The impact of flight simulation in aerospace

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The Impact of Flight Simulation in Aerospace – a UK Perspective

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Abstract

This paper explains how flight simulation has made a major contribution to flight safety over the last thirty years to become critical to the operation of civil airlines and military organisations. It not only provides effective training, but for many flight training organisations has reduced the cost of flight training significantly. The paper outlines the increasing role of flight simulation covering flight training and research and development of aircraft and systems. The contribution of the flight simulation industry to the UK economy, in terms of both employment and revenue, is highlighted.

The paper focuses on advances in the underpinning technologies of flight simulation, including mathematical modelling, real-time computation, motion actuation, visual image generation systems and projection systems.

The paper also summarises the broadening roles of flight simulation; from part-task trainers to zero flight-time training in civil aviation; in military aviation, extending to combat domes and mission rehearsal; in defence procurement, where synthetic environments are used widely in evaluation studies prior to major project commitments; in aircraft development, providing powerful design tools to enable system designers to evaluate prototype systems.

As a result of the acceptance of flight simulation in flight training, the use of simulators has been standardised throughout the world, with formal programmes of simulator qualification. These regulations, drawn up with the help of the RAeS Flight Simulation Group, ensure consistency for operators, regulators and manufacturers; the status of these regulations is outlined.

The paper concludes by reviewing the lessons learnt by the flight simulation industry over the last thirty years and summaries the potential areas of growth, which will lead to simulation becoming widespread throughout many industries, in addition to the aerospace industry.

1 Evolution

In 2007, the Flight Simulation Group of the Royal Aeronautical Society produced a specialist paper (http://www.raes-fsg.org.uk/) describing how flight simulation has evolved to become an established discipline in aerospace and has had a pivotal role in many of the fundamental improvements in flight training, which have occurred in both commercial and military aviation.

Flight simulators have been used since the early days of flying (Adorian et al, 1979). The Antoinette trainer, shown in Figure 1, was used to introduce pilots to the disorientation of flight. The cockpit was rotated by assistants and the pilot applied rudimentary control actions. In the 1930s, Ed Link, who is acknowledged as the founder of modern-day flight simulation, developed an instrument trainer, based on pneumatic actuation to rotate the cockpit and to drive simulated aircraft instruments (Link, 1930).

Figure 1 The Antoinette Flight Training Simulator circa 1911 (Courtesy The Library of Congress)

After initial reluctance to accept the Link trainer as a useful training aid (Link originally sold his device to amusement parks), the US Army Air Corps procured several Link trainers following a number of accidents in instrument metrological conditions (IMC). During the Second World War, over half a million allied airman were trained on a Link trainer, known affectionately as the 'blue box', shown in Figure 2. With the introduction of large bomber aircraft with complex hydraulics and electrical systems, the Silloth trainer was developed to train flight crews to operate aircraft systems and to practise emergency procedures for malfunctions.

The major developments in flight simulation started in the 1960s, initially with the use of analogue computers to implement the equations of motion and subsequently, using digital computers to compute the differential equations which underpin flight modelling. As computing speeds advanced during the 1980s, detailed flight models were developed for both civil and military aircraft and the use of dedicated computer systems extended to control of the motion platform actuators and also to the computer graphics need to render a visual scene.

Figure 2 A Link Trainer (Courtesy Royal Aeronautical Society)

This evolution (Allen, 1993) has been dramatic. In the 1960s, civil pilots were trained in commercial aircraft. Recurrent checks included simulated engine failures in flight, resulting in a number of accidents. By the 1980s, nearly all type conversion training and recurrent checking for airlines was undertaken in a flight simulator. In addition to the improvements in simulation technology, several supporting activities contributed to these advances:

- Aircraft manufacturers produced data acquired from flight tests to provide detailed aerodynamic and engine models in all regimes of the flight envelope.
- A substantial industry of simulator companies emerged to meet the training requirements of airlines and military organisations.
- The regulatory authorities established regulations and practices for the qualification and operation of these flight training devices.

Nowadays, flight simulation is accepted by flight crews, manufacturers, operators, unions and regulatory authorities. An airline pilot will spend two days every six months undertaking recurrent training and checking in a flight simulator. The quality (in terms of realism and pilot acceptance) is so high that, for specific simulators, all the training can be performed in the simulator. These flight simulators are known as zero flight time (ZFT) training devices. The first time the pilot will fly the actual aircraft is with fare paying passengers, albeit under the supervision of a training captain.

One particular development in both civil and military operations has been the advances in aircraft avionics, including displays, flight management systems (FMS), radars, warning systems and monitoring systems. For these aircraft, the simulator is not only a platform on which to practise flying skills, it also provides an effective training device for systems operation and crew cooperation. In addition, training on specific equipment can be provided by dedicated computer systems, for example, using a laptop computer to practise operation of an FMS.

For military operators, the simulator serves several functions. It provides a training environment with reduced risk to flight crews and minimal environmental impact. It can also reduce the cost of deployment of expensive weapons on training ranges and enable flight crews to operate in multi-aircraft formations or against computer-generated threats. These simulators also introduce a mission rehearsal capability, enabling flight crews to practise a mission. With these systems, detailed visual databases are provided from a combination of satellite imagery and mapping to enable crews to practise exercises in hostile territory.

Systems engineering is another field in which flight simulation has made a significant impact. During development of aircraft systems and avionics equipment, flight simulators are used in evaluation studies and systems validation (Allerton, 1996). These simulators provide engineers with a detailed analysis of system performance, identifying problems early in the life cycle of a programme and enabling detailed studies to be undertaken prior to commitment to a design.

This evolution over the last 50 years (Allerton, 2000) has resulted in major improvements in the quality of flight training leading to a significant increase in flight safety.

Airspace congestion from flight training and its associated environmental impact has reduced. For many airlines, the cost benefits of synthetic training versus airborne training are critical to their financial survival. International standards ensure worldwide regulation of flight simulation facilities. The flight simulator industry has become a major sector of worldwide aviation. Moreover, flight simulation is now recognised as an established discipline in aeronautics.

2 Organisation of a Flight Simulator

A modern civil airline full flight simulator is shown in Figure 3. The simulator consists of a cabin where the flight deck is fully replicated, accommodating the flight crew and the instructor. The cabin is mounted on six hydraulic (or electrical) actuators and projection systems mounted on the cabin are used to display the scene seen by the flight crew. The rear portion of the cabin includes an instructor station to enable the instructor to monitor and control a training session. For a military simulator, the instructor is usually located in a control room, communicating via a head-set, similar to airborne instruction.

The structure of a modern flight simulator (Baarspul, 1990) is outlined in Figure 4. The equations of motion, which underpin the flight model of the simulated aircraft (Boiffier, 1998 and McFarland, 1975), are the focal point of the simulator. The forces and moments which define aircraft motion are solved as a set of non-linear differential equations to compute the aircraft motion and trajectory (Foggarty and Howe, 1969).

These equations are solved by a computer program (typically executed on a PC) with sufficient accuracy that the simulator model faithfully replicates the aircraft motion (linear and angular) throughout the flight envelope. In addition, the equations must be solved at least 50 times per second (every 20 ms) so that the resultant aircraft dynamics appear to be smooth and continuous. This constraint of simulation is referred to as real-time simulation. Critically, all the simulation computations must be solved at this 50 Hz (or sometimes 60 Hz) iteration rate and at significantly higher rates in specific parts of the simulator. Consequently, considerable effort is given to the design of the simulator software, the system architecture and communications between computers.

Figure 3 A Civil Full Flight Simulator

The aerodynamics model contains all the terms to compute the aerodynamic forces (e.g. lift and drag) and moments (Hanke 1971). Typically, this data is provided as a large data package produced by the aircraft manufacturer (IATA, 2002). In addition, the data package will include validation data to check the accuracy of the implementation (Heffley and Jewell, 1972). Similar emphasis is given to the landing gear model produced by the aircraft manufacturer in the replication of ground handling (Kruger et al, 1997), particularly in the critical regimes of takeoff and touchdown. The aircraft engine manufacturer will also produce a data package to derive an engine performance model and to validate the model characteristics.

Weather conditions have a major impact on flight operations. Turbulence (Beal, 1993), wind shear, micro-bursts and winds are modelled together with icing, rain and fog conditions in a weather model, which provides variables needed in computation of the aerodynamic terms and the engine model.

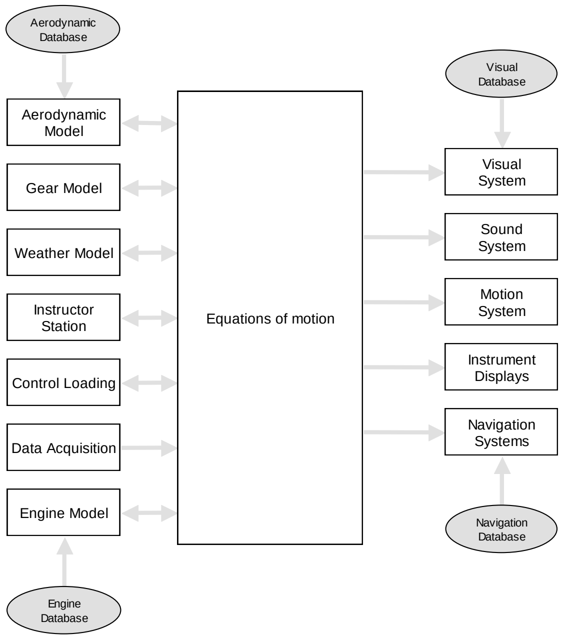

Figure 4 Organisation of a Flight Simulator

The instructor interacts with the simulator via an instructor station (Ahn, 1997), typically a touch screen with graphical displays. In a civil flight simulator, the instructor can inject faults, monitor the flight situation, monitor the flight crew and establish flight conditions. The instructor also observes the crew behaviour, particularly crew cooperation. In most military simulators, the instructor observes the pilot via a camera and monitors the simulator using replicated displays in a control room.

Pilot controls must be accurately modelled in a simulator to provide tactile feel and appropriate loads. These forces are produced by a control loading system for the primary pilot inputs and engine levers. A data acquisition system captures pilot control inputs at the simulator frame rate, typically 50-60 Hz, accessing several hundred analogue and digital inputs for the levers, switches, push buttons and selectors on the flight deck.

The visual system comprises the image generators to render a real-time scene (Barrette, 1986) and the projection system so that the flight crew see a realistic scene from the flight deck, containing airports, fields, roads, rivers, lakes and so on. Nowadays, the scene is stored as a visual database of entities, such as buildings, runways and approach lights, which are rendered at the simulator frame rate. For an airline, the visual system will include lighting and weather effects, for example fogging. In a military simulator, the scene is commonly projected inside a hemi-spherical dome and the projection system also enables other aircraft to be displayed with a high degree of visual accuracy.

A dedicated sound system produces the sounds experienced on the flight deck, for example engine noise, slipstream, aural warnings, air-conditioning and motor drives etc. The aural cues are synchronised with the flight conditions, for example the sound of rain, raising or lowering flaps or skid sounds during touchdown.

The purpose of the motion system is to apply the forces experienced in an aircraft to the simulator cabin (Reid, 1984). In practice, this cannot be fully replicated because the motion actuators are constrained to a few metres of displacement. However, the six actuators can be combined to provide the three linear forces of heave, surge and sway and the three moments of pitch, roll and yaw. The motion is very closely synchronised with the visual system to provide powerful visual and motion cues, to a surprisingly high degree of realism. For military simulators, the higher g-forces cannot be replicated and fixed-base configurations are usually used in combination with a specially constructed seat, known as a g-seat, which exerts forces on the pilot by moving the base and sides of the seat to replicate g-forces sensed in a harness.

Finally, the aircraft systems must also be faithfully replicated, including the displays and instruments. In addition, the aircraft navigation systems are also simulated so that the simulator is flown and navigated in exactly the same way as the aircraft. Two methods are employed; actual aircraft systems can be used but they must be stimulated with the same signals as an aircraft; alternatively, the equipment can be fabricated to emulate the actual aircraft functions. The decision to ‘simulate or stimulate’ depends on the relative cost of the implementation.

3 The Effectiveness of Flight Simulation

In flight training, the flight simulator is used to capture and practise skills that can subsequently be applied in an aircraft (Caro, 1973). If the training is effective, minimal time is needed to transfer the skill to the aircraft. Alternatively, if it is not effective, additional airborne training is needed. Clearly, considerable effort is given to ensuring the effectiveness of a flight trainer, matching the simulator technology to the training requirements (Bell and Waag, 1998 and Taylor, 1985).

In many aspects of flight training, only a few specific skills are trained during a particular stage of training. In such cases, a part-task training device can provide effective training, albeit limited to the specific training task. For example, the Link trainer provided a powerful training device for instrument flying but was inappropriate for practising engine starts.

Although many early simulators were designed to replicate the aircraft and its systems as closely as possible, the emphasis on fidelity can increase the cost of the simulator and may not necessarily provide effective training. Nowadays, a training needs analysis is conducted to ascertain the training requirements so that the appropriate simulator technology is used to fulfil the training at an acceptable cost. The analysis ensures that the training requirements are fulfilled by the training device and that unnecessary equipment can be omitted without reducing the effectiveness of the trainer.

A flight simulation training device (FSTD) is used for specific training tasks ranging from simple desktop devices, instruments procedures trainers (as shown in Figure 5) to navigation procedures trainers, where the flight crew can follow a flight plan even though the simulator will probably lack a motion system, a visual system or even pilot controls. These devices include laptop systems to train flight crews to operate aircraft avionics and also to train maintenance crews, for example, to practise engine start procedures without incurring any engine wear and the associated cost of operating actual aircraft engines. With such systems, the operator will simply touch the screen to press a switch or move a selector. Computer-based training (CBT) systems can combine video, sound and computer animation to replicate system behaviour. CBT systems also include training software to enable students to progress at their own pace and to monitor student performance during training.

Technology developed for flight simulation has also been applied in other sectors of aviation, where the cost difference of synthetic training versus live training offers significant benefits:

- Aircraft technicians can practise fault finding and equipment removal, without using actual aircraft parts, as shown in Figure 6.
- Cabin simulators are used to enable cabin staff to practise evacuation procedures.
- Military simulators can link flight crew trainers with mission crew trainers, enabling crews to practise specific mission profiles and to train in crew resource management.

Figure 5 A Flight Simulation Training Device (FSTD)

The results from a number of studies suggest that the effectiveness of training is not necessarily linked to the fidelity (and therefore cost) of the flight simulator (Caro, 1988). Effective training has been demonstrated with part-task training devices, where emphasis on matching the simulator technology to the training requirement produces better training and in many cases can reduce the cost of training (Allerton and Ross, 1991 and Hays and Singer, 1989).

Figure 6 An Aircraft Maintenance Trainer

5 The Benefits of Flight Simulation

Airline flight crews must undergo mandatory training and checking, for which training in an approved flight simulator is recognised in place of airborne training. Typically, one simulator is needed for 30 narrow body aircraft reducing to one simulator for 15 wide body aircraft. For an airline with 1000 pilots, the annual cost of training using aircraft would be approximately $60M.[1] Depending on the simulator, the operating costs are less than one tenth of the operating cost of an aircraft, indicating the dependence airlines place on flight simulation. There are further benefits for civil airline training; in particular, there are significantly less carbon emissions and no environmental noise.

For military organisations, the combination of reduced risk to flight crews, public concern over environmental problems associated with low-flying and the increasing cost of weapon systems has led to the armed forces accepting the compelling case for flight simulation. In particular, engagements with multiple forces and electronic warfare, if practised in peace-time, can threaten strategic and tactical secrecy, whereas exercises can be conducted with linked simulator facilities. In these facilities, instructors can select virtual forces to provide realistic engagements with simulators in several countries being linked in a virtual training space.

Analysis of aircraft accidents has enabled the regulatory authorities to introduce specific training in simulators, effectively exposing flight crews to potentially hazardous situations, thereby accelerating pilot experience. For example, runway icing conditions can be experienced by flight crews who might rarely encounter such conditions during normal flight operations. One particular example where flight simulation has contributed to aviation safety is wind shear training, where flight crews can practise procedures to minimise the risk encountered in wind shear conditions.

6 A Technology Driven Industry

The advances in the processing speed of modern computers have been exploited in flight simulation. Complex models of airframe dynamics, rotor dynamics and engine thermodynamics have been derived from analysis of flight data and also from computational fluid dynamics (CFD) packages. The graphical processing used in image generation provides detailed textured 3D scenes which include haze and fog effects, dynamic objects and a continuous view typically 220° by 40° but as much as 225° by 60° in demanding applications. A typical image is shown in Figure 7, which includes several aircraft, detailed airfield scenery and surrounding countryside.

Figure 7 Flight Simulator Visual System

The motion platform, comprising six linear actuators attached to the motion platform base, provides motion cues for the flight crew. This configuration, known as the Stewart platform (Stewart, 1965), enables hydraulic and electrical linear actuators to be used. In addition, the vestibular sensors in the inner-ear (Howard, 1986) can be stimulated with accelerations which can convince flight crews that they are experiencing the forces normally encountered in airborne situations. The artificial accelerations are computed from knowledge of the response of the vestibular sensors and the applied motion (Nahon and Reid, 1990 and Nanua et al, 1990). For example, the cabin is tilted backwards during the takeoff roll to replicate the acceleration pressing the pilot into the seat. Such techniques are used judiciously; by understanding the dynamics of the balance sensors in the inner ear, the motion can be matched to the expected response, even though actual accelerations cannot be strictly achieved with a platform configuration of this form. A typical hydraulic motion system for a civil flight simulator is shown in Figure 8.

For a military flight simulator, the high frequency buffet and sustained g-forces cannot be provided by a standard 6-DOF platform but a g-seat combined with a vibration system and a wide field-

[1] 2006 financial figures

of-view projection system, provides acceptable motion cues. A typical g-seat is shown in Figure 9.

Figure 8 Civil Flight Simulator Motion System

A pilot is subject to haptic pressure applied by moving the seat pan and sides to simulate forces on the body during high-g manoeuvres. These motion cues, often combined with visual cues provided by a high fidelity visual system, provide far more realistic cues than a traditional synergistic platform (Ashworth et al, 1984 and Keirl et al, 1995).

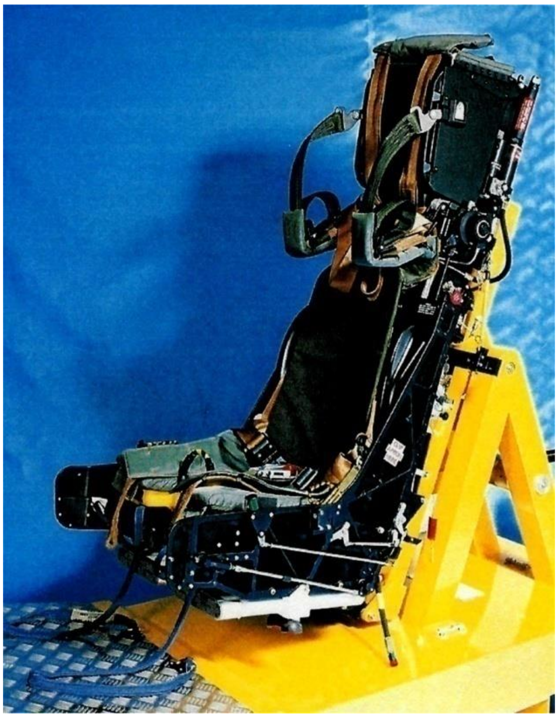

Figure 9 Military Flight Simulator G-seat

The projection of the outside world scenes needed for flight simulation introduces three problems. Firstly, the projected view must give a natural sense of distance (or depth). Secondly, the view must be seen by both pilots. Thirdly, the mass of the projection system adds a significant load to the motion system. These problems have, to a considerable degree, been overcome by the curved mirror projection system developed in the UK (Blackman, 1995). The blended image from three or more projectors, is projected onto a translucent screen and viewed through the hemispherical mirror. At the pilot station, this image is 'collimated', i.e. appears at optical infinity, reproducing the effect of depth perceived in the outside world.

The mirror is formed from a thin sheet of Mylar with a reflective coating, which is sucked into a hemispherical shape by a vacuum pump, reducing the overall mass and providing a continuous field of view for the flight crew. A typical curved mirror projection system is shown in Figure 10.

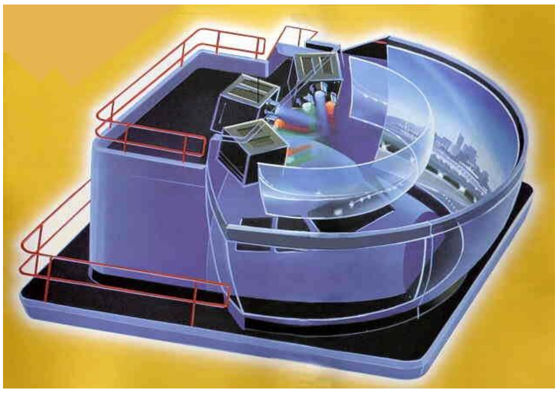

Figure 10 Curved Mirror Projection System

For civil flight training the prime advantage of this form of projection is the accurate distance of the scene as viewed through standard flight deck windscreens. However, such a scheme is not appropriate for military flight training, where a pilot needs a much wider field-of-view. One solution has been to provide dome projection systems, as illustrated in Figure 11. A fixed-base simulator is positioned at the centre of the dome with a series of projectors providing a low-resolution background scene. High resolution images of other aircraft are overlaid by special target projectors. In some military simulators, adjacent domes are used to enable pilots to undertake combat training.

Figure 11 Military Dome Projection System

An alternative method to increase the field of view is the use of a helmet-mounted display, where the visual scene is displayed using small optical devices mounted close to the eyes, slaved to where the pilot is looking, as shown in Figure 12. Although there is a slight increase in the mass of the pilot's helmet, the main drawback with this approach is that the position of both the pilot's head position and eye position must be tracked accurately. Eye-tracking and head-tracking systems have been used successfully, but small errors can lead to disorientation, where the pilot perceives a difference between the expected image and the projected image, leading in extreme cases to nausea, known as 'simulator sickness' (Kolasinski, 1995).

Figure 12 A Helmet-mounted Visual System

7 Flight Simulation in Research and Development

Flight simulation is now an integral part of aircraft design. An engineering flight simulator (Allerton, 1999) provides essential insight into system behaviour and performance. In particular, design faults detected in the early stages of the product life cycle can reduce project costs significantly. The use of simulation affords two advantages. Firstly, it is possible to acquire useful data from trials undertaken in a synthetic environment. Secondly, it enables human factors to be addressed at an early stage in the programme.

Engineering flight simulation has played an important part in many recent aircraft development programmes, including the Boeing 777 and Airbus A380 programmes. In the early stages a desktop system may be used to identify basic problems or to prove concepts. A typical desk top development is shown in Figure 13.

Figure 13 An Airbus Desktop Development System

Software developed on the desk top system is then transferred to a fixed base simulator where emphasis is placed on the evaluation of the aircraft systems during extensive simulator trials. The final phase of engineering simulation is the use of 'iron-bird' rigs, where the simulator is integrated with actual aircraft equipment, including displays, data buses and actuation systems, as shown in Figure 14. For example, spoiler and aileron hydraulic systems are installed so that they move in response to pilot inputs and flight conditions. The main advantage is that faults detected during actual flight trials would be much more costly to fix and that the combination of engineering simulation and iron-bird rigs is likely to eliminate the majority of faults.

As a consequence of the advances in engineering flight simulation, the role of flight testing has changed significantly. Rather than verifying the performance of aircraft systems, the flight test is more commonly used to verify results obtained from simulation studies. In projects such as the Eurofighter programme, data from flight trials was transmitted by telemetry to a ground station, where the results were analysed to confirm results obtained from simulation, reducing the need to repeat flight tests.

Figure 14 Airbus Iron-bird Rig (Toulouse)

Flight simulation has also extended to operational requirements where the use of simulation can clarify specific requirements or capabilities. This approach, termed 'synthetic environments' (SEs) enables proof-of-concept studies to be undertaken to identify problems and limitations or to evaluate competitive designs before committing to product development. A wide range of synthetic simulation tools are used covering aerodynamic modelling, structural analysis, operational analysis, reliability analysis and flight control system design. The detailed trade-off studies, undertaken prior to procurement, where manufacturers and procurement agencies work closely together can result in significant savings. In addition, simulators can be interconnected to provide useful insight into the operational requirements.

Modern aircraft can be viewed as systems platforms and flight simulation offers major advantages during the design and development of aircraft systems, providing detailed analysis of designs and prediction of performance prior to flight trials and possibly as part of the procurement phase.

8 The UK Flight Simulation Capability

The major development of the UK flight simulation industry occurred in the 1960s with the Link Miles and Rediffusion companies establishing a major presence in terms of worldwide sales of simulators for civil and military aircraft. Following a number of mergers, these companies now form part of the Thales Group, employing some 1200 staff in the UK.

In recent years, UK companies have manufactured approximately 10 full flight simulators per year representing an annual turnover in excess of $150M. Other UK companies are involved in the refurbishment, upgrading and maintenance of simulators, employing over 400 staff. Over 50 companies have exhibited at recent ITEC conferences, the annual European exhibition for the industry. In addition, several companies operate training centres for civil and military flight crews, with increasing privatisation of flight training by the armed forces. The major UK aircraft manufacturers Westland Helicopter and BAE Systems have extensive simulation departments supporting aircraft programmes.

The UK simulation industry has benefited from the growth in airline operations in the UK. Since 2000, the number of flight simulators has increased by 27%. In 2006, there were 75 civil full flight simulators in the UK with an average utilisation of 3000 hours per year. Assuming an operating cost of $400 per hour, the annual revenue for civil operations exceeds $90M. A further 55 flight simulators are used in training centres for the armed forces with over 1000 instructors, maintenance engineers and management and administrative staff supporting these facilities.

The major research organisations at DSTL and QinetiQ provide support for the UK armed forces and this includes the modelling of aircraft dynamics, motion cueing, wind shear, helicopter operations to ships and simulator-based evaluations to support the Harrier and Joint Strike Fighter programmes. Within BAE Systems, military simulation is concentrated at the Warton site where advanced simulation facilities have supported numerous projects, including the Eurofighter programme. Since 1995, BAE Systems, Thales and QinetiQ have established a reputation for distributed simulation in mission training with simulators in the UK connected to other simulators around the world. These research activities include the development of synthetic environments (SEs) to support UK defence acquisition projects.

Of the major developments in the UK simulation industry, three significant activities have been acknowledged as world leading:

- Development of international standards, led by the UK Civil Aviation Authority (CAA), working closely with the FAA and UK operators and manufactures;
- Development of hydrostatic seals for hydraulic actuators in motion platforms – reducing the

friction in actuators and improving the actuator response for motion platforms;

- Visual systems technology, particularly the development of wide-angle continuous field of view projection systems used in civil simulators.

The UK industry maintains a worldwide reputation for simulation technology and international regulation and the provision of training facilities for numerous airlines and military organisations. The revenue generated by the flight simulation sector is a major contributor to the UK aerospace industry.

9 The Future of Flight Simulation

Flight simulation has been widely adopted by the aerospace industry, where its benefits have been recognised for over 30 years. In effect, there is a culture of simulation, particularly in aerospace companies where simulation plays a critical role in the design of aircraft and aircraft systems. Simulation extends to flight control system design, finite element methods used in structural analysis, CFD tools used in aerodynamic analysis and the mathematical tools used in operational analysis.

Companies that have used simulation tools have appreciated the benefits afforded by simulation, in particular; faster design times, fewer design faults, more effective systems, cost saving and improved decision making in procurement. The lessons learnt by these companies are being taken up across the aerospace industry, where the advantages provided by effective simulation far outweigh the cost of investment in simulation facilities.

The same trend is identifiable in training organisations. The initial reluctance to use flight simulation because of a perceived lack of realism has been superseded by the benefits which include improved training effectiveness, reduced training costs and increased safety. This trend of increased emphasis on synthetic training and engineering simulation is likely to continue to increase in the next 10 years and it can be conjectured that flight simulation will make a more significant contribution to aerospace than the earlier developments in aerodynamics, structures and propulsion.

Simulation will become pervasive in many industries. Its techniques will be applied to provide system design tools, enabling engineers to investigate prototype design far faster and with greater understanding than possible hitherto. It is likely that, in many industries, detailed simulation studies will become mandatory in the way that simulation has been adopted in the procurement, design and evaluation of aircraft systems.

In order to achieve these advances, lessons learnt from simulation need to be taken into account. In particular, the benefits of regulation enable companies to manufacture equipment against an approved standard. However, consideration needs to be given to the critical role of the provision of data for simulation. It is said that a simulation is only as good as its data and emphasis needs to be placed on both the regulation of the models and their data.

In flight training, simulators have been mostly used in the training of airline crews and specialist military pilots. However, with the reducing cost of simulation technology, simulation is likely to extend to ab-initio pilot training. The ICAO initiative, the multi-crew pilot licence (MPL) is somewhat revolutionary, offering an alternative route to the Air Transport Pilot Licence (ATPL), but where the MPL curriculum will include extensive use of flight simulation.

The use of simulation in pilot training has been influenced by the relative cost of synthetic training versus airborne training. Similar advantages apply in other industries such as the training of drivers of trains, buses, lorries, ships, submarines and armoured vehicles, where four advantages justify the use of simulation:

- The reduced cost of training, particularly the relative hourly operating rates of the equipment during training;
- The cost of training on actual equipment, which may need to be taken out of service or be damaged in a training role, for example practising engine starts on a jet aircraft;
- Potential damage to the environment, for example extra buses on urban roads.
- Risk to the trainee or bystanders, where specific activities are significantly safer where training is undertaken in a synthetic environment.

Up to the 1990s, many simulator companies developed custom equipment, often to meet demanding real-time performance or to provide high visual fidelity. With advances in PC technologies, particularly processors, graphics and signal processing devices, it is feasible to use commercial off-the-shelf (COTS) equipment. Their competitive cost has rendered low-volume specialised development uneconomical. In particular, real-time flight simulation has exploited PC technology, computer graphics and local area networking equipment to sustain the overall processing rates needed for complex models. In these environments, additional processing is achieved by adding additional processors to a network.

A significant cost of a full flight simulator is the hydraulic system providing motion cues. The demands of the system are formidable; it must produce sufficient power to move the platform including the cabin and projectors; the dynamic response of the motion platform should replicate aircraft motion; it should be quiet in operation and reliable (to reduce maintenance costs and reduce risk to the flight crew). In the last few years, electrical actuation systems have been introduced. Electrical actuation offers considerable energy saving, where a small electrical motor used for each actuator, combined with a mass compensation scheme (to support 10-12 tonnes) can reduce energy costs by as much as 80%.

Until recently, flight simulator display systems employed CRT projectors. These are being superseded by COTS-based digital projectors. The currently favoured technology is LCoS (liquid crystal on silicon). These offer high resolution and have been modified by simulator companies to enhance their contrast ratios to levels suitable for use in the full range of daylight and night scenes. The resultant improvements include:

- High contrast, with black levels suitable for night scenes;
- Increased resolution;
- Reduced cost of acquisition;
- Reduced power consumption, of the order of 75% less than CRTs.

Other technologies are available, such as laser projectors, but these are generally more expensive. Consequently, LCoS projection systems are likely to remain the preferred solution for the simulation industry for some time.

Advances in computer systems used in domestic markets, particularly computer games and virtual reality will align this technology with the computing requirements of flight simulation. The rendering rates, increased resolution and storage capacity of these systems will be exploited by simulation applications. In the 1990s, the image generators and projection systems were the major cost in flight simulation applications. Not only has the overall cost of simulation technology dropped dramatically with COTS hardware, but the proportion of the cost needed to achieve high fidelity in the visual systems, also continues to fall, providing opportunities for wider fields of view, increased scene detail and improved resolution.

One particular area to benefit from the reduction in the cost of computing equipment is the university sector, where it is practical to purchase or develop low-fidelity flight simulators to support undergraduate and postgraduate courses. Although flight simulation is not currently recognised as an established discipline in aerospace departments, the availability of affordable simulation equipment is likely to lead to a review of teaching. Perhaps more importantly, the prohibitive cost of simulation previously excluded universities from participation in research programmes. During the last 30 years, simulation has been used in flight training applications but very little research has been conducted into the effectiveness of flight simulation. In this role, the universities may be able to undertake research activities to quantify the training effectiveness of specific technologies and training methodologies.

As an example of the development of low-cost flight simulation in the university sector, Figure 15 shows a fixed-base flight simulator developed at the University of Sheffield, comprising a single seat cockpit with an electrical control loading system, computer-generated flat panel LCD displays and a 150° by 40° projection system. This real-time simulator has a 50 Hz update rate (20 ms frame) and comprises 8 networked PCs running the Linux operating system. All the software is developed using open-source packages, in particular the displays are based on OpenGL (Shreiner, 2004) and the image generators use OpenSceneGraph. A typical channel of the image generator is shown in Figure 16, which includes a head-up display (HUD) overlay.

The EFIS displays are written in OpenGL and are shown in Figure 18.

Figure 15 University of Sheffield Flight Simulator

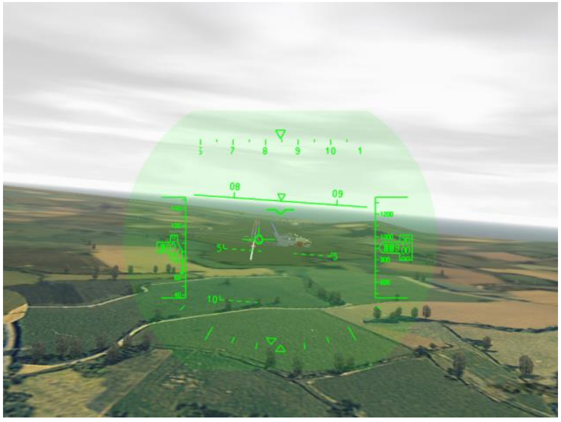

Figure 16 OpenSceneGraph Visual System

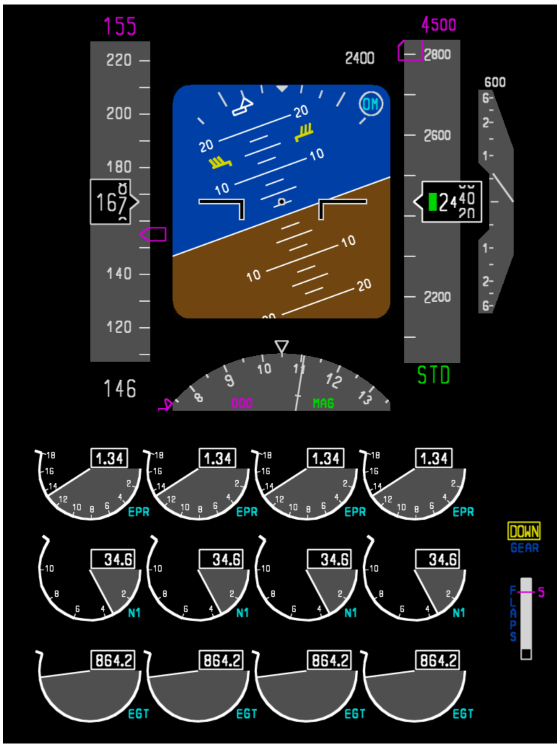

Figure 17 OpenGL EFIS Display

11 Conclusions

For both civil and military operators, a significant part of airborne training has been replaced by simulator training. The transition, resulting from improvements in simulation technology, is accepted by operators, regulators and unions. Flight simulation is critical to the operation of civil and military organisations.

International standards are now in place to ensure consistency and to provide guidelines for manufacturers, operators and regulators. As a consequence, simulation facilities can be approved by one nation and this qualification is accepted by regulators throughout the world.

Flight simulation has made a major contribution to civil aviation safety by improving the flight training provided to airline flight crews. Simulation also contributes to reductions in environmental impact, by reducing the requirement for airborne training.

A wide range of synthetic training devices has been developed to cover the training tasks in both civil and military flight training. For specific training tasks, effective training has been achieved with part-task training devices, often using low fidelity equipment.

The rapid advances in simulation technology underpin the effective training provided by flight simulation technology, ranging from basic training devices through to zero flight-time training for civil airlines and to mission rehearsal in military organisations. At the same time, synthetic training has also proved to be highly effective in other sectors of aviation, particularly maintenance engineering training and cabin crew training.

Flight simulation not only reduces the cost of flight crew training, in many areas, it has been shown to be more effective than airborne training. It extends to research and development where it is widely used in the development and evaluation of aircraft and avionics systems. Increasingly, it also supports procurement, where the complete produce life cycle is modelled and analysed in a synthetic environment.

UK industry continues to play a major role in developing flight simulation technology and makes a significant contribution to revenue generation and employment in the UK aerospace sector.

In the next few years, the cost of flight simulation equipment will continue to fall as commercial off-the-shelf technologies are exploited to increase capability and to reduce development costs. Simulation technology will become pervasive in many new industrial applications and will fulfil an increasing role in system design and evaluation studies.

Flight simulation is becoming recognised as a major discipline of aerospace and an innovative contributor to the aerospace industry.

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