, the use of unmanned airplanes was investigated for the exploration of Mars. There was renewed interest in flying an airplane on Mars in 2003, which would have coincided with the centennial of the Wright brothers' first flight. There has also been recent interest in using aerial vehicles to explore the atmosphere of Venus and Titan, a moon of Saturn, with various concepts ranging from inflatable airships to solar-powered airplanes.

One of the designs for a Mars airplane, that has been extensively studied, is the NASA Aerial Regional-scale Environmental Survey (ARES) Mars airplane (Figure 1.50). The 150 kg (330 lb) ARES design had a wingspan of 6.25 m (20.5 ft) and was powered by a hydrazine-fueled, liquid rocket engine. It had a predicted cruise speed of 145 m/s (476 ft/s, 324 mph) and range of 680 km (423 miles). Although the 2003 Mars airplane mission was cancelled, several key enabling technologies were demonstrated. In September 2002, a 50%-scale prototype of the ARES Mars airplane was flight tested by releasing it from a high-altitude balloon. Since the atmosphere of Mars is much thinner than on Earth, the release and flight of the ARES airplane at an altitude of about 100,000 ft (30 km) on Earth simulated flight near the surface of Mars. The airplane was packaged, as it would be for a Mars mission, thus the successful unfolding and deployment of the airplane's wings and tail in the test, verified this aspect of the design. After being released, aerodynamic and stability and control data were obtained for the ARES airplane at high altitudes, simulating flight on Mars.

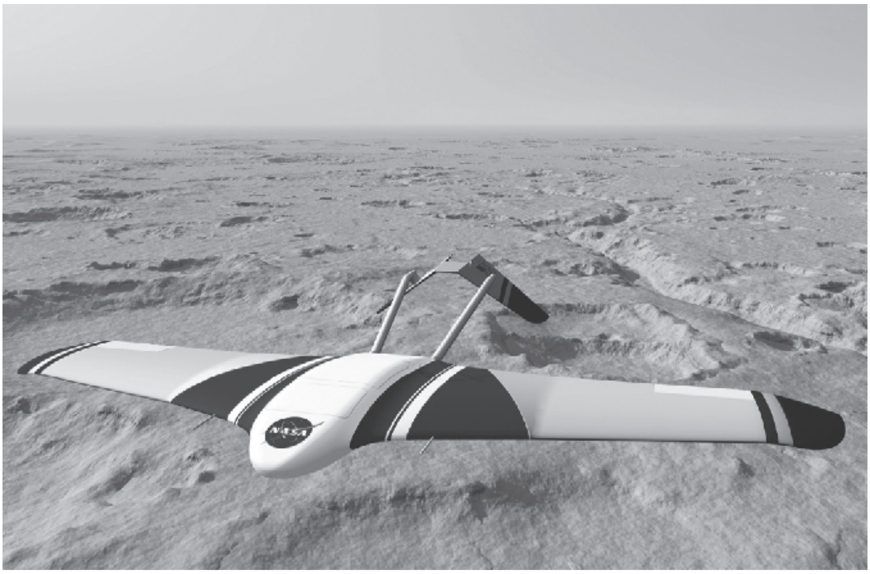

Figure 1.50 Artist's concept of NASA ARES Mars airplane flying over Mars. (Source: *NASA*.)

1.3.2 Parts of a Spacecraft

A spacecraft can often be separated into the *bus* and the *payload*. The bus is the structural framework of the spacecraft, onto which subsystem components and the payload are mounted. Typically, the spacecraft bus contains subsystems that support the operation of the payload. The support functions may include electric power and distribution, communications and telemetry, thermal control, attitude sensing and control, and in-orbit propulsion. The payload and spacecraft bus may be separate units or they may be a combined system. The spacecraft bus infrastructure is commonly used for earth satellites, especially communications satellites. The payload contains the systems to perform the primary mission of the spacecraft, which may be specialized instrumentation, sensors, or other scientific equipment. The payload could also be the people who are being transported into space.

The spacecraft structure is typically made of high-strength, lightweight materials such as aluminum, titanium, beryllium, or composite materials. The spacecraft structure must be designed for a variety of conditions, including the high g-loads experienced during launch and orbit insertion, and extremes in the thermal, pressure, and acoustic environments. There may be tight tolerances on the deformation of the structure caused by these environmental factors, driven by the critical alignment of sensors, antennas, or other components. The structure must be as light as possible, as there are usually weight limits for the launch vehicle being used.

Most spacecraft have systems for power generation, communication, thermal control, vehicle attitude control, and propulsion. Spacecraft power can be provided by a variety of sources, including batteries, solar panels, fuel cells, and even nuclear power sources. The choice of a power source usually depends on the power requirements and the mission duration. Batteries or fuel cells are often satisfactory for missions lasting days or a few weeks. Typical types of batteries include silver zinc, lithium-ion, nickel-cadmium, and nickel-hydrogen. Fuel cells produce electricity through the chemical reaction of a fuel and an oxidizer, often hydrogen and oxygen. For longer duration missions of months or years, such as interplanetary voyages, nuclear and solar power generation is usually required. An example of a nuclear power generator is the radioisotope thermoelectric generator (RTG). The RTG operation is based on the natural decay of a radioactive material, such as plutonium; therefore, radiation shielding may be needed to protect other spacecraft systems. Heat given off by the decay of the isotope is converted into electricity. Solar cells are a reliable means of power generation, but they require the deployment and pointing of solar arrays. With any of these types of power sources, systems for power distribution, power regulation, and energy storage are typically required.

Communications equipment is required to transmit information, data, and commands between the spacecraft and the ground users or controllers on Earth. The communications signal is often a radio signal, but may be a laser signal. The communications signal that is sent *to* the spacecraft is called the *uplink*, while the signal *from* the spacecraft is called the *downlink*. Receivers, transmitters, and antennas are basic components of the communications system. Spacecraft typically have redundant sets of communications equipment and antennas.

Spacecraft often have high-gain and low-gain antennas. The gain refers to the amount of radio power that can be collected by the antenna and sent to the receiver. The higher the gain, the higher the rate of data transmission of radio signals that can be sent and received. The antenna gain can be increased by making the radio signal collecting area of the antenna larger. This is why most high-gain spacecraft antennas are large, parabolic-shaped, dish antennas. Because of their high data rate, spacecraft primarily use their high-gain antennas for communications with Earth. However, high-gain antennas are also highly directional, that is, they send and receive radio signals in a narrow radio beam width. (Hence, high-gain antennas are also called directional antennas.) A stronger, focused radio signal can be sent and received from a high-gain antenna, but the pointing of this signal is more difficult. Typically, a spacecraft's high-gain antenna must be pointed to Earth within a fraction of a degree to send and receive radio signals. Hence, a high-gain antenna is more susceptible to signal loss and loss of communications. By contrast, low-gain antennas can send and receive radio signals over a wide coverage area, albeit at a lower data rate. The wide beam width of the low-gain antenna makes it less susceptible to signal loss, so they are usually used as a backup for the high-gain antenna, especially in situations where the radio signal must be reacquired after loss of signal with the high-gain antenna.

Spacecraft are exposed to a severe thermal environment in vacuum, with extremes in temperature that are dependent on the amount of sun exposure. In space, the sun-lit side of a spacecraft may have a surface temperature of over 120°C (248°F, 393 K), while the shaded side may feel a frigid −200°C (−328°F, 73.2 K). The thermal control system must maintain the spacecraft's temperature within the operating limits of the onboard systems and components. It must prevent electronics from overheating and must keep mechanical, moving parts from freezing. Thermal control may be accomplished using passive or active methods. Passive techniques include the use of insulation, blankets, surface coatings (for instance, simply painting a surface white or black), and mirrors. Active thermal control includes the use of electrical heaters, fluid-filled radiators, and louvers. The louvers act much like window blinds, opening and closing to regulate the dissipation of heat from inside the spacecraft.

Stabilization of the spacecraft is usually required in terms of attitude control in three dimensions. External forces and torques acting on the spacecraft may disturb it from a desired attitude or orientation. An attitude control system is required to sense and correct any changes from the desired orientation. It may also be necessary to intentionally change the attitude or orientation of the spacecraft for pointing of sensors, communications antennas, or solar arrays, thermal management, or docking with another structure or spacecraft. A reaction control system, composed of multiple small rocket thrusters, may be used to make attitude corrections. Another system that may be used for spacecraft stabilization is the spinning *reaction* or *momentum wheel*. By changing the speed of the spinning momentum wheel, angular momentum can be traded between the spacecraft and the wheel. For example, if a rotation of the spacecraft is desired in a certain direction, the wheel is spun up in the opposite direction. By conservation of angular momentum, the desired spacecraft rotation is obtained.

A spacecraft may have a propulsion system that consists of tankage, propellant, thrusters, and the associated feed system plumbing and valves. The propellant may be a compressed gas, such as nitrogen, a liquid monopropellant, such as hydrazine, or a solid fuel. Spacecraft propulsion may be needed for attitude or altitude changes or corrections. A spacecraft may have a separate propulsion unit or rocket motor, called an *apogee boost motor,* or *kick stage*, used to boost the vehicle into its final orbit.

Finally, spacecraft that are intended for human spaceflight, or space habitation, require life support systems. Life-sustaining oxygen must be supplied, along with the removal of carbon dioxide and other harmful contaminants. The life support systems must maintain the spacecraft cabin environment at an adequate pressure, temperature, and humidity. Protection from harmful space radiation and impacts from micrometeorites must also be provided. Systems must be available to handle human waste products.

To illustrate the parts of a spacecraft, we examine the NASA *Magellan* spacecraft, shown in Figure 1.51. *Magellan* was launched on 4 May 1989, in the cargo bay of the Space Shuttle *Atlantis*, the first interplanetary spacecraft to be carried aboard a Shuttle. *Magellan* was sent to explore the planet Venus, including obtaining radar imaging of its surface. The spacecraft was 6.4 m in height (21 ft), 4.6 m (15.1 ft) in diameter, 10 m (32.8 ft) across from tip to tip of the solar panels, and had a total mass of 3453 kg (7612 lb), including 2414 kg of propellants (5322 lb). To reduce costs, the spacecraft was built from spare parts from other spacecraft programs, including the *Voyager*, *Galileo*, *Ulysses*, and *Mariner 9* programs. As shown in Figure 1.51, the main components of the *Magellan* spacecraft were the bus, forward equipment module, antennas, solar panels, attitude control module, propulsion module, and rocket engine module.

The *Magellan* spacecraft was built around a 10-sided, aluminum bus (a spare bus from the *Voyager* program), as shown in Figure 1.52. The bus was a bolted-together, aluminum structure

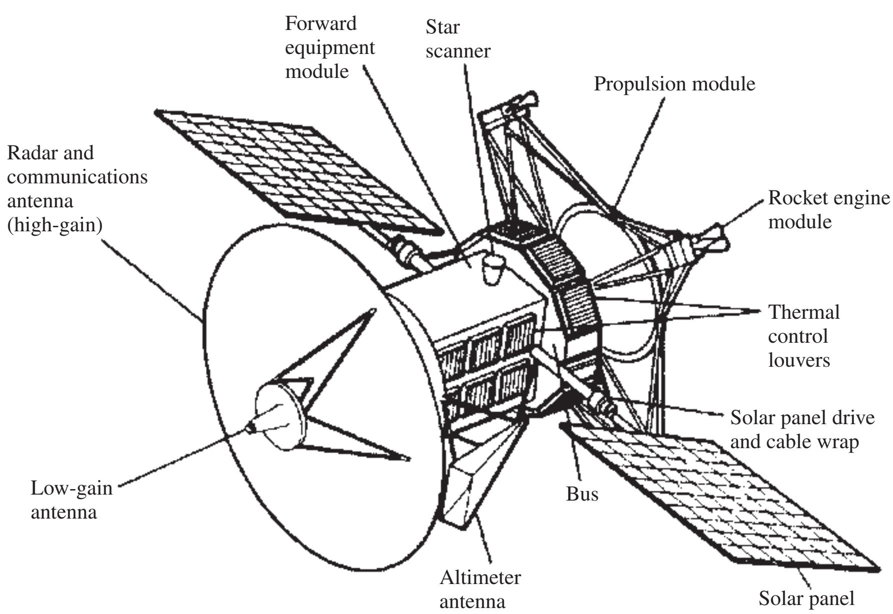

Figure 1.51 Parts of the *Magellan* spacecraft. (Source: *NASA*.)

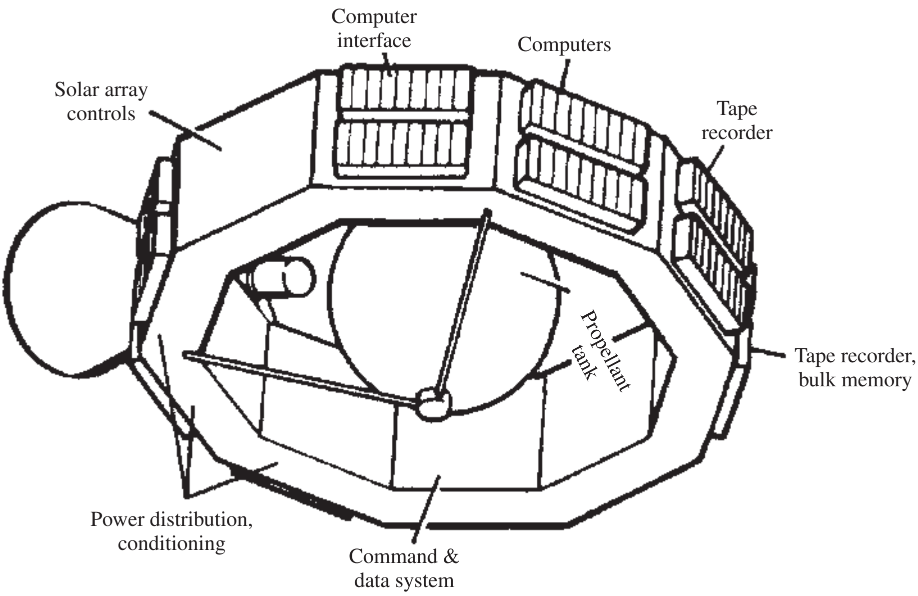

Figure 1.52 *Magellan* spacecraft bus. (Source: *NASA*.)

with ten independent compartments, designed to hold electronic components. Housed in the bus were the spacecraft's flight computers, power distribution and conditioning components, solar array controls, tape recorders, and command and data subsystem. The spherical, propellant tank for the spacecraft's propulsion module was mounted in the center of the bus.

The flight computers (from the *Galileo* program) controlled the command and data subsystem, as well as the spacecraft's attitude. The command and data subsystem stored the commands sent to the spacecraft, by controllers on Earth, and could autonomously control the spacecraft, if contact with Earth was lost. Scientific and radar mapping data were also stored on the command and data subsystem. Commands and data were stored on two digital tape recorders, which could store up to 225 megabytes of data, a meager amount of data storage by today's standards. The forward equipment module, a box-like structure, sat atop the bus. The radar electronics, telecommunications equipment, and batteries were mounted in the forward equipment module.

Spacecraft thermal control was accomplished with a combination of passive and active techniques. Multi-layered thermal blankets were wrapped around the electronic compartments. In addition to providing thermal insulation, the blankets had an outer coating that reflected solar radiation. Thermal control louvers were mounted on the face of each electronic compartment of the bus and on two sides of the forward equipment module.

The spacecraft had four different antennas to support communications and radar mapping functions. As shown in Figure 1.51, a 3.7 m (12.1 ft) diameter, high-gain, parabolic dish antenna (from the *Voyager* program) was mounted at the top of the spacecraft stack. This large dish antenna was the primary antenna for communications with Earth and for the radar mapping. A low-gain antenna (also from the *Voyager* program) was mounted in the center of this high-gain dish. A cone-shaped, medium gain antenna (from the *Mariner 9* program) was mounted to the top side of the bus. Both of these antennas augmented the high-gain antenna. The altimeter antenna, mounted on the side of the forward equipment module, was used for radar mapping.

The spacecraft electrical power was a 28 V system that was supplied by two large, square solar panels or two nickel-cadmium batteries. The solar panels supplied 1200 W of power at the start of the mission, but this gradually decreased over time as the efficiency of the panels degraded. Each solar panel measured 2.5 m (8.2 ft) on a side. The panels were hinged for stowage in the Space Shuttle cargo bay and were deployed once the spacecraft was released. The panels could also rotate so that they could be oriented towards the Sun. The rotation of the panels was controlled by the solar array controls and solar sensors at the tips of the panels. The batteries, located in the forward equipment module, could power all of the spacecraft systems when it was not in sunlight. They also provided the required additional power when the radar mapping system was in use. The batteries could be recharged with the solar panels.

The *Magellan* spacecraft's attitude was controlled using 36 cm (14 in) diameter momentum wheels, mounted in the attitude control module (Figure 1.53), located in the forward equipment module. The spacecraft's rotation rate was sensed by a set of gyroscopes, which sent their data to an attitude control computer. The computer commanded the rotation of the momentum wheels, as required, to correct the attitude of the spacecraft. The spacecraft attitude was also determined, to a high accuracy, with a star scanner, located in the forward equipment module. The star scanner data was used to correct the small errors accumulated by the drift of the gyroscopes.

Propulsion for the *Magellan* spacecraft was provided by an Inertial Upper Stage, a propulsion module, and a rocket engine module. When released from the Space Shuttle, in low Earth orbit, the *Magellan* spacecraft was attached to the Inertial Upper Stage, a two-stage solid-fueled rocket booster. The Inertial Upper Stage rocket was fired to send *Magellan* on its interplanetary trajectory from low Earth orbit to Venus. The *Magellan* rocket engine module (Figure 1.54) was a Star 48B solid rocket motor used for orbit insertion at Venus. The Star-48B motor (designed and used to

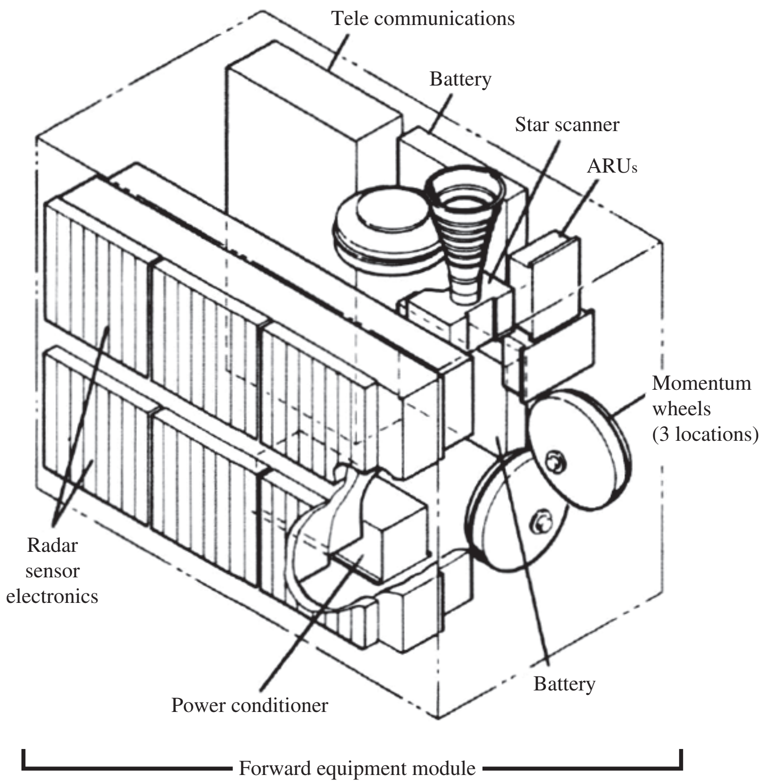

Figure 1.53 *Magellan* spacecraft attitude control module. (Source: *NASA*.)

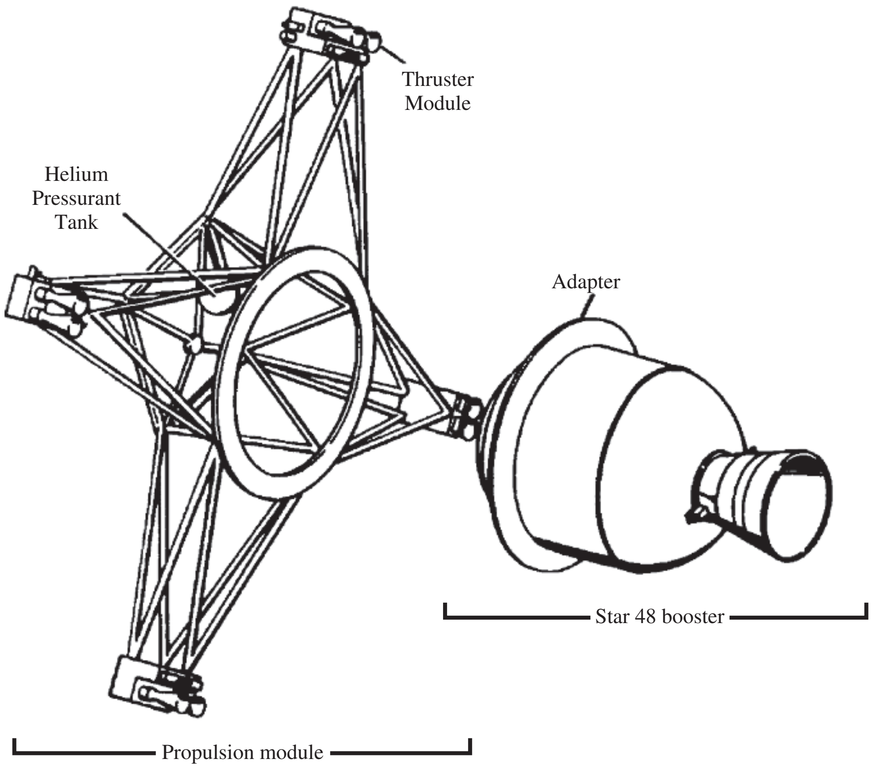

Figure 1.54 *Magellan* spacecraft propulsion and rocket engine modules. (Source: *NASA*.)

raise communications satellites from low Earth orbit to geosynchronous orbit) contained 2014 kg (4440 lb) of solid propellant and delivered a thrust of about 89,000 N (320,000 lb).

The *Magellan* propulsion module (Figure 1.54) was a four-armed truss structure with six liquid-propellant thrusters on the tip of each arm. The 24 thrusters were used for spacecraft attitude control, trajectory and orbit corrections, and reaction wheel desaturation. (The reaction wheels build up excess momentum from external torques, such as from solar pressure on the solar panels. The process of removing this excess momentum is called *desaturation*.) Each cluster of six thrusters comprised two 100 lb (445 N) thrusters, one 5 lb (22.2 N) thruster, and three, tiny 0.2 lb (0.89 N) thrusters. The 100 lb thrusters, pointed aft, were used for trajectory corrections, large corrections to the Venus orbit, and spacecraft stabilization during the Star-48B orbit insertion burn. The 5 lb thrusters prevented the spacecraft from rolling during these maneuvers. The 0.2 lb thrusters were used for reaction-wheel desaturation and small maneuver corrections. All 24 thrusters were fueled from a single 71 cm (28 in) diameter, titanium, propellant tank, located in the middle of the spacecraft bus, filled with 133 kg (293 lb) of monopropellant hydrazine. Additional pressure for the hydrazine system was provided by a small, helium-filled pressurant tank, mounted to the propulsion module struts, as needed.

1.3.3 Unmanned Spacecraft

Unmanned spacecraft include a wide variety of vehicles that operate in the space environment, performing a wide variety of missions. Different types of unmanned spacecraft include satellites that orbit the earth, probes that journey to other celestial bodies, and landers and rovers that operate on other planets and moons. We start with a discussion of satellites.

1.3.3.1 The First Earth Artificial Satellite

Spacecraft that are made to orbit the earth are called *satellites*, sometimes called *artificial* satellites as opposed to natural satellites, such as the Moon. For a spacecraft to be placed into *low earth orbit*, which we define as an altitude of a few hundred miles, it must attain an *orbital velocity* of about 17,000 mph (27,000 km/h).

The first artificial earth satellite was the *Sputnik 1* (meaning *Satellite 1* in Russian), launched by the Soviet Union on 4 October 1957 (Figure 1.55). *Sputnik* had a simple spherical shape, about the size of a beach ball, 22.8 in (58 cm) in diameter, and weighed 184 lb (83 kg). It was launched into an elliptical, low earth orbit, with an apogee (point in the orbit that is the farthest from the earth) of 584 miles (940 km) and a perigee (point in the orbit that is the closest to the earth) of 143 miles (230 km), completing an orbit about every 96 minutes (also known as the *orbital period*).

Sputnik broadcast radio pulses, using four external antennas, which were detected by radio receivers on the ground. In addition to demonstrating the ability to launch an artificial satellite into low earth orbit, *Sputnik* provided scientific data about the earth's upper atmosphere. The drag on the satellite in its orbit provided data about the atmospheric density, while the attenuation of the broadcast radio signals provided information about the ionosphere. The satellite remained in orbit for about three months, before the atmospheric drag brought it into the thicker regions of the atmosphere, where it burned up. This first satellite was visible in the night sky, as it raced around the earth every 96 minutes, broadcasting its radio pulses. The *space age* had begun.

In the USA, plans were in progress to develop the first American earth satellite, but the *Sputnik* launch caught all of America by surprise. There was a firestorm of political, scientific, and emotional turmoil over the concern that the Soviet Union was technologically ahead of the USA and that they would use this advantage to control space. There was also much concern that the Soviet Union had the capability to launch intercontinental ballistic missiles, armed with nuclear weapons, across the globe. Thus, *Sputnik* had not only started the space age, but had also set off the space race

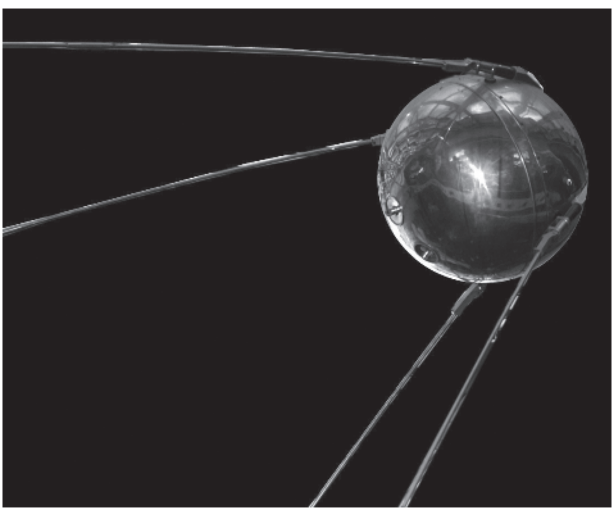

Figure 1.55 *Sputnik 1*, the first artificial satellite. (Source: *NASA*.)

between the USA and the Soviet Union. As a side note, a significant event that occurred, due to this new space race, was the creation of the National Aeronautics and Space Administration (NASA) on 1 October 1958, from its predecessor, the National Advisory Committee for Aeronautics (NACA).

Prior to *Sputnik*, the American effort to launch an artificial satellite into low earth orbit resided with the *Vanguard* program, led by the Naval Research Laboratory in Washington, DC. The *Vanguard* program was ultimately successful in placing several artificial satellites into earth orbit, but they were not the first to place an American satellite into orbit. *Vanguard 1* was successfully launched and placed into earth orbit on 17 March 1958, the fourth manmade satellite to orbit the earth, after *Sputnik 1*, *Sputnik 2* (on 3 November 1957), and *Explorer 1* (discussed below). The *Vanguard 1*, a spherically shaped satellite, was 6.4 inches (16.4 cm) in diameter and weighed 3.2 lb (1.5 kg). It was placed into an elliptical orbit with an apogee of 2387 miles (3841 km), perigee of 409 miles (659 km), and an orbital period of 132.8 minutes. Despite its small size, the *Vanguard 1* satellite had some impressive scientific achievements, including obtaining data to prove that the earth is not a perfect sphere, but rather, more "pear-shaped". It was also the first solar-powered satellite. Amazingly, the *Vanguard 1* is still in orbit today, albeit non-functioning, making it the oldest manmade satellite still in earth orbit. It is expected to remain in earth orbit into the 22nd century.

After *Sputnik*, the USA initiated the *Explorer* project to place an artificial satellite into low earth orbit. The *Explorer 1* satellite was the top stage of its rocket launch vehicle. The aft end of the satellite was the burnt-out fourth stage of the rocket and the forward end was the satellite instrumentation section (Figure 1.56). The *Explorer 1* had a total weight of 30.7 lb (13.9 kg) with the instrumentation section weighing 18.4 lb (8.35 kg). As shown in Figure 1.56, the instrumentation section had substantial instrumentation, containing a nose cone temperature probe, a cosmic ray detector, an internal temperature sensor, micrometeorite erosion gauges, external temperature sensors, a micrometeorite ultrasonic microphone detector, and low-power and high-power data transmitters. There were two different types of antennas on the satellite, two fiberglass slot antennas on the

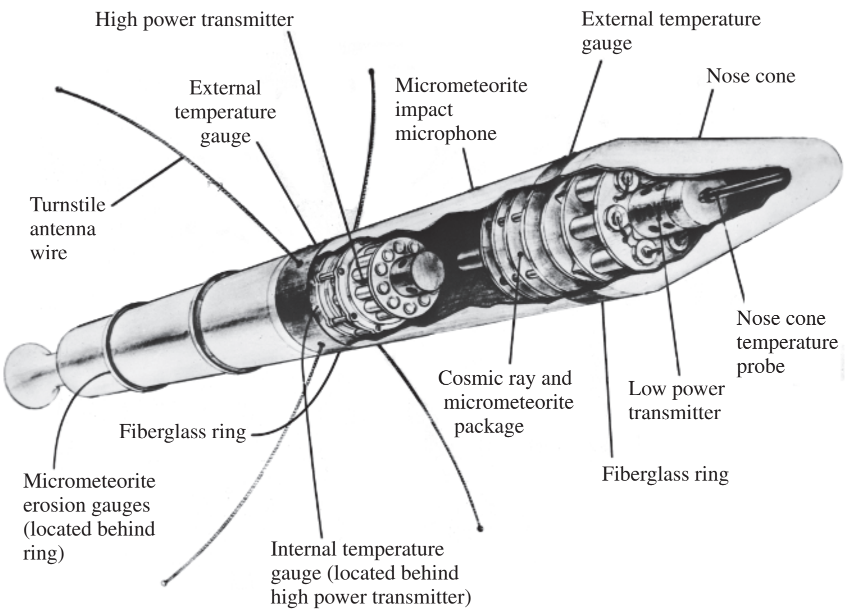

Figure 1.56 *Explorer 1*, the first American artificial satellite. (Source: *US Army Redstone Arsenal*.)

cylindrical satellite body and four flexible "whip" wire antennas located around the circumference in a turnstile arrangement. The satellite was spun about its longitudinal axis at 750 revolutions per minute, to keep the flexible wire antennas extended.

The *Explorer 1* satellite was built by the California Institute of Technology's Jet Propulsion Laboratory (JPL), under the direction of Dr William H. Pickering. The satellite instrumentation was designed and built by Dr James A. van Allen of the State University of Iowa. The satellite's *Jupiter-C* launch vehicle, a modified *Redstone* ballistic missile, was designed by a team led by Dr Wernher von Braun at the Army Redstone Arsenal in Huntsville, Alabama. Von Braun and many of his team had come to the USA after World War II, having led much of the German V-2 rocket development. He would later lead the major efforts to develop the *Saturn V* rocket engines that would take man to the Moon. The success of the *Explorer 1* satellite is a tribute to the combined contributions of these three scientists and the teams that they led (Figure 1.57). The modest size of the *Explorer 1* satellite can be appreciated in this photo.

A little less than four months after the success of *Sputnik 1*, on 31 January 1958, the USA successfully placed *Explorer 1* into low earth orbit. The small satellite went around the earth in an elliptical orbit with an apogee of 1575 miles (2535 km), a perigee of 224 miles (361 km), and

Figure 1.57 Dr William H. Pickering, Dr James A. van Allen, and Dr Wernher von Braun hold up a full-scale model of *Explorer 1*. (Source: *NASA*.)

an orbital period of 114.9 minutes. *Explorer 1* is credited with collecting the scientific data that led James van Allen to the discovery of the radiation belt that surrounds the earth and now bears his name.

Orbiting earth satellites have truly transformed our world by providing us with a variety of previously unavailable capabilities and perspectives. Earth satellites have revolutionized many areas, including weather prediction, earth observation, communications, and navigation. Satellites are placed into a variety of earth orbits, including very high orbits, called *geostationary orbits*, where they can remain over the same spot on the earth. Since the success of these early satellites, literally thousands of artificial satellites have been placed in earth orbit (some estimates place the number at over 6500). Of these, perhaps several hundred are currently operational, many have reentered the atmosphere and burned up, while others are no longer operational and have become space debris. In fact, there is so much space debris or space "junk" orbiting the earth that it has to be tracked so that collisions can be avoided with operational spacecraft, including manned spacecraft.

1.3.3.2 Detailed Descriptions of a Few Types of Unmanned Spacecraft

In this section, brief examples are given of a few types of unmanned spacecraft, a communications satellite, a scientific satellite, a deep space probe, and a planetary rover. These different types of unmanned spacecraft have distinctly different missions, which drive their individual designs and configurations. These different spacecraft look quite different from each other because of their quite different missions.

A Communications Satellite: the Iridium Constellation

Communications satellites have become commonplace in today's society, providing global coverage for the television, radio, and telecommunications industries. The concept of using satellites for global communications was proposed well before the launch of the first artificial satellite in 1957. In October 1945, Arthur C. Clarke published a short article entitled "Extra-Terrestrial Relays – Can Rocket Stations Give Worldwide Radio Coverage?" which proposed the use of artificial earth satellites for the worldwide relay of television signals. The satellite communications relay concept involves sending signals from earth to the orbiting satellite, which then relays the signal to other points on the globe. The first artificial satellite, dedicated to the communications relay, was the NASA *Echo 1* high-altitude balloon, launched to 1000 miles (1609 km) above the earth in 1960. *Echo 1* was a 100 ft (30.5 m) diameter balloon with a mirror-like, metallic surface, which passively reflected communications radio signals. Later communications satellites would have active repeaters, which could store and actively transmit radio signals and data.

An *Iridium* communications satellite is shown in Figure 1.58. This communications satellite is one of a large number of similar spacecraft that form a satellite *constellation*. The *Iridium* constellation comprises 66 satellites that provide satellite telephone communications coverage over the entire earth's surface. Each satellite is in low earth orbit at an altitude of about 485 miles (781 km). The constellation name came from the original plan to have a total of 77 satellites, matching the number of electrons orbiting the atom of the element iridium. The *Iridium* satellites orbit around the earth in six *orbital planes*, spaced 30° apart, with 11 satellites in each plane.

The *Iridium* satellites take advantage of the spacecraft bus design philosophy, making the manufacturing and assembly of so many satellites more efficient, much like the assembly line concept used in the automotive industry. The *Iridium* satellite payload consists of the communications components, such as transponders and antenna. The satellite bus contains the power, communications, and attitude control systems. As shown in Figure 1.58, the satellite has large solar panels as part of

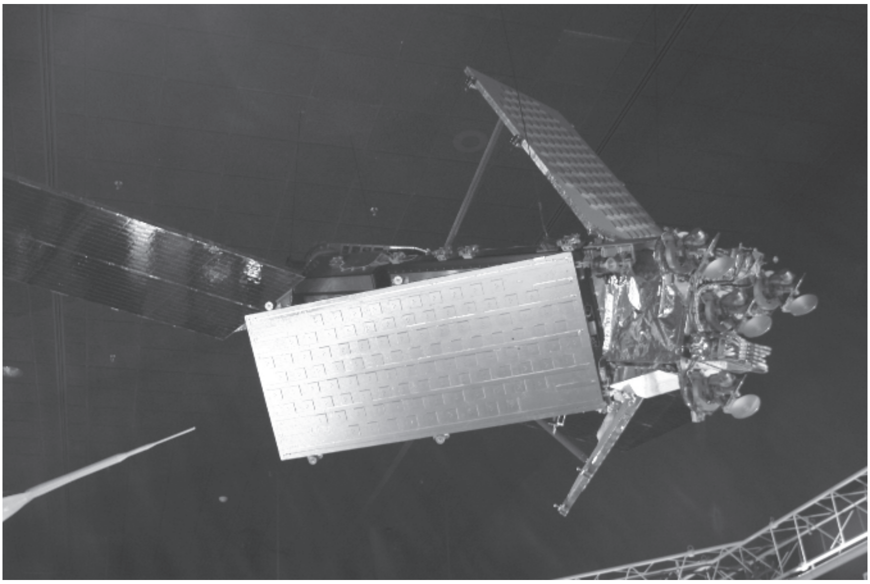

Figure 1.58 An artificial earth satellite, the *Iridium* communications satellite. (Source: *User: Ideonexus, "Iridium Satellite" https://en.wikipedia.org/wiki/File:Iridium_satellite.jpg, CC-BY-SA-2.0. License at https://creativecommons.org/licenses/by-sa/2.0/legalcode.*)

the solar power system. Due to the configuration of the solar panels, the reflected sunlight makes the satellite visible at times from the earth, even in the daytime, an event called an "Iridium flare", or more generally, "satellite glint". Batteries are also used to store power when the Sun is blocked, such as during a solar eclipse.

A Scientific Satellite: the Hubble Space Telescope

Earth-borne telescopes are handicapped by having to look through the earth's atmosphere, which distorts the images captured by the telescopes. The apparent "twinkling" of stars at night is due to this atmospheric distortion. In addition, the atmosphere absorbs some wavelengths of radiation, such as ultraviolet, gamma, and X-ray radiation, making it difficult for earth-based sensors to observe these types of radiation from astronomical bodies. Placing a telescope in space, eliminates the atmospheric distortion and absorption of visible light and other wavelengths of radiation.

Space-borne telescopes were proposed well before the advent of earth satellites. The German rocket scientist, Hermann Oberth (1894–1989), wrote about a space telescope in his 1923 book, "Die Rakete zu den Plantraumen" ("By rocket into planetary space"). Later in 1946, the American astrophysicist, Lyman Spitzer, Jr, (1914–1997) proposed the idea of an orbiting astronomical observatory in his paper "Astronomical advantages of an extraterrestrial observatory". Spitzer was instrumental in the advocacy of space telescopes throughout his career.

One of the largest space telescopes to be placed into earth orbit is the *Hubble Space Telescope* (HST) (Figure 1.59), with a length of 13.2 m (43.3 ft), diameter of 4.3 m (13.8 ft), and a mass of 11,110 kg (24,500 lb). Named after the American astronomer Edwin Hubble (1889–1953), the HST is a joint venture between NASA and the European Space Agency (ESA). Carried into space by the Space Shuttle *Discovery* (STS-31) on 24 April 1990, the *Hubble* was placed into a near-circular orbit, 569 km (354 miles) above the earth.

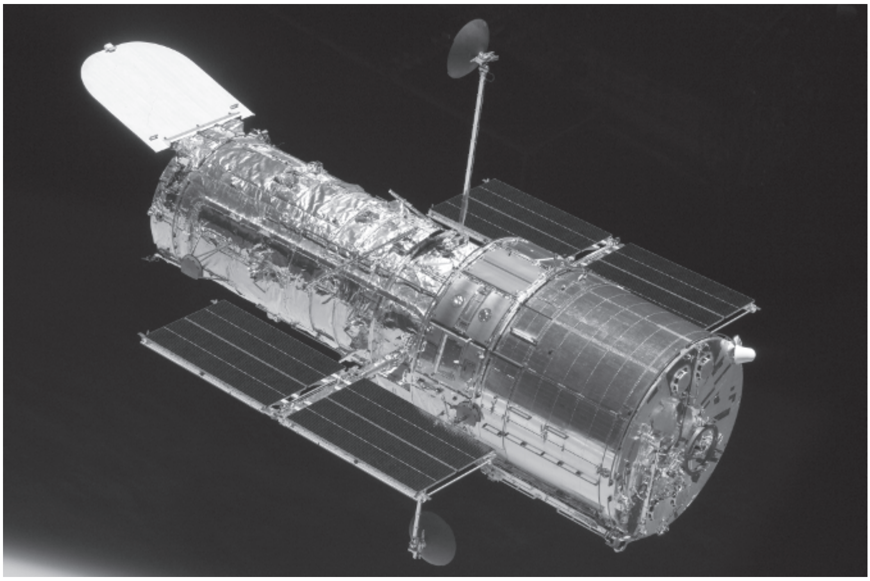

Figure 1.59 A scientific satellite, the *Hubble* space telescope in low earth orbit. (Source: *NASA*.)

The HST is one of the four large space-based telescopes in NASA's Great Observatories program. Each of these space telescopes is designed for a specific region of the electromagnetic spectrum. The *Hubble* space telescope is designed to observe primarily in the visible light spectrum. The *Compton* gamma ray observatory and the *Chandra* X-ray observatory are designed to observe in the gamma ray and X-ray radiation bands, respectively. The *Spitzer* space telescope is designed for infrared observations. All of these space telescopes are still in earth orbit, except the *Compton* gamma ray observatory, which had to be de-orbited when one of its stabilizing gyroscopes failed in 2000. Most of the *Compton* observatory burned up when entering the atmosphere, with any remaining parts falling into the Pacific Ocean.

The *Hubbl*e spacecraft is essentially a long telescope tube consisting of two mirrors, a support truss structure, an aperture door, and sensing instruments and equipment. The telescope is a type of Cassegrain reflector telescope, known as a Rictchey–Chreiten Cassegrain. As shown in Figure 1.60, the aperture door at one end of the telescope is opened and light passes down the tube to the primary mirror. The concave, primary mirror reflects the light onto a smaller, convex, secondary mirror,

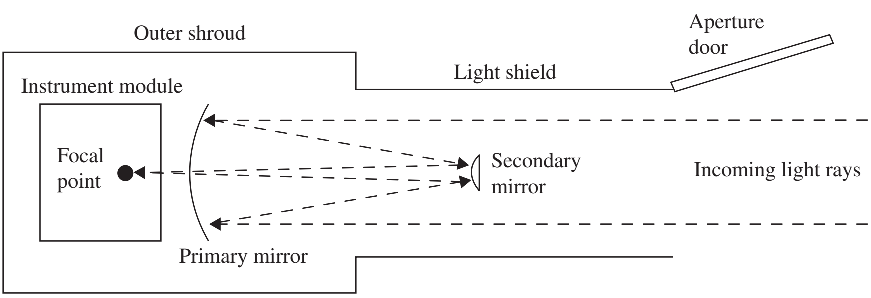

Figure 1.60 Schematic of HST Cassegrain reflector telescope operation.

which then focuses the light back, through a hole in the center of the primary mirror to the focal point where the telescope's sensing instruments are located. The HST primary mirror is 2.4 m (7.9 ft) in diameter, small in comparison to ground-based telescopes, which can be 10 m (32.8 ft) in diameter. A larger mirror can collect more light, which is critical to the size and clarity of the objects that can be "seen" by a telescope. (A telescope works by collecting as much light as possible, not by magnifying the size of an object. In fact, the HST has no magnifying lenses at all, just two mirrors for light collection.) Since the HST can collect undistorted light, in its perch high above the atmosphere, it can provide much improved optical resolution over ground-based systems, despite its smaller mirror. The HST mirrors are kept at a constant temperature of about 21°C (70°F) to prevent warping which would distort images.

Instruments, onboard the *Hubble*, include an infrared camera and spectrometer, an optical survey camera, a wide field of view optical camera, an ultraviolet spectrograph, and an optical spectrometer. The HST four main sensing instruments observe in the near infrared, visible light, and near ultraviolet wavelengths. Power for the instruments and equipment onboard the spacecraft is generated by two large solar panels, 7.56 m (24.8 ft) long by 2.45 m (8.0 ft) wide. Power stored in six nickel-hydrogen batteries is used when the HST is in the earth's shadow for about half an hour during each orbit.

Capturing high resolution images of distant objects requires a sophisticated stability and guidance system that can keep the spacecraft very stable and point it with extreme accuracy. The HST's attitude is adjusted using a set of spinning reactions wheels. The HST spacecraft does not have any propulsion systems for attitude or orbit adjustments. During its five servicing missions, the Space Shuttle boosted the HST's orbit, as required, to compensate for orbit degradation from atmospheric drag.

After the HST was in orbit, the images it sent back to earth were better than those that could be obtained from ground-based telescopes, but they were of lower quality than was expected; in fact, they were somewhat blurry. It was determined that there was a serious flaw in the telescope's primary mirror, resulting in the image distortion. After an investigation, it was discovered that when the mirror was fabricated, it had been ground (a process where the mirror is shaped by removing glass with abrasives) to the wrong shape. The error in the shape of the mirror was extremely small, about 2200 nanometers (0.0000866 in) or about 1/50th the thickness of a sheet of paper, but this was enough to make the HST images blurry. Luckily, the HST was actually designed to be serviced and maintained in space with the aid of the Space Shuttle. This original intent was for the repair and updating of instruments and components, not a major fix of the primary mirror. In a series of five complex Space Shuttle missions, astronauts successfully installed fixes for the HST mirrors, correcting its "blurry vision".

The *Hubble* has proved to be a very productive astronomical observatory, having made over a million observations since its insertion into orbit, by some estimates. Observations from *Hubble* have led to significant scientific discoveries in many areas of astronomy and cosmology. With its increased optical resolution, the *Hubble* can look farther back in time to observe the events closer to the creation of the universe. *Hubble* helped scientists discover dark energy, a mysterious force theorized to be accelerating the expansion of the universe. The *Hubble* data has led scientists to revise the age of universe from about 10–20 billion years to about 13–14 billion years. The *Hubble* Space Telescope is expected to continue providing exciting astronomical observations until at least 2020. Its successor, the James Webb Space Telescope, is planned to be launched into space sometime in 2018.

A Deep Space Flyby Spacecraft: Pioneer 10

Launched from Cape Canaveral, Florida on 3 March 1972, *Pioneer 1*0 (Figure 1.61) was the first flyby spacecraft to be sent into deep space. It was the first spacecraft to go beyond the orbit of

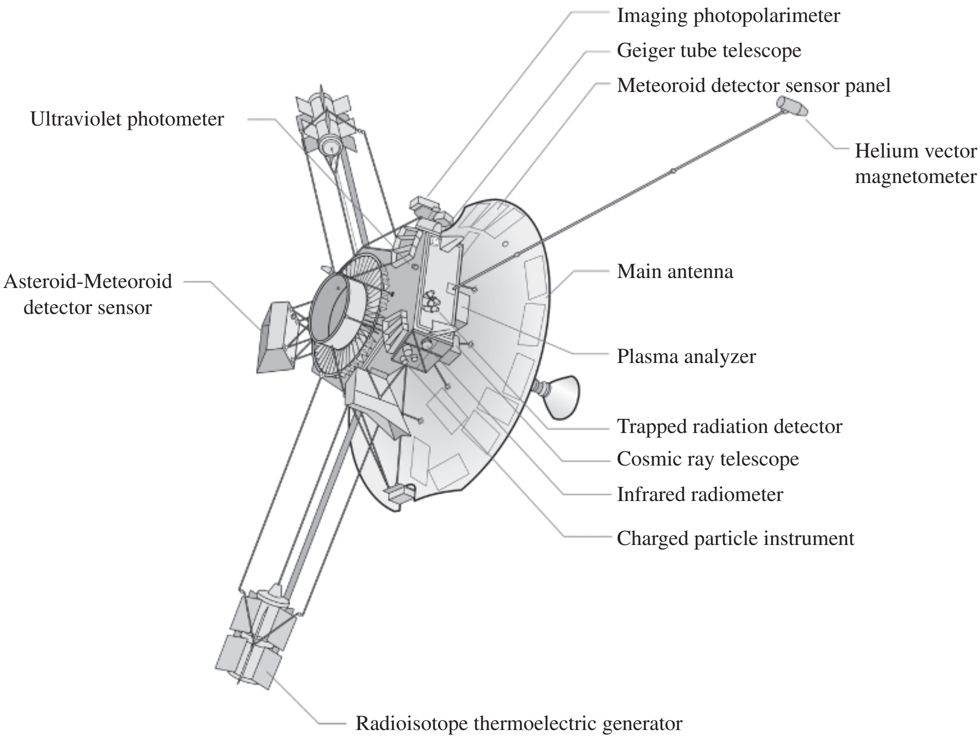

Figure 1.61 A deep space flyby spacecraft, Pioneer 10. (Source: *NASA*.)

Mars and through the asteroid belt, beyond Mars and Jupiter. The primary mission of *Pioneer 10* was to explore the gas giant planet Jupiter. *Pioneer 10* obtained scientific information about Jupiter and several of its moons, including infrared, visible light, and ultraviolet images, measurements of the planet's atmosphere and radiation environment, and data about the bodies' masses. The probe passed within about 130,000 km (81,000 miles) of Jupiter in December 1973, a distance equal to about three diameters of the planet. The probe continued its journey past Jupiter, continuing to send back scientific data about deep space and became the first manmade object to leave our solar system.

As shown in Figure 1.61, a prominent feature of the *Pioneer 10* spacecraft was its large, 27.4 m (90 ft) parabolic, dish antenna. At the base of the antenna, the main body of the spacecraft was comprised of a 36 cm (14 in) deep hexagonal bus structure with each side 76 cm (30 in) in length. Eight of the probe's eleven science instruments were housed within an equipment compartment inside the bus. Insulating blankets, made of aluminized Mylar and Kapton, provided passive thermal protection of the components in the compartment. An active thermal control system, using movable louvers, dissipated excess heat that was generated by the electrical components. The total weight of the probe at launch was 258 kg (569 lb).

The spacecraft was stabilized by spinning the vehicle around the axis of the dish antenna, a technique known as spin stabilization. Six hydrazine-fueled, rocket thrusters provided spacecraft attitude and orientation control. Each small rocket motor generated about 4.5 N (1.0 lb) of thrust. The rocket fuel was liquid hydrazine, a highly toxic, highly flammable, clear liquid monopropellant, commonly used in satellite reaction control systems. A monopropellant does not require a separate fuel and oxidizer as it can generate a hot thrust-producing gas by itself. The spacecraft was launched with about 36 kg (79 lb) of hydrazine fuel, stored in a single, 42 cm (17 in) diameter spherical tank. Two of the thrusters were used to maintain the spacecraft spin-rate at a constant 4.8 rpm. Two Sun sensors and one star sensor were used to keep the spacecraft properly oriented.

The spacecraft had two 8 W transceivers (a combination of a transmitter and receiver) for redundancy. Several antennas were connected to the transceivers, including the large dish, high-gain, narrow-beam, dish antenna and smaller omni-directional and lower-gain antennas. Data from the probe were transmitted back to earth using the transceivers and antennas at a maximum transmission rate of only 256 bits per second. This data transmission rate was degraded as the probe traveled further away from earth. Commands were transmitted to the probe from controllers on earth.

Spacecraft electrical power was supplied by four radioisotope thermoelectric generators (RTGs) that used plutonium-238 fuel. The RTGs were mounted on two 3 m (9.8 ft) support rods (Figure 1.61) to keep the radioactive fuel away from the other spacecraft equipment and instruments. The four RTGs could supply a total of 155 W of power, which decreased to about 140 W as the plutonium fuel decayed. The power system was designed to provide 100 W of power, required for all of the spacecraft systems, for two years. This design goal was far exceeded as the spacecraft continued to be at least partially operational until 2003. Eventually, *Pioneer 10* depleted its electrical power so that it could no longer transmit radio messages back to earth.

A gold-anodized, aluminum plaque was attached to the spacecraft, which was designed to provide information about the civilization on earth, in the event the probe was found by extraterrestrial beings. The plaque had unique diagrams and symbols, including a depiction of a human male and female, with the right hand of the male raised in a gesture of good will. The raised hand was also meant to inform an extraterrestrial being that humans have opposable thumbs. The human figures were drawn to scale relative to a diagram of the *Pioneer 10* spacecraft, making it possible to deduce the size of humans. A kind of interstellar map was provided showing the position of the Sun relative to the center of the galaxy. The trajectory of the spacecraft was depicted on a diagram of our solar system, tracing its path from earth to Jupiter and beyond the solar system. There were also binary numbers etched on the plaque, which provided the height of the female and the distance of the earth from the Sun. The binary numbers were defined on the plaque to be in units of the spin state transition of a hydrogen electron, which can be interpreted as a unit of length, with a wavelength of 21 cm (8.3 in), or a unit of time, with a frequency of 1420 MHz. Hydrogen was selected because it is the most abundant element in the universe.

The last signal received from *Pioneer 10* was on 23 January 2003 when it was 12 billion km (7.5 billion miles) or 80 AU from Earth (an AU is an astronomical unit equal to the mean distance from the earth to the Sun). At this distance, it takes over 11 hours for a radio signal to reach the earth. In 2012, the spacecraft was over 100 AU (15 billion km, 9.3 billion miles) from Earth. At this enormous distance, it takes about 14 hours for the light from the Sun to reach the spacecraft. *Pioneer 10* is flying towards the star *Aldebaran*, a giant, orange star in the zodiac constellation *Tarus* (the Bull). Its interstellar journey to *Aldebaran* will take over two million years.

A Surface Rover: the Curiosity Mars Rover

The exploration of other planets has always sparked the imagination of mankind. The successful landing of a vehicle on another world is perhaps one of the most difficult engineering feats in aerospace engineering. Some planetary landers are unmanned spacecraft that land in a specific location and remain stationary, collecting scientific data and information with an array of sensors and instruments, perhaps including mechanical arms to collect surface samples. Other unmanned planetary rovers have the ability to move about the surface, driving around on a set of wheels, much like a remotely controlled robotic automobile.

One such planetary rover is the car-sized, *Curiosity* robotic rover (Figure 1.62), sent to explore the planet Mars. *Curiosity* was a part of the NASA Mars Science Laboratory mission, launched

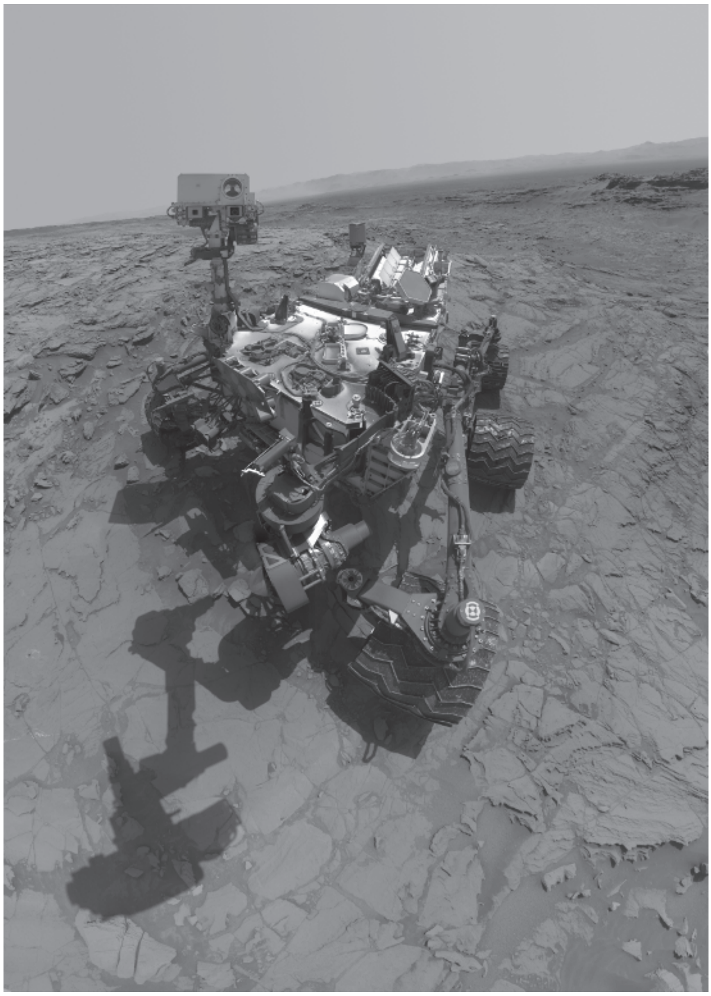

Figure 1.62 Self-portrait of a surface rover, the *Curiosity* rover on the surface of Mars. (Source: *NASA*.)

on 26 November 2011. The *Curiosity* rover successfully landed in the Gale Crater on Mars on 6 August 2012. *Curiosity* is the fourth robotic rover that has been sent by NASA to explore the surface of Mars. The rover has collected scientific data about the weather and geology of Mars, including searching for clues as to whether the Martian environment was ever suitable for microbial life.

With a length of 2.9 m (9.5 ft), width of 2.7 m (8.9 ft), and height of 2.2 m (7.2 ft), the *Curiosity* rover has a mass of about 900 kg (1980 lb), significantly heavier than previous Mars rovers. Due to its greater mass, a new descent and landing technique was required. A main parachute and retro-rockets were used to decelerate the spacecraft until it was close to the Martian surface. The new landing technique utilized a “sky crane” upper portion of the spacecraft, which lowered the rover to the surface, suspended from the sky crane by cables. After the rover touched down, the sky crane vehicle cut the cables and flew away from the rover, crash-landing away from the rover.

Components and instrumentation on the *Curiosity* rover are shown in Figure 1.63. The rover has six, 50 cm (20 in) diameter, independently actuated wheels, each with its own motor. The front and rear sets of wheels can be independently steered, allowing for a tight turning radius. With a ground

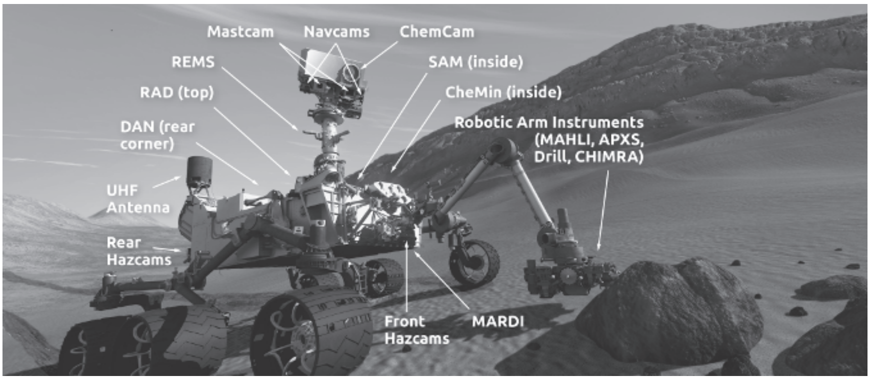

Figure 1.63 Components and instruments on the *Curiosity* Mars rover. (Source: *NASA*.)

clearance of 60 cm (24 in), the six-wheeled rover can roll over obstacles as high as 75 cm (29 in), climb slopes up to 12.5°, tilt in any direction up to 50°, and has an average speed of about 90 m per hour (300 ft/h).

The rover has a three-joint, robotic arm with a cross-shaped turret at its end, which functions much like a human hand. The turret can hold various types of tools, enabling *Curiosity* to perform geological tasks such as drilling into rocks, grinding samples, and digging in the Martian soil. Two instruments are located at the tip of the arm, the alpha particle X-ray spectrometer (APXS) and the Mars hand lens imager (MAHLI). The arm can position these instruments close to features on the Martian surface allowing for an X-ray spectrographic analysis or microscopic imaging.

Operation of the robotic rover is controlled by commands sent by a ground station on earth. *Curiosity* has two identical, radiation-hardened computers, a primary and a backup, to support the rover's robotic functions. An internal, three-axis inertial measurement unit (IMU) is used to calculate the rover's position.

A plutonium-fueled radioisotope thermoelectric generator (RTG) provides about 125 W of electrical power for the rover. The 4.8 kg (11 lb) of radioactive plutonium-238 onboard the rover supplied power for at least 687 (earth) days, equal to a Martian year. The rover also has two rechargeable, lithium-ion batteries that can provide additional electrical power. The rover and its electronic components and instruments are temperature controlled to survive the extremes in temperature on the Martian surface, ranging from about −127 to 40°C (−197 to 104°F). The passive heat from the RTGs and electric heaters are used to keep the equipment at the appropriate temperatures.

Curiosity has redundant communications capabilities, including three antennas and multiple communications links. The rover can send and receive signals directly back to Earth using a direct X-band communications link or relay signals via other spacecraft in Mars orbit using an ultra-high frequency (UHF) communications link. Antennas include a steerable, high-gain antenna and non-steerable, omnidirectional, low-gain antennas. Due to the long distance involved, it takes over 14 minutes for a communications signal to travel between Mars and Earth.

The rover has 17 cameras, eight hazard avoidance cameras, four navigation cameras, four science cameras, and one descent imager. Mounted on the front and rear sections of the rover, the four pairs of hazard avoidance cameras are used to detect terrain hazards such as large rocks and trenches. These cameras allow the rover to move autonomously, but usually the imagery data is used by Earth ground controllers to plan the rover's path. The four navigation cameras are two pairs of stereo cameras that are mounted on a vertical mast at the front of the rover. They provide three-dimensional, panoramic images that are used in conjunction with the hazard avoidance cameras to support navigation of the rover on the Martian surface. The science cameras included the MastCam, a pair of cameras mounted on the vertical mast, which take three-dimensional, stereo, color images and video from as high as seven feet above the surface. The laser-induced remote sensing for chemistry and micro-imaging camera, or ChemCam, also located on the mast, can fire a laser at a rock or soil sample up to 7 m (23 ft) away and vaporize a pinhead-sized spot on the sample. A spectrograph analyzes the vapor to determine its composition and provide information as to whether the sample is worthy of more close-up, intense scrutiny by the rover. The fourth science camera is the Mars hand lens imager (MHLI), a special type of "magnifying glass" or microscope, which can see objects smaller than the diameter of a human hair. The Mars descent imager (MARDI) provided high-resolution imagery during *Curiosity*'s descent and landing on Mars.

One of the major goals of the *Curiosity* mission is to search for signs of past life on Mars. *Curiosity* is a true science laboratory on Mars, with the capability to analyze atmosphere and surface samples using its onboard test equipment. Using its robotic arm, *Curiosity* can insert a Martian rock or soil sample into the "sample analysis at Mars" (SAM) instrument or chemistry and mineralogy (CheMin) X-ray diffraction and fluorescence instrument. The SAM instrument is used to detect organic, carbon-based molecules, a possible precursor to the chemical building blocks of life. The CheMin instrument is used to detect the minerals in the samples, which could provide information as to the past presence of water on Mars. The dynamic albedo of neutrons (DAN) instrument also searched for signs of past water on Mars. At the time of writing, the *Curiosity* rover is still operational on the surface of Mars.

1.3.4 Manned Spacecraft

Placing human beings in space is no easy task. The technological and economic challenges are enormous. To date, only three nations have successfully flown manned spacecraft, the Soviet Union, the USA, and China. The Soviet Union was the first nation to put a man in space on 12 April 1961, with the United States second, less than a month later. The Chinese are relative newcomers to manned spaceflight, flying their first manned mission in 2003. The early manned spacecraft were all capsule configurations. The airplane-like Space Shuttle was flown in the 1980s by the United States for three decades, until its retirement in 2011. The Soviets and Chinese have used a capsule-type spacecraft since the start of their space programs, although the Russians worked on a Shuttle-like vehicle, the *Buran*, for a short time. The United States is returning to a capsule configuration with the development of the *Orion* spacecraft.

In addition to manned spacecraft that can transport people from the earth into space, there are manned space structures or space stations that are placed into low earth orbit. A space station is designed to remain in orbit for long periods of time, with rotating crews of astronauts living onboard for many months. The long duration stays on space stations have provided a large amount of scientific information about the effects of long-term spaceflight on the human body. A wide range of other scientific research is typically performed on a space station, including studies in astronomy, atmospheric science, and biology. A space station usually has a modular structure, comprising connected pressurized modules, which serve as work spaces, laboratories, and living quarters. Other connected structures include large solar panel arrays to provide electrical power, airlocks allowing astronauts to exit and enter the station to and from space, and structures to allow docking of spacecraft.

The first space station was the Russian *Salyut*, launched in 1971. The International Space Station (ISS) (Figure 1.64) is currently in low earth orbit. The ISS is a large, modular structure that is visible to the naked eye in the night sky. With an apogee of 330 km (205 miles) and a perigee of

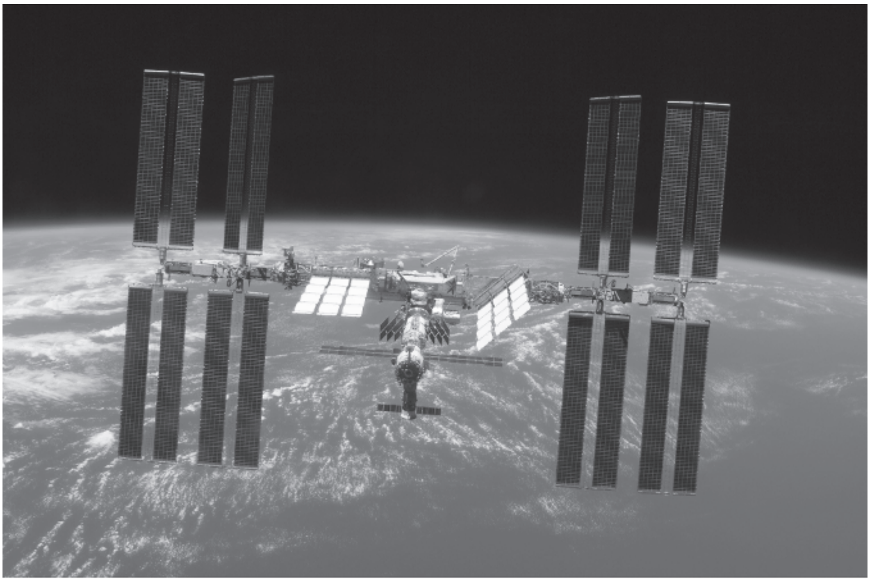

Figure 1.64 The International Space Station (2010). (Source: *NASA*.)

435 km (270 miles), the ISS completes an orbit of the earth about every 90 minutes. The ISS has had a continuous human presence onboard since November 2000. Currently, the Chinese also have a small, single module station in orbit, the *Tiangong 1*. Prior to the ISS, there were eight earlier space stations that were placed in earth orbit by Russia and the United States.

1.3.4.1 The First Manned Spacecraft

Less than four years after the successful launch of the first artificial satellite into earth orbit, the Soviet Union achieved another space first, launching the first human being into space. On 12 April 1961, the first manned spacecraft, *Vostok 1* (Figure 1.65), entered low earth orbit with 27-year-old Soviet cosmonaut Yuri Gagarin onboard. Gagarin and the *Vostok 1* completed a single earth orbit, making it the shortest manned orbital flight in history, with a flight time from launch to landing of 108 minutes.

The entire *Vostok 1* flight was controlled by either automatic systems or by ground control, even though there were manual controls that could be operated by the cosmonaut. Since this was the first time that a human being had been exposed to the space environment, including the effects of weightlessness, it was unknown whether there would be adverse reactions on the human body, incapacitating the cosmonaut. Therefore, it was decided that automatic systems or ground control would be the safest option. In fact, the manual controls were locked during the mission, requiring a code to unlock them. The unlock code was sealed in an envelope, to be opened by Gagarin in the event of an emergency.

The *Vostok 1* spacecraft consisted of a spherical capsule attached to a service module. The single cosmonaut sat in an aircraft-type ejection seat in the spherical capsule, which had three small port-hole windows (Figure 1.65). The spherical capsule was 2.3 m (7.5 ft) in diameter and weighed about 2400 kg (5300 lb). The service module contained the batteries for electrical power, consumables for life support, instrumentation and telemetry systems, the spacecraft attitude control system, and the retrorocket propulsion system, to slow the vehicle for return to earth. The spherical capsule was

Figure 1.65 Russian *Vostok 1*, the first manned spacecraft on display at the RKK Energiya Museum, Moscow, Russia. The capsule hatch, on the ground at left, is replaced by a clear window. The ejection seat is on the right. (Source: © *D.R. Siefkin, "Gagarin Capsule" https://en.wikipedia.org/wiki/File:Gagarin_Capsule.jpg, CC-BY-SA-3.0. License at https://creativecommons.org/licenses/by-sa/3.0/legalcode.*)

separated from the service module for the descent back to earth, but the cosmonaut did not remain in the capsule for the landing. At an altitude of about 7 km (23,000 ft), Gagarin ejected from the capsule and parachuted to the ground. The capsule used parachutes for its final descent and was recovered on the ground.

The spherical descent capsule was covered with an ablative material to protect it from the intense temperatures generated during entry to the earth's atmosphere. Ablation is a method of thermal protection where a material coating is allowed to vaporize or melt away. Heat is absorbed in the chemical transformations and phase changes of the material during ablation and is carried away from the vehicle by the flow of the vaporized material into the freestream flow. The black, charred appearance of the ablative material on the *Vostok* capsule, after experiencing the intense thermal environment of atmospheric entry, is evident in Figure 1.65.

Just 25 days after Gagarin's flight in *Vostok 1*, the United States launched the world's second manned space vehicle, the *Mercury Freedom 7* spacecraft, on 5 May 1961 (Figure 1.66). The first American in space was Alan B. Sheppard, Jr, who completed a sub-orbital flight, lasting 15 minutes and 28 seconds, to an altitude of over 187 km (116 miles). This was followed by another sub-orbital flight with Virgil I, Grissom piloting the *Mercury* spacecraft, *Liberty Bell 7*, on 21 July 1961. John H. Glenn, Jr became the first American to orbit the earth on 20 February 1962 with the flight of the *Mercury Friendship 7* spacecraft. Glenn and the *Friendship 7* completed three orbits of the earth with the flight lasting 4 hours and 55 minutes. The orbit of *Friendship 7* had a perigee of 98.8 miles (159 km) and an apogee of 165 miles (265 km). (These three astronauts were in the first group of seven astronauts selected by NASA. They each named their *Mercury* spacecraft, adding the number "7", at the end of the name, to represent their group of seven.)

Figure 1.66 Launch of the *Mercury-Redstone* rocket with astronaut Alan Shepard, aboard *Freedom 7*, the first American in space. (Source: *NASA*.)

The *Mercury* spacecraft was a one-man capsule with a truncated cone-shaped main body and cylindrical upper body (Figure 1.67). The spacecraft had a length of 7.2 ft (2.2 m), a maximum diameter at the base of the cone-shaped body of 6.2 ft (1.9 m), and a weight of about 2400 pounds (1090 kg). The astronaut sat with his back to the capsule base, looking forward towards the cylinder top, with a small window on the angled cone surface. Unlike, the *Vostok* capsule, there was no ejection seat. The capsule's recovery drogue, main, and reserve parachutes were packed in the forward cylindrical section.

A 17 ft (5.2 m) long escape tower was mounted on the cylinder top of the capsule. Solid rocket motors, mounted at the top of the escape tower, could be fired to pull the capsule clear of the rocket booster in the event of a launch emergency. The escape tower was jettisoned after the spacecraft had reached a safe altitude. An ablative heat shield was mounted to the base of the capsule's truncated cone shape. A retrorocket package was attached to the heat shield with metal straps.

To return to earth, the spacecraft was oriented "backwards", so that firing the retrorockets would slow the spacecraft, causing it to descend from orbital altitude. After this entry burn, the retrorocket

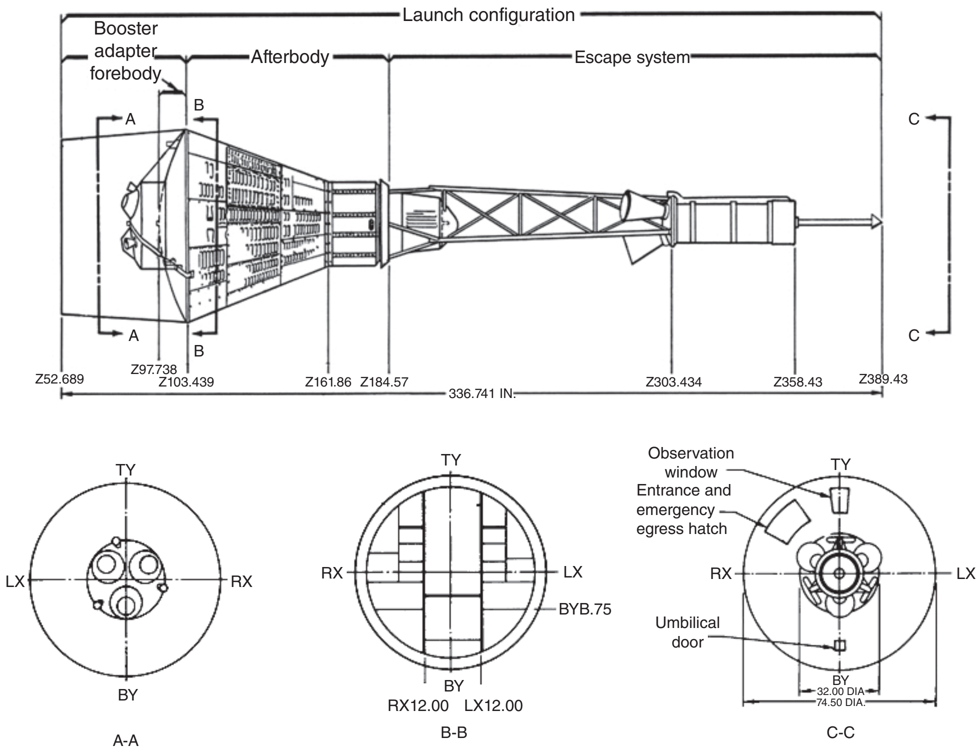

Figure 1.67 The *Mercury* spacecraft components and dimensions. (Source: *NASA*.)

package was jettisoned. The spacecraft was thus oriented with its blunt heat shield entering the atmosphere, protecting the capsule and its backwards-sitting astronaut occupant. The heat shield reached a maximum temperature of about 3000°F (1900 K) during entry. Prior to John Glenn's entry, there were some indications that the spacecraft's heat shield had come loose. Therefore, the retrorocket package was not jettisoned for entry, with the thinking that the metal straps would help retain the heat shield in place. After landing and recovery of the spacecraft, it was determined that a warning light had erroneously indicated a problem with the heat shield.

A drogue parachute was deployed at an altitude of about 21,000 ft (6400 m) to stabilize the spacecraft, followed by deployment of the main parachute at about 10,000 ft (3050 m) to slow the final descent for a landing in the Atlantic Ocean. A landing bag was inflated behind the heat shield to cushion the water impact. A fleet of US Navy ships was used in the recovery operation of the spacecraft in the ocean.

It is interesting to compare the different design approaches for the first manned spacecraft developed by the Soviet Union and the United States, as shown in Figure 1.68. Fundamentally, both spacecraft had a common design requirement, that of placing a man in space and returning him safely, but the design solutions were quite different. The *Vostok* was a two-module system, comprising a spherical entry capsule and a service module, while the *Mercury* was a single-module system with a single capsule. One of the most striking differences between the *Vostok* and *Mercury* was the shape of the spacecraft. The *Vostok* spacecraft had the shape of a simple sphere, while the *Mercury* spacecraft had the shape of a truncated cone topped with a short cylinder. Given its non-aerodynamic shape, an aerodynamic *shroud* covered the *Vostok* spacecraft at the top of the

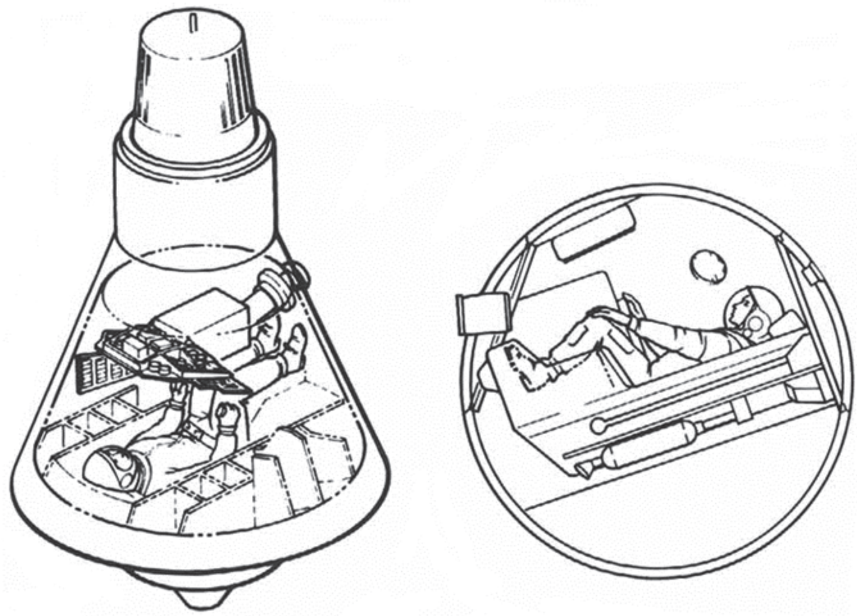

Figure 1.68 Comparison of the *Mercury* and *Vostok* spacecraft. (Source: *From Ezel, NASA SP-4209, 1978.*)

rocket booster during launch into space. The *Mercury* capsule's shape was amenable to being placed at the top of the rocket booster with no shroud. In contrast, both vehicles used a blunt-body shape for entry into the atmosphere from orbit. The *Sputnik* used a spherical shape and the Mercury entered backwards, with its blunt base facing into the flow. As discussed in Chapter 3, a blunt-body shape is optimum for minimum heat transfer at hypersonic speed.

The *Vostok* sphere is an optimum shape for a pressure vessel with maximum interior volume and minimum structural mass. The aerodynamics of the sphere was also well-known at the time. It was certainly known that the spherical *Vostok* would generate considerable drag during entry to slow the craft and it would not generate any aerodynamic lift. The *Mercury* spacecraft's shape produced a small amount of aerodynamic lift, enough to enable some control over the entry trajectory. The lift-to-drag ratio is a measure of a vehicle's aerodynamic efficiency, its ability to produce lift in relation to the drag. The *Mercury* capsule's lift-to-drag ratio was about 0.2–03, a relatively small number, but still a positive number that enabled limited trajectory control. In fact, an objective of the early *Mercury* flights was to determine if an astronaut could actively control the spacecraft's entry trajectory in a weightless environment. This highlights another difference between the *Vostok* and *Mercury*, having to do with spacecraft control. The *Vostok* entry was entirely controlled by automatic systems and by ground controllers. *Mercury*, on the other hand, allowed manual control of the vehicle by the astronaut.

Both the *Vostok* and *Mercury* had a retrorocket system to slow the spacecraft for entry. The *Vostok* retrorocket system was installed on the service module while the *Mercury* system was attached to the capsule heat shield. Both spacecraft had small thrusters for attitude control in three dimensions. After the retrorocket de-orbit burn, both spacecraft were oriented so that the occupant was facing backwards as they entered the earth's atmosphere. The Soviet engineers came up with a clever way to control the spacecraft attitude during entry. The center of mass of the capsule was offset from the centroid of the sphere, so that the spherical capsule would orient itself in the proper attitude for the entry. This passive attitude control system did not require an active reaction control-type attitude control system, as used in the *Mercury* spacecraft. The *Vostok* spacecraft was of aluminum construction with an ablative coating around the sphere. The *Mercury* had an ablative heat shield protecting the capsule and a nickel alloy pressure vessel with an outer shell of titanium. The *Vostok* cosmonauts experienced a deceleration of up to ten times the force of gravity, or 10 g during entry, while the *Mercury* astronauts felt about 8 g. The difference in the deceleration force is due to the difference between the *Vostok* ballistic entry and the *Mercury* entry with lift. The *Vostok* cosmonaut ejected from the spacecraft and parachuted down to the ground, while the *Mercury* astronaut landed in the water inside the capsule.

In summary, it is interesting and enlightening to compare the first two spacecraft that placed human beings in space. Designed by two different countries, with different design philosophies and different technical capabilities, the two spacecraft represent two different solutions to the design requirement of placing a man in space and returning him safely to earth. Both the *Vostok* and the *Mercury* spacecraft were successful in meeting this design requirement. The *Vostok* spacecraft design would be used for a total of eight spaceflights with six of those being manned missions. The *Mercury* spacecraft would fly a total of 16 times, with six of those being manned spaceflights. The legacy of the *Vostok* and *Mercury* designs would be imprinted on future Soviet and American spacecraft designs, respectively, for many years to come.

1.3.4.2 The Spacesuit: A One-Person Spacecraft

We include in this section about spacecraft, a description of the spacesuit, which in many ways, can be considered a one-person spacecraft. The spacesuit must perform many of the same functions as a spacecraft in maintaining a safe and habitable environment for a human being in space. Spacesuits are worn by astronauts for extravehicular activity (EVA), commonly referred to as a "spacewalk". In modern times, spacewalks have become almost commonplace, with the hundreds of hours of EVA time that it has taken to construct and maintain the International Space Station (ISS). The first spacewalk occurred on 18 March 1965, when Russian cosmonaut Alexei Leonov exited his *Voskhod 2* space capsule and floated in space for 12 minutes and 9 seconds. He was kept from floating too far away from his capsule by a 5 m (16 ft) umbilical, which supplied his spacesuit with oxygen. Less than three months later, astronaut Edward White performed the first American spacewalk on 3 June 1965 during the *Gemini 4* space mission (Figure 1.69). White's EVA lasted 23 minutes. In addition to EVA in earth orbit, spacesuits have been used for EVA on the moon by the *Apollo* astronauts.

Similar to spacecraft, the design of spacesuits has evolved over time, driven by changing requirements, design improvements gained by real-world experience, and advancements in technology. We examine one particular spacesuit to get some idea as to what is involved in the design of these complex systems. The NASA extravehicular mobility unit (EMU) is the EVA spacesuit system that was used for the NASA Space Shuttle program and that is currently in use for the International Space Station (ISS) program (Figure 1.70). The EMU is composed of a pressure garment, called the space suit assembly (SSA), and an integrated life support system. The SSA is attached to the hard upper torso (HUT), a fiberglass and aluminum outer shell that is the primary structural unit of the EMU. The portable life support system (PLSS) and secondary oxygen package (SOP) are attached to the HUT. The SSA, PLSS, and SOP are covered by the thermal micro-meteoroid garment (TMG), an outer garment that is a thermal and impact barrier.

The SSA is a multi-layered garment, pressurized to 29.6 kPa (4.29 lb/in^2) with 100% oxygen. The SSA layers consist of a pressure bladder, a pressure-restraint layer, and a thermal insulation layer. The innermost layer is a urethane-coated nylon pressure bladder for the spacesuit. A

Figure 1.69 The first American spacewalk, performed by Edward White, on June 3, 1965. (Source: *NASA*.)

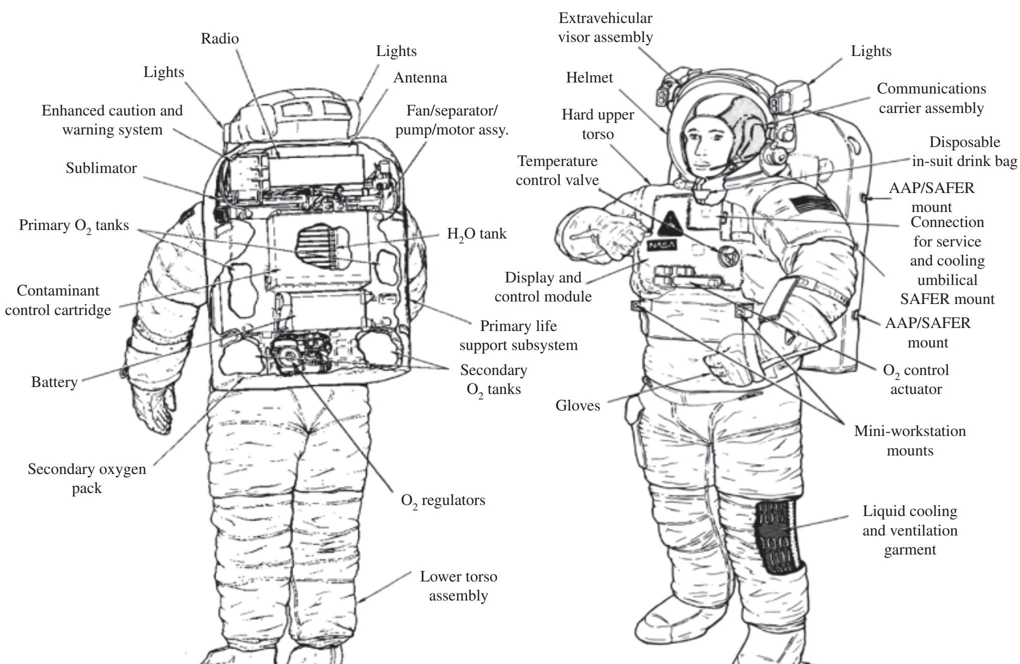

Figure 1.70 NASA extravehicular mobility unit (EMU). (Source: *NASA*.)

pressure restraint garment covers the pressure bladder and carries the spacesuit pressure loads. The outermost covering of the SSA consists of five thermal insulation layers of tear-resistant, neoprene-coated nylon and aluminized Mylar.

Underneath all of the SSA layers, the astronaut wears a liquid cooling and ventilation garment (LCVG), a kind of long underwear that keeps the wearer cool and dry. The LCVG has 90 m (300 ft) of narrow tubes sewn into it that circulate chilled water to remove excess body heat. Vents in the LCVG serve to draw sweat away from the body.

The life support system has a primary system, the Portable Life Support System (PLSS), and a backup, secondary oxygen package (SOP). The PLSS backpack houses breathing oxygen tanks, an oxygen circulation fan, carbon dioxide "scrubbers", water cooling equipment, a two-way radio, and a silver-zinc battery power source. The SOP has backup oxygen and water cooling tanks. The PLSS can provide life support for up to seven hours, but the actual duration is a function of the astronaut's metabolic rate (how much energy is being expended, impacting the suit cooling and how fast the consumables are being used) and the solar thermal environment (impacting the suit cooling). The PLSS operation is monitored and controlled using the enhanced caution and warning system (ECWS) and the display and control module (DCM), respectively, mounted on the front of the HUT. Since the front of the DCM cannot be seen while in the spacesuit, the astronaut wears a wrist mirror to read the displays which are labeled backwards so as to be legible in a mirror. The astronaut's heart rate and other vital suit parameters, such as carbon dioxide level, are telemetered to the ground for monitoring during EVA.

The spacesuit helmet is a clear plastic, polycarbonate bubble. The visor assembly covers the bubble and contains the visor, a movable sunshade, lights, and camera. The visor is coated with a thin layer of gold to provide protection from cosmic rays. Communications headphones and microphones are in the communications carrier assembly (CCA), also called the "Snoopy cap", a fabric head cover worn under the helmet. Inside the helmet, the astronaut can drink from a water bag via a plastic tube.

The gloves are one of the more complex items of the spacesuit, as they must provide adequate protection and insulation while remaining as dexterous as possible. The gloves must integrate the same layers of protection and insulation as in the SSA, yet they must allow finger motion and tactility sufficient to perform manipulation and handling tasks, such as the use of tools and operation of DCM suit controls. Since the fingers tend to get the coldest in space, the gloves have fingertip heaters.

The weight of the complete spacesuit, including the life support system and consumables, is about 120 pounds (54 kg). The spacesuit is a complex system that incorporates many of the features of a manned spacecraft, such as life support functions and protection from the space environment.

1.3.5 Space Access Systems and Vehicles

For spacecraft to operate in space, they must first get into space. In this section, we examine several different systems used to place spacecraft into space. Currently, the use of expendable rockets is the predominant means of access to space. We discuss the birth of the liquid-fueled rocket, occurring independently in the USA and Germany. Other access to space systems are explored, including air-launched systems and non-rocket-based systems.

According to the ancient Greek novel by Lucian in the 2nd century AD, a sailing ship is swept upward by a waterspout to 350 miles above the earth. After seven days atop the waterspout, the ship is deposited on the Moon where there are strange, extraterrestrial creatures from the Moon and Sun. This fictional story is the first recorded description of travel to outer space, albeit using a technically implausible launch system.

Figure 1.71 Space cannon from Jules Verne's *From the Earth to the Moon*. (Source: *PD-old-100*.)

Jules Verne, in his 1865 novel *From the Earth to the Moon*, imagined an enormous cannon to launch a projectile, with three people inside, to the Moon (Figure 1.71). Verne's fictional space cannon was 900 ft (270 m) long and had a bore diameter (interior diameter of the cannon barrel) of 9 ft (2.7 m). Made of cast iron, the cannon was 6 ft (1.8 m) thick and weighed more than 68,000 tons (60 Mkg). Due to its immense size and weight, the cannon was built directly into the ground, pointing vertically straight up. Coincidentally, Verne selected Tampa, Florida as his launch site, not far from the current Cape Canaveral rocket launch complex. Verne did make some technical calculations for the design of his space cannon, but in reality the barrel of his cannon was much too short for the projectile to achieve escape velocity from the earth. A longer barrel would enable the high pressure gases from the firing charge to push on the projectile for a longer time, producing a higher exit velocity. In addition, the acceleration loads on the people inside the projectile would not have been survivable, estimated to be over 20,000 g. However, the idea of a space cannon may have some technical feasibility, at least for unmanned payloads.

1.3.5.1 Expendable Rocket-Based Launch Systems

Currently, the only method that we have for placing spacecraft into space is using rockets. Usually the rocket is launched from a land-based pad, although there are a few sea-based launch platforms. Mobile launch platforms include submarines and airplanes, but these can only accommodate smaller rocket systems.

A rocket has a self-contained propulsion system, carrying both the fuel and oxidizer required for combustion. Since rocket propulsion does not rely on atmospheric air for combustion, rockets can function beyond the sensible atmosphere into outer space. There are two primary types of rockets: *liquid-fueled* and *solid propellant*. In the liquid-propellant rocket, the fuel and oxidizer are stored in separate tanks in the vehicle. The fuel and oxidizer are combined into a solid mixture in the solid-fuel rocket.

Most rockets used today for space access are *expendable rockets*, that is, they are used for one launch and discarded, usually by allowing them to fall back into the atmosphere and burn up or fall into the open ocean. To be a little more precise with our terminology, a *rocket booster* includes everything in the rocket (rocket engine, propellant, tankage, propellant feed systems, structure, etc.) except the payload, which may be a spacecraft.

Two of the largest liquid-fueled rocket boosters ever built, the American *Saturn V* and the Soviet N1, are shown in Figure 1.72. Both were expendable, man-rated, multi-stage, heavy-lift launch vehicles, designed to transport human beings beyond earth orbit. Both boosters had three stages, each stage containing its own rocket engines, tankage, propellants, and propellant feed system. The concept of *staging* is used to reduce the weight of the rocket as it ascends by discarding the mass of each successive stage as its propellants are consumed.

The *Saturn V* booster was developed to transport human beings to the Moon as part of the *Apollo* program in the late 1960s and early 1970s. The *Saturn V* was successfully launched 13 times from Cape Canaveral, Florida, including six moon landing missions. The five F-1 liquid-fuel rocket engines in the first stage of the *Saturn V* produced a combined thrust of over 7.6 million lb (33.8 MN) at lift-off. The 363 ft (111 m) height of the *Saturn V* booster was greater than the length of an American football field. The total lift-off weight of the *Saturn V* was over 6.5 million lb (2900 tonnes). The booster was capable of placing very large payloads into low earth orbit, including the heaviest payload ever launched of 260,000 pounds (118,000 kg or 118 tonnes).

The N1 booster was the Soviet counterpart to the American *Saturn V*. The N1 was not quite as long as the *Saturn V*, standing 344 ft (105 m) tall. Its lift-off weight of about 6 million lb (2700 tonnes) was also lower than that of the *Saturn V*. The N1 was designed to deliver up to 200,000 pounds (90,000 kg) of load to low earth orbit. The first stage of the N1 housed 30 NK-15 liquid-fuel rocket engines, making the first stage propellant feed system very complex. The 30 rocket engines produced a combined lift-off thrust of 11.3 million lb (50.3 MN), making it the most powerful rocket stage ever built. Only four unmanned attempts were made to launch the N1 booster and all failed catastrophically. The N1 never made it into space, with its longest flight of 107 seconds never reaching first stage separation. While the N1 may not have been a success, future Soviet efforts with heavy-lift, expendable rocket boosters were successful in their manned spaceflight program.

1.3.5.2 The First Unmanned Liquid-Propellant Rocket

Robert Hutchings Goddard (1882–1945) was born at a time when airplanes and spacecraft were by no mean, commonplace. He was 11 years old when the Wright brothers made their historic first flight of a heavier-than-air airplane. When Goddard was 17, he climbed a cherry tree in his backyard to prune its dead branches. Resting in its branches, he gazed up at the sky and imagined what could be. He later wrote, in an autobiographical account, of the inspiration that he felt while gazing up at the sky in that cherry tree.

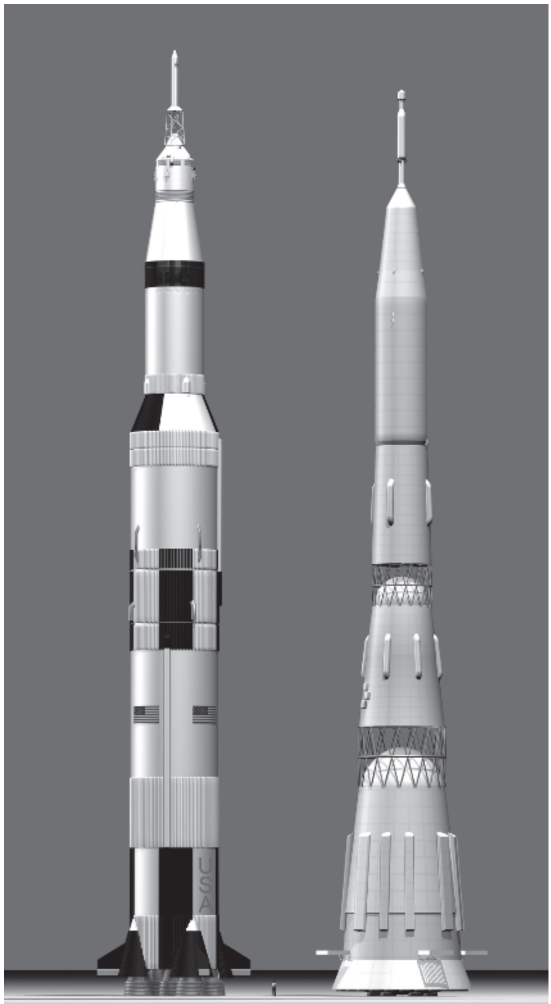

Figure 1.72 Models comparing sizes of United States *Saturn V* and Soviet N1 "moon rockets". A scale model of a person is shown at the bottom, between the boosters. (Source: *From Portree, NASA-RP-1357, 1995*.)

> On the afternoon of October 19, 1899, I climbed a tall cherry tree and, armed with a saw which I still have, and a hatchet, started to trim the dead limbs from the cherry tree. It was one of the quiet, colorful afternoons of sheer beauty which we have in October in New England, and as I looked towards the fields at the east, I imagined how wonderful it would be to make some device which had even the possibility of ascending to Mars. I was a different boy when I descended the tree from when I ascended for existence at last seemed very purposive.

The purpose to which Goddard alluded was his decision to dedicate his life to making spaceflight a reality. For the rest of his life, Goddard privately observed that day, 19 October, as the anniversary day of his inspiration.

In 1907, he began his lifelong research and testing of rockets in earnest, as an undergraduate physics student at the Worcester Polytechnic Institute, Massachusetts. After earning his PhD in physics from Clark University in Worcester, Massachusetts, he accepted a research fellowship at Princeton University in 1912. In addition to possessing exceptional academic skills, Goddard was a prolific inventor, obtaining 214 patents over his career (some of these were granted after his death).

Goddard was granted two significant patents in 1914; one described a solid-fueled, multi-stage rocket and the other, a rocket fueled with gasoline and liquid nitrous oxide, or in other words, a liquid-fueled rocket. In the fall of 1914, Goddard returned to Clark University, where he conducted experiments with different types of solid propellant rockets, much of this at his own expense. He performed *static ground tests* of these rocket engines, carefully measuring their thrust and efficiency. (A static ground test is a test of the rocket engine that is performed with the engine securely mounted in a test stand on the ground. The engine is fired *statically*, meaning that it cannot move. The engine is instrumented so that data is collected about the operation of the engine and its systems. A load cell, or other force-measuring device, is often attached to the rocket, so that the thrust force is measured. Today, static ground tests of rocket engines are a standard, engineering practice.)

In 1916, Goddard built a vacuum tube apparatus to show that the efficiency of a rocket increased with decreasing external pressure (Figure 1.73). The rocket was placed at the top of the long vertical

Figure 1.73 Robert Goddard with vacuum tube device, which he used to prove that a rocket could produce thrust in the vacuum of space, June 1916. (Source: *NASA*.)

tube, with its exhaust firing into the tube. The oval portion of the tube apparatus served to reduce the rebound of the rocket exhaust gas. It was a misconception of Goddard's time that a rocket would not produce thrust in the vacuum of space. According to this misconception, Newton's third law of "action with equal and opposite reaction" required that the rocket exhaust gas have something to "push against". It was thought that the vacuum of space could not provide the "equal and opposite" reaction to the rocket exhaust gas, to propel the rocket. The error in this reasoning is that the equal and opposite reaction is from the rocket, not the vacuum, reacting to the exhaust gas. Using the vacuum tube apparatus, Goddard was the first to prove that a rocket produces thrust in the vacuum of space. (Goddard obtained several patents, an "apparatus for vacuum tube transportation" and "vacuum tube transportation systems", which were visionary ideas of very high-speed transportation using magnetic levitation, or *maglev*, vehicles traveling inside vacuum tubes.)

During this time, Goddard made some significant advances in the design of rockets. He had the rare ability to transform his theoretical understanding into practical engineering, that is, real flight hardware. To increase the thrust and efficiency of his rockets, he understood several key design requirements. He realized that the rocket exhaust velocity and the rocket's propellant mass fraction, the mass of the propellant relative to the rocket's total mass, must both be as high as possible. To increase the rocket exhaust velocity, Goddard used a converging-diverging exhaust nozzle, called a *de Laval nozzle*. Using this exhaust nozzle, he was able to accelerate the flow exiting the nozzle to supersonic speeds, as high as Mach 7.

In the rocket designs of his day, the fuel and combustion chambers were combined, requiring a large, thick-walled, heavy chamber to withstand the high pressures and temperatures of combustion. To increase the rocket's propellant mass fraction, he separated the fuel chambers or tanks from the combustion chamber. By separating the fuel and combustion chambers, only a smaller combustion chamber was required to withstand the high pressures and temperatures, while the propellant tanks could be made as lightweight as possible. At the time, Goddard also realized that liquid propellants have much higher energy content per unit mass than solid propellants, but he resisted using these as he thought the handling of extremely cold, or *cryogenic*, propellants, such as liquid oxygen, was not practical.

Based on the substantial progress that he was making and the fact that he was unable to continue self-funding all of his research, Goddard started submitting research funding proposal to sponsors such as the Smithsonian Institution and others. In his 1916 proposal to the Smithsonian Institution, he included a paper he had written that detailed his solid propellant rocket experiments, his mathematical theories of rocket propulsion, and his vision of using rockets to explore the Earth's atmosphere and beyond. He provided a quantitative analysis of launching a rocket to the Moon with a payload of flash powder, which would explode upon impact on the Moon. He calculated that a multi-stage rocket, with an initial launch mass of 6436 lb (2919 kg), could deliver a payload of 2.67 lb (1.21 kg) of flash powder to the surface of the moon. He calculated that this amount of flash powder would make a flash "just visible" from an Earth-bound, high power telescope, confirming the rocket's impact on the Moon. The Smithsonian was impressed with Goddard's proposal and, in 1917, awarded him a $5000 grant.

Later, in 1919, the Smithsonian published Goddard's paper as Publication No. 2540 of the Smithsonian Miscellaneous Collections, entitled "A method of reaching extreme altitudes" [11]. This publication has become one of the most significant scientific contributions to the development of rocket propulsion. Unfortunately, at the time of its publication, it was not viewed as such. The public at large still thought that the idea of space travel was a fanciful dream without much scientific basis. In fact, the US government and US military did not see much use for either spaceflight or Goddard's rockets. To make matters worse, the press ridiculed Goddard's ideas of flying rockets to the Moon. This led to Goddard's distrust of the press and his penchant for working in secret, sentiments that he would have for the rest of his life.

By 1921, Goddard was conducting experiments with liquid propellants. He successfully ground tested the first liquid propellant rocket engine, using gasoline and liquid oxygen, in November 1923. He initially pursued a *pump-fed* engine design, where mechanical pumps are used to move the propellants from their tanks to the combustion chamber, but this proved to be problematic. Goddard abandoned the pump-fed system and decided to use a *pressure-fed* system, where a high-pressure, inert gas, such as nitrogen, is used to "push" the propellants out of their tanks and into the combustion chamber. On 6 December 1925, Goddard conducted a static test of a liquid-propellant rocket engine, with a pressure-fed system, in a laboratory at Clark University in Worcester, Massachusetts. The rocket engine fired for 27 seconds, lifting its own weight in the test stand, proving the feasibility of a liquid-propellant rocket engine.

The configuration of Goddard's first liquid-propellant rocket is shown in Figure 1.74. The combustion chamber and exhaust nozzle were located at the top of the rocket and the two cylindrical propellant tanks were at the bottom. Goddard chose this arrangement in his early rocket designs because he thought that the rocket would be more stable in flight with this configuration. A conical-shaped exhaust shield, with an asbestos fabric covering, protected the liquid oxygen

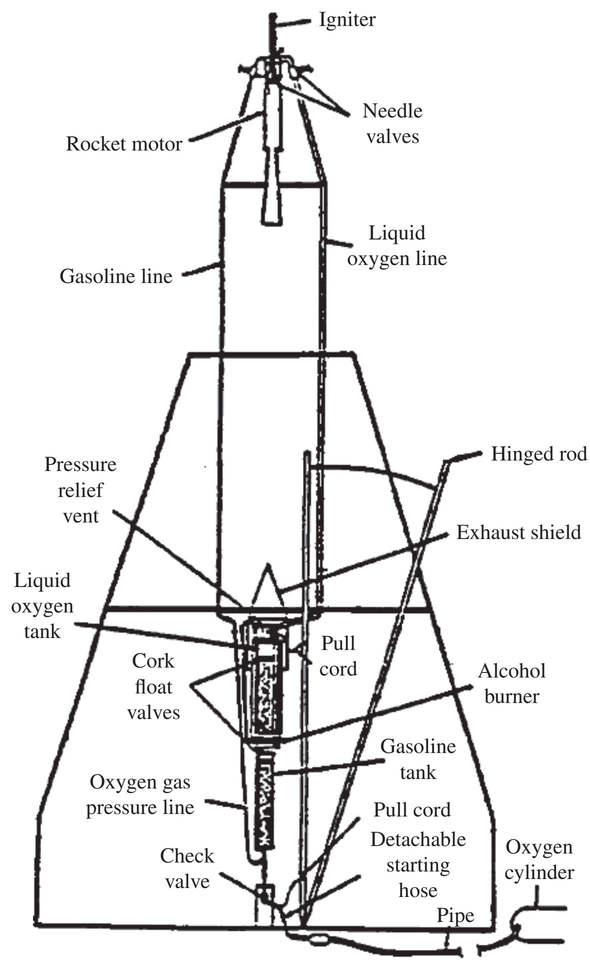

Figure 1.74 Goddard's first pressure-fed liquid-propellant rocket. (Source: *NASA*.)

tank from the hot exhaust. The gasoline and liquid oxygen lines ran from their tanks to the combustion chamber along the left and right sides of the rocket, respectively. These propellant feed lines also served as structural supports for the rocket. The rocket motor ignitor was mounted at the very top of the rocket, above the combustion chamber. The high-pressure gas generated by the boil-off of the liquid oxygen was the pressurant gas that was used to move the propellants to the combustion chamber. Goddard adopted today's conventional rocket configuration, with the combustion chamber and nozzle at the base of the rocket, in his later designs. This early Goddard design lacked any aerodynamic fairings over the rocket nose or body and had no fins for stability.

In 1926, Goddard was ready to conduct flight tests of his liquid-fueled rockets. He moved his operation to a farm owned by a distant relative, about two miles from Clark University. It offered a remote setting for conducting rocket launches, with less chance of an errant rocket crashing and hurting people or property. Despite its remote location, the neighbors still complained about the noise from the rockets. On 26 March 1926, the first flight of a liquid-propellant rocket occurred. The 10 ft (3.0 m) long, gasoline and liquid oxygen-fueled rocket (Figure 1.75) reached a maximum altitude of about 41 ft (12.5 m) and ended its 2.5 second flight in a cabbage field, about 184 ft (56.1 m) from its launch point. Since his youth, Goddard had avidly written in his daily diary. On

Figure 1.75 Robert Goddard with the first liquid-propellant rocket (Goddard is holding the trapezoidal launch frame). (Source: *NASA*.)

this auspicious day of the first flight of a liquid-propellant rocket, he rather succinctly wrote the following.

> March 16, 1926
>
> Went to Auburn with S[achs] in am. E[sther] and Mr. Roope[5] came out at 1 pm. Tried rocket at 2:30. It rose 41 ft, & went 184 ft, in 2.5 secs, after the lower half of nozzle had burned off.

The next day, Goddard wrote about the previous day's first liquid-fueled rocket flight with a bit more fanfare.

> March 17, 1926
>
> The first flight with a rocket using liquid propellants was made yesterday at Aunt Effie's farm[6] in Auburn. The day was clear and comparatively quiet. The anemometer on the Physics lab was turning leisurely when Mr. Sachs and I left in the morning, and was turning as leisurely when we returned at 5:30 pm. Even though the release was pulled, the rocket did not rise at first, but the flame came out, and there was a steady roar. After a number of seconds it rose, slowly until it cleared the frame, and then at express train speed, curving over to the left, and striking the ice and snow, still going at a rapid rate. It looked almost magical as it rose, without any appreciably greater noise or flame, as if it said "I've been here long enough; I think I'll be going somewhere else, if you don't mind." Esther said that it looked like a fairy or an aesthetic dancer, as it started off. The sky was clear, for the most part, with large shadowy white clouds, but late in the afternoon there was a large pink cloud in the west, over which the sun shone. One of the surprising things was the absence of smoke, the lack of very loud roar, and the smallness of the flame.

In 1930, Goddard moved his rocket flight test operation to remote Roswell, New Mexico, where he had plenty of open space and a clear, dry climate conducive to year-round testing. Today, New Mexico is the location of the White Sands Missile Range, the US Army's rocket test range. Covering almost 3200 square miles (8200 km^2), it is the largest military installation in the United States.

Goddard continued to design and build larger and more powerful rockets, integrating design improvements and technology advancements with each new model. Soon, Goddard's rockets resembled the configuration that is common today. Goddard's A-series rocket had an aerodynamic nose cone, a cylindrical body with a smooth aluminum skin that covered the internal tanks, a nozzle at the base of the rocket, and thin highly swept tail fins. An A-series rocket was the first rocket to fly faster than the speed of sound on 8 March 1935. Goddard was responsible for significant advancements in rocket guidance and control, including inventing a steering system using gyroscope-controlled, movable vanes in the exhaust and another using a movable or *gimbaled* exhaust nozzle, forerunners of systems in use today. He continually developed innovations in rocket propulsion technology, including eventually building turbopumps for pump-fed propellant feed systems. He was the first to launch a scientific payload in a rocket, consisting of a barometer, a thermometer, and a camera.

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[5] In addition to Goddard, three other people witnessed the first flight of a liquid-propellant rocket: Esther Goddard, his wife and photographer, Henry Sachs, the crew chief, and Percy Roope, an assistant professor of physics at Clark University.

[6] "Aunt Effie" was Effie Ward, a distant relative of Robert Goddard. Her farm was in a rural area, about two miles from Clark University in Worcester, Massachusetts. This site of the first flights of a liquid-fueled rocket is now part of a golf course.

Between 1926 and 1941, Goddard launched 34 rockets, reaching altitudes of about 8500 ft (2600 m) and speeds of about 550 mph (885 km/h). He performed many more static ground tests than flight tests, using a methodical, engineering approach to improve the designs. Many of the ground and flight tests ended with failures of the engine, nozzle, guidance system, or other components, but Goddard was never deterred. He always believed that important lessons were learned from any test results, a noteworthy perspective for anyone involved with ground or flight testing.

Robert Goddard was a true visionary, recognizing the incredible potential of rockets for atmospheric research, ballistic missiles, and space travel. Unfortunately, the US government, the US military, and the public were blind to his vision. Another aerospace visionary, Charles Lindbergh, took great interest in Goddard's work and personally helped with obtaining funds for his rocket research. Overall, Goddard's research and testing of rockets received meager funding and support throughout his career and he received little recognition for his work. Today, Robert Goddard is rightfully considered the father of rocket propulsion. Much like the Wright brothers' first flight, Goddard's first flight was a fledgling step of remarkable consequence. It would ultimately shape the future of rocketry and affect all of humanity. Four short years after Goddard's first flight, the first man to set foot on the Moon was born, destined to fly 238,900 miles (384,500 km) from the earth to the Moon atop a 363 ft (111 m) tall, 6.5 million lb (2900 tonnes) *Saturn V* rocket, a rocket that could trace its roots back to Robert Goddard's first liquid-fuel rocket.

1.3.5.3 The First Rocket to Reach Space

Robert Goddard was not alone in his quest to make rocket flight a reality. Across the Atlantic Ocean, Dr Wernher von Braun and his team of German rocket scientists and engineers were busy at the Peenemunde Army Research Center, on a small Baltic Sea island off the northern coast of Germany, developing the world's first long-range, guided ballistic missile with a liquid-propellant rocket engine. The German scientists and engineers were aware of Goddard's work and monitored it closely. Some believe that Goddard's work made a significant impact on the German rocket designs. The German efforts culminated in the development of the V-2 rocket, which was used as a weapon against the Allied forces during World War II. Over 3000 V-2 rockets were launched by the Germans against Allied targets during the war, many in London, England. On 3 October 1942, a V-2 rocket, launched from Peenemunde, soared to an altitude of 190 km (118 miles, 623,000 ft), becoming the first manmade object to reach the edge of space.

The German developed V-2 liquid-propellant rocket was substantially larger than Goddard's rockets. The V-2 rocket airframe had a length of 14 m (46 ft), diameter of 1.65 m (5 ft 5 in), and wingspan of 3.56 m (11 ft 8 in). With a total launch weight of 12,500 kg (27,600 lb), the V-2 carried 3800 kg (8400 lb) of fuel, comprising a 75% ethanol-25% water mixture, 4900 kg (10,800 lb) of liquid oxygen, and a 1000 kg warhead (2200 lb). The V-2 could reach speeds of 5700 km/h (3540 mph) and altitudes of over 200 km (124 miles, 656,000 ft). The missile had a maximum range of about 320 km (200 miles).

The V-2 rocket was technologically advanced, for its time. In addition to the liquid-propellant rocket engine technology, the rocket incorporated advancements in the areas of supersonic aerodynamics, stability, control, guidance, and navigation. The various components of the V-2 rocket are shown in Figure 1.76. The liquid rocket engine had a pump-fed propellant system, where the fuel and oxidizer pumps were driven by a steam turbine. The steam to drive the turbine was generated by the combustion of hydrogen peroxide with a sodium permanganate catalyst. The propellant tanks were made of a lightweight aluminum–magnesium alloy. The alcohol–water mixture fuel was also

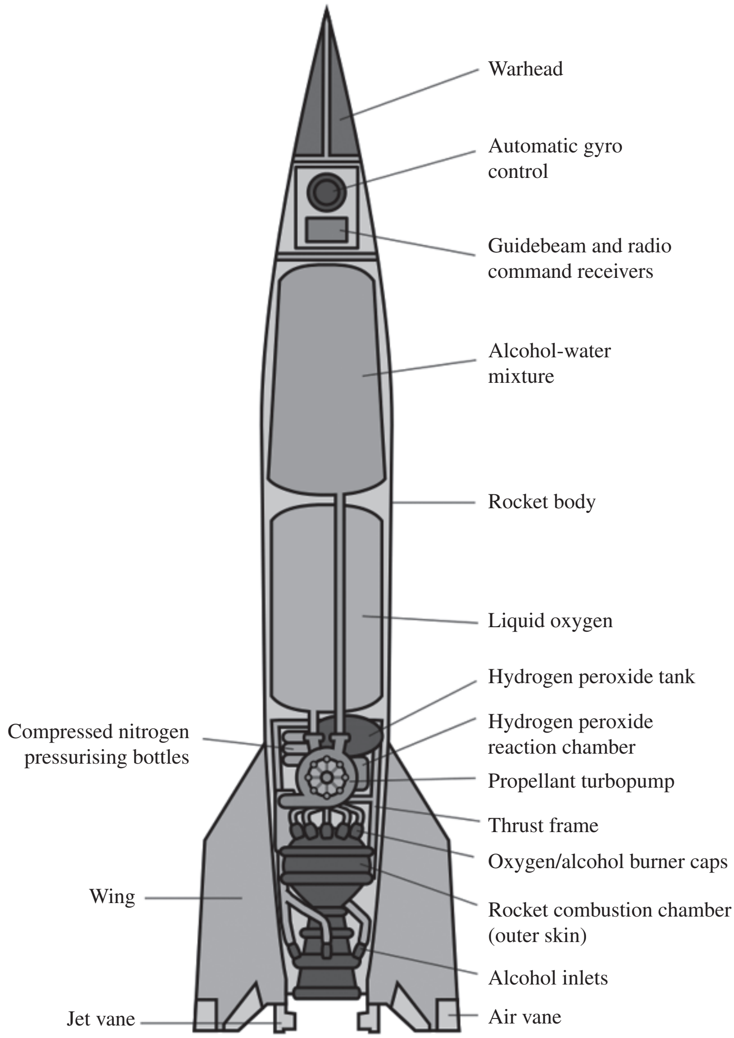

Figure 1.76 Components of the V-2 rocket. (Source: *User: PD-Fastfission, https://en.wikipedia.org/wiki/File:V-2_rocket_diagram_(with_English_labels).svg*.)

used as a coolant for the combustion chamber and nozzle. The fuel was pumped behind the combustion chamber walls, cooling the chamber and heating the fuel. The heated fuel was then sprayed into the combustion chamber. Fuel was also sprayed inside the nozzle, providing film cooling of the nozzle walls. Steering control of the rocket was provided by a combination of movable rudders (air vanes) on the tail fins (wings) and movable guide vanes (jet vanes) in the rocket engine exhaust. An automatic gyroscope control system was used for vehicle stabilization. Early V-2 rockets used a simple type of analogue computer for guidance and navigation, but later versions used a ground-transmitted, radio signal guide beam.

After World War II, many of the German scientists and engineers that had been involved with the V-2 development, including von Braun, were brought to the United States. Many of these rocket scientists and engineers were located in Huntsville, Alabama, laying the foundations for what would eventually become the US Army Redstone Arsenal and the NASA Marshall

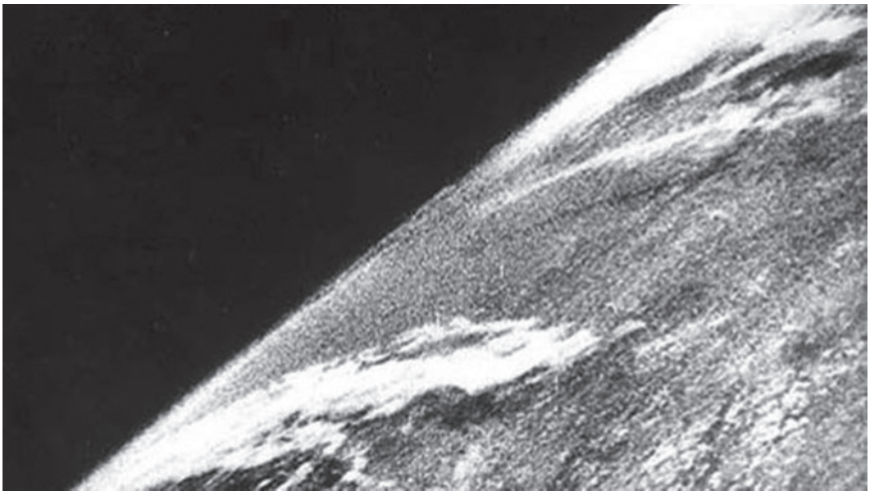

Figure 1.77 The first photograph of the Earth taken from space, 24 October 1946. (Source: *US Army*.)

Spaceflight Center. Accompanying the German personnel was significant amounts of V-2 rocket hardware and components, including complete rocket vehicles. These captured V-2 rockets were studied and launched on test flights by the US from the White Sands Missile Range in New Mexico.

On 24 October 1946, a V-2 rocket, launched from White Sands, carried a small 35-mm motion picture camera, taking black-and-white photographs every 1.5 seconds during its flight. The photographs were not telemetered back to earth; rather the camera film was recovered from a protective case after the rocket crashed back to earth. The rocket reached an altitude of 65 miles (105 km, 340,000 ft), where it took the first photograph of the Earth from space (Figure 1.77). Today, photographs of the Earth from space are quite commonplace, but this first grainy picture of the Earth from space gave us the first perspective of our planet from the new frontier of space.

1.3.5.4 The First Vehicle to Fly at Hypersonic Speed

In the 1940s, the United States developed the *WAC Corporal*, the first *sounding rocket*, specifically designed for upper atmospheric research. Designed and built by the Douglas Aircraft Company and the California Institute of Technology's Guggenheim Aeronautical Laboratory, the *WAC Corporal* was 7 ft, 11 in (2.4 m) in length, 12 in (30 cm) in diameter, weighed about 760 lb (340 kg), and carried a payload with a weight of about 25 lb (11 kg). The *WAC Corporal* was a two-stage rocket system with a solid-propellant first stage and a liquid propellant second stage. The first stage was a 5 ft (1.5 m) long *Tiny Tim* solid rocket booster with three stabilizing fins, capable of producing about 50,000 lb (11,000 N) of thrust for 0.6 s. The second stage had an Aerojet liquid-propellant motor delivering about 1500 lb (340 N) of thrust for 47 s. The rocket was not stabilized and was unguided (some references stated that *WAC* was an acronym for "without attitude control"). Later versions of the *WAC Corporal* incorporated stabilization and guidance systems. Upon reaching its peak altitude, the nosecone of the rocket separated and fell back to earth for recovery of scientific instruments and recording equipment. The first flight of a fully operational *WAC Corporal* occurred on 11 October 1945 at the White Sands proving ground, New Mexico (later to be renamed the White Sands Missile Range). The rocket reached at altitude of about 230,000 ft (44 miles, 70 km). On 22 May 1946, a White Sands-launched *WAC Corporal* reached an altitude of 50 miles (80 km, 264,000 ft), making this the first sub-orbital flight of a manmade object. (An altitude of 50 miles is the altitude boundary for space used by the US Air Force.)

Later, the liquid-propellant, upper stage of the *WAC Corporal* was mated to a much larger V-2 rocket and re-named the *Bumper-WAC* rocket. The V-2 rocket stage was about 45 ft (14 m) in length and had a thrust of about 55,000 lb (245,000 N) at launch. After launch, the V-2 rocket motor burned for only about one minute, before the *WAC Corporal* second stage was ignited, which burned for about 45 s. The *Bumper-WAC* was so-named because of the "bump" in altitude provided by the V-2 rocket.

A total of eight flights of the *Bumper-WAC* rocket were conducted, six from White Sands proving ground, New Mexico and two from Cape Canaveral, Florida. The two Cape Canaveral launches were the first two ever conducted from this fledgling rocket launch complex (Figure 1.78). The first *Bumper-WAC* flight from White Sands was on 13 May 1948, reaching a maximum altitude of about 80 miles (129 km, 422,000 ft) and a maximum speed of about 2740 mph (4400 km/h, 4020 ft/s). The firsts for this little liquid-propellant rocket were to continue. On 24 February 1949, the fifth *Bumper-WAC* flight from White Sands reached an altitude of 244 miles (390 km) and a maximum speed of 5150 miles per hour (8290 km/h), making it the first manmade object to fly at hypersonic speed, in excess of Mach 5.

Figure 1.78 Launch of the *Bumper-WAC Corporal* from Cape Canaveral, Florida, 24 July 1950. (Source: *NASA*.)

1.3.5.5 Reusable Rocket-Based Launch Systems

As one might imagine, the use of expendable rocket launch systems is very expensive and inefficient, given the fact that the rocket boosters can only be used once. Imagine the cost of air travel, if a commercial airliner was discarded after a single flight! Of course, space travel is a bit more complex than airline travel, but not having to manufacture new boosters for every flight could provide a cost and efficiency benefit. There have been several studies of reusable booster systems, where the separated booster stages are returned to earth so they can be reused. These studies have included *fly-back boosters*, where the booster is flown back as a glider or under power, using an air-breathing jet engine. There have been several recent successes by commercial space companies with returning a first stage booster for potential reuse. These have involved guiding the booster back to a landing pad, where the booster's main engines are relighted to slow the descent rate, landing gear are extended, and the booster is landed vertically. Below, we discuss a partially reusable, rocket-based launch system, the Space Shuttle.

The NASA Space Shuttle, shown in Figure 1.79, is an example of a partially reusable, rocket-based launch system. The Space Shuttle program, more formally called the Space Transportation System (STS), followed the *Apollo* program as the access to space system for the United States. The Space Shuttle was a man-rated launch system used to transport astronauts to low earth orbit for three decades. The first flight of the Space Shuttle into space was on 12 April 1981. There were a total of 135 Space Shuttle missions, until the program ended in 2011. In total, six Orbiter Vehicles were built, the *Enterprise*, *Columbia*, *Challenger*, *Discovery*, *Atlantis*, and

Figure 1.79 The first Space Shuttle launch, STS-1, 12 April 1981, the 20th anniversary of Yuri Gagarin's flight. (Source: *NASA*.)

Endeavor. The *Enterprise* was a non-space-worthy vehicle that was used for the approach and landing glide tests prior to any space flights. Tragically, two Space Shuttles were lost in accidents, *Challenger* during launch in 1986 (STS-25) and *Columbia* during entry in 2003 (STS-113).

The Space Shuttle launch system comprised the winged Orbiter Vehicle (OV), a large External Tank (ET), and two solid rocket boosters (SRBs). The Orbiter housed the various flight crew decks, a large cargo payload bay, Orbital Maneuvering System (OMS) rocket motors, and three Space Shuttle Main Engines (SSMEs). The Orbiter was attached to the External Tank, which contained the liquid hydrogen and liquid oxygen propellants that fueled the Orbiter's three SSMEs. The Solid Rocket Boosters were mounted on either side of the External Tank. The Orbiter Vehicle, along with the SSMEs, and the SRBs were the reusable components of the Space Transportation System, while the External Tank was not reusable.

The Space Shuttle was vertically launched from Cape Canaveral, Florida. The complete Space Shuttle launch stack (Orbiter, External Tank, and Solid Rocket Boosters) was 184 ft (56 m) tall with a gross lift-off weight of about 4.4 million lb (2000 tonnes). The total lift-off thrust produced by the SSMEs and SRBs was about 6.78 million lb (30.2 MN). The Shuttle was a two-stage rocket booster system with the first stage SRBs being jettisoned about two minutes after launch, at an altitude of about 150,000 ft (46,000 m). The External Tank continued to supply fuel and oxidizer to the SSMEs until main engine cut-off (MECO), just prior to orbit insertion. The SSMEs burned for about 8 minutes from lift-off to MECO. The ET was jettisoned after MECO, falling back to earth into the ocean. The Orbiter entered low earth orbit and could perform orbital maneuvers using its OMS engines. After completion of the in-orbit mission, the Orbiter used its OMS engine to slow down and enter the atmosphere as a hypersonic glider. It glided to a horizontal landing on a very long paved runway, at the NASA Kennedy Space Center, Florida or Edwards Air Force Base, California.

The Orbiter Vehicle was a space plane, designed to launch like a rocket and land like an airplane. The Orbiter flight envelope encompassed altitudes from sea level to 330 miles (530 km) and speeds from 213 mph (343 km/h) to Mach 25. At hypersonic speeds, the Orbiter lift-to-drag ratio was about 1, increasing to about 2 for supersonic flight, and about 4.5 for subsonic flight. (This is an example of the decrease in the lift-to-drag ratio as the Mach number increases and the fact that hypersonic lift-to-drag ratios are small.) The Orbiter had a length of 122 ft (37 m), height of 56.6 ft (17.2 m) to the top of its vertical tail, wingspan of 78.1 ft (23.8 m), and gross lift-off weight of about 240,000 lb (110,000 kg).

The Orbiter had a somewhat conventional high-speed airplane configuration, with a highly swept double-delta wing and single vertical tail. Flight control surfaces included elevons, mounted at the wing trailing edges, provided pitch and roll control, and a rudder at the trailing edge of the vertical tail provided yaw control. The rudder was of a split design, such that it could deflect a surface in both the left and right directions to act as a speed brake for landing. The aft end of the Orbiter housed the three SSMEs and two OMS engines, mounted in pods on either side of the vertical tail. Each SSME had a sea level thrust of 393,800 lb (1.75 MN), with a combined thrust of over 1.18 million lb (5.3 MN), and a specific impulse of 455 s. (Specific impulse is a measure of the efficiency of a propulsive device as given by the ratio of the thrust produced to the propellant consumed, to be discussed in Chapter 4.) The Orbiter also had a reaction control system (RCS) comprising 44 small liquid-fuel rocket thrusters that were distributed at the forward and aft ends of the vehicle. The RCS provided attitude control and maneuvering of the Orbiter in pitch, roll, and yaw while in orbit and during entry.

There were three flight deck areas in the Orbiter crew compartment, the flight deck where two pilots and two Mission Specialists were seated, the mid-deck where additional crew were seated, and a utility area where consumables, such as air and water were located. Typical Shuttle missions had a crew of seven astronauts, but up to 11 people could be accommodated in an emergency.

A unique feature of the Orbiter was its capability to carry a large payload in its 59 ft long (18 m) by 15 ft wide (4.6 m), fuselage cargo bay. Two long cargo bay doors ran the length of the cargo bay, allowing the deployment of large payloads. Typical payload weights that could be carried to orbit were about 50,000 lb (22,700 kg). In addition to transporting payloads to orbit, the Orbiter could also capture payloads from orbit and return them to earth. The Orbiter could land with payloads weighing up to 32,000 lb (14,400 kg).

To survive the 3000°F (3460°R, 1922 K) temperature of atmospheric entry, the Orbiter was covered with a thermal protection system (TPS). The type of TPS on different parts of the Orbiter varied depending on the heat load. TPS material included reinforced carbon-carbon for high heat load areas and various types of lightweight ceramic and composite tiles for lower heat load areas. Unlike the ablative heat shields used in the previously discussed space capsules, the Orbiter TPS was reusable, although it did require careful maintenance and repair between flights. The TPS was very lightweight, especially as compared to ablative materials, but it was also fragile, requiring careful handling.

The Solid Rocket Boosters were the largest solid rocket motors ever flown, each producing a peak thrust of over 3 million lb (13.3 MN). The SRBs provided over 70% of the total thrust at lift-off and during the first stage ascent. With a length of 149.2 ft (45.5 m) and diameter of 12.2 ft (3.7 m), each SRB weighed about 1.3 million lb (590 tonnes). The solid fuel in the SRB was ammonium perchlorate composite propellant, a mixture of ammonium perchlorate oxidizer and aluminum fuel. Other ingredients in the solid fuel included iron oxide catalysts, polymer binders (to hold the solid fuel together), and epoxy curing agents. The SRB had a sea level specific impulse of about 240 s. After being jettisoned, the SRBs descended back to earth under parachutes, falling into the ocean. The SRBs were recovered by ship and were refurbished for use on another launch.

The External Tank was the largest and heaviest component of the Space Shuttle, with a length of 153.8 ft (46.9 m), diameter of 27.6 ft (8.4 m), and lift-off weight of about 1.67 million lb (756 tonnes). The ET contained the liquid hydrogen and liquid oxygen propellants to fuel the SSMEs. The ET was covered with a thermal protection system (TPS) primarily composed of a spray-on foam insulation. Thermal protection and insulation was required to prevent aero-thermodynamic heating of the cryogenic propellants and to prevent the cryogenic propellants from liquefying the air next to the metal propellant tanks. The weight of the TPS on the ET was about 4800 pounds (2180 kg). The ET is jettisoned 10 s after MECO. The majority of the tank disintegrates in the atmosphere, with the remaining pieces falling into the ocean.

1.3.5.6 Air-Launched Space Access Systems

So far, we have discussed multi-stage, access to space systems where all of the stages utilize rocket-power. Another option that has been developed is an *air-launched system* where the first stage is an airplane rather than a rocket. The second stage is typically some kind of rocket-powered vehicle that is dropped from the carrier aircraft or "mothership", as it is sometimes called. A variety of schemes have been investigated, using different types of carrier aircraft and different configurations for the attachment of the second stage vehicle to the carrier aircraft. The carrier aircraft could be a fighter-type jet, business jet, transport aircraft, or a new purpose-built aircraft. Of course, an existing aircraft design requires modifications to accommodate carriage of a second-stage vehicle.

An example of an air-launched system for small, unmanned spacecraft is the Orbital Sciences L-1011 and *Pegasus* launch system. The *Pegasus* rocket booster is carried aloft, underneath a Lockheed L-1011 jet (Figure 1.80), to a nominal release altitude of 40,000 ft (12,000 m). The booster has three, solid propellant rocket motor stages. The first stage of the booster has a small delta wing that provides lift to help the vehicle transition from the horizontal launch attitude to the desired

Figure 1.80 Orbital Sciences ASB-11 *Pegasus* launch vehicle dropped from Lockheed L-1011 carrier aircraft. (Source: *NASA*.)

ascent climb angle. The *Pegasus* is capable of placing small payloads of about 1000 lb (450 kg) into low earth orbit.

The Virgin Galactic *White Knight Two* mothership is a specially designed carrier aircraft for the *Spaceship Two* rocket-powered, sub-orbital, manned spacecraft (Figure 1.17). The *Spaceship Two* vehicle is attached to a pylon between the unique dual fuselage configuration of the *White Knight Two*. After release from the *White Knight Two* at about 47,000 ft (14,000 m), the *Spaceship Two* is designed to carry up to six people on a sub-orbital trajectory into space, reaching an apogee of about 100 km (62 miles) before gliding back for a horizontal landing on a runway.

All of the air-launched systems to date have release conditions at subsonic speeds and altitudes below about 50,000 ft (15,000 m). There may be benefits, in terms of payload weight delivered to space, if the first stage can reach a higher energy state prior to release of the second stage. Several concepts have been studied where the first stage vehicle is capable of releasing a second stage vehicle at supersonic speeds and much higher altitudes, but none of these have been attempted in actual flight.

1.3.5.7 Non-Rocket-Based Space Access Systems

We now consider a few non-rocket concepts for space access, returning first to the idea of the space cannon. As improbable as Jules Verne's space cannon may have seemed, it does have some technical feasibility. In the 1950s, the United States and Canada investigated the use of "superguns" to launch research probes into the upper atmosphere and small unmanned satellites into orbit. Significant progress was also made in developing the electronics and instrumentation that could survive the huge acceleration forces associated with gun launching. Much of these efforts culminated in the High Altitude Research Project (HARP) during the 1960s, a joint project of the United States and Canada, to develop a gun-launched system to place a satellite into orbit.

Several HARP superguns were built, constructed from decommissioned US Navy 16 in (400 mm) battleship gun barrels. The "16 in" specification denotes the inner diameter or *bore* of the gun barrel and also defines the maximum outer diameter of the projectile that can be fired. Each 16 in gun barrel was about 60 ft (18 m) long and ultimately, two of these barrels were welded together to form 120 ft (36.6 m) long superguns that weighed about 100 tons (90,700 kg).

The island of Barbados was selected as the first HARP gun launch site due to its proximity to the equator and its general remoteness. Placing a space launch site near the equator is beneficial in terms of launching in the direction of the earth's rotation, thereby imparting the earth's rotational velocity to the vehicle. Hundreds of instrumented projectiles were launched from the Barbados supergun, many reaching sub-orbital altitudes (Figure 1.81). On 18 November 1966, a supergun in Yuma, Arizona fired a 180 kg (400 lb) projectile to a record altitude of 180 km (590,000 ft,

Figure 1.81 The HARP supergun being fired on the island of Barbados. (Source: *US Department of Defense*.)

110 miles). The program was cancelled shortly after this, prior to achieving the goal of placing a satellite in orbit with a supergun or space cannon.

Another imaginative, non-rocket-based space access concept is the *space elevator*. In 1895, the Russian rocket scientist, Konstantin Tsiolkovsky, postulated the building of a tower that would reach from the surface of the earth to space. A huge technical hurdle to this concept is the enormous compressive weight that has to be borne by the structure, just as for a very high building. In contrast to this, the space elevator is based upon a *tensile* structure, where the weight of the system is borne from above by a counterweight in space. The components of a notional space elevator are shown in Figure 1.82. The space elevator cable or tether extends from the counterweight in space to the surface of the earth near the equator. The tether is in tension due to the circular motion of the counterweight. The tether remains vertically centered over the same position on the earth as the earth rotates. An elevator or climber, attached to the tether, mechanically ascends and descends along the cable, to and from space. Advances in materials technology are required to actually build a tether that is strong and light enough to make the space elevator concept a reality. One area that is being pursued is the use of high-strength, lightweight carbon nanotubes, but much more work must be done to build the large structures required, based on this technology.

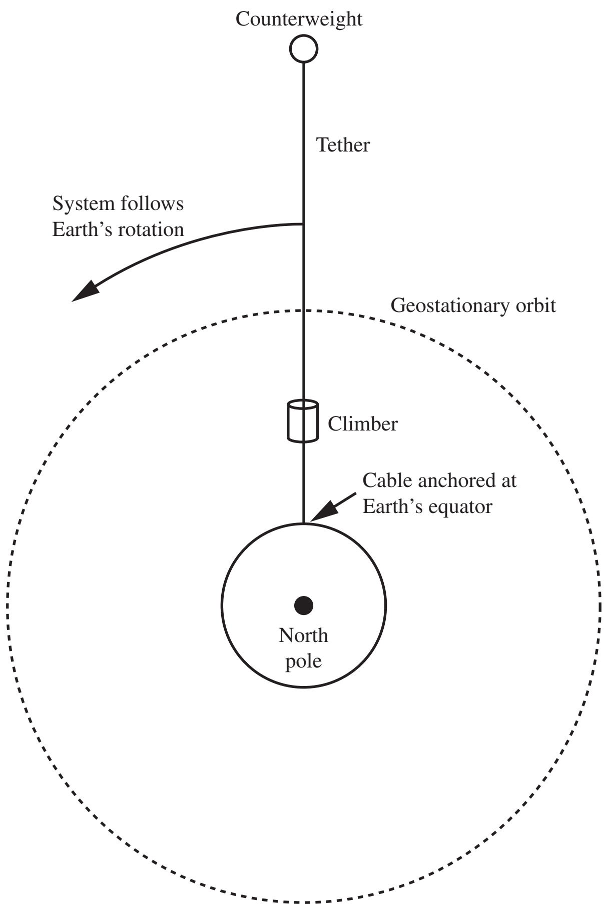

Figure 1.82 The space elevator concept (not to scale).

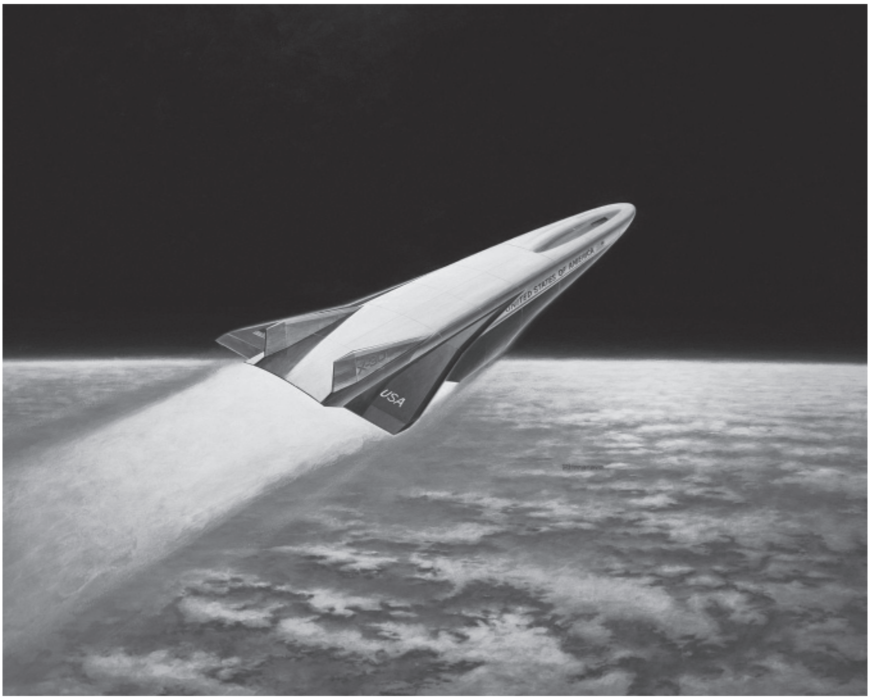

Figure 1.83 The X-30 National Aerospace Plane single-stage-to-orbit concept, 1990. (Source: *NASA*.)

The epitome of reusability and efficiency in space access is perhaps the concept of a single-stage-to-orbit (SSTO) vehicle. An SSTO vehicle would fly into space without the need for rocket stages or expendable boosters and then return to earth as a hypersonic airplane. The ideal SSTO vehicle would be completely reusable, much like an ordinary airplane, able to fly back into space after re-fueling, with a minimum of refurbishment and maintenance.

During the 1990s, the US National Aerospace Plane (NASP) program was a national effort to design and flight test the X-30 SSTO vehicle (Figure 1.83). Utilizing supersonic combustion ramjet, or *scramjet*, engines, the X-30 would use the air in the atmosphere as its propulsion system oxidizer, rather than carry it onboard like a conventional rocket. Reaching hypersonic speeds within the denser parts of the atmosphere, the X-30 would be exposed to extremely high heat loads, making thermal management and thermal protection a difficult design problem. While the X-30 program was eventually cancelled, there have been several significant technological advancements in the development of hypersonic vehicles and hypersonic propulsion that may one day make access to space, using an SSTO vehicle, a reality.

References

1. Anderson, J.D., Jr., *Introduction to Flight*, 4th edition, McGraw-Hill, Boston, Massachusetts, 2000.
2. Crouch, T.D., *A Dream of Wings: Americans and the Airplane*, W.W. Norton & Company, February 2002.
3. Crouch, T.D., *The Bishop's Boys*, W.W. Norton & Company, April 2003.
4. Federal Aviation Administration, US Department of Transportation, *Methods Techniques and Practices – Aircraft Inspection and Repair*, Advisory Circular (AC) **43**.13-1 (as revised), Oklahoma City, Oklahoma, September 8, 1998.
5. Federal Aviation Administration, US Department of Transportation, *Balloon Flying Handbook*, FAA-H-8083-11A, Oklahoma City, Oklahoma, 2008.

6. Federal Aviation Administration, US Department of Transportation, Code of Federal Regulations, Federal Aviation Regulations, 14 CFR Part 1, Definitions and Abbreviations, 2014.
7. Federal Aviation Administration, US Department of Transportation, Code of Federal Regulations, Federal Aviation Regulations, 14 CFR Part 401, Organization and Definitions, 2014.
8. Federal Aviation Administration, US Department of Transportation, *Instrument Flying Handbook*, FAA-H-8083-15B, Oklahoma City, Oklahoma, 2012.
9. Federal Aviation Administration, US Department of Transportation, *Rotorcraft Flying Handbook*, FAA-H-8083-21, Oklahoma City, Oklahoma, 2000.
10. Gessow, A. and Meyers, G.C., Jr., *Aerodynamics of the Helicopter*, Frederick Ungar Publishing Company, New York, New York 1952.
11. Goddard, R.H., *Rockets: Comprising "A Method of Reaching Extreme Altitudes" and "Liquid-Propellant Rocket Development",* Facsimile Edition, American Institute of Aeronautics and Astronautics, Reston, Virginia, 2002.
12. Griffin, M.D. and French, J.R., *Space Vehicle Design*, 2nd edition, AIAA Education Series, American Institute of Aeronautics and Astronautics, Inc., Reston, Virginia, 2004.
13. Hurt, H.H., Jr, *Aerodynamics for Naval Aviators*, US Navy NAVWEPS 00-80T-80, US Government Printing Office, Washington, DC, January 1965.
14. Hybrid Air Vehicles, Ltd., http://www.hybridairvehicles.com/
15. Jackson, P. (ed.), *Jane's All the World's Aircraft: 2002–2003*, Jane's Information Group Limited, Coulsdon, Surrey, United Kingdom, 2002.
16. Page, B.R., "The Rocket Experiments of Robert H. Goddard," *The Physics Teacher*, November 1991, pp. 490–496.
17. Leishmann, J.G., *Principles of Helicopter Aerodynamics*, 1st edition, Cambridge University Press, New York, New York, 2000.
18. Lilienthal, O., *Birdflight as the Basis of Aviation*, translated from the 2nd edition by A.W. Isenthal, Markowski International Publishers, Hummelstown, Pennsylvania, 2001.
19. Young, H.D. and Freedman, R.A., *University Physics*, 11th edition, Addison Wesley, San Francisco, California, 2004.