1

Introduction

1.1 Historical Perspective

1.1.1 The First 40 Years of Flight 1905–1945

The aviation pioneers learned to fly by making short 'hops', progressively increasing the length of the 'hop' until actual flight was achieved (Turner, 1913). Training was mostly limited to advice given on the ground. There are a few examples of early training devices, but these were designed to enable pilots to experience the effects of the controls. The Sanders trainer (Haward, 1910), developed in 1910, comprised a cockpit which could be turned into the prevailing wind; if the wind was sufficiently strong, the cockpit would move in response to the pilot's inputs. Similar devices were developed by Walters and Antoinette (Adorian *et al*., 1979) in the same year, where motion of the cockpit was controlled by instructors, as shown in Figure 1.1.

During the First World War, flight training became established in dual-seat aircraft, notably the AVRO 504 which was adopted as a basic trainer by the Royal Air Force (RAF) from 1916 until 1933. The instructor demonstrated manoeuvres, which were practised by the student pilot until a satisfactory standard of proficiency was achieved to 'go-solo', with pilot and instructor communicating via a 'Gosport speaking tube'. Despite the rapid advances in the early years of aeronautics, the handling qualities of these aircraft were poor and many were unforgiving if flown badly. It is claimed that more lives were lost in training[1] than in combat during the First World War (Winter, 1982).

By 1912, Sperry had developed rudimentary autopilot functions incorporating a gyroscope. In a public demonstration in 1914, he flew a Curtiss flying boat 'hands-off' while a mechanic walked along the upper wing surface to the wing tip! By the late 1920s, flight instrumentation enabled pilots to fly safely in cloud and rain, without visual reference to the ground. In instrument meteorological conditions (IMC), an artificial horizon, altimeter, airspeed indicator and a compass enabled pilots to fly by reference to these instruments. Although the flying training syllabus had matured by the 1930s, throughout this period the aircraft was accepted as the natural classroom for flight training, including training for instrument flying, with ground schools providing the theory to support flying training.

In the late 1920s, Edwin Link, who is recognized as the founder of modern day flight simulation, developed a flight training device which enabled a significant part of instrument flying training to

[1] In his book *The First of the Few*, Winter claims that 8000 of the 14,166 pilots killed in the First World War died while training in the United Kingdom. In Parliament, on 20 June 1918, the Secretary of State attributed the losses to the lack of discipline of the young pilots.

Principles of Flight Simulation D. J. Allerton

Figure 1.1 The Antoinette flight training simulator circa 1911 (Courtesy: The Library of Congress)

be conducted in a ground-based trainer (Rolfe and Staples, 1986). Link worked in his father's factory in Binghamton, where they manufactured air-driven pianos and church organs. He had a sound grasp of pneumatics and mechanisms and, having obtained a pilot's licence in 1927, applied his knowledge of engineering to the construction of a flight trainer (Link, 1930), using compressed air to tilt the cockpit and to drive pressure gauges to replicate aircraft instruments. However, Link experienced considerable resistance to his ideas and initially sold his trainer (complete with a slot for coins) to amusement parks.

Advances in aircraft design following the First World War saw a rapid expansion in aviation, including the delivery of freight and mail. The US Post Office subcontracted mail deliveries to the US Army Air Corps. But in the early 1930s, they extended mail delivery to all-weather operations, leading to an alarming increase in fatalities. As a consequence, the US Army Air Corps purchased six flight trainers from Link, specifically for the task of instrument flight training – probably the first time that the value of flight simulation was recognized in flight training.

Link's early contributions to flight training were fundamental:

- He exploited specific engineering technologies to produce a successful flight training device;
- The flight trainer was developed to meet a specific training requirement;
- Although his flight model was simple and inexact, the trainer was effective – it had a positive benefit on pilot training;
- The introduction of the Link trainer established the concept that flying training was not limited to airborne training – effective training could also be undertaken in a ground-based trainer.

The problems of aircraft accidents occurring in instrument flight conditions resurfaced during the Second World War, with aircrews flying long distances in night-time operations and

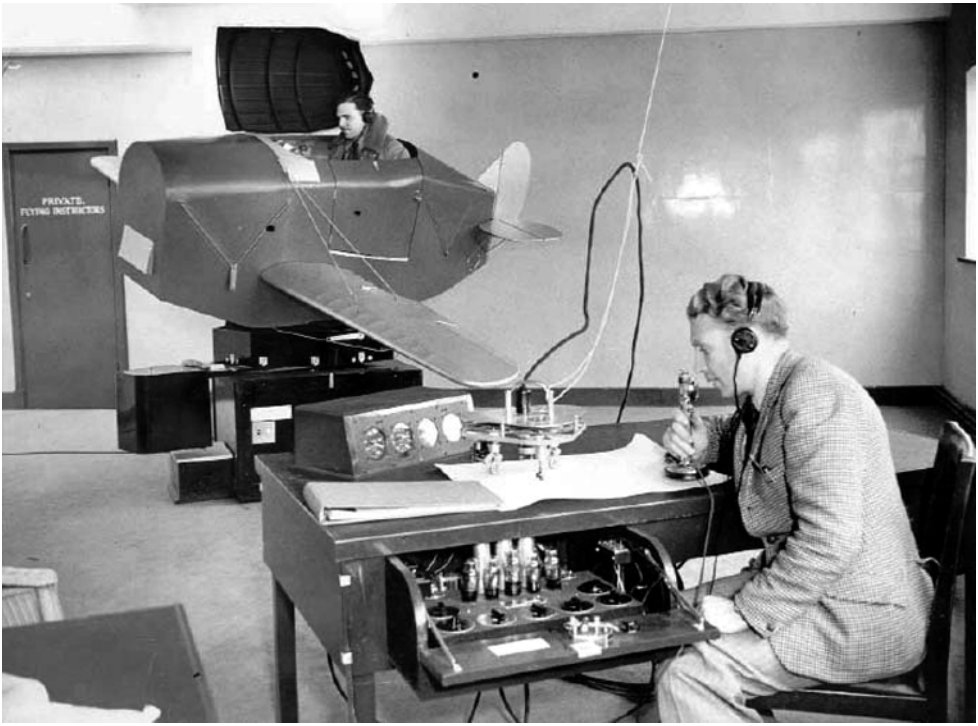

Figure 1.2 A Link trainer (Courtesy: Royal Aeronautical Society)

frequently in bad weather. Under conditions of stress and fatigue, pilots could become disorientated and the ground-based 'Link trainer', shown in Figure 1.2, which was known affectionately as the *Blue Box* (because most were painted blue), enabled pilots to practice in instrument flight conditions; they also provided instructors with a device to assess the instrument flying skills of pilots. Although based on an empirical model, the Link trainer simulated both the environment of an aircraft cockpit and also the dynamic behaviour and performance of an aircraft. Pneumatic actuators were used to inject motion into a small cabin and the instruments were driven to resemble the response and characteristics of an aircraft. In addition, a plotting table was provided so that the instructor could monitor the track flown – the forerunner of the instructor station. Over half a million allied airmen trained on a Link Trainer during the Second World War.

One further development in flight training occurred during the Second World War. As aircraft became more complex to operate, in terms of engine controls, electrics, hydraulics and navigation systems, simulators played an important role in training for the cockpit drills to operate these aircraft and to respond correctly to emergencies. The Silloth trainer (Rolfe and Bolton, 1988), developed by the Royal Air Force, provided a significant amount of training for bomber crews at this time. These flight trainers were fixed-base devices (no motion was provided) – an early example of a part-task trainer, optimized for a specific training application.

1.1.2 Analogue Computing, 1945–1965

Feedback control systems evolved during the Second World War, with servomechanisms being used to stabilize gun turrets for ships and aircraft. The underlying differential equations could be solved by electronic circuits. At the heart of these developments was the operational amplifier, constructed from thermionic valves. By providing a high gain amplifier with resistive feedback, signals could be summed algebraically and more importantly, by providing capacitive feedback, the mathematical operation of integration could be applied to signals. These developments heralded the introduction of the analogue computer. Each amplifier could be configured as a summer or integrator with gains implemented by potentiometers. Short wires were used to connect these elements allowing complex sets of differential equations to be solved in real-time. The simplicity, relative low cost and capability of analogue computers to solve the equations inherent in nuclear power generation, chemical reactions and electrical motor control established analogue computation as a major engineering discipline up to the mid-1960s.

In aeronautics, the analogue computer was used to model the equations of motion of aircraft dynamics (Allen, 1993) as sets of non-linear differential equations, giving the aircraft designer the opportunity to develop advanced control systems in the research laboratory. Indeed, the TSR-2 and Concord programmes made extensive use of analogue computers. Analogue computation offered major advances: it enabled complex differential equations (including non-linear equations) to be solved; it offered real-time simulation; a program could be altered easily by changing the gain of a potentiometer or by patching a few wires. However, this technology also had a number of major drawbacks:

- The valves were unreliable and prone to drift, necessitating regular and complicated calibration;
- The voltage range was limited – the equations had to be scaled manually in order to ensure that the voltage range of the computer was not exceeded, without compromising the resolution of variables used in the computation;
- Multiplication and division of two variables was difficult and slow – mechanical multipliers and inverters were developed, but they lacked resolution;
- Non-linear terms, for example trigonometric functions were difficult to implement – resolvers, with predefined set-points were developed, but these elements were expensive and often limited to a few linear segments.

Although analogue computation made a significant improvement to the fidelity of flight models, advances in motion systems and visual systems were much slower. These early simulators were limited to simple motion drive platforms, often constrained to two or three degrees of freedom and, for the most part, were used to simulate instrument flight conditions. One significant development was the provision of model boards, with very detailed scenery, where a camera was suspended from a small gantry to follow the aircraft flight path over the terrain. The camera was mounted on a gimbal mechanism, allowing the camera to be synchronized with the flight model in pitch, roll and yaw. The camera video output was displayed on a monitor placed directly in front of the pilot, with the model board scaled exactly to the geometry of the pilot eye position. Although very high levels of realism were achieved with detailed model boards, these systems had two pitfalls. First, the pilot could fly off the edge of the model board. One solution was to construct the model board on a flexible base, passing over large rollers, so that the model board effectively repeated. The second limitation was that the camera could collide with the model board, necessitating expensive repairs to the model board and even to the camera. These systems also provided endless opportunities for the prankster, for example, by placing a spider in front of the camera during finals.

There were two significant achievements during this period. First, airlines started to appreciate the benefits of flight simulators, not only to reduce training accidents but also to reduce training costs. Secondly, a significant industry developed in the United Kingdom and the United States to manufacture flight simulators for airlines, notably Redifon and Link Miles in the United Kingdom.

1.1.3 Digital Computing, 1965–1985

While analogue computers were used for real-time applications after the Second World War, digital computers (developed from code-breaking devices) evolved more slowly, initially being introduced into commercial applications, particularly data processing and payroll systems. During this period, the processing speeds advanced, early programming languages were developed and the capacity of storage devices increased. However, it was the development of the transistor in the mid-1960s that initiated the major advances in digital computation. By the 1970s, mini computers were used widely for scientific computing, evolving from the mainframe computers of the 1960s. As the processor speeds increased, sufficient instructions could be executed to enable the equations of motion of an aircraft to be solved at least 15 times per second (15 Hz). At rates below 15 Hz, delays in the computation can be perceived by human pilots, giving rise to unexpected or unusual responses to pilot inputs. The early digital computers achieved this processing rate by using fixed-point arithmetic rather than the slower floating-point arithmetic and by optimizing the code, typically by programming the equations in assembler code. However, by the late 1970s, the mini computers could be programmed in a high-level language, using hardware floating-point processors to achieve an update rate of 50 or 60 Hz. Indeed, several of the simulator companies developed their own processors to meet the very demanding requirement of real-time processing, at this time.

As mini computers advanced in processing speeds, simulator manufacturers applied digital technology to the development of visual systems with two notable achievements. First, with the use of special-purpose hardware, light points defined in a scene could be transformed to the coordinates of a cathode ray tube (CRT). With very fast response video amplifiers, the electron beam of a CRT could be deflected to draw several thousand light points to provide a night or dusk scene. Not only could the light points be rendered accurately, to provide a realistic night-time image, but the intensity of each light point could be modulated to simulate the effects of range or fog. The second advance came with projection. Up to this point, CRT displays were placed in front of the pilot. However, the image lacked realism; the pilot's eyes were focused on the CRT screen, looking at points apparently several miles away. In addition, CRTs were much smaller than the windscreens of transport aircraft. After some experimentation with different lenses (including Fresnel lenses) the collimated projector was introduced into airline simulators. The beams from a CRT reflected from a semi-silvered mirror onto a segment of a spherical mirror, passing back through the semi-silvered mirror to be seen by the pilot. This arrangement afforded two advantages:

- The image was magnified so that it was possible to fill an aircraft window with the image provided by a small CRT. The windows of a commercial transport aircraft are approximately rectangular, allowing the projection system to be mounted on the outside of the simulator cockpit – correction for optical distortion or reversal of the image was provided by adjustment to the CRT beam deflection circuits;
- The light rays from the CRT seen by the pilot were almost parallel, producing an uncanny effect of distance (hence the phrase collimated).

Collimated projection systems were widely used from 1970 to the early 1990s. As monochrome CRTs gave way to colour CRTs to provide daylight images and the scene content increased with faster graphics processors, the collimated projector had sufficient resolution and bandwidth to sustain the 60 Hz frame rate provide by the image generators. However, these projectors had three inherent disadvantages:

- Manufacturing an accurately machined curved mirror was expensive;
- The weight of three or four mirrors added significantly to the (off-axis) load on the motion platform;

- The image was only correct at the pilot eye-point – distortion increased away from the focal point of the projector mirror, to the extent that a pilot would be unable to see anything in the windscreen in front of the other pilot.

1.1.4 The Microelectronics Revolution, 1985–present

Gordon Moore, one of the founders of the Intel Corporation, is widely attributed with encapsulating the advances of the microelectronics revolution in 'Moore's Law' (Moore, 1965). By the 1980s, semiconductor companies were fabricating processors and memories as integrated circuits (ICs). Moore observed that the rate of progress was such that performance doubled with a fixed period of time (and without a concomitant rise in cost), typically 18 months. In other words, every 18 months or so, the capacity of memory chips or the processing speed of processor chips would double, largely driven by a demanding and expanding domestic market for desktop PCs, computer games and audio and video equipment.

By the late 1980s, the standard desktop PC outperformed the mini computers of the 1970s. For flight simulation, the equations of motion could easily be computed at 60 Hz on a single processor. Attention now focused on the development of visual systems. The simulator companies had hitherto developed their own image generators (Barrette, 1986), but with advances in games technologies, they were able to exploit the capability of the graphics ICs. The dusk calligraphic displays were replaced with daylight imagery, with textured surfaces and atmospheric effects rendered at 60 Hz to increase the visual fidelity (Schachter, 1983). The model board was replaced with a digital database of objects to define the terrain, airfield and other geographic features. One further advance was the wide angle projection systems developed in the 1990s. The collimated projectors (Spooner, 1976) were replaced with a light-weight flexible mirror, providing a lateral field of view up to 220° for both pilots, while at the same time significantly reducing the weight of the projection system. The images projected by three (or more) projectors were carefully blended to provide a continuous 'wrap-around' view. The advances in image generation, in terms of the scene detail and image quality, are evident in Figure 1.3, which shows an image taken from a modern civil flight simulator.

Figure 1.3 An image from a civil flight simulator (see Plate 1) Reproduced by permission of Thales

Hydraulics had been introduced to motion platforms in the 1960s. However, by the 1990s, smooth motion could be provided for hydraulic actuators controlled by microprocessors updating the motion system at rates in excess of 500 Hz. Two further advances in motion systems enhanced the fidelity of motion platforms. First, friction at low speeds can induce jerky motion which is detectable on the simulator flight deck. The use of hydrostatic seals largely overcame this problem. The second improvement was to provide sufficient motion cueing in the three linear axes (surge, heave and sway) and the three angular axes (pitch, roll and yaw) of conventional flight. The Stewart platform (Stewart, 1965), with six linear hydraulic actuators reduced some of these limitations. By moving the actuators independently, motion in these different axes could be blended, for example, tilting the platform to simulate surge or raising the platform to replicate heaving motion. By understanding the human balance sensor mechanisms and with the availability of very low friction actuators and high fidelity visual cues, the physical displacement of the hydraulic actuators could be constrained to 'fool' the brain to induce the sensation of motion. In practice, the motion of these actuators is limited to a few metres. Nevertheless, for the range of accelerations in commercial aircraft operations, these platforms provided a remarkably realistic sensation of motion.

As the fidelity of flight simulators increased during this period, airlines realized the benefits to their operation in terms of both increased safety and reduced training costs. Consequently, the operators sought approval from the regulators to replace airborne training with flight simulation. However, the regulators were faced with a proliferation of flight simulation technology and a range of engineering fidelity afforded by these flight simulators. Realizing the need to resolve this situation, the UK Civil Aviation Authority (CAA) and the Federal Aviation Administration (FAA) in the United States, together with the Royal Aeronautical Society (RAeS), arranged a series of meetings leading to the publication of guidelines for the qualification of flight simulators, which were ratified at the RAeS in 1992 (Anon, 1992). These guidelines form the basis of the International Civil Aviation Organisation (ICAO) document 9625 'Manual of Criteria for the Qualification of Flight Simulators (MCQFS)', which enable a flight simulator to be approved for specific training in a training organization. This was a very important milestone in flight simulation:

- It established the international acceptance of flight simulation;
- It enabled training to be conducted in flight simulators to an agreed standard throughout the world;
- It defined several levels of acceptance for flight simulators;
- It enabled flight simulator manufacturers to build flight simulators to comply with a consistent standard of fidelity, defined in engineering terms.

These advances in simulation technology were not limited to the full flight simulators operated by the major airlines. As the complexity of aircraft systems and avionics systems increased, a significant amount of training was needed to operate these systems. Rather than utilize a flight simulator for a specific training activity, part-task trainers were developed, in effect to off-load expensive simulator training to dedicated training devices, optimized for specific tasks. One particular example is the flight management system (FMS). Learning to operate an FMS can require several days of training, depending on the pilot's experience and the aircraft type. However, by simulating an FMS on a laptop computer, flight crews can practise operating an FMS and also be trained and assessed for the cost of a laptop computer and the training software. Part-task trainers are used to train flight crews in many activities which would otherwise be practised in a flight simulator, including navigation procedures, engine-start procedures, aircraft electrical and hydraulic systems operation, FMS operation and radio management procedures. A modern airline flight simulation training device (FSTD) is shown in Figure 1.4, where the panels replicate the aircraft displays and centre pedestal, with additional displays providing course material in the form of diagrams, illustrations and video clips, focusing on the training of the operation of the aircraft systems rather than flying skills. Note that the training may be provided for pairs of students, encouraging crew cooperation at an early stage.

Figure 1.4 A flight simulation training device (FSTD) (see Plate 2) Reproduced by permission of Thales

One other role for flight simulation during this period has been to support engineering design (Allerton, 1999). The cost of flight trials of new equipment and aircraft systems is very expensive and flight simulation has enabled engineers to design and evaluate aircraft systems. Errors eliminated in the design phase are much less costly to rectify than at the flight trials stage. In addition, the simulator provides the designer with much more insight into ‘what-if’ studies, enabling the designer to compare prototype designs before committing to aircraft equipment. Consequently, the emphasis of flight trials has shifted towards the validation of data derived in simulator studies, rather than expanding the flight envelope. In both the Boeing 777 and the Airbus A380 programmes, engineering simulation made a major contribution to the design of these aircraft.

Since 1985, flight simulation has had a major impact in military flight training. It is arguable that flight simulation was introduced too early into military flight training, giving rise to the view that military flight training was more effective in an aircraft. This argument was further reinforced by the lack of fidelity of flight trainers in the 1960s, giving simulation a bad reputation in many military organizations.

As the cost of training came under strict scrutiny and environmental issues became more prominent, military organizations reviewed the benefits that had been achieved by civil flight training organizations and simulation became an integral part of flying training programmes throughout the world. However, the technology of civil flight training is not appropriate to all military training programmes. In particular, the pilot of a fighter aircraft is not constrained to a forward looking windscreen and during turning manoeuvres, the sustained G-force cannot be replicated with a conventional motion platform. Two advances have, to a limited degree, ameliorated these problems. The motion platform has been replaced with a G-seat in a fixed-base cockpit (White, 1989), to provide more effective training (Ashworth, 1984). As the pilot is subject to G-forces, actuators control the tightness of the harness and provide tactile cues to exert additional pressure on the pilot’s body. In addition, the buffet experienced in combat manoeuvres near to the stall limit is provided by vibration of the seat assembly. Two solutions have been developed to provide a pilot with a 360° field of view. In some simulators, the pilot's helmet is instrumented to detect head and eye movement. The image is derived from the eye and head position and is projected directly onto the pilot's eye by a small optical system mounted on the front of the helmet. An alternative approach is the hemispherical dome, used in conjunction with an array of conventional projectors to project the terrain (at relatively low resolution) and several laser projectors to provide high-detail imagery (e.g. aircraft in the scene). The cockpit is placed at the centre of the dome and the projectors are positioned near the base of the cockpit, giving the pilot an all-round view.

One particular area of success in military simulation has been mission rehearsal. By generating the visual database of a combat area (typically derived from satellite mapping), flight crews can rehearse a mission in a flight simulator, even to the extent of applying lessons learnt in the simulator to the mission. Military simulators are also linked via high speed networks to enable flight crews to practise multi-ship missions, either to test tactical manoeuvres against each other or to practise tactics for a specific mission.

1.2 The Case for Simulation

Nowadays, the use of flight simulation in both civil aviation and military training is commonplace and widely accepted (Allerton, 2000). These simulators allow flight crews to practice potentially life-threatening manoeuvres in the relative comfort of a training centre. Similarly, military pilots are able to rehearse complex missions and to practise piloting skills that may be unacceptable in environmental terms (in peace time) or prohibitively expensive, for example, the release of expensive weapons.

1.2.1 Safety

Aviation is underpinned by safety. The primary role of the aviation authorities is to ensure the safety of all aircraft operations, including flight training. As recently as the 1970s, airlines would train with actual aircraft, practising circuits, takeoffs and landings and even simulate system failures. Unfortunately, there were a significant number of training accidents and one major benefit of flight simulation has been to eliminate these accidents.

An airline pilot undergoes two days of training and checking every six months. Quite probably, if pilots had been asked in the 1960s if they would be prepared to renew their licence in a simulator, there would have been universal reluctance to consider such an option. Nowadays, if pilots were asked to undertake this training in an aircraft, there would be a similar rejection of the suggestion.

This is a remarkable transition in a very short time and is simply attributable to the technical advances in modelling, visual systems and motion systems. Flight simulation is accepted by the pilots, operators, unions, regulatory authorities and manufacturers. Indeed, some simulators are qualified for zero flight-time (ZFT) training. With these flight simulators (and an approved flight training organization), all the conversion training is undertaken in a ZFT flight simulator. The first time the pilot will fly the aircraft is with fee-paying passengers on a scheduled flight. Of course, the pilot will be closely monitored by a training captain, but it reflects the advances and acceptance of simulation technology throughout the world.

One further aspect of flight safety is reflected by air accident statistics. Following an accident, the regulatory authorities and airlines will study the report of the air accident investigators and may require airlines to incorporate similar events in their training programmes to enable flight crews to be aware of similar situations. The flight simulator allows pilots to experience a very wide range of flight conditions, so that a pilot will have experienced situations in a simulator within the last six months that most pilots would not normally encounter in their full career. The crew of the Apollo 13 mission attributed their success in coping with the malfunctions on their mission to the many hours spent in a simulator, rehearsing the hundreds of possible flight situations they might encounter.

With the increase in air traffic since the 1970s, flight simulation has made a major contribution to increased flight safety. In particular, flight simulation accelerates experience. In the flight simulator, the instructor can select fog, turbulence, wind-shear or icing conditions in a couple of touch-screen inputs. In normal operations, a pilot might only experience specific wind-shear once in five years. Indeed, with extended operations and four pilots per sector, airline pilots can struggle to complete sufficient manual landings to remain current. In such situations, landings practised in a flight simulator are accepted by the regulatory authorities. One future role for flight simulation may be to maintain the proficiency of pilot handling skills.

In the 1970s, a number of regulators and airlines recognized that a significant proportion of air accidents and incidents were attributable to pilot error, particularly in multi-crew operations, where communications between flight crew or the management of situations broke down. The flight simulator provided the ideal platform to practise crew cooperation procedures and to improve the training of flight crews to respond to hazardous situations. In many training organizations, the flight crew response is recorded and reviewed in debriefing sessions. Lessons learnt from the analysis of cockpit flight data recorders and cockpit voice recorders, following aircraft incidents and accidents, have been incorporated in simulator training programmes. It is probable that the aviation industry has led the world in the use of simulation technology to improve training and safety.

1.2.2 Financial Benefits

A wide body transport aircraft typically has eight flight crews per aircraft and one flight simulator per eight aircraft. With 128 pilots requiring four days flight training per year (four 8-hour shifts), simulation utilization approaches full capacity, without allowing for type conversion programmes for flight crews joining the airline or converting onto type. With airborne operations at least 10 times the cost of simulator operations, the cost of equivalent airborne training would bankrupt an airline. There is a strong case that flight simulation has enabled budget airlines to grow and that, without flight simulation, they would not be able to operate.

The major costs of flight training include:

- The cost of purchasing the flight simulator;
- The cost of building the simulator facility;
- The running costs of the simulator facility (electricity, air conditioning, computer maintenance, spares provision, etc.);
- The staff costs to provide flight training and maintenance of the simulator (instructors, maintenance engineers, administrators, etc.).

The income to a simulator organization comes from selling training time on the simulator. Typically, flight simulators operate 23 hours per day and over 360 days per year. Assuming the simulator and the training organization have the appropriate approvals, the role of the simulator manager is to ensure utilization of the simulator and optimize the income.

In addition to the day-to-day operation of a simulation facility, the procurement of a simulator can also affect the financial return. First, there is a lead-time of the supply of both aircraft and simulators to an airline. An airline will procure specific aircraft for its route structure and then train its pilots to operate these aircraft. Balancing the number of simulators to aircraft types is difficult as route structures can change. Secondly, delays in construction of the building, the delivery of the aircraft or delivery of the simulator can cause a significant loss of revenue. Revenue can be generated by selling spare capacity to other operators. Alternatively, a lack of availability may require pilots travelling to train on simulators operated by other airlines. Thirdly, the long lead times can result in variation of bank rates (for loans) or changes in customer markets.

Clearly, these are tightly balanced financial equations for any simulator operator. However, many of the operational costs are fixed (such as instructor salaries and electrical consumption).

The simulator operator will try to reduce both the purchase cost and the operational cost of the simulator. For the purchase price, the cost of the visual system (the image generators and the projection system) has been as high as 50% of the overall cost of the simulator. However, with the availability of off-the-shelf processors and graphics cards, these costs have dropped dramatically. Although motion systems have been of the order of 10% of the purchase price, as the overall cost has dropped, manufacturers have looked to electrical drive systems to replace the hydraulic systems approved for motion platforms. The operational costs depend on the reliability and availability of the simulator. Simulator slots are often booked several months ahead and loss of a simulator for a few hours in a daily schedule can cause severe disruption to a customer. Reliability of simulator facilities has improved in three ways:

- The simulator sub-systems are much more reliable – there are fewer components and increased redundancy is built into modern microelectronics equipment;
- The modular structure of simulator components enables faulty equipment to be detected and swapped out quickly;
- Simulator systems are continually monitored and checked for variation in performance, allowing preventative maintenance to be undertaken to replace failing components before they actually fail.

For the airline, the choice is to buy or lease a flight simulator. Owning a simulator gives the airline full control of its training programme, a margin of error for operational changes to the airline and spare capacity to generate significant revenue for the airline. The major risk is to ensure revenue earning over a period of 10 years or more, where airlines may change route structures and aircraft types to respond to changing markets. Leasing simulator time can be beneficial, but the airline is dependent on the hourly charging rate of the supplier, the availability of slots, access to other facilities (to keep its aircrew current) and travel costs. Furthermore, if leasing proves impractical, there is a two-year lag to rectify the situation.

1.2.3 Training Transfer

The obvious benefit of training on a flight simulator is that time spent training in a simulator can replace time spent training in an aircraft (Caro, 1973). If the simulator is effective (Thompson, 1989), then an hour of training in a simulator could replace an hour, or even several hours training in an aircraft. For example, to practise cross-wind instrument landing system (ILS) approaches in an aircraft requires an acceptable cross-wind and can take at least 15 minutes between approaches. In the simulator, the wind direction and wind speed can be selected and the aircraft can be re-positioned on the approach without flying a circuit or obtaining a landing clearance. Arguably, if the simulator fully replicates the aircraft in this situation, the simulator provides better training than the aircraft.

The term *training transfer* is used to indicate the effectiveness of training in a simulator (Rolfe and Caro, 1982; Caro, 1988; Telfer, 1993). If the number of hours of airborne training needed to achieve a specific level of performance is reduced by synthetic training, the training transfer is positive. Of course, with a poor simulator, an hour spent in the simulator might result in additional time being needed to train in the aircraft, resulting in negative training transfer.

There are three considerations with training transfer. First, how is training transfer measured (Taylor, 1995)? Secondly, are there cost benefits arising from the relative hourly operating costs of the simulator compared with training in an aircraft? Thirdly, does the fidelity (or realism) of a simulator influence the training transfer?

A widely used measure of training transfer (as a percentage) is given by

$$\text{transfer} = \frac{T_c - T_e}{T_c} \times 100 \qquad (1.1)$$

where T_c is the amount of airborne time needed by a control group and T_e is the amount of airborne time needed by an experimental group to reach a specific criterion. Clearly, this measurement is independent of the amount of time spent in the simulator. A transfer effectiveness ratio (TER) is more commonly used (Hays, 1992) and is given by

$$\mathrm{TER} = \frac{T_c - T_e}{X_e} \tag{1.2}$$

where X_e is the time spent in the training device. This value equates the number of hours spent in the trainer to equivalent training in an aircraft (for the first X_e hours). One other measurement of training transfer is known as the *incremental transfer effectiveness ratio* (ITER) (Povenmire and Roscoe, 1971). Clearly, after a certain number of hours, the benefit of an extra hour in the training device starts to reduce. In other words, there is a point where (depending on the relative hourly training costs) the cost effectiveness of using a flight simulator is a maximum; thereafter it reduces towards zero. The ITER is given by:

$$\mathrm{ITER} = \frac{Y_{x-\Delta x} - Y_x}{\Delta_x} \tag{1.3}$$

where $Y_{x-\Delta x}$ is the time required to reach a performance criterion by a group having received $x - \Delta_x$ units of training, Y_x is the time required to reach a performance criterion by a group having received Δ_x units of training and Δ_x is the incremental unit of time. In a study of training effectiveness in *ab initio* flight training, Allerton and Ross (1991) obtained the results summarized in Table 1.1.

Assuming that such figures are available to a training organization, then the final column provides insight into the cost effectiveness of training. If the ratio of training costs of the simulator to the aircraft is known, then the cost effectiveness is negative when the value of ITER falls below this ratio.

The issue of fidelity (Hays and Singer, 1989) is very difficult to resolve. The assumption has been that better training is provided by increasing the realism of the simulator. However, this simplification depends very much on the training task. For example, to demonstrate non-directional beacon (NDB) holds with a cross-wind, a desktop animation where the pilot does not actually fly the simulator, but commands heading might prove far more effective than actually training in a full flight simulator. However, operation of an auto-land system in marginal turbulence conditions would probably be best conducted in a flight simulator with good motion and an accurate flight model. There is a view that such issues are best resolved by undertaking a training task analysis. However, there are many examples where effective training has been achieved on very low fidelity equipment and also examples where negative training has occurred with high fidelity equipment.

In order to measure training transfer it is necessary to undertake the simulator training with a group of trainee pilots and compare their performance with a control group who received no simulator training. A number of extensive studies have shown significant transfer of training with the use of synthetic training devices (Waag, 1981; Bell and Waag, 1998). In practice, this option

Table 1.1 Results of a training transfer experiment

Group	Time to first solo (hours)	Simulator training (hours)	Training transfer (%)	ITER
1	14.94	0	–	–
2	11.60	3	22.15	1.10
3	8.24	7	44.70	0.84
4	8.43	11	43.42	– 0.05

may not be practical. One group might justifiably argue that they received poorer training. More significantly, it is necessary to take objective measurements of pilot performance to show the benefits (or not) of simulator training. There are remarkably few instances of such research programmes and for airlines or military organizations, the cost of the experiment would be very high. The corollary of course, is that without such guidelines, nobody is really sure how effective a particular approach to synthetic training is likely to be.

1.2.4 Engineering Flight Simulation

The majority of flight simulators are used for pilot training. However, flight simulation also plays an important role in aircraft design. The major design effort of the modern civil or military aircraft is in the development of systems rather than development of the airframe or engines. Up to the mid-1980s, the testing or validation of aircraft systems would be conducted during flight trials. However, finding a design fault at this stage of the system life cycle is very expensive. In the development of automatic flight control systems, say, a design error could jeopardize the safety of the trials aircraft and detection and isolation of a fault depends on capturing the appropriate data. If these developments are undertaken in a flight simulator, there is no threat to safety, large amounts of data can be acquired and experiments can be quickly modified or repeated.

An engineering flight simulator differs from a training simulator in several ways:

- It only needs sufficient components to undertake the study – irrelevant items can be omitted;
- There is no training element, such as an instructor station;
- There is no requirement to qualify the simulator to meet any specific approvals;
- Data acquisition is very important – the amount and detail of data acquired in an engineering simulator is far higher than in a training simulator.

Design decisions are based on studying the results of trials undertaken in the engineering flight simulator. As the cost of further trials or tests is effectively a computing cost, it is feasible to undertake additional comparative studies or to take prototype designs much further. Of course, the engineering simulator must be based on a detailed and exact model of the actual aircraft and its systems. In practice, this is difficult. If the aircraft is a new combat type, and control systems are being developed which operate near limits of the flight envelope, estimates or approximations used in the modelling may be incorrect. Consequently, airborne flight trials are often used to validate data acquired in simulation studies, where the same inputs are applied to the actual aircraft under the same flight conditions. The data acquired in flight is then scrutinized and compared with data generated in the simulation studies. In some advanced programmes, such as the BAE Systems Typhoon programme, using telemetry, data is transmitted to a ground station where the results can be checked quickly in order to assess if further airborne measurements are required or if the flight test can proceed to the next stage. Otherwise, a lack of airborne data can necessitate an additional airborne trial, increasing the development cost of the programme.

In some aircraft development programmes, particularly for new aircraft, the engineering simulator provides the basis of the software for the subsequent training flight simulator. With the increasing levels of systems integration in modern aircraft, the avionics design teams may require an airframe model and an engine model and similarly, the engine design teams require avionics systems models. Considerable effort is given to the development of modules for an engineering flight simulator and companies developing these modules seek to recover their development costs by charging for data packages. Since early 1990, while the overall cost of flight simulators has dropped, the relative costs of data packages for aerodynamic data, engines data and avionic systems data has increased to a level that has given rise to several international seminars and conferences, focusing on these problems.

One further area where engineering simulators are used is in 'iron-bird' rigs. Aircraft systems, such as undercarriages or braking systems are themselves complex systems, closely integrated with other aircraft systems and connected to the aircraft databuses. In the latter phase of development of an aircraft, the complete set of aircraft systems is constructed (in a large hangar). The airframe dynamics and engine dynamics are simulated but otherwise actual hydraulic and electrical actuation is used to exercise the interface cards, databuses, actuators and sensors. External loads can be applied to actuators to simulate flight conditions and actual aircraft equipment is used for displays, flight computers and avionics. From a systems perspective, the modules of an iron-bird rig are identical to the aircraft modules and extensive tests and fault detection are undertaken to reduce the amount of airborne flight testing.

1.3 The Changing Role of Simulation

Before the mid-1980s, flight simulation was a specialist subject. To achieve the processing necessitated in real-time flight modelling, motion actuation and visual systems, simulator companies developed special-purpose hardware. However, the arrival of the microprocessor and the supporting microelectronic technologies has changed flight simulation in two ways. First, it is possible to model complex non-linear systems using standard off-the-shelf hardware. Secondly, the performance of modern graphics systems simplifies the visualization of simulation.

The flight simulators prior to 1980 focused on replication of the actual aircraft to enable airlines to operate approved flight simulators for their fleet. These simulators cost in excess of $10 million and were designed for one specific aircraft type. The software for these simulators was designed and supported by the simulator manufacturers with the end user (the operator) being dependent on the manufacturer to maintain and support the simulator software.

As computing speeds increased, other industries realized the benefits that simulation could offer. In the field of electronics, IC design moved from the simulation of components at the gate level to the system level, for example, to fabricate an integrated circuit of several hundred thousand gates. Graphics was used in the simulation and visualization of circuit analysis to detect electrical and logical faults prior to fabrication. Modelling packages were used at the block diagram level to simulate mechanical, chemical, nuclear and environmental dynamics. All these developments focused on the provision of powerful design tools to give the designer better insight into system behaviour, often to optimize the system design. For the most part, there was no requirement for real-time performance – there was either no human in-the-loop or alternatively, these tools were used to reduce simulation runs from hours to minutes.

However, it is probably in the aerospace industry where most diversification of simulation technology has occurred. Although the advances in flight simulation have pegged the advances in the related computer technologies, the acceptance of flight simulation has been much slower. There is a sense of ‘Catch-22’ about flight simulation. Until an organization has used simulation it cannot appreciate the benefits of simulation and while it cannot see the benefits of simulation, it is unlikely to invest in simulation technology. Consequently, it is the reducing cost of simulation technology that has fired the diversification in aerospace.

The financial case for airline simulation has already been outlined. However, if the exacting requirements of airline simulator qualification are applied to other aircraft types, such as regional jets, commuter aircraft, turboprops and general aviation (Allerton, 2002), the case is less convincing. Although the regulatory authorities introduced different levels of qualification, the levels identified by the FAA differ from their European counterparts and have been restricted to fixed wing aircraft, with regulations being extended to rotary wing aircraft in 2001.

The drive for diversification has come from the simulator manufacturers who have tried to match the reducing cost of simulation technology to the markets for simulators. Arguably, this trend has been influenced by the games technologies. For several years, pilots had observed that their children seemed to have better simulation technology in their games than they had in their own training departments. This is understandable – a games company shipping 100,000 games can reduce the end product cost whereas the specialist simulator manufacturer developing a product for a few customers is not able to discount the product or invest in product development at the same level.

The first major development occurred with instrument flight trainers. The availability of computer graphics provided a visual system; stepper motors and servo motors were adapted to replicate aircraft instruments and the equations of motion were solved by a single processor. In addition, mechanical or electrical control loading can be applied to the primary flight controls and an instructor station provides a supervisory role (to set up flight conditions or fail systems) and a monitoring role (to observe tracks and record sessions for debriefing). Such instrument trainers have most of the characteristics of full flight simulators:

- They are real time;
- They are approved for specific training roles;
- They are operated in exactly the same way as the equivalent training aircraft.

In many training organizations, the ground school is distinct from flying training. The ground school lessons are delivered in classrooms and the teaching methods are based on the standard classroom equipment of static overhead projection, whiteboards and blackboards and teaching material that includes hand-outs, notes and textbooks. However, the advances in simulation technology since the mid-1980s have blurred this distinction.

One of the early developments in computer-based training (CBT) was to provide the student with a computer-based textbook. The student could select a page or a topic or was directed through the teaching material according to their rate of learning, typically by their response to questions. In many ways, the early CBT systems were simply one-to-one replacements for conventional learning. However, with the introduction of animation, in the form of computer graphics, more information can be embedded in diagrams or illustrations and more importantly, a student can interact with the computer. For example, an engine-start sequence might require turning on a fuel pump and waiting for the fuel pressure to rise. With a mouse or touch screen, the student can select the appropriate pump and watch the fuel pressure rise.

With the availability of multimedia PC technology, video clips can be combined and merged with animated graphics to illustrate system interactions. More interestingly, if the software for a flight simulator is organized as a re-usable module which can be executed on a workstation, fragments of simulator code can be invoked by CBT software, to operate in exactly the same way that it does in the real-time simulator. With increased display sizes of flat-screens, multiple screens can be combined to show video clips and diagrams in parallel. Although the cost of CBT hardware is low, the major cost is in the development of diagrams and animations. Simple tasks such a detecting mouse actions to select a valve or to show fluid flow in a pipe can require several hours of production. In general, successful use of CBT has been restricted to large programmes, where the cost of CBT development was included in the initial training budget.

Where CBT does offer significant gains is in procedural training. For example, a flight control unit (FCU) may have several selectors, knobs and push switches and interact with other aircraft systems (the aircraft flight control systems and the FMS, in this case). Using a laptop computer, flight crew can practise selections and actually fly a flight plan, where the simulated aircraft responds to FCU inputs and the displays are presented on the laptop screen in the same formats as the aircraft displays. Such an approach to training offers three important advantages:

- The student does not need to learn in a classroom; they can access lesson plans via the Internet, at any time and at any location;
- The result of their exercises can be recorded for assessment by the training organization;

- Students can progress at their own pace; if the lesson plans are carefully structured, the student can be directed back to earlier material to consolidate their understanding or alternatively, where they are progressing quickly, and have demonstrated a good understanding, they can progress faster.

Although the airlines and military organizations have focused on pilot training, recent attention has also been given to maintenance training. Up to the mid-1990s, a large part of maintenance training was conducted with actual aircraft equipment or specially fabricated replicas to enable maintenance engineers to practise the removal and replacement of faulty items. Such training can be very expensive if it takes an aircraft out of service or if mistakes are made with actual equipment, for example, bending the pins of a connector. However, with a synthetic training aid, the student can select the appropriate connector from options displayed on the screen or remove the connector by clicking on the part. A voltmeter probe can then be placed on a specific pin with a simulated voltmeter displaying the voltage. Such systems provide instruction in maintenance procedures and techniques; with increasing dependence on modular hardware in aircraft, technician training concentrates on efficient detection of a faulty module and thorough testing of the replaced unit. The important point to bear in mind is that, just as in the case for pilot training, maintenance trainers are designed to meet a specific training task. If the technician is being trained to tighten nuts with a torque wrench, CBT is not appropriate. However, if the technician is being trained to detect faults when the airline needs to minimize ramp time, then CBT can provide very effective training (and checking).

Flight simulation is moving away from the emphasis on realism in many areas. While it is clearly essential in full flight simulators, in other applications, better understanding may be gained with simplified diagrams, or by answering one of a choice of questions, where the effectiveness of the training is the acquisition of understanding rather than immersion in realistic environments. However, very little research has been conducted into the effect of fidelity in training applications and not surprisingly, with this lack of knowledge in the subject, many organizations opt for realism in training packages.

1.4 The Organization of a Flight Simulator

Baarspul (1990) gives an excellent overview of flight simulation techniques, outlining the technology used in modern flight simulators. The main components of a typical flight simulator are shown in Figure 1.5.

1.4.1 Equations of Motion

The equations of motion are the focal point of all flight simulators. They determine the states of the simulator, taking all the inputs, including pilot controls, winds, aerodynamic terms and engine terms to compute the variables that represent the state of the simulated aircraft, particularly forces, moments, attitude, altitude, heading and velocities. This translation of inputs to outputs depends on the equations of motions used to resolve the linear and rotary motion of the aircraft and includes the aerodynamic data for the aircraft, details of the undercarriage and engine (and possibly propeller) data, usually provided in the form of tables and graphs of data. Note that several of the arrows imply a bi-directional link, for example, several aerodynamic terms are a function of aircraft variables such as angle of attack, Mach number or altitude. In most flight simulators, the equations of motion are updated 50 or 60 times per second, where the forces and moments are computed and applied to the aircraft in less than 1/50th or 1/60th of second.

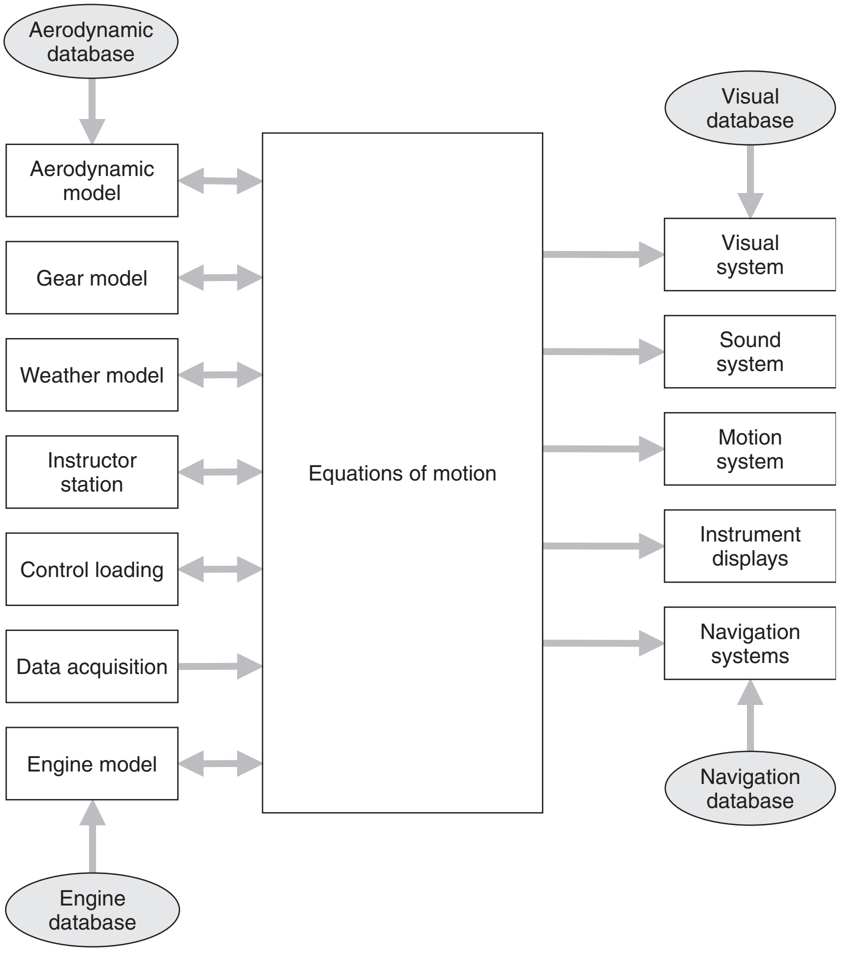

Figure 1.5 Organization of a flight simulator

1.4.2 Aerodynamic Model

The aerodynamic model enables the aerodynamic forces and moments to be computed. For example, the coefficient of lift may be derived as a function of the angle of attack where the specific aerodynamic coefficients are defined in the aerodynamic database. The aerodynamic data is provided as a large (nowadays electronic) database, typically in the form of several thousand graphs of the aerodynamic variables, often as functions of two or three variables. This database is likely to have been obtained from a combination of flight testing, wind tunnel tests and possibly computational fluid dynamics (CFD) analysis. The database will also include a vast amount of validation data to enable the simulator developer to compare the simulator dynamics and performance with actual aircraft data. From the manufacturer's perspective, this data has high commercial value and is usually provided as part of a confidential agreement between the operator, the aircraft manufacturer and the simulator manufacturer.

The aerodynamic model is possibly the most critical element of a flight simulator. An error in modelling the aircraft aerodynamics can lead to a simulation which might fail in the qualification process or be unacceptable to pilots who are experienced on this type of aircraft. Consequently, the aerodynamic data package produced by the aircraft manufacturer is expensive. For this reason, there are very few detailed data packages available in the public domain. Although it is possible to acquire this data from flight trials, the cost of aircraft instrumentation, operation of flight trials, data recording and data analysis can be prohibitive to simulator companies. This is an issue sometimes missed by prospective simulator developers; there is no simple way to acquire this data and just a few errors in the aerodynamic data package can result in an unacceptable aircraft model.

1.4.3 Engine Model

Many of the comments in the previous section also apply to the engine model. The engine manufacturer will undertake extensive tests in engine development. Moreover, the engine manufacturer is likely to be responsible for the engine control systems, so will be using this data to develop an engine model to be used in any control system design activities. In some data packages, the engine dynamics will be provided by the aircraft manufacturer, either because they have undertaken flight tests to identify the engine characteristics or because they have purchased the data from the engine manufacturer for use in the simulator development. Note that the engine data is dependent on the state of the aircraft; implementation of the engine model requires access to variables computed in the flight model.

From the simulator designer's perspective, the engine model is a model of the engine dynamics, rather than a thermodynamic model, which is used to derive engine thrust, fuel flows and engine pressures and rotation speeds. Quite often, the engine model is as detailed as the aerodynamic model. For simulator qualification, the regulatory authority will need to undertake extensive tests of engine failure modes (e.g. surge, stall or total failure) and the engine manufacturer must provide this data. In particular, the engine characteristics change considerably at low speeds and at very low altitude where the engine flow interacts with the ground. For these reasons, there are also very few examples of detailed engine models in the public domain.

1.4.4 Data Acquisition

In a full flight simulator the flight deck is an exact replica of the aircraft flight deck. Indeed, some of the equipment in the simulator may use actual aircraft parts, as it may be more expensive to fabricate a facsimile than to purchase the certified aircraft equipment. In addition to the primary flight controls (control column, rudder pedals, brakes, flap selector, gear selector, etc.), every lever, selector, knob and switch must be interfaced to the appropriate simulator module.

Some of these inputs provide digital data (0 or 1), often referred to as *discrete data*, whereas other inputs are analogue data. The current selection of inputs must be sampled during each frame, converted to an appropriate value and passed to the relevant simulator module. For some sub-systems, for example, a radio panel, these inputs are monitored and computed by a local processor in the module and passed as serial data or parallel data. Nevertheless, a full flight simulator may have several hundred inputs. Typically, the sampling and storage of this data is handled by one (or more) processor(s), dedicated to the data acquisition function.

For analogue data, particularly for the flight controls, data capture is critical to the fidelity of the simulator. The data acquisition software is responsible for minimizing any delay in capturing the data, for ensuring that the resolution of the data is as high as possible and that any signal conditioning or filtering of the data is correctly applied. In practice, data is derived from simulator signals by analogue-to-digital conversion hardware. Although sampling at rates up to 60 Hz is straightforward with modern data acquisition hardware, the typical resolution of sampled data is only 12–16 bits, which is far below the resolution of data used elsewhere in the simulation. In addition, this data is measured by potentiometers that are inherently noisy or linear voltage differential transformers (LVDTs); as the signals are small (in terms of current), they are susceptible to noise and interference from other signals and considerable effort is given to providing a good earth connection and cable shielding for analogue signals in order to minimize any signal distortion from interference.

1.4.5 Gear Model

During taxiing, the undercarriage is in contact with the ground and the interaction between the runway, the tyres, the wheels and the oleos will result in very different dynamics from the aircraft in flight. An additional model is usually provided for ground handling to include the effects of the tyres and the undercarriage assembly. For many simulator applications, the handling of the aircraft during takeoff and around touch down and during the ground roll is critical in terms of fidelity. Many of the emergencies practised by flight crews include incidents prior to rotation (e.g. tyre bursts, engine failures and runway icing) and following touch down (e.g. reverse thrust failure, brake overheat and aquaplaning).

In practice, there are additional state transitions, just prior to takeoff and just after landing, where the aerodynamic contribution to motion is combined with the dynamics of the undercarriage assembly. At this point, the airspeed is such that the pilot has some authority and the aerodynamic forces interact with the undercarriage forces. In addition, ground effect on the aircraft aerodynamics depends on the height of the aircraft above the runway and the speed of the aircraft and this effect must also be included in both the aerodynamic model and the ground handling model. Similarly, high speed turn offs to taxiways can cause tyre scuffing requiring detailed dynamic models of the wheels, brakes and nose wheel steering. There may be a dearth of data for ground handling situations (e.g. a tyre burst) and consequently, elements of the dynamic model may be derived from computed estimates or pilot experience of similar events. It is also important to bear in mind that, for an airline, a simulation sortie may be gate to gate. Pilots have to learn taxiing skills and to manoeuvre a large transport aircraft around an unfamiliar airfield, which can be difficult at night. The consequence to an airline of an unexpected excursion from the runway tarmac to the grass is likely to prove expensive and is best practised in the simulator.

1.4.6 Weather Model

The atmosphere clearly has a major effect on aircraft performance. The equations to compute air pressure, air density and air temperature are well known and straightforward to implement. These terms are used in the flight model and engine model modules. However, other aspects of weather are also modelled in most simulators, particularly wind. Wind has an effect on both navigation but also on the aircraft handling, for example, in cross-wind landings or in turbulence.

Winds also play an important part in flight planning for airline operators, so the wind model must be three dimensional and time varying. Two methods are currently used. The simplest method is to use a wind model to take into account pressure fronts, altitude and location. The alternative approach is to use wind data acquired from agencies that monitor global wind currents; this is generally appropriate as there is no requirement to model current wind patterns in a training exercise.

Atmospheric turbulence also plays an important part in airline training; pilots need to demonstrate that they can handle turbulence and also monitor the interaction of turbulence with automatic landing systems. Normally, turbulence is generated as a set of pseudo random processes, causing perturbation in the three linear aircraft axes. Variation of turbulence components over an airframe can also induce rotational disturbance on the airframe. Two turbulence models are widely used, the Dryden model (Beal, 1993) and the Royal Aircraft Establishment (RAE) model (Tomlinson, 1975) and although they exhibit slightly different characteristics, they have been almost universally adopted.

Following a number of major accident investigations, a better understanding of wind-shear and microburst was gained (partly as a result of simulation studies) and models of both wind-shear and microburst are now included in the training of commercial pilots, to detect the onset of wind-shear and to avoid actions which could lead to an adverse outcome. This is a very good example of flight simulation making a significant contribution to flight safety; the reduction of wind-shear related accidents, since the introduction of mandatory training, has significantly reduced this problem.

The other aspect of weather modelling is to simulate potentially hazardous flight conditions, particularly icing and heavy rain. Airframe icing and runway slush can increase drag during takeoff, affecting takeoff performance, while slush and runway surface water can reduce the effectiveness of braking and steering. In addition to modelling these effects, the conditions for icing should reflect the ambient weather conditions and in the case of ice, snow or rain, these conditions would also be implemented in the visual system.

1.4.7 Visual System

The visual system provides a number of channels of real-time images seen from the pilot eye position. Initially, a database of objects is loaded into the visual system memory. The database may contain fields, airfields, roads, lakes, coastline, vehicles, buildings, trees, forest, vegetations and aircraft. Various standards exist to generate these entities, with OpenFlight™ probably the most widely used format. Each object is reduced to coloured and textured polygons (usually triangles), defined in the coordinate system (and units) of the database. Quite often these objects are arranged in some geometric order so that different levels of detail can be displayed according to the distance from the object.

As the aircraft manoeuvres, the pilot eye position and orientation are computed in the equations of motion and the scene is rendered every frame (typically 60 Hz). Depending on the imaging system, there is a delay between acquiring a new eye position and the pilot seeing the projected image (in addition to any delay in computing the pilot eye position and passing this information to the visual system). This delay, often referred to as *visual latency*, must be kept to a minimum but can extend to three or four frames (four frames at 50 Hz is 80 ms). A value of 100 ms is generally accepted as the worst case allowable latency (depending on the aircraft dynamics) and figures of 20–50 ms are more commonly quoted for current flight simulators.

The quality of the visual system depends very much on the characteristics of the underlying graphics engine. A graphics card will be bounded in terms of the draw rate to render polygons and also the fill rate to texture the polygons. As more scene detail is added, the frame rate may drop below the minimum value for a particular simulator. Similarly, if the polygon count is reduced to increase the rendering rate, the scene detail may reduce to an unacceptable level. These values also depend on:

- The display resolution (in terms of pixels) – if the resolution is increased, the drawing rate is reduced as more pixels need to be drawn per unit area;
- The display refresh rate – if the refresh rate is increased, less time is available per frame for rendering;
- The memory access speed of the graphics frame buffer memory – each pixel must be written to the frame buffer every frame;
- The architecture of the graphics processor – particularly, its interface to the frame buffer memory;
- Any anti-aliasing applied to smooth polygon edges – considerable processing is needed to generate smooth edges.

Each image generator provides a video signal output containing red, green and blue colour components. Each channel is offset according to the projected channel. For example, if there are three channels covering a total of 180°, the forward channel is offset by 0° and the other channels are offset by −60° and +60°. In practice, the projected channels overlap by a few degrees, to avoid any visible gaps in the projected image. Strictly, two pilots seated at the front of an aircraft would not see identical views. In practice, the angular differences are small and are ignored. The image formed by the image generator is generated as a 2D image, in effect for a flat screen. If this image is projected directly onto a curved screen, it will appear distorted. To ensure correct geometry in the projection, as viewed at the pilot eye-point, the distortion of the image is corrected in the projector circuitry. This alignment is set up during installation and is checked regularly during maintenance schedules.

1.4.8 Sound System

The aircraft cockpit or flight deck is a noisy environment. Pilots hear a wide range of sounds including slipstream, engines, sub-systems, air conditioning, ground rumble, actuators, radio chatter, navigation idents, warnings, weapon release and alarms. Although sounds are provided in a simulator to increase fidelity, they are also important cues and they must be consistent with the sounds heard in an aircraft.

Some sounds, such as airspeed or engine revolutions per minute (RPM), vary with flight conditions whereas other sounds give a constant tone (or set of tones), for example, a fire warning. Usually, a separate sound system is provided, taking inputs from other modules, for example, engine RPM from the engine module, slipstream magnitude from the flight model or marker ident from the navigation module.

Generally, two methods are used to generate cockpit sounds. The obvious technique is to record actual aircraft sounds, using a high quality sound recording system placed in the cockpit or flight deck, typically with a microphone suspended from the roof of the cabin. The drawback with this approach is the number of recordings needed to cover all flight conditions. For example, engine sounds vary with airspeed, altitude and engine state (RPM and thrust) and it would be necessary to cover the full range of these variables. The recordings are then accessed every frame to output a small fragment, 1/60th of a second at 60 Hz. The sound signals must also be continuous – any discontinuities between frames would result in interference which would be detectable. Although many commercial sound cards are designed to replay recorded sounds, there are in excess of 50 separate sound components which need to be generated and combined every frame.

The alternative method, and the one more commonly adopted, is to analyse the source of each sound and generate the appropriate waveform. For simple sounds, such as a warning alarm, this is straightforward as these sounds comprise a set of tones. The sound of jet engines, propellers and rotors are more complicated. Nevertheless, the fundamental frequencies of these noise sources can be identified and combined with different forms of white (i.e. random) noise. In effect, each sound consists of several components and for each sound, these components are computed as a function of its primary variables every frame. With earlier sound cards, synthesizer ICs were used but nowadays the sound waveform can be generated by a digital signal processor. One further attraction of this method is that synthetically generated sounds can be compared with actual aircraft sounds to confirm the authenticity of the generated sound, typically by applying a fast Fourier transform (FFT) to the respective sounds and comparing the frequency spectra.

1.4.9 Motion System

As the simulated aircraft is manoeuvred, the pilot will expect to feel the accelerations that would be experienced in actual flight. The accelerations are computed in the flight model and are passed to the motion system. For the standard motion platform comprising six linear hydraulic actuators, each actuator is moved to a new position to try to replicate the accelerations on the pilot's body.

Very fast response actuators are used and these are updated at rates in excess of 500 Hz to eliminate jerkiness in the motion.

Of course, true motion cues cannot be generated. For example, a military aircraft can fly a 4G turn for several minutes whereas the only positive G available from the platform is vertical heave, which is constrained by the length of the hydraulic actuators (typically 2–3 m). Similarly, in a rolling aerobatic manoeuvre the pilot is subject to lateral accelerations and angular moments. The arrangement of the legs of the platform restricts angular motion to 30–40°. However, the human motion sensors and the brain can be fooled. The brain responds to the onset of motion but cannot detect very low rates of motion, so that motion can 'leak away' without the pilot realizing that motion has changed. In addition, if the motion cues are reinforced with strong visual cues by the visual system, the pilot can sense motion that is not actually applied to the platform. In some fixed base simulators, the motion sensed from visual cues can convince pilots that the simulator has a moving platform. Indeed, there are (undocumented) instances where the motion system has been switched off without the flight crew realizing that motion cues had been suppressed.

The motion system contains computers to derive the actuation equations to move the platform to the desired position, together with filters to optimize the platform trajectory and provide appropriate motion for the pilot's balance sensors. Of course, this is a compromise and moreover, different pilots have different perceptions of motion. However, assessment of the motion is a very important aspect of simulator qualification and is checked for critical phases of flight, particularly takeoff, landing and engine failures.

One final and important consideration for the motion platform is safety. The cabin could fall several metres under active control, as a result of a system failure, causing injury to the occupants. Redundant computer systems and extensive monitoring is used to detect unexpected motion, shutting down the hydraulic actuation within a few milliseconds to avoid any injury, if any undesired motion of the platform is detected. One other aspect of safety is that the platform is 4–5 m off the ground. In the case of a fire or emergency, the hydraulic system should lower the platform to its lowest point to allow the flight crew and instructor to escape via ladders.

1.4.10 Control Loading

As an aircraft flies, the slipstream passing over the control surfaces changes the load on these surfaces, particularly the primary flight controls: the elevator, aileron and rudder control surfaces. The force per unit displacement increases (non-linearly) with airspeed and affects the handling of an aircraft. Such effects must also be simulated and this is the function of the control loading system. Control loading is provided by attaching actuators to the flight controls in the simulator so that the actuator provides resistance to motion, typically varying with airspeed.

Prior to 2000, most simulators used hydraulic actuators for control loading. By driving the actuator with a computer system, the control loading system can be programmed to emulate springiness, damping, end stops, backlash and dead bands. The characteristics of hydraulic actuation are so good, that an emulated mechanical end stop feels as though the control column is in contact with a mechanical end stop. Since 2000, advances in electrical motor drives have enabled control loading to be implemented with a single motor drive per channel. Control loading is also an important part of simulator qualification and there have been concerns that residual torques can be detected around the centre position, at very low values of torque where electrical systems lack response. With both hydraulic and electrical control loading systems, the trimming function is simply implemented as a null datum offset for the zero load position. To provide force feedback for the control column or centre stick, the inceptor displacement is sensed using an LVDT or stick force is measured by means of a strain gauge.

Both hydraulic and electrical control loading systems must meet strict safety requirements. A control column, some 12 in. in front a pilot could cause considerable harm if accidentally driven at full power towards the pilot. Similarly, an auto-throttle lever quadrant has the potential to sever a pilot's fingers if moved unexpectedly. Consequently, the applied forces of control loading systems are very closely monitored by separate systems, which can remove any control loading within a few milliseconds.

1.4.11 Instrument Displays

Aircraft instruments cover two eras of flight. Prior to 1980, most aircraft had mechanical instruments. Many of these instruments had complicated mechanisms, including multiple pointers, rotating cards, digital readout and clutch mechanisms. Since 1980, many civil and military aircraft have moved to electronic flight instrument systems, known as *EFIS displays*. These EFIS displays are based on computer graphics with 8-in. ruggedized monitors, typically with the displays updating at least 20 times per second (20 Hz). The graphics hardware in the display has a very fast drawing speed to sustain the frame rate and includes anti-aliasing algorithms to smooth any jagged lines or edges as characters and lines are rendered.

The conventional mechanical displays have been implemented since the Link trainer, initially using mechanically driven pointers or using pneumatics to drive adapted pressure gauges. Nowadays, simulated instruments are driven by servo motors or stepper motors, using specialized mechanisms to provide all the functionality of aircraft instruments, for example, the fail flags of a VOR instrument or the barometric pressure setting for an altimeter. Such instruments are driven by analogue voltage via an I/O card. Many of these instruments contain complex mechanisms to drive several pointers, rolling digits, rotating compass cards and clutch mechanisms for pilot settings. Consequently, with older simulators, these mechanical instruments are often unreliable, requiring regular inspection and maintenance.

With EFIS displays, the simulator manufacturer has the option of using the original aircraft equipment. Alternatively, a modern processor with a low performance graphics card is capable of emulating the EFIS displays found on most aircraft. This option is sometimes referred to as the *stimulate or simulate* debate; either original equipment is stimulated, but the simulator must provide the correct input signals or the equipment is simulated, but then the simulator manufacturer must ensure that all the possible operating modes and functionality have been correctly implemented. In terms of cost, the latter option (in effect, reverse engineering) is generally preferred by simulator developers.

For military aircraft, and more recently for some civil transport aircraft, the simulator may also require a head-up display (HUD). If the original aircraft equipment is used, the appropriate video signal format must be generated for the HUD. Actual HUDs are collimated so that the image appears to be overlaid on the outside world. The optical attenuation is small, so that the external world can be seen through the HUD together with the flight data optically projected via a CRT. One option is to place a small monitor in front of the pilot, combining both 2D graphics (the HUD) with 3D graphics aligned to the projection system. However, such systems can give rise to pilot fatigue as the focal length varies between looking at the HUD and looking at the projected image. This problem can be overcome by projecting the HUD information as a graphical overlay on the visual system; in this case, the pilot simply looks through an open frame representing the HUD frame. This method has the advantage that the pilot does not need to accommodate the HUD information as it is effectively focused at infinity. On the other hand, slight movement of the pilot's head can cause information on the HUD to appear outside the HUD frame.

1.4.12 Navigation Systems

A significant part of flying training covers navigation training. Flight simulation offers two advantages: first, an airborne navigation exercise consumes fuel and secondly, navigation errors in training can be hazardous. Consequently, simulators provide varying degrees of navigation capability. For instrument approaches, VOR, automatic direction finding (ADF) and ILS systems are emulated. This requires integration with radio management panels or an FMS to select receiver frequencies and an up-to-date database of navigation aids. In addition, the errors associated with these systems must be modelled correctly. For example, a VOR operates in the very high frequency (VHF) band and therefore is line-of-sight; it can fail if the aircraft is too low to receive the signal or if the transmitter is obstructed by a hill. Similarly, false glide slope indications, common at some ILS installations, need to be modelled.

For enroute navigation, VOR, inertial navigation systems (INS) and the Global Position System (GPS) are also simulated. In addition to simulation of the correct functionality, it is important to model the error properties of these systems. For example, an INS will drift and exhibit the slow 'Schuler loop' oscillation. Similarly, GPS accuracy varies with the geometric dilution of precision (GDOP) caused by variations in the GPS satellite constellation. In an aircraft, these navigation systems are integrated with the FMS and flight displays (typically via the aircraft databus) and such functionality must be replicated in the simulator, particularly the appropriate behaviour for the relevant failure modes.

For short-range navigation, a 'flat earth' model may be adequate for navigation. Beyond ranges of 100 miles or so, a full spherical earth model is needed for navigation, transforming the aircraft motion to earth latitude and longitude axes. For longer distances, Coriolis acceleration terms (the effect of earth rotation on perceived motion) need to be modelled.

1.4.13 Maintenance

In addition to the systems outlined above, the simulator must be regularly checked to ensure that it is operating within limits. Indeed, for qualified simulators, the operator must keep a log of all scheduled and unscheduled maintenance and repeat diagnostic tests to confirm that the simulator characteristics have not changed significantly, following any maintenance procedures.

Specific tests are conducted for all the sub-system modules. If the module contains a processor or memory, these will be exercised and tested for failures. The visual system and projection system will be checked for alignment, where patterns of rectangles and dots are used to detect drift in the optical systems. Light levels and grey scales are also checked for illumination intensity, together with variation in colour bands for the red, blue and green components, often caused by ageing of the projector bulbs.

For mechanical systems, tests are made for excessive wear or increased friction. Such tests are typically computer-based, where tests are initiated and the results compared with results from previous bench-mark tests. In addition to problems with wear in actuators, sensors may also fail, with ingress of dirt or hydraulic fluid contamination. When sensors or actuators are replaced, extensive diagnostic software is run to check the sensor: that it operates over its full range, that it has been reconnected correctly and that there is no discontinuity or noise on the sensor input.

In airline flight simulators, the simulator usage is constantly monitored and recorded. Usage is an important issue. If, for example, a simulator has been subjected to heavy landings, large jolts can affect the visual system mirror or reduce the life of projector bulbs or motion platform bearings. All faults are logged and at the end of a training session, the instructor can report any malfunctions or anomalies that occurred during the session. Moreover, to guarantee over 95% availability, the airline will have technical support teams, with specialized knowledge of the simulator modules, to provide fast response to any failures or problems and a large inventory of spares to minimize any down time.

1.5 The Concept of Real-time Simulation

In normal everyday life, everything seems to be continuous and instantaneous. The motion of a car along a road is continuous; a ball follows a smooth trajectory through the air; a tree branch waves smoothly in the wind. Of course, we are not strictly solving any equations nor is a tree computing the positions of all of its branches.

Computation is a very different world. We write software programs and the computer executes the instructions of the program. These instructions may involve additions of machine registers, comparing memory locations and jumping from one address in the computer memory to another address. However, each of these instructions takes a finite number of machine cycles and each of these cycles is clocked at the speed of the processor. In other words, for a given computer, a small fragment of code may take several microseconds to execute. This time may also vary depending upon the program and its data. For example, to sort 100 numbers may take much longer than sorting 20 numbers.

Anyone using a computer for office activities is subject to these delays. For example, spell checking a document may take several seconds for a large section of text. The computer has to load its dictionary of words, access the file containing the text and then search for each word in the dictionary. These operations may require several million computer instructions, but generally, a user is not too concerned whether it takes two seconds or three seconds to spell check a document. Of course, if it took five minutes, we might seek an alternative solution (e.g. a better algorithm or a faster computer or a faster disk).

There is one area of office computing where we might notice even small delays. If we move the mouse we expect the cursor to move instantly over the screen, or if we press a key, we expect the appropriate character to appear on the screen. In this case, there is a human in-the-loop and we would expect a response within 1/10th of a second, anything less would be intolerable to the average computer user.

Consider an example where the user moves the mouse around the screen. The computer is, in effect, executing the following code:

```
Check to see if the mouse needs redrawing, and if so
 read the new mouse position
 compute the screen coordinates (x, y) of the mouse
 erase the cursor at its current position
 draw the cursor at (x, y)
```

For each of these actions, a set of computer instructions is executed, but if the computer can execute 10^7 instructions per second, say, then if we only need 10,000 instructions for this code, the software will be executed in 1 ms – from the human perspective, instantaneously. However, on an older computer, the same number of instructions might take 100 ms (or 1/10th of a second) and we might discern a slight jerky motion of the mouse.

Of course, an office computer may be executing other tasks, such as printing a file and therefore, it will need to suspend the printing task frequently to check the mouse for movement. If the mouse handling task is serviced 50 times per second, the cursor will appear to move smoothly in response to the mouse input. However, if the computer is occupied with other tasks, so that the mouse is only serviced twice a second, the mouse will seem unresponsive or slow. Generally, office operating systems provide acceptable mouse management and the mechanism to ensure that the mouse software is activated 50 times per second is part of the operating system and is transparent to the user.

What the operating system does is to discretize time, into very small time steps, so that the mouse management code is guaranteed to be executed 50 times per second. These time steps are smaller than we can discern with our eyes (and hand and brain), giving the mouse what appears to be instantaneous and continuous motion, although it is actually implemented at discrete intervals. Of course, we are all used to such systems; television cameras at a football match capture frames every 1/25th of second, which are transmitted to the television in a house. Because the time step is so small, it appears that the players on the pitch are moving in the normal continuous way that we would expect to see if we sat in the stand at the match.

Exactly the same situation occurs in flight simulation. In an aircraft, the pilot moves the control column. Assuming direct cable linkage to the control surfaces (and ignoring the inertia of the control surface), the elevator moves immediately, causing a perturbation to the aircraft, which is seen as a change in pitch by the pilot who responds with another movement of the control column to correct the pitch attitude. In a flight simulator, the stick position is sampled, the elevator deflection is computed, a new pitch attitude is computed and an image is displayed by the visual system with the new pitch attitude, enabling the pilot to correct the aircraft attitude. The important point is that the overall time for this computation must be sufficiently short so that it appears instantaneous to the pilot. In a modern simulator, these computations must be completed within 1/50th of a second or 20 ms.

This concept is illustrated in Figure 1.6, which depicts 10 frames of a simulation. The arrow for each frame shows the proportion of the frame used in computation of the simulation. If the frame time is sufficiently small, say 1/50th of a second and if the computation in any frame never exceeds the frame time, then the simulation is real-time.

Note that there is an important distinction between real-time computing and fast computing. Although a real-time simulation may require a fast computer, all the computations must be completed within the frame time (Burns and Wellings, 2001), whereas, for a fast computing task, the only metric is the overall time. Some simulation packages imply that generating the code in a more compact form ensures real-time computing. Although this may be true for some applications, in all of the examples covered in this book, the term *real-time* is used to mean that all the computations are solved within one frame during every frame of the simulation.

There is one other important consideration that was touched upon. In addition to the main simulation tasks, the processor may also be required to perform other background tasks. If this additional computing load results in contravening the frame period limit for the simulation task, real-time simulation cannot be sustained. An operating system is therefore a critical part of any real-time simulator. The operating system must guarantee that it will execute the simulation task every frame and never introduce delays that cause the simulation task to exceed its frame limit.

In a safety critical real-time environment, it is necessary to demonstrate that the real-time frame rate can never be violated beyond any reasonable level of doubt (which may be never more than once in 10^7 hours, or once every 1141 years). Although flight simulation software is not safety critical, the real-time constraint must still be fulfilled; usually this is the responsibility of the simulator designer. It is possible to monitor the real-time performance of a flight simulator and record any frame period violations. However, if the frame rate does drop, it is usually apparent to the flight crew as there are observable discontinuities in the visual system, or discernible lags in the aircraft response or even changes of frequency in the sound system outputs.

The simulator designer has, in effect, a time budget to complete all computations within the frame and consequently, tries to exploit as much of the frame time as possible, leaving a small margin for error in these estimates (or for future expansion), particularly as some computation times are data

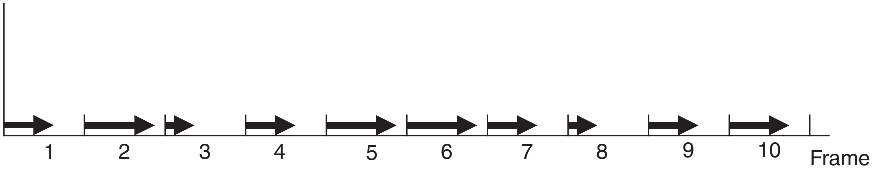

Figure 1.6 Real-time frames

dependent. Given all the constraints on the scene content of the visual system, the processing of the flight model, the engine model, the weather model and so on, it is not uncommon for the frame period to be exceeded occasionally, even for a full flight simulator, particularly as the simulator manufacturer may not have full control over the behaviour of a graphics card under all flight conditions. Nevertheless, ensuring real-time performance, particularly for worst-case conditions is an essential part of system validation and acceptance tests.

1.6 Pilot Cues

A pilot in an aircraft perceives the sensation of flight from the stimulation of the pilot's senses. Of course, these are the same sensors we use in everyday life. They have evolved over millions of years and are optimized for survival. For example, we can perceive the colour, size and distance of a car on a motorway using our visual sensors or run down an escalator using our balance sensors. In flight simulation, these stimuli are referred to as *cues* and, if we are to provide the same sensation of flight in a simulator, it is necessary to provide the same cues as those detected in flight. It is therefore important to understand the cues we use in flight and also the mechanisms in the human body to detect these cues. In addition, if it is not possible to provide the same cues, an understanding of the sensors of the human body and the priority attached to specific cues in processing these cues, may enable the simulator designer to reduce or simplify the cues that need to be provided in a simulator.

The issue of fidelity was discussed briefly in Section 1.2.3. The AGARD (Advisory Group for Aeronautical Research and Development) Flight Mechanics Panel observed in their report on 'Fidelity of Simulation for Pilot Training' (AGARD, 1980) that 'The degree of realism required of the simulation will depend upon the nature of the training task, the level of experience of the students and the level of proficiency they are required to attain'. In reducing fidelity, care is needed to ensure essential cues are not omitted, while on the other hand, considerable savings can be made if unnecessary cues can be eliminated.

There are four stimuli we perceive as humans:

- Chemical – particularly smell and taste – generally, these do not need to be provided for flight simulation;
- Thermal – temperature – for most simulators, the ambient operating temperature of the flight deck or cockpit is sufficient;
- Photochemical – brightness and colour detected by the eyes;
- Mechanical – these include auditory sensors to detect sounds, vestibular sensors to detect gravity and angular and translational motion, kinaesthetic sensors to detect the position and movement of joints and pressure applied to the body and tactile sensors to detect pressure on the skin.

In addition to these sensors, the brain provides a fusion function, combining and processing information to provide the pilot with an understanding of position, orientation, speed and acceleration in the environment. This is an important consideration for the flight simulator designer; it may allow one stimulus to be substituted for another. For example, motion is sensed by cues provided by the visual system (the eyes) and by the motion platform (the vestibular system) offering a potential trade-off of visual cues against motion cues. These stimuli also have different paths through the nervous system of the human body and necessitate different amounts of processing by the brain. Consequently, the brain is able to compensate for these delays. However, if these delays are different in a simulator (e.g. the response of instruments, the visual system or the motion platform to a pilot input), then this can lead to an unacceptable 'feel' of the simulator and in extreme cases, even lead to anxiety resulting in sweating and nausea (the so-called simulator sickness).

1.6.1 Visual Cueing

Visual cues (Buffet, 1980) are sensed by the eye. With two eyes, binocular vision provides further information of size and distance. The characteristics of the human eye are summarized in Table 1.2.

Note that, for a projection system with a lateral field of view of 180°, acuity of 1 arc minute corresponds to 1 part in 10,800. Assuming that three projectors are used, with each channel providing 1000 pixels laterally (allowing for overlap), then current image generators and projectors need to increase resolution by a factor of almost four, to achieve images that correspond to the acuity of normal vision, implying an increase by a factor of 16 of the pixel rendering rate.

The external world seen by a human observer covers the region within touch (1 m) of the observer, the immediate vicinity (up to 30 m), where there is considerable detail and the likelihood of dynamic objects and the far field (beyond 30 m), which is remote and provides a stable 3D environment. The human observer acquires different information in these three regions to perceive images, distance and movement (Farmer *et al*., 1999).

We perceive images by recognizing familiar shapes, for example, a tank with a turret and barrel would be recognized over a wide range of distance and in different orientations. The brain is combining colour and knowledge – basing its decision-making on the expected image, not necessarily the actual image. In other words, the context in which an image is generated will affect its credibility. For example, in a desert scene, an acceptable tank might be generated by a few hundred polygons, whereas in an urban scene, more detail may be necessary to provide an acceptable image of the tank.

We perceive depth in several ways. Muscles in the eye are used to focus on an object. Other muscles in the eyes converge both eyes to provide a single image (binocular vision). The brain is also able to process the different images formed on the retinas to provide further depth perception. From knowledge of the external world, occlusion (one object in front of another object) and relative size of objects provide important depth cues. In other words, depth might be emphasized by the positioning of objects in the environment. We are used to seeing perspective cues, such as a railway line converging in the distance to provide depth cues. In a simulator, the arrangement of fields might provide useful depth cues in comparison with a more bland landscape. Also, objects placed on the ground appear higher in the visual field towards the horizon. Accordingly, known objects on the

Table 1.2 Characteristics of the human eye

Attribute	Characteristic	Value
Field of view	The angular range detected by the eye. Colour and detail is best in the central region and attenuates significantly towards the limits.	±90° horizontally 50° above 70° below
Colour	Cones in the eye detect the red, green and blue components in colour. The three types of cone receptors are most sensitive at specific wavelengths of light and overall, in the green–yellow region.	Wavelength 400–700 nm
Resolution	The acuity of the eye allows the human to resolve detail. It is maximum in the 3° band in the centre of the field of view. Towards the limits of the field of view, only movement can be detected.	1 arc minute
Brightness	A very wide range of luminance can be detected from darkness to bright sunlight, although discrimination between different levels is best with dark stimuli and significantly reduced with bright stimuli.	
Contrast	Contrast is the ability to distinguish an object from the background, in terms of brightness or colour. Contrast depends on brightness, reducing in sensitivity at low or high levels of luminance.	

ground can reinforce depth cues. One further effect of depth is atmospheric attenuation, where distant objects appear hazy, providing a further (albeit coarse) estimate of distance.

In the personal space, occlusion, size, convergence and accommodation are most important. In the nearby region (up to 30 m) occlusion, height in the visual field and size are important whereas convergence is negligible. Beyond 30 m, binocular vision reduces (both eyes receive the same image) and height in the visual field, occlusion, size and perspective are dominant.

The brain derives motion from visual cues in three ways: the angular field of an object increases moving towards the object; the appearance of an object may alter (e.g. windows in a building become visible); there is a visual reference to motion over a fixed terrain. In a static image, there is no implied motion of the viewer or the object. However, if the object moves it triggers a succession of receptors in the eye. Alternatively, if the head and eyes follow the target, there are sufficient changes to the background to trigger the receptors.

In flight simulation, with the pilot looking forwards, the visual scene not only moves towards the viewer, but points in the scene move towards the edge of the display, which is known as *visual streaming* (or optical flow). Strictly, this depicts relative motion – the same scene would be seen if the pilot moves towards the runway at 250 kt or if the runway were (somehow) moving towards the pilot at 250 kt. Of course, in an aircraft, the pilot may be moving towards a fixed runway at 250 kt but in the simulator, the pilot is stationary and the scene is rendered so that it appears to be moving towards the pilot at 250 kt. The brain finds it hard to distinguish between these cases and assumes that the pilot must be moving as the scene is static. A similar effect can occur in a railway station – if the adjacent train moves off there is a brief sensation that your train is moving and the other train is stationary. In many simulators, the effect of motion provided by a good visual system (known as *vection*) is compelling and has been used to support arguments to reduce the requirement to use a motion platform to provide motion cues.

The very nature of the simulator environment limits the visual cues that can be provided. For the most part, objects are several miles in the distance reducing the contrast, resolution and colour and losing visual cues from accommodation, convergence and retinal disparity. Often there are few objects to provide cues from occlusion, relative size or linear perspective. In addition, the field of view may be limited by the windscreens.

The simulator designer is therefore constrained in the cues that can be provided while needing to ensure that there is sufficient scene content and image resolution. The other requirement for visual fidelity depends on the application. In a civil simulator, considerable detail is usually provided in airport scenes, so that the approach and takeoff have appropriate visual cues, whereas a military helicopter simulator may need to provide occlusion from groups of trees and vection cues for height and speed estimation from detailed texture of the terrain. In subjective terms, the pilot is expecting to see the dominant visual cues that are experienced in flight and the content of the visual database and the performance of the visual system must match these expectations. Objectively, it is difficult to quantify matching the requirements of the visual system with the performance of the image generators. Clearly, there are some cues that cannot be provided. For example, the binocular vision from looking at a screen placed 3 m in front of the pilot may conflict with the binocular vision cues provided during ground handling.

Remarks: these problems would for example occur in a Formula One racing car simulator, where the driver sees the wheels and suspension within 1 m range, the track in the range 2–5 m and also distant objects beyond 5 m. Yet, rendering tyres so that they appear in the correct position does actually work surprisingly well with a collimated visual projector system in racing car simulators.

1.6.2 Motion Cueing

While it is clear that a motion platform, securely anchored to the ground inside a hangar cannot produce the same forces on the human body as an aircraft that can fly at 600 kt and climb to 60,000 ft, an understanding of the human motion sensing system is essential for two reasons:

- It explains the way the human body detects and responds to motion;
- It may identify limitations with the human sensing systems that enable forces to be mimicked in a way that is indiscernible to the pilot in a flight simulator.

The motion sensors of the human body comprise the vestibular system (Howard, 1986) and the haptic system. The vestibular system detects static and dynamic orientation of the head. It also stabilizes the eyes so that clear vision is achieved during movement of the head. In many ways, the vestibular system is equivalent to a gyro-stabilized inertial platform. The haptic system consists of the pressure and touch sensors over the human body, particularly interaction with the seat, pedals and hand controls.

The vestibular system consists of two sets of sensors, one in each ear, which measure the angular and linear accelerations. The angular accelerations are sensed by the semi-circular canals, organized in three mutually perpendicular planes. At low angular frequency (below 0.1 Hz) they measure acceleration. At high frequency (above 5 Hz) they measure displacement. In the mid range, they measure velocity. Engineers will recognize this behaviour as similar to a second order filter. These are heavily damped systems with time constants of 0.1 s and approximately 11 s (yaw axis), 5 s (pitch axis) and 6 s (roll axis). There is also a minimum value of acceleration below which no motion is detectable. For flight, this threshold is between $0.5°/s^2$ and $2°/s^2$. In other words, someone placed inside a large box with no visual stimulus will be unable to detect that they are being moved about one of the three axes, if the acceleration is below $0.5°/s^2$. If this box is a flight simulator cabin, this observation implies that:

- The pilot can be rotated by applying a signal to the motion platform without being aware of the rotation;
- Initial motion can be leaked away to allow additional acceleration to be applied, also without the pilot being aware of the additional motion.

This threshold is exploited in motion systems to regain some of the limitation on displacement of the motion platforms used in flight simulation.

Whereas the semi-circular canals measure angular acceleration, the otoliths sense linear accelerations. The transfer function is similar to the semi-circular canals but with time constants of 0.66 s and 10 s and a threshold of $0.0004\,m/s^2$. For combined motion of angular and linear accelerations, the semi-circular canal signals dominate with the otoliths providing measurements of predominantly linear motion.

There is one further advantage in knowing the response of the body's acceleration sensors. If the transfer functions of the motion actuators are known, the desired motion of the platform can be matched as closely as possible to the actual motion. Nevertheless, it is important to note that the traditional platform has, for the most part, been abandoned in military simulation in favour of high quality image generation systems, wide-angle projection systems and the use of G-seats to provide tactile motion cues.

1.7 Training versus Simulation

Flight simulators are used in flight training and it is easy to assume that both terms are synonymous and interchangeable. However, flight training is provided to fulfil a training requirement. The equipment used to provide this training may well include a flight simulator but in this role, the simulator is simply equipment. The simulator, together with an instructor and a training syllabus constitutes the training package. Confusion has arisen because, in some cases, the flight simulator is purely a replacement for the aircraft and arguably this has led in the past to the procurement of flight simulators that were poorly matched to the training requirement and therefore provided poor training.

The first stage of procurement for any flight training programme is to undertake a training requirement analysis. This establishes what is required in the training programme, and also what is not required. On the one hand, if the training equipment is underestimated, it may not provide effective training. On the other hand, if the training equipment is overestimated, the cost of the simulation equipment may be excessive.

An often cited example of an effective trainer is the ‘cardboard bomber’. In the early stages of flying, pilots have to learn a range of checks, including pre-flight checks, in-flight checks, shut down checks and emergency checks. Sitting in an ordinary seat, in front of a cardboard facsimile of the cockpit, with no moving parts whatsoever, a pilot can point to an instrument or touch a switch appropriate to each check. Photographs are used so that each item resembles physically the actual equipment and is located in approximately the same place as in the aircraft. However, the training requirement of the equipment is simply to help the pilot to remember the checks. Obviously, such equipment would be inappropriate at later stages of training where actual aircraft instruments or switches are needed. Similarly, the use of actual aircraft equipment would be an unnecessary expense in the initial phase of training.

For a major training programme, the training analysis will be conducted by a specialist team, with a good understanding of flying training, simulation technology, instructional methods and human factors. The team will not include flight instructors who will give the subsequent training or the simulator companies who will manufacture the equipment. For an airline or military training organization, the training will be specified in terms of the desired outcomes (or output) of the training. For example, for an instrument trainer, the requirement might state ‘on completion of training, a pilot shall be able to demonstrate an ILS approach with a cross-wind up to the maximum allowable value for the aircraft with one engine failed’ as part of the training requirement. The implication of just this single statement is that the simulator requires an ILS instrument, a realistic model of engine failure, a weather model which includes cross-winds and presumably a database of navigation aids including ILS beacons. Note that the requirement omits the engine controls, the details of the weather model or the maximum number of ILS approaches to be provided. Presumably, such information would be given elsewhere in the training requirement.

The training needs analysis team will review the training syllabus, discuss the detailed requirement with the customer (possibly to modify or clarify the requirement), review the technical options (to establish any constraints or parameters) and discuss the training methods used by the instructors. For example, some of the questions to be asked about the ILS simulation might include the following:

- The need for aural cues (e.g. Morse idents or marker idents);
- The accuracy of the simulated ILS;
- The range of the ILS;
- The failure modes of the ILS;
- The method of selecting an ILS frequency;
- The number of ILS channels;
- The failure modes that can be set by an instructor;
- The physical representation of the ILS.

This final consideration might give the option of using a graphics display to represent the ILS instrument rather than a mechanical emulation, leading to the clarification of further issues, including

- The resolution of the ILS display;

- The need for anti-aliasing;
- The update rate of the display.

The important point to bear in mind is that the training requirement extends across the whole scope of the training programme, and even includes non-functional requirements, such as

- Access dimensions;
- Power requirements;
- Emergency lighting;
- Reliability and availability figures;
- Air-conditioning;
- Safety issues.

Once the training requirements are clearly defined, these are passed to prospective manufacturers who will be invited to tender to supply the training equipment. There is often some variability in these requirements. For example, the requirement may simply state the tasks to be trained and the level of skill to be attained, and possibly the time available to attain it, using the training equipment. In this case, the simulator manufacturer can match their equipment to the training requirement, advocating one technology rather than another.

One further issue covered in a training requirement is the method of acceptance. For an airline, their senior pilots are likely to retain close links with the simulator company and go through a formal series of acceptance tests at the factory, prior to shipment and delivery of the simulator, followed by further acceptance tests following the installation.

1.8 Examples of Simulation

1.8.1 Commercial Flight Training

The classical application of flight simulation is the training of airline pilots. The simulator comprises a motion platform, supporting an aircraft cabin with visual systems mounted above the cabin, as shown in Figure 1.7.

Pilots joining an airline from flying schools, general aviation or military organizations are trained on a specific type. Their previous training for the commercial pilot's licence will have covered basic flying skills and instrument flying whereas the simulator training for the airline covers operation of the aircraft type on the company's routes. Pilots converting from one type to another type are trained on the specific operational characteristics of the aircraft type, with the amount of training depending on the similarity between types. Pilots are also checked every six months as part of the regulation of pilot ratings. These checks and recurrent training, lasting two days, cover a wide range of operating conditions and in particular, check that flight crews are able to manage all possible emergency conditions. Because the training is specific to an aircraft, a Level-D full flight simulator is used. The simulator is checked regularly by the regulatory authorities and the fidelity of the flight model, the motion platform and visual system is at the limit of current simulator technology. It is important to appreciate that a poor performance during these simulator exercises can lead to loss of a type rating for a pilot and therefore, the level of fidelity of the simulator is required to be as high as possible. In addition, given the criticality of the simulator availability to the airline, the reliability of the simulator must be very high and this is achieved by the quality of both the simulator equipment and maintenance undertaken by the airline.

In other areas of civil training, the relative cost of training in the aircraft compared with the equivalent training cost in an approved flight simulator is the dominant factor in determining

Figure 1.7 A civil full flight simulator (see Plate 3). Reproduced by permission of Thales

the usefulness of simulator training. It is most significant in instrument flight training for flying schools. Although the cost of a flight simulator for instrument training is similar to the cost a light twin-engine aircraft, the hourly operating costs of the simulator are far lower. Moreover, the simulator can accelerate training in comparison with airborne training, where hours are lost to bad weather, aircraft serviceability or obtaining clearances to practise navigation procedures. For example, in an instrument procedures trainer, the student can practise an NDB hold, being re-positioned close to an ADF beacon. As the student progresses, the effect of wind on hold patterns, which is arguably a difficult concept to understand for many students, can be added progressively; such structured training is impractical in airborne training.

The other major advances in civil training have occurred in ground school training. With advances in avionics, flight crews must operate EFIS displays, an FMS, an FCU, weather radar, ground proximity warning systems (GPWSs), traffic collision avoidance systems (TCAS), INS, engine management systems, fuel management systems, electrical systems, hydraulic systems, radio management systems and so on. The use of part-task training devices has off-loaded time that would otherwise be needed on a full flight simulator. There may be no requirement for motion or a visual system and rather than fabricate a facsimile panel, computer generated panels containing knobs, switches and displays can be produced as ‘soft’ panels. Switch selection or rotation of a knob is provided by a touch screen. As the simulation is computer-based, it can be combined with multimedia inputs for commentary, video, diagrams and animation. In addition, student interaction can be monitored, with the training package designed to fulfil a specific set of training tasks.

1.8.2 Military Flight Training

In military flight training, most basic training is undertaken in the aircraft. Instrument flying training is provided in flight simulators together with system familiarization trainers. However, the major developments in military flight training have occurred in operational flight training, where the cost of airborne training (particularly the deployment of munitions) and safety issues justify the cost of simulation. In these advanced simulation facilities, simulators can be linked together, enabling flight crews to practice mission sorties, with instructors introducing enemy forces (land and airborne) often where these synthetic forces have intelligent decision-making capabilities. Such techniques extend to networking flight simulators over large distances allowing international groups to combine their training resources. In addition, much military simulation involves the training in the use of specialist equipment (particularly radar and mission systems) where it is necessary to combine the pilot training with navigator training or training of mission specialists. In these roles, a mission training simulator can also be connected to a flight training simulator to provide realistic training situations and also to practise crew cooperation.

An increasingly important role for flight simulation is mission rehearsal. For flight crews undertaking a mission into unknown territory, they can practise tactics and mission management prior to the mission. In these simulators, data from satellite mapping is used to generate an accurate visual database and knowledge of enemy air defences provides very realistic training to practise for a mission. In some cases, lessons learnt in the simulator result in changes to the mission tactics.

1.8.3 Ab Initio *Flight Training*

Although there is an understandable desire to get the student pilot into an aircraft in the early stages of a flight training programme, with the reducing cost of simulation technology, there is a case to achieve more effective training by replacing some elements of airborne training with simulator-based training. However, the financial case is not strong; Allerton (2002) outlines the advantages for recurrent training of general aviation pilots but points out that there is no financial incentive for flying schools to invest in simulation technology. A few studies with *ab initio* pilots have shown that the quality of flight training can be improved with part-task training in simulators (Lintern *et al*., 1990; Allerton and Ross, 1991) but generally, the use of simulation in general aviation training is mostly restricted to instrument training in the training of private and commercial pilots.

1.8.4 Land Vehicle Simulators

For many applications, the case for simulation versus 'live' training is based on the relative training costs. For large vehicles such as trucks, earth moving equipment and buses, the cost of a training simulator is less than the cost of training in the vehicle and the cost of damage to the vehicle and its systems in the case of misuse resulting from inexperience. Such systems also present danger to the public where inexperienced drivers are instructed in urban areas. For example, decision making for overtaking other vehicles, can be assessed for a wide range of pre-programmed situations, allowing the driver to be trained and debriefed in the safety of the training centre. In vehicle training simulators, considerable effort is given to the provision of a wide-angle projection system, computer generated imagery for mirrors and realistic urban scenery and traffic.

Similar ideas extend to the training of train drivers. However, in this case, the visual system is simplified because the train is constrained to move along the track; the only variable is the train speed. Some systems are based on pre-recorded images captured by photography to provide very realistic scenes, which are projected at update rates dependent on the train speed. In such systems, track signals are provided as computer generated overlays. In practice, the capability of modern visual systems provides better training, allowing different track layouts to be modelled; the time of day (or season) can be varied and human entities can be modelled to simulate other trains, different signal patterns, trackside maintenance gangs and commuters on platforms.

Several racing car companies have realized the benefits of simulation. Placing the car cockpit in a wide-angle visual system and providing G-loading cues and vibration with a motion seat, the companies can develop driver interfaces, evaluate suspension system settings or modify gearbox ratios to optimize the behaviour of the car for a specific race track. Moreover, with very limited lap practice times, the simulator familiarizes the driver with the track layout, adverse cambers or braking requirements. One current limitation of these simulators is that the driver experiences high G-loads on the neck muscles resulting from a combination of accelerations on bends and during braking. The obvious health and safety considerations of active head loading in a racing car simulator have (not surprisingly) deterred the development of such cues.

1.8.5 Engineering Flight Simulators

For the aircraft designer, the development, installation and testing of complex aircraft systems can require many hours of airborne flight tests, which, depending on the equipment can be expensive and dangerous, for example, in developing a military terrain following system. By providing an engineering flight simulator (Allerton, 1996), where the simulator equipment closely matches the aircraft equipment, the system designer can install, integrate and evaluate aircraft equipment in the simulator. The simulator is still flown with the same exercises as the actual flight trials aircraft. The major gain is that design faults are easier to detect in the simulator and more importantly, that early detection of a fault in a programme can reduce the life cycle costs significantly.

Data is acquired in the engineering simulator to assess the performance and behaviour of the aircraft system. Typically, high performance data acquisition equipment is used to support the system analysis. Analysis of the data is also helped by the provision of visualization tools which enable unexpected behaviour or anomalies in the system response to be identified. Alternatively, these tools can assist the designer to determine optimal operating conditions or to confirm that the system fully meets the design requirements. Often, a set of engineering simulators are used as the system is developed, where each simulator is optimized for the phase of development. Initially, a workstation may be sufficient to prove the design concept. Simple pilot-in-the-loop studies are possible with basic desktop simulators. Once the functional specification is established, the aircraft system is developed in a prototype form with interfaces to other aircraft systems, where it can be flown in an engineering simulator, often referred to as an *iron-bird* rig. Such a simulator may have a rudimentary visual system or no motion, but the cockpit controls, sensors, actuators and databuses are often based on actual aircraft equipment. Following tests in an iron-bird rig, the equipment is subsequently installed in the aircraft. A primary objective of the flight test programme is to validate results of the engineering simulator tests and to identify discrepancies between the aircraft and the model used in the simulator.

The requirements of the development programme define the structure and fidelity of an engineering simulator. For example, during the development of cockpit displays, lighting levels may be tested in a simulator that simulates external lighting conditions from very bright sunlight to dark night to establish that the range of display lighting levels is appropriate. In developing an FMS, there is no need for a motion platform but the pilot interface and controls must be exact. Similarly, for a TCAS, or GPWS system, the visual system database must correlate accurately with the position of traffic or terrain detected by these systems.

An engineering simulator may contain software used on the full flight simulator as it is simpler to reuse this software than develop software adapted for the engineering simulator. Alternatively, software developed in an engineering flight simulator may subsequently be used in training simulators. The engineering simulator is often used as a datum, where updates or revisions may be checked in the engineering simulator before being released for training; software modifications can be checked against baseline models. Engineering simulation has possibly provided the most significant advances in aircraft design in the last 20 years, integrating aerodynamics, flight dynamics and structures within a common design framework.

1.8.6 Aptitude Testing

The qualities needed for a pilot include hand-eye coordination, motor skills, spatial awareness, interpersonal communication skills and judgement and management skills. Many training programmes are expensive and consequently, there are considerable benefits in detecting potential deficiency in pilot skills prior to the commencement of any training. Aptitude testing equipment has been developed to isolate these skills and identify areas where a trainee pilot is likely to encounter learning difficulties. In programmes where there is a surfeit of applicants, failure in aptitude tests can result in an immediate rejection from the course. In other programmes, it may identify possible training problems leading to alternative training routes. The overall aim is to use low-cost aptitude testing to detect faults well before they would be identified in a training programme.

An aptitude testing device typically includes a set of inceptors, for example, joysticks, knobs and buttons and a computer screen. For motor skills, the applicant may track a small target or balance a small beam. The input–output relationships are designed to test the applicant's perception and response, for example, by introducing lag or nonlinearities into the inceptor. For cognitive skills, the applicant's response times to tests are measured. Several of these tests may be designed to assess the applicant's performance in situations of high work load. However, the tasks performed by an airline pilot in a low visibility approach, say, or a military helicopter pilot hovering behind a ship in high winds and heavy sea swell, say, are difficult to replicate in an aptitude test where the applicant may have no flying experience. Although aptitude testing may identify potential problems, and considerable effort has been expended by psychologists in devising effective aptitude tests, the concern is that a problem may not be detected in an aptitude test or that a competent pilot may be lost at this early stage. Of course, it is possible to track the performance of pilots in training and correlate this with their rating in aptitude tests although such analysis is not viable for applicants failing an aptitude test.

1.8.7 Computer-based Training

With the availability of high performance computers in flight training, it is not clear how the training syllabus is best presented. Traditionally pilots have been trained by a combination of ground school and airborne training. The flight simulator provides a link between these two elements of training; a pilot is able to undertake training in a simulator to replace training in an aircraft. CBT extends this concept into the ground school training. Recent trends in computer animation and audio-visual computing enable diagrams, photographs, video clips and sound tracks to be organized as a lesson in front of a screen rather than in the classroom with an instructor.

Consider the engine-start procedures for a modern military aircraft. A pilot must learn the 50 or so tasks so that they can be executed without error in a minimum time. The tasks involve switching on pumps, selecting valves, checks on fuel flow rates, waiting for temperature or pressure rises and detection of fault conditions. CBT is positioned midway between practising these tasks on a flight simulator and remembering checks from a chart. The trainee pilot is presented with a screen which can show fuel selectors and flows; the pilot can use a mouse to turn a selector or switch on a pump, where the switch moves and the flow is displayed in a diagram; the engine instruments can be displayed to indicate pressure or temperature just as they would in the aircraft; any interaction by the pilot is matched to an audio track appropriate to the aircraft systems.

CBT now extends to all phases of flight training for both civil and military organizations, covering engine systems, cockpit drills, navigation systems, radio panel operation and FMS training.

However, the intention is not simply to replicate these aircraft systems on a screen. Rather, the lesson can be organized in a linear and logical manner, presenting information at different levels supported with diagrams, animation, photographs and video clips. There is one further extension to CBT which has underpinned its growth; the lesson plans are designed in a structured way where the trainee's interaction and responses are monitored. Not only is the rate of progress available to the instructor, but the students can learn at their own pace, being directed to previous material where there is a lack of understanding. One further extension of this approach is to make training available via the Internet. For example, a CBT lesson on FMS operation can provide an interactive training programme but if the flight is activated, then a server provides the correct flight equations to stimulate the laptop FMS. CBT has seen an increasing use in both airline and military training where it can provide very effective training for procedural tasks. The main problem with CBT systems is the cost and time to develop material. Ratios of 50 : 1 are quoted, depending on the lesson content where it can take 50 hours to produce a 1-hour lesson.

1.8.8 Maintenance Training

Advances in CBT have extended to maintenance training. Rather than dismantle a complete gas turbine engine, the student can interact with images of the engine, selecting a bolt or hose to remove. Inspection of a filter can show evidence of contamination requiring further disassembly. The order and sequence of removal and installations is presented in a logical sequence and fault finding methods are monitored to check on the student's fault diagnosis. In addition, the instructor can monitor a student's progress and deliberately inject fault conditions and failures. The CBT models provide a degree of dynamic fidelity so that test equipment can be connected interactively where observed readings correspond to the system characteristics.

This approach is particularly useful in training electronics technicians. Test equipment can be simulated so that a voltmeter or oscilloscope will give appropriate readings when connected to test points and any fault conditions are correctly represented by the measured conditions. Such ideas extend to facsimile equipment where, for example, a replica of a circuit board can be provided. Although the circuit board is inert and has no functioning electronics, the position of a probe can be detected and display the appropriate signal. The economic benefit of training with synthetic systems is clear:

- The equipment cannot sustain any damage in the training role;
- The cost of synthetic equipment is significantly less than the equivalent aircraft system;
- Potentially major faults can be injected by the instructor;
- The student's progress in failure detection and repair can be monitored by the computer system and provide a record of progress for the instructor.

With modern aircraft, these concepts of maintenance accord with the aircraft systems found on the aircraft, where faults are recorded in flight and downloaded by maintenance crews who undertake fault detection and correction at the board level to facilitate a fast turnaround of the aircraft. Much of the information provided by the onboard data logging equipment enables maintenance crews to rectify the failure quickly and reliably. Exactly the same system software is used in the maintenance trainer to provide sufficient experience of fault finding in a synthetic environment for maintenance crews.

References

Adorian, P., Staynes, W. and Bolton, M. (1979) The evolution of the flight simulator. *RAeS Conference Fifty Years of Flight Simulation*, London.

AGARD (Advisory Group for Aeronautical Research and Development). (1980) Fidelity of Simulation for Pilot Training, Advisory Report AR-159, Flight Mechanics Panel.

Allen, L. (1993) Evolution of flight simulation. *AIAA Conference Flight Simulation and Technologies, AIAA-93-3545-CP*, Monterey.

Allerton, D.J. (1996) Avionics, systems design and simulation. *Aeronautical Journal*, **100**(1000), 439–448.

Allerton, D.J. (1999) The design of a real-time engineering flight simulator for the rapid prototyping of avionics systems and flight control systems. *Transactions of the Institute of Measurement and Control*, **21**(2/3), 51–62.

Allerton, D.J. (2000) Flight Simulation–past, present and future. *Aeronautical Journal*, **104**(1042), 651–663.

Allerton, D.J. (2002) The case for flight simulation in general aviation. *Aeronautical Journal*, **106**(1065), 607–618.

Allerton, D.J. and Ross, M. (1991) Evaluation of a part-task trainer for Ab Initio pilot training. *RAeS Conference Training Transfer*, London.

Anon. (1992) *International Standards for the Qualification of Airplane Flight Simulators*, The Royal Aeronautical Society, London.

Ashworth, W.R., Mckissick, B.T. and Parrish, R.V. (1984) Effects of motion base and G-seat cueing on simulator pilot performance. NASA Technical Paper, No. 2247, NASA, Langley Research Centre.

Baarspul, M. (1990) A review of flight simulation techniques. *Progress in Aerospace Sciences*, **22**, 1–20.

Barrette, R.E. (1986) Flight simulator visual systems–an overview. *SAE Aerospace Technology Conference*, Long Beach.

Beal, T.R. (1993) Digital simulation of atmospheric turbulence for Dryden and Von Karman models. *Journal of Guidance Control and Dynamics*, **16**(1), 132–138.

Bell, H.H. and Waag, W.L. (1998) Evaluating the effectiveness of flight simulators for training combat skills: a review. *International Journal of Aviation Psychology*, **8**(3), 223–242.

Buffet, A.R. (1980) The visual perception of depth using electro-optical display systems. *Displays*, **2**, 1980.

Burns, A. and Wellings, A. (2001) *Real-time Systems and Programming Languages*, Pearson Education, Harlow.

Caro, P.W. (1973) Aircraft simulators and pilot training. *Human Factors*, **15**, 502–509.

Caro, P. (1988) Flight training and simulation, *Human Factors in Aviation*, Academic Press, San Diego, CA.

Farmer, E., Riemersma, J., Van Rooij, I. and Moraal, J. (1999) *Handbook of Simulator-based Training*, Ashgate.

Haward, M. (1910) The sanders teacher. *Flight*, **10**, 1006–1007.

Hays, R.T. (1992) Flight simulator training effectiveness: a meta-analysis. *Military Psychology*, **4**(2), 63–74.

Hays, R.T. and Singer, M.J. (1989) Simulation fidelity, *Training System Design*, Springer-Verlag, New York.

Howard I.P. (1986) The vestibular system, in *Handbook of Perception and Human Performance: Sensory Processes and Perception* (eds K.R. Boff L. Kauffman and J.P. Thomas), John Wiley & Sons, New York.

Link, E.A. Jr. (1930) U.S. Patent No. 1825462.

Lintern, G., Roscoe, S.N., Koonce, J.M. and Sega, L.D. (1990) Transfer of landing skills in beginning flight training. *Human Factors*, **32**, 319–327.

Moore, G.E. (1965). Cramming more components onto integrated circuits. *Electronics*, **38**(8), 114–117.

Povenmire, H.K. and Roscoe, S.N. (1971) Incremental transfer effectiveness of a ground based general aviation flight trainer. *Human Factors*, **13**(2), 109–116.

Rolfe, J.M. and Bolton, M. (1988) Flight simulation in the Royal Air Force in the Second World War, paper No. 1560. *Aeronautical Journal*, **92**, 315–327.

Rolfe, J.M. and Caro, P.W. (1982) Determining the training effectiveness of flight simulators: some basic issues and practical development. *Applied Ergonomics*, **13**(4), 243–250.

Rolfe, J.M. and Staples, K.J. (1986) *Flight Simulation*, Cambridge University Press, Cambridge, England.

Schachter B.J. (ed.) (1983) *Computer Image Generation*, John Wiley & Sons, New York.

Spooner, A.M. (1976) Collimated displays for flight simulation. *Optical Engineering*, **15**(3), 215–219.

Stewart, D. (1965) A platform with six-degrees-of-freedom. *Proceedings of the Institution of Mechanical Engineers*, **180**, (Part 1, 5), 371–386.

Taylor, H.L. (1985) Training effectiveness of flight simulators as determined by transfer of training. *NATO DRG Panel VIII Symposium*, Brussels.

Telfer R.A. (ed.) (1993) *Aviation Instruction and Training*, Ashgate, Aldershot

Thompson, D.R. (1989) Transfer of training from simulators to operational equipment–are simulators effective? *Journal of Education Technology Systems*, **17**(3), 213–218.

Tomlinson, B.N. (1975) Developments in the Simulation of Atmospheric Turbulence, Royal Aircraft Establishment Technical Memorandum FS-46, Farnborough.

Turner, L.W.F. (1913) *Teaching flying, Flight*, **5**(12), 326–328.

Waag, W.L. (1981) *Training Effectiveness of Visual and Motion Simulation*, AFHRL-TR-79-72, USAF Human Resources Laboratory, William Air Force Base, TX.

White, A.D. (1989) G-seat heave motion cueing for improved handling in helicopters. *AIAA Conferecne Flight Simulation Technologies*, Boston.

Winter, D. (1982) *The First of the Few: Fighter Pilots of the First World War*, University of Georgia Press, Georgia.