VISUAL AND MOTION CUES

IN THE REAL WORLD
AND IN SIMULATORS

by
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The author

Wing Commander Ian William Strachan was a Test Pilot \(^1\) in the UK Royal Air Force. He was an A1 category Flying Instructor, Instrument Rating Examiner, Air-to-Air Refuelling Instructor, and flew both fixed wing aircraft and helicopters. He commanded a Squadron at the test-flying base at Boscombe Down and the Flight Test Wing at the research base at Farnborough. At Farnborough he led the team that pioneered fast-jet night low flying using Night Vision Goggles, Low-Light TV and Forward Looking Infra Red (FLIR) imagery. He has flown over 150 types of aircraft and over 60 types of flight simulators for 32 types of fixed-wing aircraft and helicopters, also simulators for land vehicles and ship handling.

He was awarded the AFC \(^2\) for flight test flying at Farnborough, a Queen’s Commendation for flight test at Boscombe Down, and is a Fellow of the London-based Royal Aeronautical Society (FRAeS). He is a glider pilot, an ex British Standard and Club Class Champion, and in 2006 was awarded the highest annual FAI award for gliding, the Lilienthal Medal of the Fédération Aéronautique Internationale (FAI), for his work in Chairing the International Gliding Commission GPS committee and developing international standards for GPS-based flight recorders.

Between flying tours, he was a lecturer in Guided Weapons technology at the RAF College of Air Warfare, becoming Senior Guided Weapon Specialist at the College and awarded the MBE \(^3\) for this work. He is a graduate of the RAF Staff College and RAF courses on Electronic Warfare and Weapon Employment. After front-line flying, he was posted to the Flight Simulation office of the Operational Requirements branch of the UK Ministry of Defence in London, and started testing simulators using similar methodology to that used in aircraft flight test, and documenting the results.

After retiring from the Air Force, he edited the publication Jane's Simulation and Training Systems (JSTS), using his background to more than double its contents. After this he edited the Newsletter of the European Training and Simulation Association (ETSA) for several years.

He is an ex-Chairman and current member of the Flight Simulation Group Committee (FSG) of the Royal Aeronautical Society (RAeS). In this capacity he was a member of the International Committee on Aircraft Training in Extended Envelopes (ICATEE) that was created under FSG chairmanship to reduce upset and stall events in Commercial Air Transport, after several high-profile fatal accidents. ICATEE reported to ICAO in 2013 with recommendations for Upset Prevention and Recovery Training (UPRT), now adopted by ICAO and world civil aviation Regulatory Authorities. The result has been a significant improvement of the handling characteristics of Full Flight Simulators in critical situations.

He is now a consultant and writes regularly for several publications in the UK, Europe and the USA. He has lectured at a number of Universities, RAeS Groups, and to other bodies in Europe, the Middle East, China and the USA.

History of this paper

Papers were presented to conferences organised by the Royal Aeronautical Society in London on "Future Flight Simulation", "Visual and motion Cueing" and "Future Helicopter Simulation". These were refined in a paper on Simulator Cueing that was also presented at the Royal Aeronautical Society. A further update was presented at the I/ITSEC training and simulation conference in Orlando, USA, and became the basis for this paper. This paper has been expanded and updated several times, and has been made available on the ETSA and RAeS web pages. In particular, new simulator test results have been added to Annex G as they became available.

Graphics

The graphics in this PDF file are low resolution images, so that the overall size of the file can be kept down

Comments. Comments are very welcome, please send to: ian@ukiws.demon.co.uk

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\(^1\) Graduate of the Empire Test Pilot School (ETPS), founded in 1944 at Farnborough

\(^2\) AFC = Air Force Cross

\(^3\) MBE = Member of the Order of the British Empire
THE REAL WORLD AND SIMULATION - VISUAL AND MOTION CUES

SUMMARY

(i) Simulation Today. Training using simulation now fundamental in both civil and military applications. The Full Flight Simulator (FFS) design is used in Commercial Air Transport (CAT) for almost all training instead of the airliner itself. In the military, simulation-based training is now universal because it is much less costly that using the real equipment for training. Furthermore, military simulators can be connected or "networked" together so that multi-aircraft, multi-role, multi-service or multi-nation training can take place.

(ii) Visual Cues - Real World. Visual cues in the real world include those from the Outside-World (OTW), from Head Down and Head-Up Displays (HDD / HUD), from sensors such as Night Vision Goggles (NVGs) and Forward-Looking Infra-Red (FLIR). The outside world picture includes changes in perspective and streaming of features that have visual contrast. These factors give cues of height and speed. The paper evaluates these and other visual cues in conditions of good and poor visibility, at night, and flight in cloud.

(iii) Visual Cues - Simulators. The resolution of modern Image Generation (I.G.) systems is close to that of the real world. Simulator display systems can use TV monitors, flat screens, forward- or back-projection. Curved mirrors can be used to reflect a screen image, and when the subject looks at the mirror, the image is seen at a realistic distant focus because the mirror has a vertical curvature. In this case the correct perspective can be seen by subjects seated side by side such as pilot and copilot - this is not the case with direct projection on a screen that is a short distance ahead of the pilots. The geographical area of a simulator database is limited only by the size of computer memory, and imagery can be called up from memory, displayed, and then returned to memory.

(iv) Motion Cues. Nine types of real-world motion cues are analysed and compared to those that can be created in a simulator. When an aircraft or other vehicle is disturbed from a steady-state condition, medical science confirms that for the pilot, driver or operator, acceleration cues are perceived first whereas visual cues of change in the Outside World scene, are registered by the brain some time later.

(iv-i) Therefore, if realistic motion cues of acceleration can be generated in a simulator, this will give early warning of a change from the previous state, before visual cues are processed by the brain. This will enable quick control movements to be made in response to conditions such as turbulence, stall, loss-of-control, or to avoid terrain or collision with other aircraft. Realistic motion cues are also important in simulating manoeuvres, particularly where precise control is required. Real motion is therefore needed in aircraft simulators if handling fidelity is required when a pilot is operating the primary flight controls. It follows that it is vital in Upset Prevention and Recovery Training (UPRT) to reduce the possibility of further fatal accidents involving upsets including stall and spin.

(iv-ii) The basic principle of simulator motion platform operation is "acceleration-onset cueing", in which the initial acceleration is closely replicated. Subsequently the movement is backed-off below human sensory threshold so that the platform can be ready for the next acceleration. This works well because it matches the way that the motion sensors of the human body respond in a real-world environment. Platforms with 6 jacks ("hexapods") are readily available, and can generate accelerations in all of the 6 Degrees of Freedom (6-DoF) that can be experienced by a body or vehicle able to move freely in air or space.

(iv-iii) G Cues. Cueing for normal acceleration (Gz) is discussed. Systems that cue for G include simulator motion seats, inflation of the pilot's anti-G suit, visual system dimming at high G, and the use of man-rated centrifuges that produce real G for training.

(iv) Conclusions. Conclusions are drawn on the best mix of simulator systems, the interfaces and phasing between systems, and the training tasks best carried out by combinations of different simulator systems.

(v) Cost Ratios. Costs for the use of simulators are compared to using the aircraft itself for training, showing that simulators save enormous amounts of money compared to using the real vehicle. Simulator-to-aircraft cost ratios vary from about 1:40 for a large airliner such as the Airbus 380 or Boeing 747, to about 1:15 for fighter aircraft. For most military aircraft, simulator training needs to be reinforced in the real aircraft except for training that is either too hazardous or too costly in the real vehicle, or involves enemy action.

(vii) Commercial Aviation. Simulator training for Commercial Air Transport (CAT) is working well under a sound system of standards and regulation that includes the "Full Flight Simulator" (FFS) design with a 6-axis motion platform and wide-angle visual system. The rules and procedures for FFS originate from the International Civil Aviation Organisation (ICAO) and are mandated for many aspects of training by civil aviation Regulatory Authorities such as the US Federal Aviation Administration (FAA), European Aviation Safety Agency (EASA) and other Authorities. The "Level D" FFS design is the current highest level. After a series of "upset" and stall accidents involving considerable loss of life, the latest FFS design is part of worldwide Upset Prevention and Recovery Training (UPRT).

(viii) Military Aviation. Simulators for large transport aircraft and heavy helicopters generally use the civil Level D Full Flight Simulator design. However, most fighter aircraft simulators do not have motion platforms, wide-view visuals being preferred that are not compatible with mounting on motion platforms. As well as motion platforms, other motion cueing systems are available including simulator G-seats, G suit inflation, and the visual system can give tunnel-vision under high computed G. Man-rated centrifuges are available for real high-G training. The high cost of training using the aircraft itself has increased the use of flight simulation in the military. Furthermore, connecting simulators though network links enables multi-role, multi-Service and multi-nation training, allowing training that cannot be carried out on the real vehicle. Further, enemy action can be modelled and alternative situations investigated. Use of simulation reduces wear-and-tear on the main vehicle, with the potential to extend the life of the vehicle fleet. These developments are now recognised at the highest military levels and a ratio of 50:50 between simulator and live training is now common. Overall, the proportion of simulation is increasing, and networking with other simulators enables more realistic training than ever before.
CONTENTS

Paras Subject
1 Introduction - Simulation today - Current Civil and Military use
2 Image Generation (I.G.) Systems
3 Instrument cues
4 Visual Cues
   4.2 Perspective changes
   4.3 Stereoscopic effects
   4.4 Visual streaming
   4.5 Effects of high G
5 Display Systems (DS)
   5.1 Collimated displays
6 Motion cues
7 Analysis of motion cues
   7.1 The six degrees of freedom
   7.2 Control of flight path
   7.3 The Inner Ear
8 Time delays in detecting cues - receipt of cues by the brain
9 Simulator cueing systems available
   9.1 Motion platforms
   9.2 Cueing for High G
   9.3 Vibration cueing
10 Motion Platforms - General
11 Principles of Acceleration-Onset Cueing and Wash-Out
12 Cues of continuous acceleration and sideslip
13 Motion feedback in aircraft and simulators
14 Replication of real-world cues by a Motion Platform
15 Poor motion cueing
16 Smaller Platforms and Platforms with 4-DoF or Less
17 Civil Aviation Terminology- FFS Levels, FTD, ZFT and others
18 Tests on flight simulators
19 Simulators without Motion Platforms
20 Simulator Sickness and Cue Conflicts
21 Flight Simulators of the World - annual statistics
22 Vehicles other than aircraft - Ground vehicles and Ships
23 Cost ratio - Simulator to Real Vehicle training

Summary and Conclusions

24 Visual cues
25 Motion cues
26 Conclusions

Annexes (in a separate PDF file)
A The six degrees of freedom, table
B Real world motion cues - Part 1 - Visual Cues of Motion, table
C Real world motion cues - Part 2 - Cues of Real Motion, table
D Cues from a simulator, table
E Civil Regulatory Rules - Summary
F BAES Hawk simulator test results
G Simulator Test Reports
H Cueing for G forces
I Flight Simulators of the world - Civil and Military - numbers and analysis
J References

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THE REAL WORLD AND SIMULATION
VISUAL AND MOTION CUES

1 Introduction - Simulation Today

1.1 Civil Aviation. In the Commercial Air Transport (CAT) area, the "Full Flight Simulator" (FFS) design is now used instead of the aircraft itself for conversion of pilots to new types of airliners. Simulators are also used for regular "recurrency" training on a pilot's current type. The FFS has a replica cockpit that precisely models the real aircraft, a wide-view display of the outside-world (OTW), and a motion platform that moves the cockpit with similar initial accelerations to those in the aircraft. An experienced pilot converting to a new type of airliner is trained on a the highest level of FFS and makes the first flight on the aircraft on a revenue flight with passengers. However, this pilot is supervised by a Training Captain until he or she is checked out to fly without supervision. Over the next 20 years, the world airliner fleet is forecast to double, so there will be a proportionate increase in the number of FFS and flight training schools. Outside the aviation area, simulation is extensively used for training for other vehicles on land and sea.

1.2 Military. Training using real military equipment is necessary but is expensive and can be hazardous. Simulations are less costly and databases can include enemy and other forces that are not available for live training, and future scenarios can be tried out. Simulators can be networked to others and to live assets. This allows multi-role, multi-Service and multinational training that is not otherwise possible. Some examples follow.

1.2.1 Simulators are highly cost-effective when compared to the expense of using the military vehicle itself for training. Cost ratios vary from 10:1 to 40:1 in favour of simulators (more detail, para 23). Mission Simulators for large aircraft and heavy helicopters generally follow the design of the Level D Full Flight Simulator (FFS, see para 1.1. above). Military Level D equivalents have extra facilities such as weapons, defensive aids, detailed terrain data for low flying, etc.

1.2.1.1 The simulator for the US Air Force C-17 Globemaster III strategic transport aircraft is a Level D Full Flight Simulator design with enhancements to match the C-17's role. Conversion of new pilots to the C17 is after only two training flights in the aircraft before the check ride itself. Before this, over 20 simulator sorties are flown.

1.2.1.2 A very similar situation is pilot conversion to the Australian Air Force Multi Role Tanker Transport (MRTT) that is based on the Airbus A330 airliner. Qualification on type requires only two training flights before the qualification test, preceded by sorties on a Level D Full Flight Simulator.

1.2.2 The word "networking" is crucial in future training systems, and enables simulators at different locations to work together in combined training exercises. Network links work over inter-continental distances, and for well-prepared training exercises real military vehicles can also be networked in to the exercise. An example is the US Air Force Distributed Mission Operations (DMO) system that became operational in the early 2000s and connects simulators together for combined training. The principle has now been expanded to multi-Service and multinational training throughout the world, using standard network links.

1.2.3 A 2015 US Government Business Council paper on the theme of "Going Virtual" pointed out that integration of simulation into training not only reduces costs, it also prepares for new situations. Figures in the paper include US Air Force savings of some 350 million dollars per year by using simulation to replace training previously flown on aircraft. On Naval aviation, the paper noted a saving of about 60 million dollars per year per aircraft type by increasing the proportion of training by simulation.

1.2.4 A 2015 Canadian Air Force paper stated that training using real aircraft is becoming difficult to afford in a country with a large land area but a small population and limited military resources. It acknowledges that training through simulation continues to improve in quality and reduce in cost, whereas the expense of real flying hours in complex modern aircraft has greatly increased. The Canadian Air Force now uses a "Networked Common Synthetic Environment" for future training. At the same time, there have been reductions in live training that will make aircraft more available for combat operations and prolong their Service lives.

1.2.5 An aim of the last UK Defence Review was to achieve about a 50:50 balance in training between Live training and Simulation. The vehicle can only be a military aircraft but also an Armoured Fighting Vehicle (AFV), an artillery piece; a ship's bridge, control room, or weapon system.

1.3 Simulator Technology. What follows is a non-mathematical survey of simulator systems. It mainly covers situations in which the control of steering or flight path is by the simulator subject rather than through automatics such as an aircraft autopilot. It analyses the cues used for control of vehicles on land, sea and air, relates the cues to simulator systems, and draws conclusions. Aircraft systems are mainly discussed because all six degrees of freedom are constantly involved, and the principles of visual and motion cueing are demonstrated in aircraft better than with vehicles with less than all six degrees. Visual systems are analysed first, followed by motion and other systems.

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4 Pitch, Roll, & Yaw rotations plus Heave, Sway & Surge linear movements, see Annex A for more detail
2. **Image Generation (I.G.) Systems.** Modern computer-generated imagery (CGI) is now so realistic that it approaches real-world fidelity. This is due to ever-increasing computer power, the availability of high-resolution real-world terrain data, and computer graphics with colour, shading and textures to model the real world. Detailed three-dimensional terrain databases can be stored in computer memory, “paged up” for active display, then being returned to memory ready for further use.

![Image of computer-generated imagery](image)

### 2.1 Wavelengths of Imagery

The visual spectrum to which the human eye is sensitive is between wavelengths of about 400 and 700 nanometres\(^5\). 400nm is seen as Violet and 700nm as dark red, with blue, green, yellow and orange between. In many simulators, imagery is needed for Night Vision Goggles (NVGs) that operate in the near Infra-Red up to wavelengths of about 1000 nanometres (1 micron\(^5\)). Imagery may also be needed for Thermal Imaging (TI) and Forward-Looking Infra Red (FLIR) systems operating in the far Infra-Red at about 10 microns. For aircraft and ship simulators, radar imagery is required. Images at these different wavelengths must be compatible with each other so that when used in a simulation, there are no mis-matches or irregularities.

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### 2.2 Variations within Polygons - use of Electronic Tags, Attributes or Material Codes

Real world Computer-Generated Imagery (CGI) includes many shapes, the corners of each polygon being precisely defined in three dimensions (x, y, z) in the computer database. Each polygon is then coloured, shaded, and textured through electronic “tags” that call up the appropriate characteristic. These can be varied with conditions such as time-of-day (dusk, dawn, night, day with different sun/shadow angles), different visibilities, rain, snow, special effects such as lightning, weapon effects, etc. It is not difficult to add extra electronic tags for imagery for NVGs, Thermal Imaging and radar, which can be called up when those images are required. The function of what is described above as “Electronic tags” can also be carried out by so-called “attributes” or “material codes”.

![Image of Rockwell Collins simulated night imagery](image)

### 2.3 Level of Detail (LoD) Scheduling

To reduce the amount of image processing needed at any one time, full-fidelity imagery is only called up when it is close to the eye-point, lower-fidelity being used when distant from the eye-point.

3. **Vehicle Instruments.** For the control of air, land and sea vehicles, extra visual cues are available by looking at instruments mounted in a dashboard or panel. Such instruments can easily be replicated in a simulator. Where outside visual cues are reduced, instruments and motion cues become even more important. This includes reduced visibility and reduced outside illumination such as at dawn, dusk and night. In aircraft this includes flight in cloud, Instrument Flying (“I.F.”).

### 3.1 Flight Instruments and Motion Thresholds

The interpretation of flight instruments and motion sensations requires conscious effort and considerable training for flight by sole reference to instruments. Low motion-rates are not detected by the body sensors, and one consequence is that loss of aircraft control eventually results from any attempt to cloud-fly using manual control without reference to flight instruments. Therefore, pilots are taught to interpret sensations with care, and when outside visibility is reduced, to rely on instrument readings for judgement of spatial orientation. These conditions are well-replicated in a modern simulator.

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\(^5\) A Nanometre is 10\(^{-9}\) metre, one thousandth of a millionth of a metre, and a Micron is a millionth of a metre.

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VISUAL CUES

4. Visual Display. Computer Generated Imagery from the Image Generation (I.G.) System is shown on a simulator Display System (DS). Where the external scene is displayed it is called Outside-World (OTW) imagery, to differentiate from instrument displays. The OTW display has characteristics such as Field of View (FoV), scene content (terrain, objects, cultural features), textures, shadows, brightness, resolution, and the focal distance of the imagery as perceived by the simulator crew.

4.1 Cues from Visual Displays. The judgment of height, speed, and direction by the simulator subject is by comparing short-term changes in the OTW visual scene to those with which the subject is familiar in the real world. Many visual cues are automatic and require little or no conscious thought, particularly where the subject is experienced in the real environment and the brain is used to receiving and interpreting the cues. There is also a Design Eye Point (DEP) from which the display is optimised so that the geometry of the scene from the DEP is as near real-world as possible.

4.2 Rate of Change of Perspective (RCP). A strong cue of movement in the real world is the rate-of-change of perspective of objects at different distances. That is, the way objects move relative to each other as the eye-point moves across a scene. In the diagram a man stands in front of a house, behind which is a tree. As the eye-point transits from left to right, the relative angles of the man, house and tree change. Few simulator visual scenes are static for long, and RCP is a compelling cue.

4.2.1 Stereoscopic Imagery. The RCP effect means that a stereoscopic (two-channel) display system is not required, because 3D cues come from the rate of change of the relative positions of objects in the scene, as shown in the diagram. For instance, a probe-and-drogue refuelling simulation can be effective without stereoscopy because the relative positions of probe, drogue, hose and tanker aircraft change with time and give the cues required without needing a second visual channel.

4.3 Stereoscopic Images and Optical Infinity. So-called "Optical Infinity" is the distance beyond which the image of an object in the left and right eyes is essentially the same. That is, there is no noticeable stereoscopic effect due to different left and right images. For the average adult this distance is about 9 metres (29.53 ft, or about 30 feet). At that distance, the left and right eyes see a small object with a difference of about half a degree. For objects at greater distances, there is no case for even considering the additional cost and complexity of a two-channel stereoscopic system, and at lower distances with a moving scene, the RCP cue is strong (4.2.1 refers). In any case, if a two-channel stereoscopic display system is used, the setting up of the channels has to be very precise or disorientation can result.

4.3.1 Disorientation. There have been instances of disorientation and even nausea from stereo systems in which the two channels were even slightly misaligned. In these cases the visual imagery looked normal but after a while the brain reacted adversely to the misalignment and triggered symptoms of disorientation.

4.3.2 Stereo effect from RCP. A stereoscopic effect was obtained from a prototype Night Vision Goggle system with a single intensifier tube, from which an identical image was presented to each eye through a binocular splitter. When looking sideways from a fast-jet when flown at low level, the RCP cue was so strong that a 3D image was perceived. As experts from the RAF Institute of Aviation Medicine (IAM) said at the time, "the eyes are the sensors but the brain is the data processor". This effect can also be experienced when close to a large TV screen (at a distance of about the screen diagonal) where the picture is showing a rapidly changing scene such as looking sideways from a moving vehicle or transiting through a scene with high vertical objects at different distances.

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6 Such as during an evaluation of a stereoscopic system for a generic fighter simulator, see Annex G page 14

7 Paper on low flying by reference to Electro-Optical Sensors, RAE Farnborough, 1981
4.4 Visual Flow / Visual Streaming. Another strong visual cue uses the angle and speed that points of visual contrast "stream" or "flow" though a scene. This "visual streaming" is sensed in the peripheral vision and needs no direct look or precise focus on any of the points of contrast that flow through the scene. To a subject used to the real-world situation (such as aircraft piloting or driving a vehicle) the interpretation of this cue does not require conscious effort. This is because, in the real world, the brain is used to registering the speed and angles of points-of-contrast that flow through the visual field. To an aircraft pilot, the brain interprets this in terms of height above ground and the direction and speed of the vehicle. Visual streaming is sometimes called "Vection" or "Picture Flow". The cue is particularly strong in a situation with high-contrast texture and a high density of other points-of-contrast in the scene. Texture and terrain alone are capable of producing the streaming cue; 3D objects in the scene are a bonus. The streaming cue also works in poor visual conditions, because only a few contrast points flowing through the visual scene are needed for the cue to work, and this is safe as long as the terrain is not too rugged or the aircraft is very low.

4.4.1 Visual Flow Patterns. Typical visual flow patterns for an aircraft are illustrated above. In the "nose below horizon" situation on the right, the centre point of the streaming arrows is the direction of the aircraft Velocity Vector (VV). This is the eventual point of impact with the ground if the pilot does not raise the nose above the horizon before getting too close to the ground. This is a situation often met in low level contour-flying where the pilot is constantly adjusting pitch angle to fly at the desired height above ground.

4.5 Visual effects of High G. Acceleration along the vertical axis is described as Gz. In aviation this is normally abbreviated simply as "G", together with a number which denotes multiples of what is felt in straight-and-level flight. For a pilot weighing 150 lbs, under 2G will feel as if it was 300 lbs; at 4G, 600 lbs; at 9G, 1350lbs.

4.5.1 Eye-Point Lowering under G. As G increases in a steep turn, a loop, or other manoeuvre, the body is compressed and the pilot's eye-point lowers. Pilots use muscular effort to maintain the familiar eye-line. This effect can be used in simulator G-seats where the seat pan is lowered under high computed G, to simulate this effect.

4.5.2 Very High G. In many fighter aircraft, the cleared flight envelope includes loadings up to 9G. Symptoms at such values can include loss of peripheral vision ("tunnel vision"), reduction in colour perception ("grey-out") and finally loss of vision altogether. This is dangerous because complete loss of consciousness ("black-out") is imminent unless action is immediately taken. Simulator visual systems can easily produce these effects for training purposes.

4.5.2.1 G-LOC. Black-out due to G is more precisely known as G-induced Loss of Consciousness (G-LOC), and is particularly dangerous because it takes some time to recover even when G is reduced. During a G-LOC event, the brain is starved of oxygen, and after oxygen deprivation, after-effects include mental confusion. In recovering from G-LOC, the period of confusion and spatial disorientation is between 10 and 20 seconds, which has been fatal in many G-LOC events in single-seat aircraft.

4.5.2.2 Training. For a trained and fit pilot, the above effects are unlikely at less than 6G without an anti-G suit, 9G if wearing good anti-G protection such as an anti-G suit and partial pressure breathing under high G. More detail is at para 9.2, and Annex H deals specifically with cueing for high G. This includes the use of an anti-G suit in the simulator, motion-seats designed for simulators, pressure breathing under G, visual system G-dimming; and the use of man-rated centrifuges for real high-G training.
5 Simulator Visual Display Systems. Display of Outside World (OTW) imagery varies from simple systems with one or more TV screens positioned ahead of the subject, to more complex systems through which the subject sees objects at exactly the same angles as in the real world. Wide angle display systems have three, five or more display "windows", giving a continuous Field of View (FoV) of 180 x 45 degrees (3 windows) 220 x 45 (5 windows), etc. The imagery where a Window is next to another needs to be specially "edge blended" to avoid visual discontinuities at the boundaries of each image. The diagrams below show systems with three Image Generator channels. On the left is a layout designed for a single subject. On the right is a system for two subjects seated side by side, where the two centre windows display the same I.G. channel. The geometry in the right hand diagram is not ideal because there are anomalies when looking across the simulator cab in the direction opposite to the subject’s seat. For a better solution, see 5.2.1.

5.1 Wide Angle Displays. A large Field of View (FoV) is required in fighter aircraft simulators. The inside surface of domes or partial domes can be the projection surface. Another solution is to use back-projection on flat semi-transparent screens ("facets") that surround the subject of the simulation. The pictures below show two domes and two faceted systems.

5.2 Focal Distance. For displays using direct projection, the focal distance of the image is the distance of the display from the simulator crew. The use of a screen with short focal distance leads to perspective errors if the subject is laterally (sideways) displaced from the Design Eye Point (DEP) of the display. An example is an aircraft that has two crew seated side-by-side, or ground vehicles where the driver, gunner or commander are seated side-by-side.

5.2.1 The diagram on the right shows the error angle or "image offset" for the second crew member in a short focal length display optimised for the design eye-point (DEP) of the left crew member. Although experience has shown that about 10 degrees of image offset can generally be tolerated without too many adverse effects (see later, para 20.1), another display solution is needed if perspective errors for the second crew member are to be avoided.

The next para illustrates a system that eliminates such image offset errors and is in worldwide use for Full Flight Simulators (FFS) for Commercial Air Transport (CAT) and many military aircraft.
5.2.2 Distant Focus ("Collimated") Display Systems. The diagram below shows from left to right, (1) the problem, (2) the real-world situation, and (3) a display solution.

A display with optics that give a distant focus is said to be "collimated". This can be achieved in a simulator display by replacing the screen by a mirror that has vertical curvature as well as horizontal extent, shown on the right of the three diagrams above. The amount of vertical curvature in the mirror sets the focal distance of the imagery. This design is sometimes referred to as a "Cross-Cockpit Collimated Display", CCCD or C3D.

5.2.3 CCC Display Layout. The three pictures below show the layout, first developed by the Rediffusion company of Crawley, UK, first offered for sale in 1982 under the name WIDE (Wide-angle Infinity Display Equipment). Imagery is back-projected on a screen above the cab, out of view of the crew, who see its reflection in the mirror. The focal distance might be set at a hundred metres for a simulator for a large transport aircraft, less for a helicopter that often operates close to objects such as trees or buildings. Such large mirrors would be very heavy if they were made of glass, so C3D systems generally use lighter materials such as Mylar, coated with a reflective surface. When the simulator is in use, a suction pump pulls the mirror material against an a shaped surface so that the correct curvature is produced.

CUES OF REAL MOTION

6. Motion Cues for Control of Vehicle Path

6.1 Constant Unaccelerated Motion. When a vehicle is moving at a constant speed and height in smooth conditions, if the observer’s eyes are closed, no movement may be sensed. The vehicle can be on land, sea, air or in space.

6.2 Disturbance Cues. It is disturbance from the above steady-state condition that provides the cues on which the vehicle driver or aircraft pilot bases control movements, in order to either regain the set condition or to change the condition as required. However, a change from constant velocity requires an acceleration to initiate the change. Acceleration comes first and displacement follows. After an initial acceleration, the displacement in angle or distance from the original steady-state condition becomes progressively greater unless the acceleration reverses, for instance as a result of operator control inputs to resist disturbances such as due to a turbulence in aircraft. Because acceleration precedes noticeable displacement, if the human body sensors of acceleration can detect the initial change, corrective action can be quicker than if only visual cues are used.

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The word “collimation” is derived from "Co-Linear", implying parallel lines or infinity focus. In a collimated display the focal distance is set by the vertical curvature of the collimating mirror, and is generally set at about 100 metres.
6.3. Acceleration Cues - the Key to Rapid Control Response. In the real vehicle, acceleration cues are important in sensing short-term disturbances (ie over a few tens of milliseconds). In the longer term, (tenths of a second, seconds) visual cues of displacement reinforce the motion cues. In aircraft, cues such as sustained G forces become important, but take some time (seconds) to build up. Therefore, where quick control responses are required, particularly in aircraft, cues of initial acceleration are the key. An experienced pilot is used to making such control movements automatically, for instance to maintain straight-and-level flight when flying in turbulence. In a flight simulator, quick and accurate operation of the flight controls similar to the aircraft itself is a measure of so-called "handling fidelity". In flight test, handling qualities are assessed using systems such as the Cooper-Harper rating scale, which can also be used in assessing simulator control and stability characteristics.

MOTION CUES IN THE REAL VEHICLE

7 Analysis of Cues. The motion cues available to the driver or pilot in a real vehicle can be analysed, so that their relative importance in various situations can be assessed. This can then be compared with how well they can be simulated. Particularly important are the cues that are critical to operation of the primary controls that alter the vehicle path, also cues relating to tasks such as tracking and weapon aiming and, for aircraft, formation flying and landing. First we need to establish what types of motion are available and then look at the ways it is cued in the real world.

7.1 Six Degrees of Freedom. There are six so-called "Degrees of Freedom" (DoF) that relate to any single rigid object capable of unconstrained movement, such as an aircraft in flight, a spacecraft or a submarine when underwater. The six are made up of three angular rotations and three linear movements. The angular rotations are known as pitch, roll and yaw, the words being common to aircraft, ship, spacecraft and simulator terminology. In simulator terminology the linear movements are called "heave", "sway" and "surge". Heave is "up and down" (vertical movement), sway is "left and right" (lateral) and surge is "fore and aft" (longitudinal). More detail is in the table in Annex A.

7.1.1 More than 6-DoF? Sometimes papers and articles are seen that refer to more than 6 DoF. These concern vehicles that have articulated systems. For instance, where two 6-DoF systems or vehicles are connected together it may be claimed that "the (overall) system has 12 DoF". This may be true in a mechanical sense, but a single point or observer free to move in space, can only experience the basic 6 degrees of freedom, and no more.

7.2 Cues used for human control of the path of a vehicle. Cues used by a driver or pilot for control of the vehicle path are tabulated in the Annexes. Annex B deals with visual cues and Annex C with cues of real motion. In summary, these show the following:

7.2.1 Visual cues. These include the position of the horizon, terrain generally, and the recognition and tracking of known types of objects in the scene. Other cues include the changing perspective of objects and terrain, movement of the horizon (sensing pitch, roll, and yaw), streaming of points of contrast through the visual scene, and high-G effects such as eye-point lowering, tunnel vision, grey-out and black-out. More detail was given in para 4.

7.2.2 Cues of real motion. These include feedback to the brain from a number of body sensors. These sensors are the inner-ear, pressures on the skin, small movements of the torso and limbs, and feedback from general forces on the body. More detail is in Annex C.

7.2.2.1 Skin Pressures. Pressures on the skin include "seat-of-the-pants", varying pressures from harness straps, and pressures due to small movements of the torso and limbs; these are sometimes called "kinaesthetic" cues.

7.2.2.2 Muscle and Joint Sense. Inside the body there are sensors that give signals to the brain under movement and pressure. These are in muscles, joints, and the abdominal viscera (loosely, "the gut"), and are called "proprioceptive" cues, sometimes the "Muscle and Joint sense".

Visual and Motion Cueing -7- Stra chan 2017-9
7.3 The Inner-Ear. The human Inner-Ear, Vestibule, or "Vestibular Apparatus" consists of left and right sets of semicircular canals and otoliths. Receptors in the semicircular canals respond to angular acceleration. The word Otolith means "ear-stone" and refers to a small mass of calcium carbonate (the "stone") at the top of sensory hairs, which bend under linear acceleration and transmit a signal to the brain. The general layout is shown below:

The diagram on the right shows how the semicircular canals relate to aircraft angular rate changes in pitch, roll and yaw.

A similar diagram could be drawn for the three linear accelerations heave, surge and sway, for which the sensor is the Otolith organ at the base of the semicircular canals.

The same principles apply to other vehicles moving on the ground or sea.

8 Time Delays in Detecting Real-World Cues. Acceleration, which includes buffet and vibration, is felt quickly by the body's acceleration and motion sensors. As indicated earlier, the visual cues are sensed some time later when a displacement of the visual scene has built up to a value above the visual sensory threshold. The visual scene can be the Outside World, an instrument display, or both. An example is shown in the next diagram from a paper by Zacharias and Young of the Massachusetts Institute of Technology. This was used by Dr Alan Benson, then Head of Vestibular Science at the UK RAF Institute of Aviation Medicine (IAM), in a lecture on simulator cueing to the Royal Aeronautical Society (RAeS) in London (references, Annex J). Three plots illustrate responses over a period of 30 seconds to a change in angular velocity of 5 degrees per second. In terms of aircraft manouevre, this is a fairly low figure but is what might be met in light turbulence or when the pilot is making small control inputs such as to fly accurately by instrument reference.

8.1 Vestibular Response. The top left graph shows the rapid response of the human vestibular system. The subsequent decay illustrates why specific blind-flying instruments are essential in aircraft, since at the end of the 30 sec period the vestibular response has become virtually zero despite the continued real movement.

8.2 Visual Response. The lower left graph shows that the visual response takes time to start and build. The different nature of the two sensor systems may be seen by the responses over longer times where the vestibular acceleration signal reduces, whereas the visual approaches the 5 deg/sec rate of true motion.

8.3 Combined Response. In visual conditions the green plot applies and shows the excellent cueing when both vestibular and visual sensors are combined. This illustrates why aircraft are easy to control in good visibility, particularly with a clearly visible horizon.

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8.4 Receipt of Motion Cues by the Brain. The above graphs are for a specific condition but they illustrate the general point about the early receipt of motion cues by the brain and the later receipt of the visual cues for the same disturbance. Aero-medical specialists (flight surgeons) confirm that the other body sensors of direct motion (tactile, proprioceptive, kinaesthetic; see para 7.2.2 and annex C) transmit their messages to the brain in a similar timescale as the vestibular apparatus. Therefore, the initial control responses that pilots are used to making in an aircraft are quick and automatic, for instance to maintain level flight in turbulence. The task of good quality simulation where control fidelity (“handling quality”) is required, is to ensure that this is replicated.

**SIMULATOR MOTION CUEING SYSTEMS**

9. **Simulator Systems giving Cues of Motion**. These are tabulated at annex D, which shows that the systems with most cueing capability are (1) the Outside World (OTW) visual scene, (2) a motion platform capable of moving the simulator cabin, and (3) the vehicle instruments. In conditions such as night or reduced visibility, the instruments and motion platform become more important as outside visual cues reduce. For aircraft capable of high G loadings, the use of an anti-G suit in the simulator, visual system dimming at high G, and a simulator motion-seat provide important extra cues. The following simulator systems produce forces, pressures, rotations and other movements.

9.1 Motion Platform. This is positioned below the simulator crew cabin and driven by jacks. The most common design is the hexapod (six leg) design with three mounting points on the floor. To each mounting, two jacks are attached and are displaced from each other at an angle, connected to different points on the simulator cabin baseplate in a criss-cross or zig-zag fashion. All the 6-Degrees of Freedom (tabulated in Annex A) can be obtained from such a platform by co-ordinating the movement of the jacks through the simulator computer. This principle is sometimes called “synergistic”, indicating mutual support.

9.1.1 Origin of the Hexapod motion platform. The geometry of the hexapod design was first given in a 1956 paper by Eric Gough to the Institute of Mechanical Engineers in London 10 - this was used for testing automobile parts such as tyres. Ten years later, D Stewart presented a paper to the same body “A platform with six degrees of freedom” 11. This hexapod layout is often called a “Stewart platform”, although it would be more correct to call it a “Gough / Stewart platform”.

9.2 Simulations of High G. A training centrifuge can be used so that pilots can directly experience the effects of high G. However, in other simulators that cannot create continuous G, some G effects can be produced. Tunnel vision and loss of colour can be simulated by a “G-dimming” function in the visual system, as shown in the next diagram. A simulator motion-seat can simulate eye-point lowering under G by lowering the seat-pan as computed G increases. Motion seats can also have strap tightening and loosening, and inflatable pads can create pressure via the seat pan and

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11 Published in Volume 180 of the Proceedings of the Institute of Mechanical Engineers, London, 1966
seat back. Motion seats are also known as G-Seats, sometimes as "Dynamic Seats", and more detail is in Annex H. Other effects can be produced such as G-Suit inflation, also pressure breathing under G (as fitted to aircraft such as the Eurofighter Typhoon, to ease the strain on the pilot at high G). Inflation of the pilot’s own anti-G suit is straightforward in response to computed G, and can be demonstrated on simple seat models at training exhibitions.

9.3 **Vibration devices.** Simple devices can be used in a simulator to produce vibration, typically by a rotating weight on the end of a short arm, fitted under the trainee's seat or under the simulator cabin floor. This is particularly useful in helicopter simulators where vibration is an important cue. Frequency and amplitude can be varied by using different rotation rates and weight offset.

**MOTION PLATFORMS - METHOD OF OPERATION**

10 **Motion platforms - general.** The modern hexapod motion platform with smoothly-operating jacks is a well-tried device. The annual reference work Jane's Simulation and Training Systems (JSTS) has listed some 70 different types of electric and 60 types of hydraulic motion platforms worldwide. The latencies (transport delays) of modern motion platforms show significant advances over 1970s designs, which could have transport delays as high as 300msec for the heavier platforms. Current designs have latencies of less than 100msec, many modern electric types claiming better than 50 and even 30 msec. All platforms produce short-term cues of real acceleration, and electric jacks have advantages in latency, cost and maintenance compared to hydraulic jacks.

11. **Principle of Acceleration-Onset Cueing and Wash-Out.** Motion platforms can reproduce initial accelerations of the real vehicle in all 6 axes. Clearly, hexapod platforms cannot roll through 360° or create continuous G forces. Despite this, hexapod platforms are highly effective motion cueing devices, for the following reasons.

11.1 They are basically acceleration devices ("kickers") that produce the initial accelerations in the appropriate degrees-of-freedom (see the diagram on the right).

11.2 After the initial acceleration has been produced, the platform program then uses the rest of the jack "throw" to "wash-out" the motion and then re-set the platform ready for the next control input. This is done by moving the platform back to a neutral position (the lower diagram) at a rate below the pilot's vestibular threshold. Because the human vestibular apparatus is basically an accelerometer, this process of "acceleration onset cueing" corresponds to short-term motion effects in the real world and so works well in simulators. See also the top of the three graphs in para 8 that shows the rapid "washout" of the human vestibular cue as time passes. It is this that allows a motion platform to be re-set without the washout and re-set process being detected.

11.4 The author has tested many flight simulators and has been pleasurably surprised at the realism of motion cues in platform-based devices, even in snap rolls through 360 degrees in fighter simulators where the simulator is not rolling over but is using acceleration-onset cueing to produce the sensory effect.

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12 Hexapod = six-leg or six-jack
12. Cues of continuous acceleration and sideslip. Since acceleration-onset cueing can only produce short-duration accelerations, it might be thought that some cues cannot be simulated such as longer-term acceleration, deceleration and conditions such as sideslip in aircraft. However, because a platform can take up a steady angle in pitch (longitudinal angle) and bank (lateral angle) these can be simulated as follows:

12.1 Cues of sustained longitudinal acceleration. Platform pitch angles can be used to give the "kick-in-the-back" sensation for acceleration (right picture), and "hanging in the straps" for deceleration (left picture). To obtain these effects, the simulator computer ensures that the visual picture takes up the same pitch angle as the platform. For instance, during an aircraft takeoff the platform may be pitched to, say, 25 degrees at a rate below the pilot's sensory threshold so that the pilot does not sense the pitch movement. At the same time the visual horizon is also pitched up to the same angle, therefore to the pilot there is no visual indication of pitch. The effect of leaning the seat results in a continuous force on the pilot's back (for acceleration) or on the straps (for deceleration) which, because the visual system has moved as well, is interpreted as sustained longitudinal acceleration or deceleration. This is sometimes called "Tilt Co-ordination".

12.2 Cues of sideslip. In aircraft, a lateral out-of-balance sensation is felt during sideslip. This is where the airflow is at a sideways angle ("beta") to the fuselage, and is an important cue in the use of rudder to reduce drag and in engine-failure cases. It can easily be simulated by leaning the platform at a constant lateral angle.

13 Motion Feedback. In real aircraft, the pilot's motion sensors ensure quick reaction when involved in a "high-gain" flight control task. The pilot may not know why he or she is making a particular short-term control input, but after many hundreds or thousands of hours of real flying, control responses to short-term acceleration stimuli are made without conscious thought.

13.1 Application to simulators. The UK Royal Air Force Institute of Aviation Medicine (RAF-IAM) has stated that motion platforms are the only simulation devices capable of fully stimulating the body motion sensors, other than for high-G situations. The Institute confirms that motion platforms can impart accelerations in all of the 6 DoF to the whole body and therefore exercise the automatic motion feedback-loop that pilots are used to experiencing. The IAM has also stated that in the case of simulators that do not replicate the normal cues that are experienced in the real aircraft, a cue-mismatch will eventually be detected by the brain and pre-dispose to symptoms of "simulator sickness" (see later, para 20). Number 4 in the list of references in Annex J is a presentation to the RAeS in London by Dr Alan Benson, then Head of Vestibular Science at the IAM, in which the above was confirmed in more detail.

14 Replication of real-world cues. Cues of initial acceleration are replicated by a 6-DoF motion platform. These cues are important in situations needing precise control of flight path, or where outside visual cues are poor. This applies to critical control tasks such as takeoff and landing, instrument flying (particularly in turbulence), upset and stall events, tranisiting through microbursts, helicopters at the hover, and for military aircraft, tactical manoeuvres, formation flying and air refuelling. Also for failure cases that require precise flight path control, including engine failures with roll, yaw and sway.

14.1 Realism - overall effect. Motion cueing from a well set-up simulator motion platform has been found by the author to be remarkably good, particularly when combined with a good visual system. This is so for all aircraft types including fighters, transports and helicopters. The realism of motion includes wheel rumble effects when on the ground, yaw cueing for taxiing, touchdown of individual undercarriage legs on landing, and pitch-down effects simulating nose oleo compression on braking. Such effects, although small in themselves, convey an "ambience" of good simulation and contribute to pilot motivation towards the simulator, even "immersion" where the simulation is particularly realistic and the pilot is working hard.

14.2 Replicating the whole flight environment. There are many papers on this subject (see Annex J). A useful summary is in "The Need for Motion: a Pilot's Perspective", a paper by Captain Bryan Burks of the Training Council of the Airline Pilots Association International (ALPA), number 22 in the list in Annex J. In sum, he said the simulator motion is required because real aircraft operate "in an arena of motion", and the pilot's vestibular system provides "the most powerful and quickly sensed cue for motion". All other sources of motion cueing (visual, sound, tactile), he said, are important but complementary. He concluded that: "to leave motion out will mean that pilots will use differing, and incomplete, cues during training. To develop the required skills we simply must recreate the flight environment as closely as possible". A similar point was made by Dr Eric Groen of TNO in The Netherlands (paper 30 in the list of references) who looked at training for airliner "upset" and stall events. These events are described as Loss of Control In flight (LOC-I). He concluded that for this training, fixed-base simulators are unacceptable, whereas simulators with 6-axis motion platforms are acceptable for such training, and cues using a centrifuge with a realistic cockpit and controls (see Annex H for cueing for G forces) are virtually identical to the aircraft. Finally, Dr Jeff Schroeder of the US FAA concluded that over 80% of LOC-I cases can be trained in a Full Flight Simulator with 6-axis motion as long as the simulator systems are optimised for LOC-I training (paper 31 in the references).

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13 Extreme turbulence and wind-shear below thunderstorms due to a strong downcurrent of cold air hitting the ground and spreading out
15 **Quality of Motion Cueing.** Cues of real motion need careful setting up and proper synchronisation with other simulator cues, in particular the visual system.

15.1 High Latencies (Transport Delays). Latency is a critical factor in high-gain closed-loop control situations that are typical of many training tasks. Some motion platforms in the past had high latencies, up to 300 milliseconds in some heavy platform designs of the 1970s. This figure quickly reduced with the second-generation lighter-weight platforms of the 1980s that were able to meet the 150 ms then required by the US FAA (table, Annex E). Today, substantially lower latencies are being obtained, particularly for modern platforms with electric jacks, and 50 msec is now common. Platform latencies can be compensated by adjusting the latencies of the simulator flight model so that there is no mismatch compared to the real-world situation, see the next para.

15.2 Synchronisation with Visual System Latencies. The human body senses motion cues before cues of visual displacement (see paras 7-9). Therefore, the **visual system time delay must never be less than that of the motion platform**, or the brain will sense a cue-mismatch compared to the real world. This may not only lead to unrealistic control inputs but, after a time, cause the subject to feel symptoms of “simulator sickness” (see para 20). The synchronisation of motion and visual cues should be monitored during simulator use, such as through Built-In Test Equipment (BITE) before a training sortie is undertaken. In terms of the acceptable lag of visual cues **after** motion, it has been suggested that the transport delay of visual cues should not be more than 30 ms after motion.

15.3 Degradation of Platform Performance. Another problem in the past was that motion platform performance degraded with time and usage. If this was not corrected, lack of synchronisation with other systems occurred. Now, with Built-In Test Equipment (BITE), simulator system responses can be checked each time before a training sortie so that mismatches with other simulator systems do not occur during training.

16 **Smaller Motion Platforms and Platforms with 4-DoF or Less.** The full-size industry-standard 6-DoF platform with about 60 inch jack throw complies fully with the US FAA and EASA Level D standard and is to be recommended. The many smaller platforms that the author has experienced, particularly those of less than 6-DoF, do not produce motion cues of which the larger ones are capable. However, for smaller 6-DoF platforms it is also true that low latency can compensate for lack of size, as long as the platform is correctly set-up for the simulator concerned and is well synchronised with movements of the visual imagery.

16.1 Degrees of Freedom. In view of the many 6-jack platforms available that produce all 6 DoF, there is no point in using a platform with less. A special case for platform design is for a specific role such as a ground vehicle simulator optimised for “start and stop” (surge) events. Here, platform geometry can be optimised for longitudinal acceleration (surge) and used for simulators for ground vehicles that often start and stop such as buses, trains and trams.

17 **Aviation Simulation Terminology.** In civil aviation, the designation "Flight Simulator" (FS) or "Full Flight Simulator" (FFS) is only applied to devices with motion platforms (detail, Annex E). Other types of trainers go under different names such as FTDs (Flight Training Devices), FNPT (Flight Navigation Procedures Trainers), PC ATDs (PC Aviation Training Devices), Advanced Aviation Training Devices (AATD), etc.

17.1 Zero Flight Time Training. The US FAA and the European Aviation Safety Agency (EASA) allow high quality Level D flight simulators to be used for the conversion of experienced pilots to similar types of aircraft, without any use of the aircraft itself for training. This is called Zero Flight Time (ZFT) training and leads directly to flying the real aircraft on revenue flights with passengers, initially under supervision of a Training Captain until the pilot is checked out to fly without supervision.

17.2 Simulator Types - 27 to become 7. A rationalisation of flight training devices will lead in the future to 27 different types and names used by different Regulatory Authorities, to be reduced to only 7 classifications under ICAO Document 9625 Volume 1 (Aeroplanes), Edition 3, initially produced by an International Working Group (IWG) led by members of the Royal Aeronautical Society Flight Simulation Group (RaS FSG). When this comes into effect, the new Type 7 is an enhancement on the Level D design, with increased motion and visual fidelity and improvements in Air Traffic and communications simulation.

17.3 Upset Prevention and Recovery Training (UPRT). As a result of high-profile stall accidents such as Air France 447 over the Atlantic, Colgan Air 3407 at Buffalo, Turkish Airlines 1951 at Amsterdam, and so forth, UPRT is now a normal part of simulator training. Enhanced simulator training was recommended by the International Committee on Aircraft Training in Extended Envelopes (ICATEE) which was formed in 2009 under RaS Chairmanship and reported to ICAO, the US FAA, EASA and others in 2013. The author of this paper was a member of ICATEE. The majority of UPRT can be achieved on a Level D Full Flight Simulator (FFS) as long as the aircraft manufacturer supplies the coefficients and derivatives for the aircraft’s full flight envelope to the simulator manufacturer, including the stall. In a 2013 paper to the RaS (number 31 in the list of papers in Annex J), Dr Jeff Schroeder of the US FAA suggested that an FFS could cover 82% and in the 2013 Captain Ray Jones Memorial Lecture by Captain Larry Rockcliffe, chief test pilot of Airbus China, suggested that 85% of UPRT could be trained in a FFS. Clearly for replication of upset manoeuvres, motion is a crucial cue. See also para 14.2 on the Burks paper on replicating the whole flight environment.

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14 Royal Aeronautical Society conference on simulation, November 2012

*Visual and Motion Cueing* -12-  *Strachan 2017-9*
17.4 Military applications. Zero Flight Time training cannot be applied to military operations because of their different nature and more complex tasks. Fighter and other combat aircraft are obvious examples. Even military counterparts of civil aircraft have extra roles such as air refuelling, low flying, tactical operations, formation flying, etc - such aircraft generally have simulators equivalent to civil level D but with additions to train for the extra roles. However, pilot conversion courses can be carried out using only a small amount of aircraft time but a larger amount of simulator time first.

17.4.1 US Air Force C-17. New pilots for the US Air Force C-17 Globemaster III strategic transport aircraft have to fly only two training sorties in the aircraft before their check-ride. However, this follows 26 sorties in an FSI-built Level D-equivalent Full Flight Simulator with a 6-jack electric motion platform. This training schedule has been running successfully since the 1990s.

17.3 2 Australian MRTT. In 2017 the Royal Australian Air Force (RAAF) introduced a similar training programme to that of the USAF C-17. This was for new pilots for the RAAF’s KC-30A Multi Role Tanker Transport (MRTT) that is based on the A330. The training programme uses a CAE-built FFS with electric motion which more than halved the aircraft training flights needed to qualify new pilots. Like the USAF C-17 training programme, only two training flights are now required before the check flight. In addition, the KC-30A FFS can be networked with other trainers such as that for the KC-30A Air Refuelling Officer (ARO) who controls the air refuelling boom.

TESTS ON SIMULATORS

18 General. The author carried out a schedule of tests on a wide variety of simulators, which continue today. The tests are based on flight test methodology similar to that employed in his test pilot flying at Boscombe Down and Farnborough. These include assessment of sortie phases from engine start, taxiing out, takeoff, flight manoeuvres, then approach, landing, taxiing in, and shut-down. Tests were made with simulator cueing systems on and off in a variety of combinations. Some extracts from the reports follow. Key passages are in italics and more detail is at Annexes F and G which also include test results from other sources.

18.1 Handling Characteristics - General. With both visual and motion platform cues, handling was realistic. The general “ambience” of realism, competent simulation, and perceived training value, was noted. Crews would give credibility to such a simulator and would be well-motivated towards it. Conversely, with the motion platform off, adverse simulator handling and stability characteristics occurred. Oscillations in pitch and roll were noted, and landings were heavy and not under precise control in pitch.

18.1.1 Correcting adverse simulator handling. The above adverse effects can be corrected in a simulator that is designed without motion from the start. For a fixed-base simulator, the aircraft stability and control characteristics can be altered, generally “damped”, to eliminate oscillations and over-control. Following these adjustments, the simulator stability and control characteristics and simulator handling will clearly not be “as aircraft”.

18.1.2. Network links. These are now fundamental to military simulation so that multi-simulator exercises can be carried out. These include multi-aircraft, multi-role, multi-Service and multi-national exercises, including with live assets where these are available and have the appropriate network links.

18.1.3 Handling Characteristics - Simulators for Fighter aircraft. A combination of motion, visual, g-suit, and g-seat, gave the best cueing. G-seat cueing was particularly noticeable, G-seat positive but less so. If pitch rates or bank angles were changed, the motion platform cues were very effective. With visual only (no motion, g-suit and g-seat) the exercise was very bland and unrealistic, felt like a computer-game, and over-stressing (too high G) frequently occurred.

18.2 Rolling Manoeuvres. The prime cue was the visual system but strongly backed by the motion platform which gave very good vestibular sensations of roll acceleration. Moderately rapid rolling through 360 degrees gave very realistic vestibular cues of roll (both roll acceleration and deceleration), despite the inability of the platform to physically roll. In instrument flying, roll motion was realistic with the platform, and very unrealistic without motion, resembling an arcade game.

18.3 Pitch. With visual only and the motion platform disabled, pitch manoeuvres felt very bland and unrealistic, like a computer-game, and at high pitch-rates over-stressing frequently occurred. The aircraft G limits were exceeded in the simulator due to “over-controlling”. It is significant that this was suppressed when motion cues from the platform were available.

18.4 Formation Flying. When the motion platform was disabled, the characteristics became much less stable. Control was untypical of the aircraft and it was not possible to fly close echelon or line astern positions. Approaches to refuel (probe and drogue) were attempted but were too oscillatory and would have failed both to make safe contact with the drogue and to hold a steady refuelling position.
18.5 Instrument Approaches. Approaches were flown by the author using the Instrument Landing System (ILS) without cues from the external visual system (i.e. conditions of simulated cloud-flying) in a simulator for the BAES Hawk aircraft. The simulator had a 6-DoF motion platform and a three window collimated visual. An overshoot was carried out from about 300 ft. The author was experienced on the Hawk and assessed the instrument approach as very realistic compared to the aircraft. The graph on the right shows this approach, the slight oscillation showing normal manual corrections to maintain the glidepath. The wavelength is probably associated with the aircraft's natural longitudinal Long-Period Oscillation (LPO), sometimes called a "Phugoid". The slight oscillations in the altitude trace before climbing away were due to trim changes as the gear and flap retracted.

18.5.1 Approach with platform off. After the first ILS approach, the motion platform was taken off-line and a further approach carried out, also without external visual cues. Despite the practice gained from the previous ILS, the second approach was difficult to fly and was unstable in pitch. On attempting to overshoot from a range of about 1.5 miles from the threshold, the trim changes due to flap and gear retraction cause pitch instability. This could not be controlled and the approach ended in a crash into the ground at a range of about 1 mile from the runway threshold (not shown on the graph, which ends before the overshoot).

18.5.2 Longitudinal characteristics. In the lower plot, note the completely different and unrealistic aircraft longitudinal characteristic compared to the upper graph. This clearly shows that "handling fidelity" in a simulator needs well-adjusted feedback of real motion if the aircraft control and stability characteristics are to be reproduced correctly. Damping the oscillations in the lower graph is possible, but it involves altering the simulator stability and control coefficients and responses, making it handle less like the aircraft itself, as mentioned above in 18.1.1.

DISCUSSION

19 Simulators without Motion Platforms. A legitimate question after the above evidence is: "if there is such a case for motion platforms, how is it that large numbers of military simulators do not have them?" One answer is that instability and over-control as recorded in the tests without platform motion can be reduced by altering the aircraft model used in the simulator. This will involve making the short term control responses less, the stability and damping factors higher, and, where the control forces are light in the aircraft, making them heavier in the simulator (18.1.1 and 18.5.2 also refer).

19.1 Control Response not "As-Aircraft". Such a process of deliberately altering the control responses and stability characteristics from those of the real aircraft will be an ad hoc, not particularly scientific, exercise. However, care must be taken to avoid adverse characteristics such as unusual control strategies and pilot visual scan patterns that do not correspond to those in the aircraft. If such "negative training" can be avoided, and the customer's training requirement is based on learning checks, practising procedures, networking with other simulators, or limited by resources, then a motion platform is not needed.

19.2 Simpler Training Devices. If good control and cue fidelity is not needed, a much simpler device than a full simulator will be sufficient, such as a part-task-trainer (PTT) or Flight Training Device (FTD). Examples include the USAF Distributed Mission Operations (DMO) simulators at Kirtland AFB that have simple visuals and no motion. Indeed, for basic procedural or system training, a laptop PC, Tablet or i-Pad may be all that is needed. Additions to a basic PC can include a computer-type control column and a slider control for throttle or a collective lever for helicopters. The view of the author is that you should either fund a full flight simulator (or military equivalent) with good visual and motion cues, or accept more limited training on a FTD or PTT. In the military case, such a training solution backed up by use of the real equipment in a training mode, must accept its higher cost and wear-and-tear on the equipment itself.
20 "Simulator Sickness" and Cue Conflicts. Pilots fly thousands of hours in real aircraft and the brain becomes used to receiving both visual and motion cues (See para 5 and annexes B and C). In a simulator, if there is a wide-view outside-world visual but no motion, there is what has been described as a "Vestibular Mismatch" because the brain senses an unfamiliar situation and causes adverse symptoms such as Simulator Sickness. This can also occur in a simulator with motion if the motion cues are mis-matched with the visual, such as being sensed after visual changes, the opposite of what happens in the real world. The author started testing simulators in the late 1980s and the cases of "Simulator Sickness" that he has experienced were all in simulations with wide visuals but no motion platform, cases of "cue mismatch" compared to the real world. The author has experienced nausea, the "leans" (a strong feeling of false pitch and roll attitudes), and post-simulation disorientation. The tendency to simulator sickness is reduced when motion and visual cues are correctly sequenced, in which motion cues must be received slightly before visual cues.

21 Vehicles Other than Aircraft. The movements of ground vehicles are more limited than those of aircraft, but the same principles of motion and visual cueing apply. The relative transport delays of motion and visual systems, and the need to monitor simulator performance, are equally important for ground vehicle simulators. Cue mismatch between visual and motion can lead to symptoms of simulator sickness just as in aircraft simulators.

22 Cost ratio - Training using the Real Vehicle compared to using a Simulator. For all but the simplest vehicles, cost is always in favour of simulator training rather than using the vehicle itself in a training mode. To make a proper comparison, costs of both the vehicle and its simulators should be estimated over several years and preferably using Life-Cycle Costs (LCC). This averages out the initial procurement costs of the real vehicle and the simulator, and allows for in-service running costs, servicing and updates of both the real vehicle and the simulator.

22.1 Flight Simulators. On the basis of LCCs, figures from a conference on training at the Royal Aeronautical Society indicated that the cost ratio for a Boeing 747 Jumbo was 42:1 (training using the Aircraft : training using the Simulator), a major factor being loss of revenue while the aircraft is used for training. The cost ratio is between 10 and 20:1 for a military fighter or a helicopter, taking long-term costs over several years. US Navy figures give about 18:1 for the F/A-18 fighter and 15:1 for the Blackhawk/Seahawk helicopter. For the Chinook transport helicopter 10:1 has been quoted and 5:1 for the simpler Puma helicopter. With increased costs of complex aircraft such as Eurofighter Typhoon and F-35 JSF Lightning II, the cost ratio in favour of simulation will increase further. In the case of large military transport aircraft such as the C-17 Globemaster III, the cost ratio approaches those for large commercial aircraft and has been estimated as about 30:1.

22.2 Vehicles other than Aircraft. 10:1 has been quoted for training on the US Navy Landing Craft Air Cushion (LCAC), a large maritime landing craft with a simulator that looks very similar to an FAA/EASA Level D. In the case of the M1 Abrams main battle tank, 33:1 has been quoted. This huge figure is due to the cost of wear-and-tear on tracks, engine and guns when the real tank is used for training on military ranges.

22.3 Extending Service Life. The "big one" in cost is the possibility of extending the service life of the vehicle fleet by judicious use of training by simulation, compared to fatiguing the vehicle itself by over-using it for training. The reverse is having to retire the real vehicle early, as happened to the very capable F-14 Tomcat naval fighter which had been subject to much high-G training in the aircraft itself, and less use of simulation.

15 Dr Helen Hoar, lecture at the Royal Aeronautical Society, October 2015
SUMMARY AND CONCLUSIONS

23 Visual Cues. Computer-generated imagery closely matches the real world in resolution and image content. Simulators are therefore able to give similar visual cues to the real world.

23.1 Imagery. Realistic real-world visual scenes are created by computer-based Image Generation (IG) systems. For simulators, large-area databases can be stored and the relevant data can be "paged up" into active memory for use in visual display before being returned to store. Such imagery includes terrain, cultural features and objects, weather and weapon effects, time of day, night and season, and the generation of scenes for Night Vision Goggles (NVGs), Infra Red, and Radar.

23.2 Visual Display. Imagery can be presented at various resolutions and fields-of-view by a simulator Display System (DS). This can vary from simple computer screens up to large wide-angle displays. The latter include projection on the inside of domes and back-projection onto an array of screens ("facets") arranged round the subject of the simulation. Domes and faceted displays can provide up to 360 degree view. A combination of realistic imagery and wide display view encourages "immersion" in the training scenario.

23.2.1 Distant-Focus Displays. Where two crew are seated side-by-side, if the visual scene is displayed on a screen a short distance ahead, false angles and distorted perspectives will be seen by the crew member who is not close to the Design Eye-Point of the display. This can be corrected by the use of distant-focus ("collimated") display systems that use curved mirrors to create an image that is seen at a focal distance further away than the distance of the mirror. In such a "Cross-Cockpit Collimated Display", imagery seen by both crew is at the correct angle for both crew. Such systems are almost universally used in simulators for Commercial Air Transport aircraft, for which almost all training is carried out in simulators rather than the aircraft itself.

24. Motion Cues. The principle of "acceleration-onset cueing" describes the working of the motion sensors of the human body in the real world, and can be replicated in a simulator motion platform because it depends on acceleration rather than speed or displacement. Crew members are used to real world cues, and when in a simulator the brain will expect them. For an aircraft simulator with motion, "handling qualities" can be similar to those of the aircraft so that many exercises that require precise control can be carried out in the simulator.

24.1 Motion System Set-up. In the real world, accelerations experienced by the human body are strong cues, particularly when outside-world visual cues are degraded such as at night, in cloud, poor visibility, and when using NVGs and/or FLIR systems that may have limited fields-of-view. In the real world, after a displacement has occurred the various human motion sensors deliver acceleration inputs to the brain quickly, followed up later by the visual effects of the displacement. This time-sequence must be followed in simulators, or the brain will sense a "cue mismatch" which can lead to degraded performance and, in some cases, symptoms of "simulator sickness". In simulators, motion cueing systems must therefore be set-up carefully and their operation synchronised correctly with visual displays and instrument indications.

24.2 Cueing for G. For the crews of aircraft capable of G loadings over 4 and up to 9, low-cost simulator G-cueing systems include the use of aircraft equipment such as an anti-G suit and pressure-breathing under G (where the latter is fitted to the aircraft), visual system G-dimming, and the use of a motion-seat designed for use in simulators. Motion seats can produce other G effects felt by pilots such as strap tightening and loosening, eye-point lowering under G, pressures on the seat and back, and so forth. For real high-G training, a centrifuge can be used with a model aircraft cockpit at the end of its rotating arm.

25. Conclusion - Simulation is not only capable but can save money. Training on a modern simulator is now very realistic and much training can be transferred from the real vehicle. The more it costs to use the real equipment, the more savings are made through use of simulation technology. Furthermore, training for conditions that are too hazardous to train in the real vehicle can be covered using simulation, as can exercises with different forces including other services, allied nations, and various simulated enemy responses.

25.1 This is particularly shown in the Commercial Air Transport (CAT) area, in which high quality Full Flight Simulators (FFS) are used worldwide for training rather than the airliner itself. The cost-ratio can up to 40:1 in favour of using FFS because of the enormous costs of using a large airliner for training and the need to take it out of revenue service while training takes place.

25.2 In the military, where real vehicles and weapons are used for training there are constraints in their use, including failure cases and the safety of weapon firing and live combat training on military ranges. There is also the complexity of arranging live exercises with other forces. Simulation does not have these constraints, and can be used for hazardous situations or those that are simply not possible in live training in peacetime. Simulation can also include the various possible reactions of a potential enemy. For exercises, network links can be used for multi-role, multi-Service and multi-national exercises, and future scenarios can be explored.

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Visual and Motion Cueing -16- Strachan 2017-9
ANNEXES - in a separate PDF file.

A. The six degrees of freedom, table
B. Real world motion cues - Part 1 - Visual Cues of Motion, table
C. Real world motion cues - Part 2 - Cues of Real Motion, table
D. Cues in a simulator, table
E. Civil Aviation Simulator Regulatory Rules -Summary
F. BAES Hawk simulator test results
G. Extracts from Simulator Test Reports
H. Cueing for G forces
I. References

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