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A Discussion Paper by the Royal Aeronautical Society

The impact of flight simulation in aerospace

Royal Aeronautical Society Flight Simulation Group

EXECUTIVE SUMMARY

The aim of this paper is to summarise the role and importance of flight simulation in both civil and military aviation, notably its beneficial effect on the environment and its increasing impact upon training strategies.

It has been prepared to provide background information to assist decision makers in government, industry, airlines and academia.

Much of the training previously undertaken in aircraft is now conducted in flight simulators.

Flight simulation is critical to the operation of civil and military aircraft organisations.

International standards for flight simulation training devices have been established to ensure consistency for operators, regulators and manufacturers.

Flight simulation continues to make a major contribution to improving aviation safety.

Compared with airborne training, flight simulation reduces markedly the impact on the environment.

A wide range of synthetic training devices has been developed for specific flight training tasks.

For certain training tasks, effective training can be achieved with low fidelity synthetic devices.

Advances in computer technology enable flight simulation to provide very effective flight crew training.

Flight simulation is used from basic training through to zero flight-time training for civil airlines and to mission rehearsal for the armed forces.

Synthetic training is highly effective in other sectors of aviation, particularly in maintenance engineering training and cabin crew training.

Flight simulation reduces significantly the cost of flight crew training.

Training in a flight simulator can be more effective than airborne training.

Simulation plays a fundamental role in research, development and evaluation of aircraft and aerospace systems.

Increasingly, simulation supports procurement, where the complete product life cycle is modelled and analysed in a synthetic environment.

The UK plays a major role in developing flight simulation technology.

The UK flight simulation industry makes a significant contribution to revenue generation and employment in the UK economy.

The Royal Aeronautical Society Flight Simulation Group plays a pivotal role in advancing international standards for flight simulation training devices.

The flight simulation industry exploits advances in commercial off-the-shelf technologies to increase capability and reduce development costs.

Simulation will become pervasive in many industries and simulators will become essential tools in system design studies.

Flight simulation is becoming recognised as a major discipline of aerospace.

Figure 1. Civil airline full flight simulator.

EVOLUTION

Flight simulation has evolved to become an essential component of civil aviation operations and military capability. International standards ensure world-wide regulation of flight-simulation facilities. Flight simulation has radically changed flight training and is now an established discipline in aerospace.

Today, a significant amount of civil and military flight crew training is undertaken in flight simulators utilising computers to create the illusion of flight. Many of the airborne exercises that dominated flight training as recently as the mid 1970s, have been replaced with training in flight simulators (Figure 1). Concerns that flight simulators were unrealistic and that aircraft provide better training have been dispelled and a wide range of part-task training devices has been developed to provide synthetic training on specific systems and procedures. This remarkable transition in flight training is accepted by flight crews, operators, unions, manufacturers and the regulatory authorities.

The complexity of both civil and military aircraft has increased as a result of advances in avionics, expanding flight-crew training requirements and increasing the reliance on flight simulation. Many civil airlines operate large flight-training centres to undertake their flight-crew training and regular competence checking to maintain flight crew licences.

Recognising the impact flight simulation has made in civil training, international regulations have been established to ensure that all civil flight crew training simulators operated by different organisations meet an approved standard. These standards not only ensure consistent regulation of flight simulators and flight training organisations throughout the world, they also enable manufacturers to build flight simulators that are compliant in different countries, encouraging competition while ensuring quality.

Most armed forces also utilise training centres with flight simulators for basic training, type conversion and tactical training for both fixed-wing and rotary-wing aircraft. In addition, flight simulators are used by aircraft and equipment manufacturers, systems developers, research organisations and academia for proof-of-concept studies and the design, development and evaluation of aircraft systems.

Flight simulation has not only radically changed flight training methods, reducing the training risk and improving training quality; it has also resulted in significant improvements in flight safety, alleviating airborne congestion and the impact of aviation on the environment, while reducing the cost of training. These trends are likely to continue for the foreseeable future.

THE EFFECTIVENESS OF FLIGHT SIMULATIONS

Training in a flight simulator can be more effective than training in an aircraft. High levels of training transfer can be achieved with low-fidelity devices. For some simulators, all the flight-crew training can be conducted in the simulator.

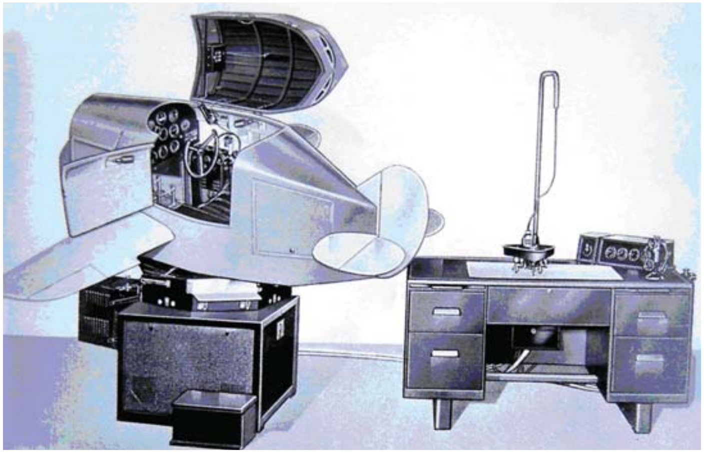

Figure 2. Link trainer and plotting table.

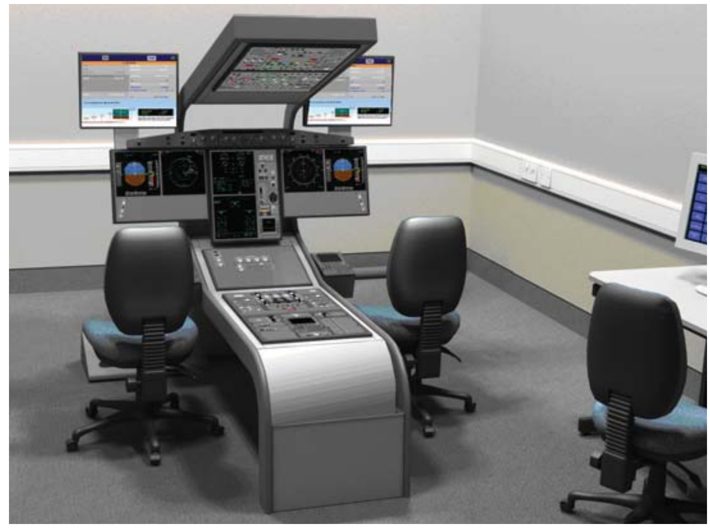

Figure 3. An FSTD.

The Link Trainer was the forerunner of effective synthetic training devices (Figure 2). Developed in the USA in the late 1920s by simulation pioneer Edwin Link and used during the Second World War, it provided over half a million allied pilots with essential training in instrument flying. Nowadays, such a device would be termed a part-task trainer or Flight Simulation Training Device (FSTD) as it was optimised for a specific set of training tasks, eliminating time that would otherwise be spent in an aircraft (or, nowadays, in a full flight simulator).

In flight simulation, the effectiveness of a training task is the 'training transfer' resulting from training in a synthetic device compared with that in an aircraft, often measured as the ratio of the number of hours of airborne training that can be replaced with training in a simulator. Studies have shown that, for certain tasks, high levels of training transfer can be achieved with low-fidelity training devices.

Flight simulation technology now allows the balance to be weighted more heavily towards synthetic training and away from airborne training. To determine this balance, the training tasks are analysed in detail to assess the training benefits afforded by each training device. In some cases, flight simulation may achieve all the training objectives through using a combination of a full flight simulator and part-task trainers; in other roles, simulation is used to prepare for, and subsequently augment, airborne training.

FSTDs are used as instrument trainers and flight navigation procedures trainers (Figure 3). Simple desktop training devices and laptop computers are also used to train flight crews and maintenance technicians, for example, to operate complex avionics or to practise engine start procedures without incurring actual engine wear and the associated cost.

This use of flight simulation technology, with a computer-based approach to training, allows students to proceed at their own pace, while at the same time providing feedback on their performance.

Modern full flight simulators replicate aircraft handling characteristics with a high level of fidelity and offer a way to accelerate pilot experience which can be more effective than airborne training. For example, severe weather conditions (cross-winds, microburst, wind shear and turbulence) can be selected by the instructor, exercises can be repeated and a sortie recorded for subsequent debriefing analysis. Flight crews can also experience system failures and operational conditions that would be too hazardous to practise in an aircraft. A pilot encountering an engine failure will have practised the emergency in a flight simulator within the previous six months even though, with improvements in aircraft reliability, most pilots will rarely experience a real engine failure. In Line Oriented Flight Training in a simulator, a pilot can depart from Heathrow with ice and thick fog for a night-time landing at Frankfurt with one engine shut down and runway lighting failure, while coping with *en route* emergencies introduced by the instructor.

For experienced flight crews, type conversion can be conducted in a flight simulator. For the most part, this involves familiarisation with aircraft systems and procedures specific to the aircraft. For simulators qualified to the highest level (and with the approval of the regulatory authorities) flight crews can undertake all type conversion training in a flight simulator. The term 'zero flight-time' (ZFT) has been coined for these flight simulators. The training afforded by a ZFT simulator is accepted as being so good, that the first time a pilot may fly that aircraft type is with passengers, albeit with a training captain on the flight deck.

BENEFITS

Flight simulation has made a major contribution to improved aviation safety. It also offers considerable financial saving to airlines and reduces the environmental impact of civil aviation. Military pilots can practise for situations that would be impractical in airborne training exercises.

Airline flight crews must undergo two days training and checking in a flight simulator every six months. Typically, the ratio of simulators to aircraft is 1:30 for narrow-body aircraft increasing to 1:15 for wide-body aircraft, with capital costs amortised over 15 years. For an airline with 1,000 pilots, recurrent training and checking using aircraft would cost some $60m annually[1]. Flight simulator operating costs are less than one tenth of this figure and the economic benefit is critical to airline success. Moreover, many flight simulators are operated intensively for over 20 hours each day, producing significantly less carbon emissions and environmental noise than equivalent airborne training.

Recent military operations, together with public concern over environmental issues, increasingly complex weapons systems and the risks to flight crews, have convinced the armed forces of the

[1]2006 financial figures.

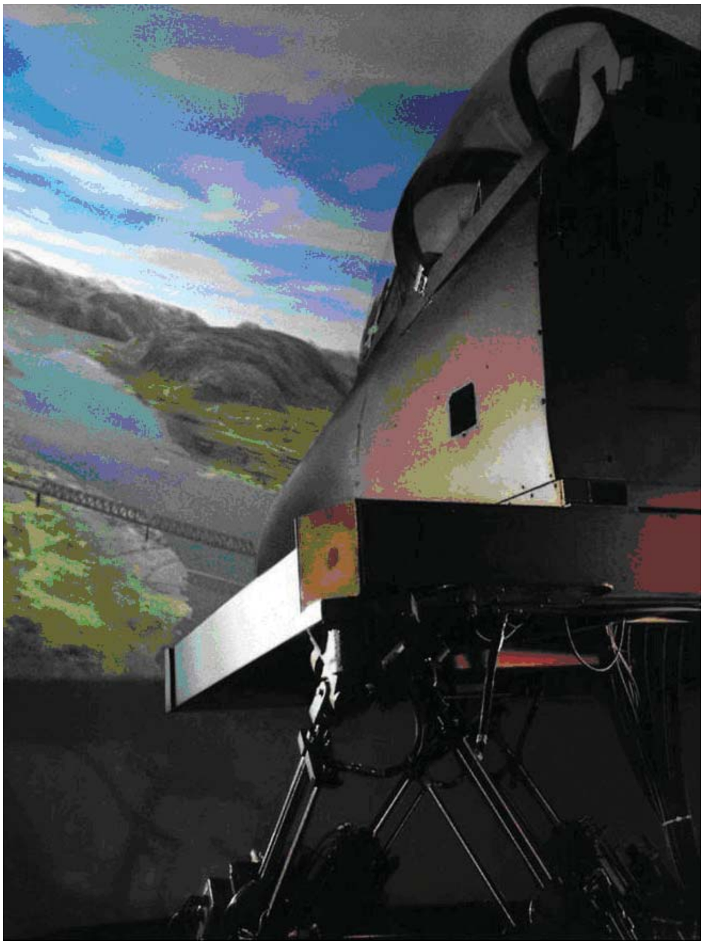

Figure 4. A military flight simulator.

compelling case for flight simulation (Figure 4). With acceptable training transfer, the use of weapons ranges can be reduced. Moreover, some scenarios involving multiple forces and electronic warfare cannot be practised in the aircraft in peacetime while ensuring strategic and tactical secrecy whereas they can be practised in flight simulators. For example, using the six simulators at RAF Benson, helicopter crews can engage in multiple aircraft sorties where the instructor can draw on virtual forces to provide realistic engagements without the cost of airborne aircraft. An area where simulator training has proved particularly effective is in mission rehearsal. Prior to an operational sortie, crews can practise in a flight simulator, often flying over unfamiliar territory, and are able to adapt the mission from the lessons learnt in the simulator.

The technology developed for flight simulation has been applied in other sectors of aviation, where simulation provides safer and more effective training but at significantly reduced cost in comparison with ‘live’ training:

Aircraft technicians can practise installation, removal and fault-finding of equipment in a synthetic environment without using actual aircraft parts (Figure 5);

Cabin simulators provide valuable training for civil airline cabin crew, particularly emergency procedures;

Military simulators afford unique training opportunities for the mission crew, where flight deck simulators and rear crew mission simulators can be linked electronically to provide both mission rehearsal and crew resource management training.

Figure 5. Aircraft maintenance trainer.

Figure 6. Civil flight simulator motion system.

TECHNOLOGY DRIVE INDUSTRY

Flight simulation is at the leading edge of several technologies, particularly in computer graphics, distributed computing and mechanical actuation.

Since the early 1990s, advances in flight simulation have paralleled the computing revolution and the growth in PC-based technologies, with dramatic increases in computing speeds and memory capacity together with falling costs.

In a flight simulator, a pilot’s visual, motion, aural and tactile sensors must be stimulated in such a way to provide the same cues as in flight. The illusion of flight must be sustained at all times, smoothly and consistently, and the instructor’s interaction must be unobtrusive. False cues will break the illusion, possibly reducing the training benefit.

The mathematical modelling of the dynamics of an aircraft, its engines and electrical and mechanical systems, emulating the

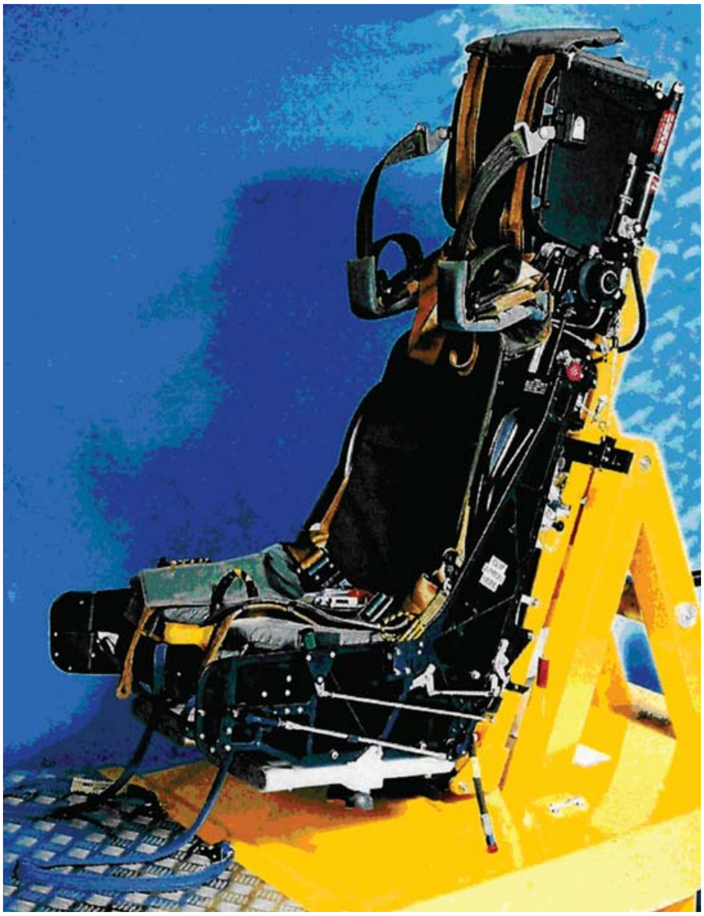

Figure 7. Military flight simulator G-seat.

Figure 8. Flight simulator visual system.

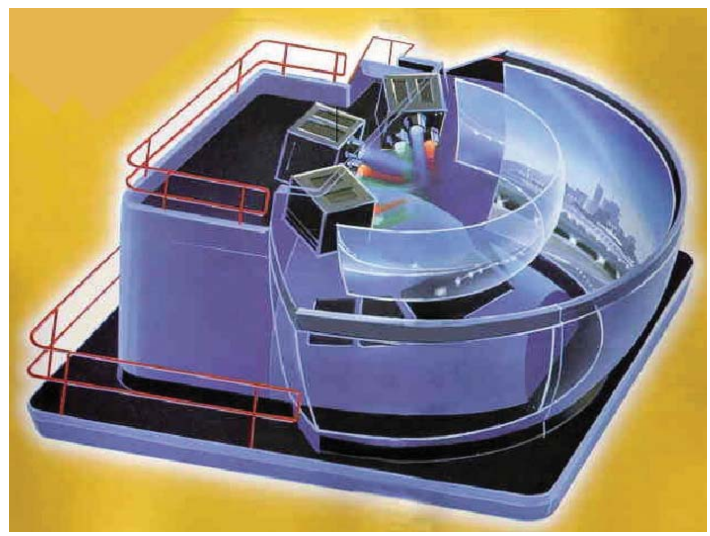

Figure 9. Curved mirror projection system.

avionics systems, moving the heavy motion platform on which the simulator cabin is mounted and generating high-fidelity out-of-the-window images are all very demanding tasks in terms of computer processing. In a modern simulator, these computations must be completed in less than 20 milliseconds; nowadays, this high computational performance can be achieved with a distributed network of microprocessors.

Aircraft motion is simulated by moving the simulator platform vertically, fore and aft, and side-to-side, and rotating it about these three axes (Figure 6). This is a particularly challenging requirement for mechanical actuators which must be adequately responsive to stimulate realistic acceleration cues, while ensuring safe, reliable and noise-free operation.

Although the displacement of a simulator platform is typically limited to a few metres, by combining knowledge of the physiology of the human motion sensors with a mathematical model of the actuators, the flight crew in a simulator can experience motion cues remarkably similar to those in an aircraft. For military applications, where sustained G-forces cannot be simulated simply by displacing the simulator motion platform, these cues are provided by a special simulator seat, known as a G-seat (Figure 7). The base and sides of the G-seat are moved in response to perceived accelerations, applying pressures to the pilot's body that are similar to those felt during high G-force manoeuvres in flight.

Visual cues are provided by computer-generated images viewed through the cockpit windscreen or in a helmet-mounted display. The observed scene must faithfully replicate all appropriate geographical features and airfields and be displayed with the correct depth of image and with the scene viewed without distortion by all flight crew, and possibly an instructor. This image rendering process is achieved by graphics engines, developed specifically for flight simulation or, more recently, adapted from PC graphics technologies. The quality of the images generated by a modern visual system is shown in Figure 8.

The most common type of visual system uses three or more projectors to display the image via a curved mirror (Figure 9).

For military systems, where very large fields of view are required, an array of projectors may be used to display the image on the inner surface of a spherical dome containing the cockpit. Alternatively, a helmet-mounted system displays the visual scene using small optical devices mounted close to the eyes, slaved to where the pilot is looking (Figure 10).

FLIGHT SIMULATORS IN RESEARCH AND DEVELOPMENT

The modern aircraft is a systems platform. Flight simulation offers major advantages in designing and developing aircraft systems to analyse designs and to verify system performance prior to airborne trials.

Figure 10. Helmet-mounted visual system.

Figure 11. Airbus Desktop Development System.

During the development of aircraft systems, a simulator can provide valuable insight into system behaviour and performance, recording data to verify the design. In addition, a simulator can be used to analyse human factors' issues which are often required in pilot-in-the-loop studies. An engineering flight simulator provides this essential design support and enables designers to monitor system behaviour and the interaction between the pilot and the systems. Large amounts of data can be recorded and analysed to confirm that the system fulfils its design specifications and meets its requirements.

A range of engineering flight simulators is used from desktop systems (Figure 11), through to fixed-based simulators. The use of engineering flight simulators achieved significant reductions in cost and design time on the Boeing 777 and Airbus A380 programmes. Aircraft manufacturers also use 'iron-bird' rigs, fitted with actual aircraft equipment and systems, to verify the performance of actuators and sub-systems and to support systems integration (Figure 12).

The role of flight testing has changed significantly as a consequence of the capability of engineering flight simulators. It was used previously to verify the airborne performance of aircraft equipment; however, with advances in simulation and modelling, it may be used to verify results obtained from simulation. For example, in the Eurofighter programme, flight trials data were transmitted from the aircraft to the ground and analysed in real-time to ensure the validity of data derived in flight simulation, reducing the need to repeat flight tests.

Some systems evaluations extend to operational environments, where several aircraft interact with an air-traffic management

Figure 12. Airbus Iron-Bird Rig.

system or a mission-control system. In these environments, proof-of-concept trials conducted in a flight simulator provide valuable insights into system capabilities and limitations.

During the development of an aircraft or aircraft systems, several different simulations may be undertaken, including aerodynamic modelling, structural analysis, operational analysis and flight control system design. Advances in computer technology now allow the designer to combine simulation tools and provide visualisation tools to assess system performance.

These concepts, termed 'Synthetic Environments' (SEs), may be applied to the whole life cycle of a system or platform from initial concept through design and production to flight test and in-service use. Such end-to-end simulations afford more degrees of freedom for 'what-if' studies. Detailed trade-off studies, undertaken prior to the procurement phase of a large project can result in major overall saving and considerable emphasis is now being given to the development of SE tools and methods where manufacturers and procurement agencies work closely together to optimise the capability and cost of large-scale programmes. Simulators can now be interconnected and combined to provide insight from the initial operational requirements, through all phases of development to maintenance and operational deployment. The considerable potential benefits of SEs have become possible only as a result of the advances in flight simulation over the past decade.

THE UK FLIGHT SIMULATION CAPABILITY

The UK has led many of the major initiatives in flight simulation and has been a key player in flight simulation developments over the past 30 years. The UK flight simulation industry is still positioned strongly in the world aerospace industry.

The current UK flight simulation industry can be traced back to the Link Miles and Rediffusion companies. Both companies established a major presence in terms of world-wide sales of civil and military simulators in the 1960s. Since then, following a number of mergers, these companies now form part of the Thales Group, employing some 1,200 staff in the UK, with world-wide sales to major airlines and military organisations.

Flight simulation plays an increasingly important role in the UK aerospace industry. In recent years, UK companies have manufactured some ten full flight simulators per year, representing an annual turnover in excess of $150m. Many other companies are involved in refurbishing, upgrading and maintaining simulators, and producing simulator systems and components, employing over 400 staff in the UK. Some 55 UK companies exhibited at the 2006 International Training Equipment Conference (ITEC), the annual European exhibition for the industry. In addition, several companies operate training centres for civil and military flight crews and flight simulators support R&D programmes in research organisations, aircraft manufacturers and equipment suppliers. Both Westland Helicopter and BAE Systems have large simulation departments supporting aircraft development programmes.

Simulation closely follows the growth in airline operations in the UK and, since 2000, the number of civil flight simulators in the UK has increased by 27%. This growth rate is forecast to increase both in the UK and world-wide. Indeed, the shortage of flight simulation capacity world-wide will continue to provide opportunities to develop new training facilities in the UK for several years to come. In 2006, there were some 75 civil full flight simulators in the UK, with an average utilisation of 3,000 hours per year. Based on an operating cost of $400 per hour, the annual revenue for civil operations exceeds $90m. There were a further 55 flight simulators in training centres for the Royal Navy, the Army and the RAF, many of which are operated under private finance or partnering arrangements. Over 1,000 instructors, maintenance engineers and management and administrative staff support these facilities.

Flight simulation technology research at the Defence Science & Technology Laboratory (Dstl) and QinetiQ (formerly the Royal Aircraft Establishments at Farnborough and Bedford) provides support for the UK armed forces. The modelling of aircraft dynamics, motion cueing, wind shear, helicopter operations to ships and simulator-based evaluation to support the Harrier and Joint Strike Fighter programmes is acknowledged widely. Expertise in military simulation in BAE Systems is concentrated at Warton, where advanced simulation programmes have supported the development of many platforms, 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 simulators in other countries. These research activities have extended to software development for SEs and support for UK defence acquisition activities.

The UK has led many specific developments in flight simulation since 1970:

- Initiatives to develop appropriate international standards, led by the UK Civil Aviation Authority, working closely with the Federal Aviation Administration in the USA and UK operators and manufacturers;
- Development of hydrostatic seals for hydraulic actuators in motion platforms;
- Visual systems technology, notably, the wide-angle continuous field-of-view projection systems used in civil simulators.

THE ROLE OF THE ROYAL AERONAUTICAL SOCIETY (RAeS)

The RAeS Flight Simulation Group (FSG) plays a significant international role in bringing together manufacturers, operators and the regulatory authorities to progress important initiatives and formulate policy. Its role is unique in the world.

The RAeS recognises that flight simulation has become an important field of aeronautics, covering research, development and flight-crew training programmes. The FSG provides an international forum to encourage technical excellence, enable collaboration and facilitate progress on significant issues in flight simulation. The Group organises two conferences every year, provides evening lectures and supports Society Branch activities. It also increasingly supports the professional development of engineers in the flight simulation industry, in related departments in universities and student members of the Society.

With its impartial role in a Learned Society, the FSG has facilitated the building of trust between various bodies and has played a significant role by leading three International Working Groups (IWGs) with representation from simulator manufacturers, airlines and the regulatory authorities:

- In the 1990s, the FSG led an IWG that produced the document subsequently adopted as the *ICAO Manual of Criteria for the Qualification of Flight Simulators*; this manual provides the basis of national regulations on the subject.
- During 2003-4, similar work resulted in the handbook *Data Package Requirements for Design and Performance Evaluation of Rotary Wing Synthetic Training Devices*.
- In 2005, the US Federal Aviation Administration asked the FSG to set up a further IWG to define a new ICAO standard for the full range of FSTDs, from basic instrument trainers to ZFT full flight simulators.

These documents, together with the *International Civil Flight Simulator Evaluation Handbook* (Figure 13) used for the qualification of civil flight simulators (and also developed under RAeS auspices), are now in day-to-day use throughout the world by operators and regulatory authorities. The RAeS FSG continues to play a leading role that is unique in the world.

THE FUTURE OF FLIGHT SIMULATION

Flight simulation is a fast advancing set of technologies in a fast expanding area of aviation. As the cost of computers falls and their capabilities grow, the scope and application of flight simulation are also likely to expand at a dramatic rate. Significant technical advances will result in improvements in the quality of flight simulation systems.

To date, the acceptance of a culture of simulation applies to companies and organisations that have been using simulation across a range of applications in procurement, design, development and training. More organisations are starting to appreciate the benefits and, over the next ten years, flight simulation and flight training will play a major role in aerospace, possibly more significant than earlier developments in aerodynamics, propulsion and structures.

With the realisation of their potential benefits, synthetic training devices will become pervasive in many industries. Engineers have used computer-aided design tools for many years and in many areas the simulator will become an extension of these design tools. Simulation will become accepted as an effective method of system evaluation for designers, engineers and in the procurement of equipment.

The widespread use of simulation in airline training is now being extended to *ab initio* pilot training. A recent ICAO initiative, the Multi-Crew Pilot Licence (MPL), is likely to revolutionise the training of airline pilots, offering an alternative to the Air Transport Pilot Licence, where the MPL curricula will make extensive use of flight simulators.

Figure 13. Flight Simulator Evaluation Handbook.

Many of the technologies developed originally for flight simulation have been adopted in other industries and applied to a wide range of applications, such as the training of drivers of trains, cars, lorries, buses and armoured vehicles and ships' bridge and submarine crews. Similar developments are likely to extend to medical training, maintenance engineering and mission rehearsal for emergency services.

Companies that previously developed custom equipment to obtain a leading-edge product will rely more heavily on commercial off-the-shelf (COTS) and PC-based equipment developed for commercial markets where the benefits of customised equipment are far outweighed by the relatively low development costs associated with COTS systems. In particular, real-time simulation is well matched to a distributed architecture of processors connected to a high-speed local area network. COTS network cards supporting transfer rates in excess of 100 million bits per second are commonplace, providing the capability to add additional processors to increase overall performance.

Electrical drive systems have recently started to replace the hydraulic systems which simulate the forces felt by a pilot as the flight controls and engine levers are moved. The use of electrical drive systems also extends to motion of the platform, where the previous hydraulic systems have been replaced with electrical motors, each controlled by a power amplifier to provide the accelerations to replicate the motion cues perceived by the pilot. These advances afford significant energy saving, where a small electrical motor for each actuator, combined with a mass compensation scheme (typically to support 10-12 tonnes) can reduce energy costs by as much as 80%.

Figure 14. A University flight simulator.

With the rapid developments in light valve projection, LCoS (Liquid Crystal on Silicon) projectors offer a major improvement in image quality, in comparison with the traditional CRT (cathode ray tube) projection systems. In the past few years, advances in LCoS projection techniques have overcome the problems associated with poor black levels, image blurring in dynamic scenes and a poor range of pixel visibility. In particular, LCoS projectors support high contrast lights. With a substantial reduction in the cost of acquisition and maintenance combined with improved reliability and a reduction in power consumption of the order of 75%, LCoS projection will become adopted throughout the simulation industry over the next ten years.

The computing requirements of flight simulation are becoming closely aligned with domestic markets, including computer games and virtual reality. Advances in terms of image quality of computer graphics, speed of processing and memory storage will fuel future developments in flight simulation.

With reducing costs of simulator hardware, university departments have started to purchase or develop low-fidelity flight simulators to support teaching on undergraduate and postgraduate courses (Figure 14). Flight simulation needs to be recognised as an established but still evolving scientific discipline, taught in universities and with an established track record of research, to provide the answers needed for the next generation of engineers and flight crews.

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Royal Aeronautical Society
No.4 Hamilton Place, London W1J 7BQ, UK
Tel +44 (0)20 7670 4300 Fax +44 (0)20 7670 4309 e-mail raes@aerosociety.com Web http://www.aerosociety.com