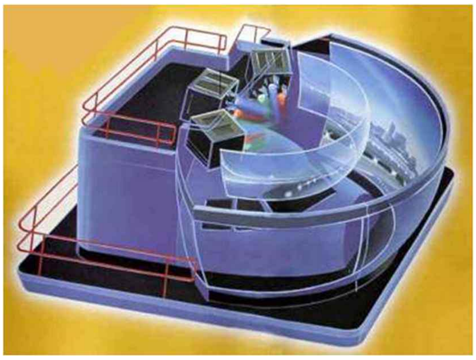
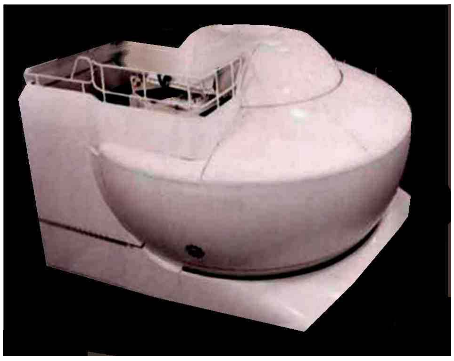
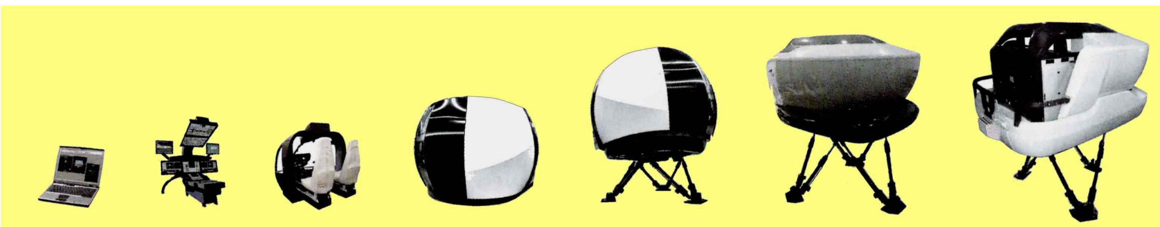
VISUAL AND MOTION CUES

IN THE REAL WORLD
AND IN SIMULATORS



by
Ian Strachan



Updated November 2019

Introduction

The Author. Ian William Strachan 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 RAeS FSG chairmanship to reduce upset and stall events in Commercial Air Transport (CAT) aircraft, after several high-profile fatal airline accidents. The ICATEE report made recommendations for Upset Prevention and Recovery Training (UPRT) and was submitted to ICAO in 2013. UPRT is now adopted by ICAO and civil aviation Regulatory Authorities worldwide. The result has been a significant improvement of the handling characteristics of Full Flight Simulators, and better training for areas of critical handling including upset and other potentially dangerous events.

In his military career he was a Test Pilot [1] in the UK Royal Air Force, 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 was Wing Commander Flying at the research base at Farnborough, commanding the Flight Test Wing. 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 33 types of fixed-wing aircraft and helicopters, and has tested simulators for land vehicles and ship handling.

He was awarded the AFC [2] for test flying at Farnborough, a Queen's Commendation for flight test at Boscombe Down, and is a Fellow of the 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 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 and test 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, followed by 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), developing it into a regular update on current world simulation projects.

He is now a consultant and writes for several publications in the UK, Europe and the USA, and edits a regular summary of World Simulation News for the Flight Simulation Group of the RAeS. 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. The author has presented papers to conferences at the Royal Aeronautical Society in London on "Future Flight Simulation", "Visual and Motion Cueing" and "Future Helicopter Simulation". These were refined into a paper on Simulator Cueing that was also presented at the RAeS. A further update was presented at the I/ITSEC training and simulation conference in Orlando, USA, and became the basis for the first edition of this paper. This paper has been expanded and updated several times, and has been made available on the ETSA and RAeS web sites. In particular, new information on simulator cost-effectiveness, new simulator systems and test results have been added as it became available.

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

Mathematics. Formulas and complex mathematics are deliberately not used in this paper so that is can be read and understood by the maximum number of people who have an interest in Simulation technology.

Terminology. In this paper the term "motion" refers to real movement and the body cues that follow, in contrast to cues detected by the eyes such as the outside world or instruments in the type of vehicle being considered. The word "Vehicle" is used to mean an aircraft, ship, or one that operates on land. It should be noted that other papers may use the word "motion" in a more general way and include changes of the visual scene that indicate movement.

Title page. The three pictures at the top of the title page illustrate Computer-Generated Imagery (CGI) for use in simulators.

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, UK

[2] AFC = Air Force Cross

[3] MBE = Member of the Order of the British Empire

VISUAL AND MOTION CUES - THE REAL WORLD AND SIMULATION

SUMMARY

(i) Simulation Today. Training using simulators is fundamental in both civil and military applications. The Full Flight Simulator (FFS) is used in Commercial Air Transport (CAT) instead of the airliner itself. In the military, simulation-based training is now universal because it can train for conditions that would be hazardous, or not possible, if the real equipment was used, it is less costly than using the real equipment, and can prolong the life of the real equipment because it is not worn out by over-use in training. In addition, 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 movement of features that have visual contrast, giving cues of height and speed. The paper evaluates these and other visual cues in conditions of good and poor visibility, at night, and in 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 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) Cues of Real Motion. Nine types of real-world 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 processed first by the brain, compared to cues of visual scene change which are registered later.

(iv-i) Timing of Cues. Therefore, if realistic motion cues of acceleration can be generated in a simulator, this will give early warning of a change of velocity and/or position, before changes in visual cues are registered by the brain. In aircraft simulators, this enables quick control movements to be made in response to conditions such as turbulence, loss-of-control, stall, or to avoid terrain or collision with other aircraft. Realistic cues of real motion are also important in simulation of manouevre, particularly where precise control and accuracy of flight path is required. Cues of real motion are therefore needed in aircraft simulators if "handling fidelity" is required. It follows that it is vital in Upset Prevention and Recovery Training (UPRT) to reduce the possibility of accidents including loss-of-control, stall and spin.

(iv-ii) Acceleration Cues. The principle of simulator motion platform operation is "acceleration-onset cueing", in which the initial acceleration of the vehicle being simulated is closely replicated. The movement is backed-off below human sensory threshold so that the platform can be ready to generate the next cue of acceleration. Onset-cueing works well because it matches the way that the motion sensors of the human body work. Specially designed Motion 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) Cues of high G. Fighter aircraft are able to manoeuvre up to about 9G. Simulations for high G include special 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.

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

(vi) Cost Ratios. Costs for the use of simulators are compared to use of the real vehicle in a training mode. Simulator-to-vehicle cost ratios vary from about 1:40 for a large airliner, over 1:30 for a Main Battle Tank, to about 1:15 for fighter aircraft. In addition, use of simulation for training can extend the life of the main vehicle, a large saving compared to early replacement of expensive vehicles.

(viii) Commercial Aviation. Simulator training for Commercial Air Transport (CAT) is working well under a worldwide system of standards and regulation. This includes the "Full Flight Simulator" (FFS) design which includes 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 implemented by civil aviation Regulatory Authorities such as the US Federal Aviation Administration (FAA), European Aviation Safety Agency (EASA) and other regional Authorities. After a series of "upset" and stall accidents involving considerable loss of life, the latest standard of FFS is part of worldwide Upset Prevention and Recovery Training (UPRT), for which a combination of high-quality motion and visual cues is required.

(ix) Military Aviation. Simulators for large transport aircraft and the larger helicopters generally use the civil Full Flight Simulator design. However, most fighter aircraft simulators have wide-view visuals based on domes or an array of screens, and these are often not compatible with mounting on motion platforms. Other cueing systems are available including simulator G-seats and inflation of the pilot's anti-G suit. Also, a simulator visual system can give realistic tunnel-vision effects at high computed G, culminating in simulated "black-out" if corrective action is not taken. In addition, man-rated centrifuges are available for real high-G training. Connecting simulators together using network links enables multi-role, multi-Service and multi-nation training - enemy action can be modelled and alternative responses investigated. Use of simulation reduces wear-and-tear on the main vehicle, with the potential to extend the life of the vehicle fleet. These factors are now recognised at the highest military levels and a ratio of 50:50 between simulator and live training is common. Overall, the proportion of training using simulation in the military is increasing, as is networking with other simulators that enables realistic training that is difficult to achieve in the real military vehicle.

CONTENTS

THE REAL WORLD AND SIMULATION
VISUAL AND MOTION CUES

1 Introduction - Simulation Today

1.1 The Civil Area. In Commercial Air Transport (CAT), the "Full Flight Simulator" (FFS) design is now used instead of the aircraft itself for conversion of pilots to new types of airliners. Simulators continue to be used during the rest of a pilot's career for regular "recurrency" checks to ensure that standards are being maintained, also for Upset Prevention and Recovery Training (UPRT) using the current highest standard of FFS, "Level D". FFS have a replica cockpit that precisely models the real aircraft, a wide-view display for Outside-World (OTW) imagery, and a motion platform that moves the simulator cockpit with similar initial accelerations to those in the aircraft. An experienced pilot converting to a new type of airliner is trained on an FFS, and may make the first flight on the aircraft itself on a revenue flight with passengers, initially supervised by a Training Captain until checked out to fly without supervision. The world airliner fleet is forecast to double over the next 20 years, so there will be a proportional increase in the number of FFS, particularly in regions of large growth such as the Middle and Far East. Outside aviation, simulation is used to train operators of vehicles on land and sea.

1.2 The Military Area. Training using real military hardware will always be necessary but is expensive and can be hazardous. The occasional death in military training is not unusual. Simulators are safe, less costly that the equipment being simulated, and databases can include enemy and other forces that are not available for live training. Also, future combat scenarios can be tried out. Simulators can be networked to others, also to an "exercise control" centre, even to live assets. This enables multi-role, multi-Service and multi-national training that is not otherwise possible.

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 10:1to 40:1 in favour of simulators (see para 23). Mission Simulators for large aircraft and heavy helicopters generally follow the Level D Full Flight Simulator design (para 1.1. above). Military simulators have extra facilities such as weapons, defensive aids, high-resolution wide area terrain data for low flying, etc. Examples follow and others are given later in para 17.4.

1.2.2 The use of "networking" is crucial to military training because it enables simulators at different locations to work together in combined training exercises. The US Air Force Distributed Mission Operations (DMO) system became operational in the early 2000s and connects simulators together for combined training. The principle has now been expanded to multi-Service and multi-National training throughout the world, using standard network links. If required, after suitable preparation, real military vehicles can participate in large training exercises in addition to networked simulators.

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.

SIGN ON THE LOCKHEED MARTIN BOOTH AT A TRAINING EXHIBITION

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

1.2.5 The UK Ministry of Defence (MoD) aims to achieve about a 50:50 ratio between Live training and Simulation. This applies not only to aircraft but also Armoured Fighting Vehicles (AFVs), artillery, ship bridge operations, and ship's weapon systems.

1.3 Simulator Technology. What follows is a non-mathematical evaluation of simulator systems. It mainly covers situations in which the control of steering or flight path is achieved by controls operated by the operator rather than through automatics such as an aircraft autopilot. The paper analyses the cues used for control and steering of vehicles on land, sea, and air, relates cues to simulator systems, and draws conclusions. Aircraft systems are mainly discussed because all six degrees of freedom (6-DoF) [4] 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 of movement. Visual systems are analysed first, followed by motion and other systems. In this paper, the term "motion" refers to real movement and the body cues that follow, in contrast to cues detected by the eyes such as the outside world or instruments in the particular type of vehicle. In this paper, the word "Vehicle" is used generically to mean an aircraft, ship, or one that operates on land.

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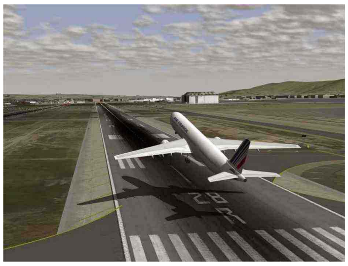
[4] The 6-DoF are Pitch, Roll, & Yaw rotations and linear movements Heave, Sway & Surge, see 7.1 and Annex A

2. **Image Generation (I.G.) Systems**. Computer-generated Imagery (CGI) is now so realistic that real-world fidelity is approached, see the images below and on the cover pages of this document and the separate document with its annexes. 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 that can be used to model real-world imagery. Large and detailed three-dimensional terrain databases can be stored in computer memory, imagery then being "paged up" for active display.



3. **Vehicle Instruments**. For control of air, land and sea vehicles, extra cues are available through instruments in a dashboard or panel, and these can easily be replicated in a simulator. Where Outside-World (OTW) visual cues are reduced, instrument and real motion cues are even more important. This includes conditions of low visibility and reduced outside illumination such as mist, fog, in cloud, and during the night. In aircraft this includes so-called Instrument Flying ("I.F.") in which pilots are trained and regularly checked on Instrument Rating Tests (IRTs) carried out by Instrument Rating Examiners (IREs). The author of this paper was an IRE on two types of aircraft.

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 an attempt to cloud-fly without reference to the appropriate flight instruments. Pilots are taught to interpret sensations with care, and when outside visibility is reduced, to rely on instruments for judgement of speed and spatial orientation.

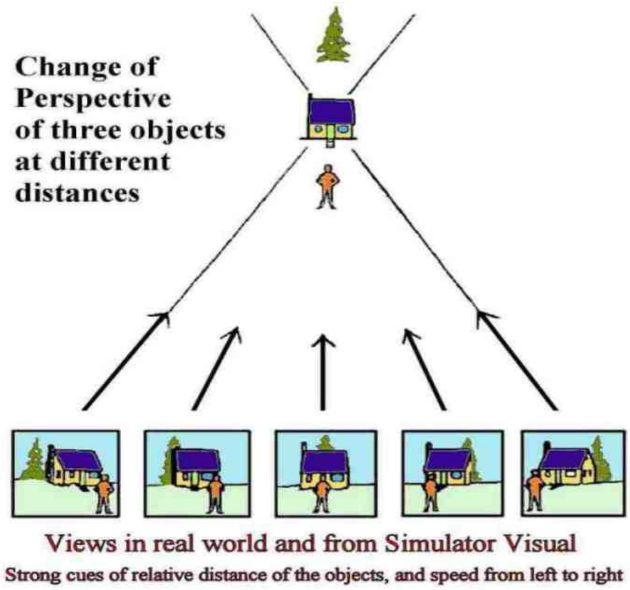
These conditions are well-replicated in a motion-based simulator.

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.

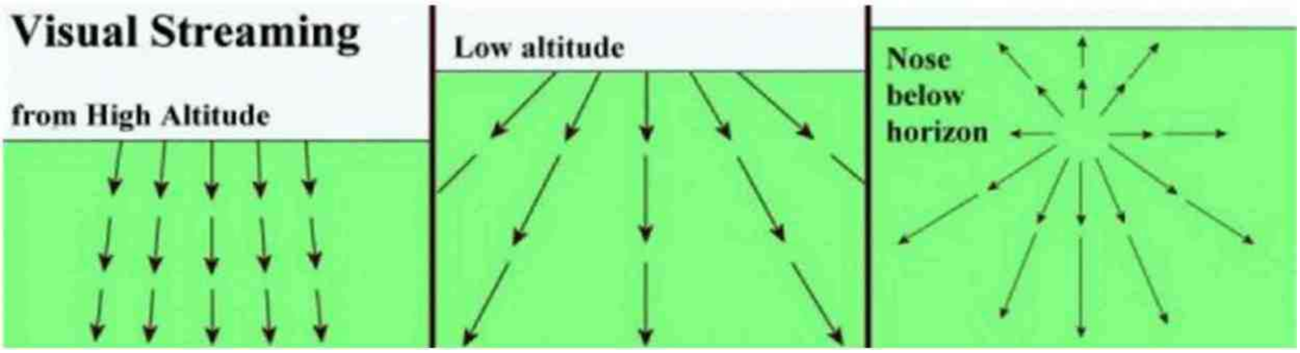
4.1 Cues from Visual Displays. The judgment of height, speed, and direction by the simulator subject is by comparing short-term changes in the OTW visual scene to those with which the subject is familiar in the real world. Many visual cues are automatic and require little or no conscious thought, particularly 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 on the right, a man stands in front of a house, behind which is a tree. As the eye-point moves from left to right, the relative angles of the man, house and tree change. This is a simple example to show the principle. In simulator visual systems, as the eye-point moves across a scene, the RCP of objects at different distances is a compelling cue, for instance for aircraft flying at low level.



4.2.1 Stereoscopic Imagery. The RCP effect means that a stereoscopic (two-channel) display system is not required, because sufficient 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. See also 4.3.2 below

4.3 Visual Picture Flow / Visual Streaming. Another strong visual cue uses the angle and speed that points of visual contrast "stream" or "flow" though a scene. This streaming of the moving visual scene 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 ground vehicle, the interpretation of this cue does not require conscious effort. This is because, in the real world, the brain is used to processing 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 with high-contrast texture and where there is a high density of points-of-contrast in the scene. Texture and terrain alone are capable of producing the streaming cue; other vertical objects in the scene such as buildings, are a bonus. The streaming/flow cue works in poor visual conditions because only a few contrast points streaming through the visual scene are needed for the cue to work. For aircraft simulators, this is safe as long as the terrain is not too rugged or the aircraft is very low.

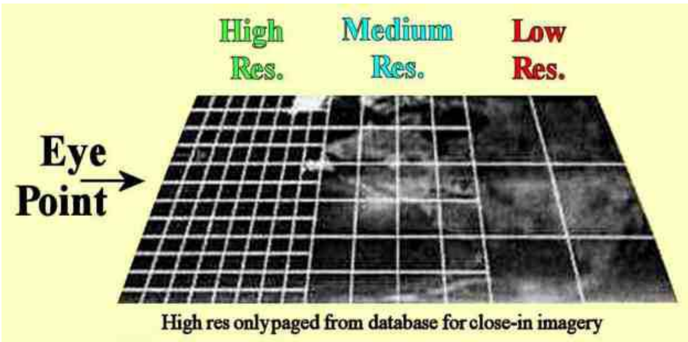


4.3.1 Visual Flow Patterns. Typical visual flow patterns for an aircraft are illustrated above. In the "nose below horizon" situation on the right, the centre point of the streaming arrows is the direction of the aircraft Velocity Vector (VV). This is the eventual point of impact with the ground if the 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.

4.4 Level of Detail (LoD) Scheduling. To reduce the amount of image processing needed at any one time, high-resolution imagery is only processed when it is close to the eye-point, see the diagram on the right.

Lower-resolution imagery is used for imagery distant from the eye-point. This needs less processing by the simulator computer to call it up from memory into active display. As the eye-point changes, the process is repeated, low resolution imagery being transformed to "high res" when required, other imagery being returned to memory.

This process is continually repeated as part of display system LoD Scheduling.



4.5 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 considering the additional cost and complexity of a two-channel stereoscopic system, and at smaller distances with a moving scene, the RCP cue is strong (4.2 and 4.3.2 refer). 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.

4.5.1 Disorientation. There have been instances of disorientation and even nausea from stereo systems in which the two channels were even slightly misaligned [5]. In these cases the visual imagery looked normal but after a while the brain reacted to the misalignment and triggered symptoms of disorientation.

[5] Such as during an evaluation of a stereoscopic system for a fighter simulator, see Annex G page 14

4.5.2 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" [6]. 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. This further illustrates why the complication of a two-channel stereoscopic system is not needed, as long as the quality of imagery in the single-channel system is appropriate to the training task.

4.6 Variations within Polygons - use of Electronic Tags, Attributes or Material Codes. Real world Computer-Generated Imagery (CGI) includes many polygons, the corners 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, and 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 these images are required. The function of what is described above as "Electronic tags" can also be carried out by what are also called "attributes" or "material codes".

4.7 Visual effects of High G. Acceleration along the vertical axis is described as Gz. In aviation this is 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, 2G will feel as if it was 300 lbs; at 4G, 600 lbs; at 9G, 1350lbs.

4.7.1 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.

4.7.2 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.

4.7.2.1 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 for several seconds. In recovering after a G-LOC event, the period of confusion and spatial disorientation is between 10 and 20 seconds, which has often been fatal in fighter aircraft where they are relatively close to the ground.

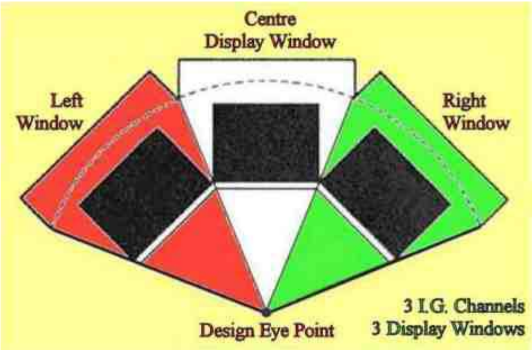
G-induced Loss of Consciousness (G-LOC)

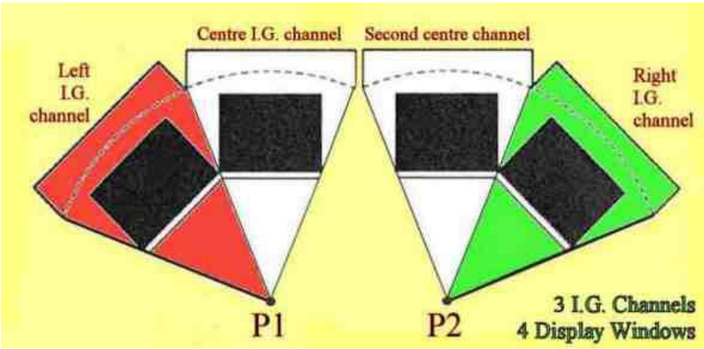
4.7.2.2 Training. For a trained and fit pilot, the above effects are unlikely at less than 6G without an anti-G suit, 9G if wearing good anti-G protection such as an anti-G suit and partial pressure breathing under high G. More detail is at para 9.2, and Annex H deals specifically with cueing for high 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.

[6] Paper on low flying by reference to Electro-Optical Sensors, RAE Farnborough, 1981

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 about 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 the diagrams in 5.2.2.

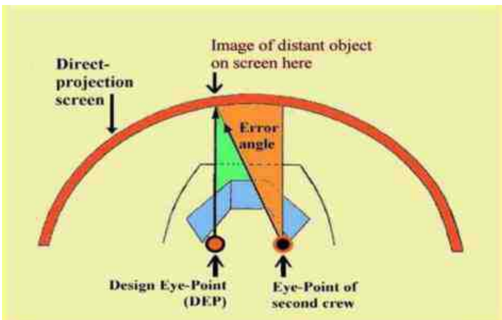




5.1 Wide Angle Displays. A large Field of Vew (FoV) is required in fighter aircraft simulators. The inside surface of domes or partial domes can be the projection surface. Another solution is to use back-projection on flat semi-transparent screens ("facets") that surround the subject of the simulation.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

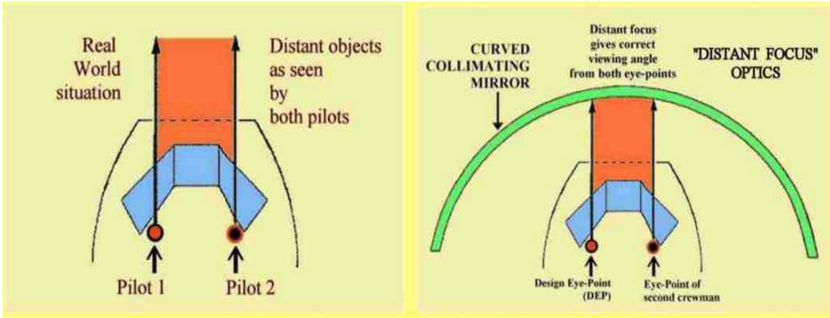


Direct projection - errors for P2

The next paragraph describes 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 on the right shows the real-world situation, and on its right is a display solution using a curved mirror. A display with optics that give a distant focus is said to be "collimated" [7]. This can be achieved in a simulator display by replacing the screen by a mirror that has vertical curvature as well as horizontal extent. The amount of vertical curvature in the mirror governs the focal distance of the imagery. This design is sometimes referred to as a "Cross-Cockpit Collimated Display", CCCD , C3D or just a "Collimated Display".



Real world　　Mirror with vertical curvature

5.2.3 Cross-Cockpit Collimated Display. This was first developed by the Rediffusion company of Crawley, UK, by a team led by Stuart Anderson [8]. It was first offered for sale in 1982 under the name WIDE, standing for Wide-angle Infinity Display Equipment, and the principle is now used by many simulator manufacturers. Imagery is projected on a screen above the cab, out of view of the crew, who see its reflection in the mirror, as shown in the left diagram below.

Optics from side　　3D drawing　　Simulator application

The focal distance depends on the vertical curvature of the mirror, and might be set at over a hundred metres for a simulator for a transport aircraft, less for a helicopter that operates close to trees or buildings. Such large mirrors would be very heavy if they were made of glass, so CCCD systems generally use lighter materials such as Mylar, coated with a mirror surface. When the simulator is in use, a suction pump pulls the mirror material against an accurately 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 unwanted disturbances such as air turbulence in aircraft. ***Because acceleration comes before 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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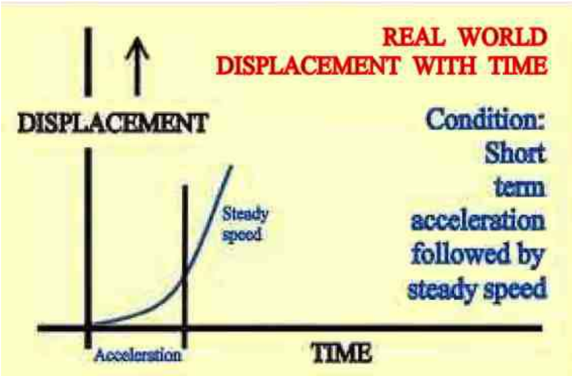
[7] The word "collimation" is derived from "Co-Linear", implying parallel lines or infinity focus. In a collimated display the focal distance is set by the vertical curvature of the collimating mirror.

[8] Later awarded the flight simulation Silver Medal of the Royal Aeronautical Society for this work

6.3. Acceleration Cues - the Key to Rapid Control Response. In the real vehicle, acceleration cues are important in sensing short-term disturbances (over a few tens of milliseconds). In the longer term, (tenths of a second, seconds) visual cues of displacement reinforce the motion cues, and more detail is in the diagram in Para 8. 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 in a way similar to using them in 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 the control and stability characteristics of flight simulators.



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, takeoff 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 **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 are about 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.

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:

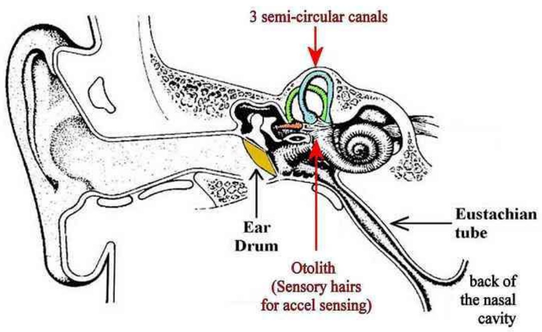
7.2.1 Visual cues. These include the position of the horizon, terrain generally, and the recognition and tracking of known types of objects in the scene. Other cues include the changing perspective of objects and terrain, movement of the horizon (pitch, roll, and yaw), streaming of points of contrast 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.

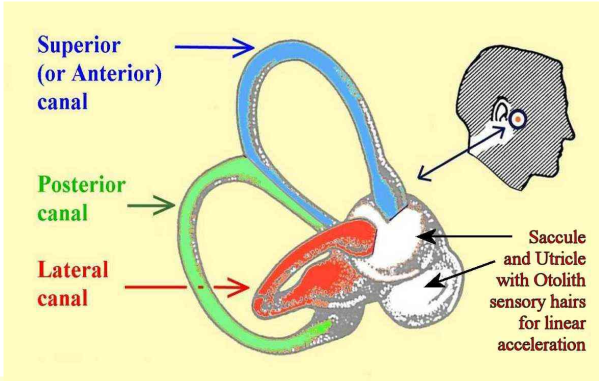
7.2.2 Cues of real motion. These include feedback to the brain from a number of body sensors. These sensors are the two inner-ear "Vestibular" sensors, pressures on the skin, small movements of the torso and limbs, and feedback from general forces on the body. More detail is below and in Annex C.

7.2.2.1 Skin Pressures. These include "seat-of-the-pants" pressure, 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"). These are called **"proprioceptive"** cues, sometimes "Muscle and Joint sense".

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.

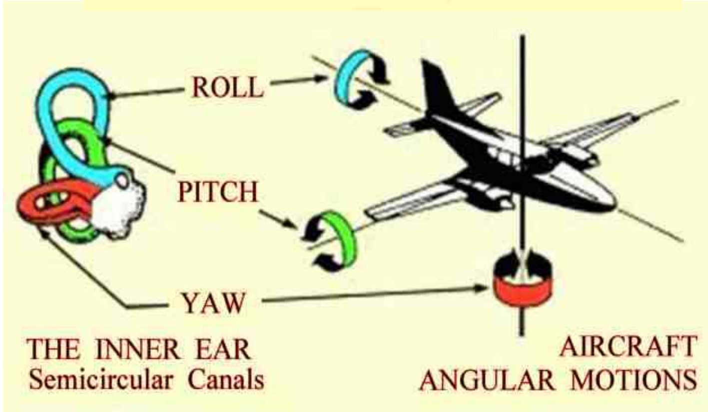




The diagram on the right shows how the semicircular canals relate to aircraft changes of angle rates in pitch, roll and yaw.

Similar diagrams 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.

These principles of how motion is sensed apply to any changes of position registered by a human in a 3D environment.

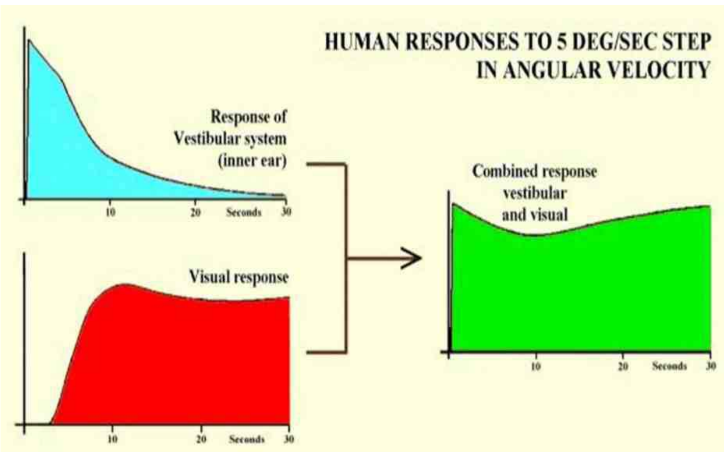


8 **Time Delays in Detecting Real-World Cues**. Acceleration is felt quickly by the body's motion sensors, including its short-term variants buffet and vibrations. As indicated earlier, visual cues are sensed some time later when a displacement of the visual scene has built up to a value above the visual 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 [9] of the Massachusetts Institute of Technology (MIT). 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 (reference 6 in Annex I). The three plots show responses over 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. This data illustrates one of the most important principles that define the way that motion Simulation is effective.

8.1 Vestibular Response. In the diagram on the right, the top left (blue) graph shows the rapid response of the human vestibular system. The subsequent reduction in response shows why 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 red graph shows that the visual response takes time to start and build. Meanwhile, 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 excellent cueing when cues from both vestibular and visual sensors are available. This is why aircraft are easy to control in good visibility, particularly with a clearly visible horizon.



9 Paper on Visual & Vestibular Cues in Human Perception & Control, by G L Zacharias and L R Young of M.I.T., Experimental Brain Research magazine, published by Springer-Verlag 1981

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 processing of the visual cues for the same disturbance.

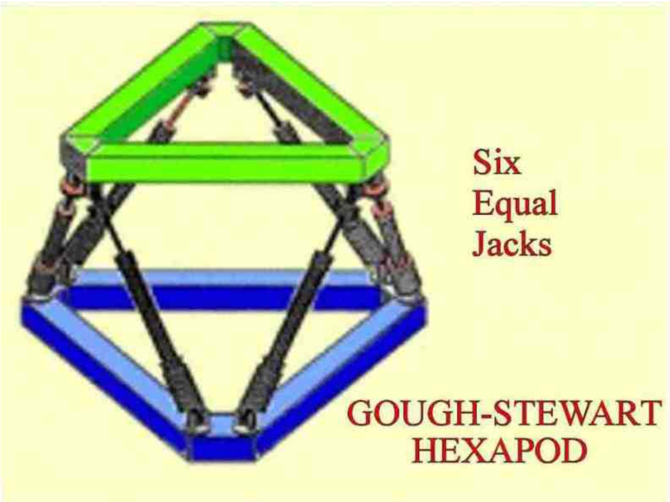
Aero-medical specialists (flight surgeons) have confirmed that the other body sensors of direct motion (tactile, proprioceptive, kinaesthetic; see para 7.2.2 and annex C) transmit their messages to the brain in a similar timescale to that of the vestibular apparatus.

Therefore, the initial control responses that aircraft pilots are used to making 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. The data in the above diagrams is vital in understanding how modern motion-based Flight Simulators work effectively.

SIMULATOR MOTION CUEING SYSTEMS

9. **Simulator Systems giving Cues of Motion**. Theses are tabulated at annex D, which shows that the systems with most cueing capability are (1) changes in the Outside World (OTW) visual scene, (2) a motion platform capable of moving the simulator cabin with initial accelerations similar to those in the real vehicle, and (3) the vehicle instruments. Cues of real motion are processed by the brain before cues of visual change, and this is important if simulator control actions are to match those in the real vehicle - more detail is in paras 8 and 13. In conditions such as night or reduced visibility, the instruments and motion platform become more important. For aircraft capable of high G loadings, important extra simulator cues can be provided by the use of an anti-G suit, visual system dimming at high computed G, and a simulator motion-seat. The following simulator systems produce forces, pressures, rotations and other movements.

9.1 Motion Platform. This is 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.



The diagram on the left shows the jack layout, with an example on the right of a typical hexapod platform supporting a simulator cab. The clean lines of the platform jacks without hydraulic pipes show that they are electrically operated.

9.1.1 Origin of the Hexapod motion platform. The geometry of the hexapod was first described in a 1956 paper by Dr Eric Gough of the Dunlop Rubber Company, in a paper to the London-based Institute of Mechanical Engineers (I Mech E) [10] in a design used for testing automobile parts. Then in 1965, D Stewart of Elliot Automation presented a paper "a platform with six degrees of freedom" [11] to the I Mech E, with a view to its use in flight simulators. This hexapod layout is often called a "Stewart platform", although it would be more correct to call it a "Gough / Stewart platform". Meanwhile in the USA, Klaus Cappel of the Franklin Institute in Philadelphia obtained Patent 3295224 in 1967 for a hexapod motion platform for use by the Sikorsky company for a helicopter simulator.

[10] Proceedings of the Auto Division of the Institute of Mechanical Engineers, London, 1956, pages 392-394

[11] Published in Volume 180 of the Proceedings of the Institute of Mechanical Engineers, London, 1966

9.2 Simulation 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 at high G 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 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 in a simulator such as G-Suit inflation, also pressure breathing under G as fitted to aircraft such as the Eurofighter Typhoon, to ease physical strain on the pilot at high G. Inflation of the pilot's own anti-G suit is straightforward in response to computed G in the simulator, and has been demonstrated on simple seat models at training exhibitions.

9.3 Vibration devices. Simple devices can be used in a simulator to produce vibration, typically using 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 in the real vehicle. Frequency and amplitude can be varied by using different rotation rates and weight offset.

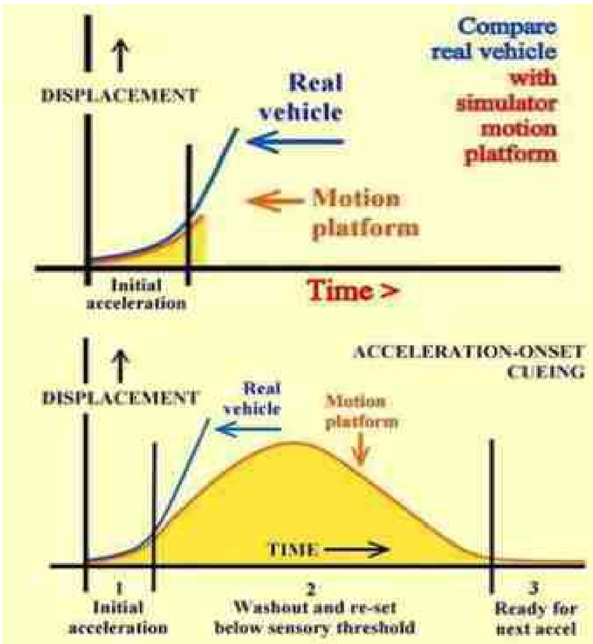
MOTION PLATFORMS - METHOD OF OPERATION

10 **Motion platforms - general**. The modern hexapod [12] motion platform with smoothly-operating jacks is a well-tried engineering 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 designs of the 1970s, which could have transport delays up to 300msec for the heavier platforms, and sometimes produced adverse effects. Current designs have latencies of less than 100msec, many modern electric platforms giving 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 360º or create continuous G forces. Despite this, hexapod platforms are highly effective motion cueing devices, for the following reasons:

11.1 Initial Acceleration. Motion platforms are basically acceleration devices ("kickers") that produce the initial accelerations in the appropriate degrees-of-freedom (see the diagram on the right).
11.2 Wash-Out Phase. After the initial acceleration has been produced, the platform program then uses the remaining jack "throw" to "wash-out" the motion and re-set the platform ready for the next control input. This is done by moving the platform back to a neutral position (the right side of the lower diagram) at a rate below the subject'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 works well in simulators. See also the top of the three graphs in the diagram in para 8 (the blue graph) which 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 processes of washout and re-set being detected.

11.4 Overall Effect. The author has tested many flight simulators and has been impressed with the realism of motion cues in motion 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 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 other 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 can be used to give pressure on the back 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 does not display the motion platform pitch angle, so that the cue can be sensed as acceleration or deceleration instead. For instance, during an aircraft takeoff the platform may be pitched to, say, 20 degrees, at a rate below the pilot's sensory threshold so that the pilot does not sense the change of pitch.

The effect of leaning the seat results in a continuous force on the pilot's back (for the acceleration cue) or on the straps (for deceleration) which is interpreted as sustained longitudinal acceleration or deceleration. This cueing system 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 so that the appropriate side-force is experienced in the simulator.

13 **Motion Feedback**. In real aircraft, the pilot's body motion sensors ensure quick reaction when flying a "high-gain" control task without relying on Autopilot control. The pilot may not know why a particular control input is being made, but after many hundreds or thousands of hours of real flying, control responses to short-term accelerations are made quickly and automatically, without conscious thought, such as, in turbulence, to maintain level flight or to sustain an even rate of turn to conform with Air Traffic requirements.

13.1 Application to simulators. In 1989, the UK Royal Air Force Institute of Aviation Medicine (RAF-IAM) 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 confirmed 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. The IAM 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" particularly when outside-world (OTW) visual cues are strong (see later, para 20). Number 6 in the list of references in Annex I 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-axis 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, transiting through microbursts [13], and to helicopters at the hover near the ground. Also for failure cases that require precise flight path control, including engine failures with roll, yaw and sway. For military aircraft, tactical manoeuvres, low flying, visual weapon aiming, formation flying and air refuelling.

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. This applies to all aircraft types including fighters, transports and helicopters. The realism of motion includes wheel rumble effects when on the ground, yaw cueing for taxying, 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 psychological "immersion" where the simulation is particularly realistic and the pilot is working hard.

[13] Extreme turbulence and wind-shear below thunderstorms due to a strong downcurrent of cold air hitting the ground and spreading out

14.2 Replicating the whole flight environment. There are many papers on this subject (see Annex I). A useful summary is in "The Need for Motion: a Pilot's Perspective", by Captain Bryan Burks of the Training Council of the International Airline Pilots Association (ALPA), paper 23. He said that simulator motion is required because the pilot's vestibular system provides "the most powerful and quickly sensed cue for motion", and other sources of motion cueing (visual, sound, tactile) are important but complementary. He concluded that: "to leave motion out will mean that pilots will use differing, and incomplete, cues during training, and 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 31) who looked at training for airliner "upset" and stall events, also 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 produce acceptable cues. He also stated that cues using a centrifuge with a realistic cockpit and controls (see Annex H for cueing for G forces) are very similar to the aircraft in a high-G situation. Finally, Dr Jeff Schroeder of the US FAA concluded (paper 32) said 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.

15 **Quality of Motion Cueing**. Cues of real motion need careful setting up. In particular, motion cues must be properly synchronised with corresponding changes in simulator visual imagery, so that they correspond to how these cues are sensed in the real world.

15.1 High Latencies (Transport Delay). Latency is a critical factor in high-gain closed-loop control situations that are typical of many training tasks. Some heavy and not very agile motion platforms in the 1970s had latencies up to 300 milliseconds. This figure reduced in 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.

15.2 Synchronisation with Visual System Latencies. The human body senses and processes 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 will lead to unrealistic control inputs and, after a time, cause the subject to feel symptoms of "simulator sickness" (para 20). The synchronisation of motion and visual cues should be monitored during the life of a simulator, such as using Built-In Test Equipment (BITE) before a training sortie is undertaken. In terms of the acceptable lag of simulator visual cues ***after*** motion, it has been suggested that the transport delay of visual cues should not be more than 30 ms after motion cues [14] are received by the brain (diagrams, para 20.1)

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 simulator systems occurred. Now, with Built-In Test Equipment (BITE), simulator system responses can be checked before each 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 industry-standard 6-DoF platform with jack-throws of between 4 and 5 ft, complies fully with the US FAA and EASA Level D standard. Many of the 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, high quality 6-DoF platforms, low latency can compensate for lack of size, as long as the platform accelerations are properly synchronised with matching changes in visual imagery.

16.1 Degrees of Freedom. In view of the many platforms that produce all 6 DoF, for most applications there is no point in using a platform with less. A special case is for a specific role such as a ground vehicle simulator where many "start and stop" (surge) events need to be modelled. Here, platform geometry can be optimised for longitudinal acceleration (surge) and used for simulators for vehicles that often start-and-stop such as buses, trains and trams. Alternatively, a separate surge system used in addition to the main motion platform, and n some research simulators for ground vehicles, a complete 6-axis motion base is mounted on a moving platform that has further horizontal movement over several metres (see text and picture in para 21.1).

17 **Aviation Simulation Terminology**. In civil aviation, the designation "Full Flight Simulator" (FFS) is only applied to devices with motion platforms and other defined characteristics (detail, Annex E). Other categories of trainers have different names and initials such as FTDs (Flight Training Devices), FNPT (Flight Navigation Procedures Trainers), PC ATDs (PC Aviation Training Devices), Advanced Aviation Training Devices (AATD), and so forth.

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 the supervision of a Training Captain until the pilot is checked out to fly without supervision.

[14] Royal Aeronautical Society conference on simulation, November 2012

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 (RAeS FSG). The new International Type 7 is an enhancement on the Level D design, with increased fidelity for motion and visual systems plus 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 many others, UPRT is now a mandated part of World Airline simulator training. This level of enhanced simulator training was recommended by the International Committee on Aircraft Training in Extended Envelopes (ICATEE) which was formed in 2009 under RAeS Chairmanship and reported to ICAO, the US FAA, EASA and others in 2013. The author of this paper was a member of ICATEE and contributed his military simulator and training expertise to this essentially civil training environment. The majority of UPRT can be achieved on a Level D Full Flight Simulator (FFS) as long as the aircraft manufacturer supplies appropriate data on the aircraft's full flight envelope to the simulator manufacturer, including the stall. In a paper to the RAeS (Annex I, paper 32), Dr Jeff Schroeder of the US FAA suggested that an FFS could cover 82% of UPRT and in an RAeS Ray Jones Memorial Lecture, Captain Larry Rockliffe, chief test pilot of Airbus China, suggested that 85% of could be trained in a FFS. 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.

17.4 Military applications. "Zero Flight Time" training before flying the aircraft itself cannot be applied to military operations because of their different nature and more complex tasks. Training in fighter and other combat aircraft are obvious examples. However, military counterparts of civil aircraft have roles such as air refuelling, low flying, tactical operations, formation flying, etc, and such aircraft generally have simulators equivalent to civil level D but with additions to train for the extra roles. These high quality simulators can enable pilot conversion to be carried out using only a small amount of aircraft time and a larger amount of simulator time first. A few examples follow.

17.4.1 USAF Globemaster. The simulators for the US Air Force C-17 Globemaster III strategic transport aircraft are Level D Full Flight Simulator designs with enhancements to match extra military roles such as formation flying, low flying, air drop and STOL operations. Conversion of new pilots to the C17 is after only two handling flights in the aircraft itself before the check ride itself. Before this, over 20 simulator sorties are flown including training for the military roles listed above.

17.4.2 Tanker Aircraft. Pilot conversion to the Australian Air Force Multi Role Tanker Transport (MRTT) aircraft (based on the Airbus A330) requires only two training flights before the qualification test, preceded by comprehensive training on a Level D Simulator.

17.4.3 Apache Clearence for Ship Operations. In the 2011 campaign in Libya against the Ghadaffi regime, the UK had an Urgent Operational Requirement (UOR) to operate its Apache attack helicopters from sea-based Aircraft Carriers, which had not been done before. The Apache Carrier clearance was achieved through simulation, rather than flight tests with real aircraft on the Carrier deck. Fortunately, a high quality Apache simulator was available with 6-axis motion and wide-angle visuals, at the UK Army Air Corps base near Salisbury. Using this, an updated model of the Apache's characteristics at new combat loadings was added to the simulator, and airflow over the carrier was modelled at different speeds and wind conditions, plus models of deck movement in different sea states. This resulted in clearance for war operations from Carriers. When operational missions were flown by the real aircraft, the accuracy of the simulation used for clearance was confirmed.

TESTS ON SIMULATORS

18 **General**. The author has 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 flying at Boscombe Down and Farnborough. These include assessment of sortie phases from engine start, taxying out, takeoff, various flight manouevres including those in which aircraft handling is critical, then approach, landing, taxying 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.*** Of course, the above adverse effects can be corrected in a simulator that is designed without motion from the start, but ***without cues of real motion, the simulator stability and control characteristics and the way the pilot handles the controls, will not be "as aircraft"***. For a fixed-base simulator, the correct aircraft stability and control characteristics have to be "damped", to eliminate oscillations and over-control in the simulator.

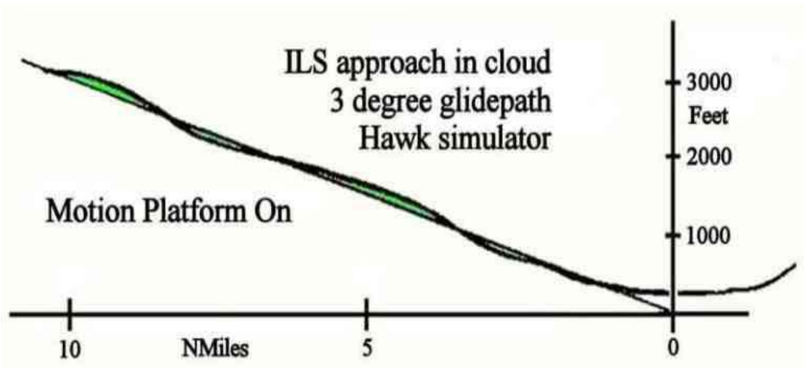
18.1.1 Pitch. With visual only and the motion platform disabled, pitch changes felt ***very bland and unrealistic, like a computer-game, and at high pitch-rates over-stressing frequently occurred.*** Aircraft G limits were exceeded in the simulator due to "over-controlling" in pitch. This was suppressed when motion cues from the platform were available.

18.1.2 Roll. The visual system gave strong cues, re-inforced by the motion platform which gave 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, but ***very unrealistic without motion, resembling an arcade game***.

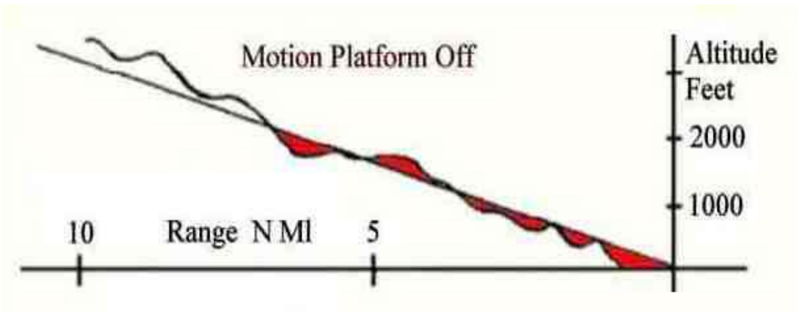
18.1.3 Formation Flying. This was realistic when both motion and visual cues were available. When the motion platform was disabled, the characteristics became much less stable. ***Control was untypical of the aircraft and it was not possible to fly close echelon or line astern positions***. Approaches to refuel (probe and drogue) were too oscillatory and would have failed both to make safe contact with the drogue and to hold a steady refuelling position. With the addition of motion cues, approaches to the drogue were more stable and it was possible to make contact and hold a close-formation refuelling position.

18.1.4 Fighter Aircraft - Simulator Characteristics. A combination of motion, visual, g-suit, and g-seat, gave the best cueing. Motion platform cues were particularly effective where pitch and roll changes were made and when visual conditions were poor. At high G, cueing from the pilot's anti-g-suit was particularly noticeable, the simulator g-seat gave positive cues but less than the g-suit. ***With visual only (no motion, g-suit and g-seat) simulation was bland and unrealistic, felt like a computer-game, and over-stressing (too high G) frequently occurred.***

18.2 Instrument Approaches. Instrument Landing System (ILS) approaches were flown without external visual cues (i.e. 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, also because the author was out of practice on the Hawk at this time. 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.



18.2.1 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, and is shown below. 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.



18.2.2 Longitudinal characteristics. In the second plot, note the completely different and unrealistic aircraft longitudinal characteristic compared to the first approach. 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 evidence in this paper is: "if there is such a case for motion platforms, how is it that large numbers of military simulators do not have them?" Aside from cost, 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 somewhat heavier in the simulator (18.1.1 & 18.5.2 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. Care must be taken to avoid adverse effects such as unusual control strategies and 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 primarily on learning checks, practising procedures, or networking with other simulators, and precise handling is not a requirement, then a motion platform is not needed.

19.2 Simpler Training Devices. *If good control and motion 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 US Air Force Distributed Mission Operations (DMO) simulators at Kirtland Air Force Base that have simple visuals and no motion - three examples are shown on the right, in use during a multi-simulation exercise with simulators at other bases.

Indeed, for basic procedural or system training, a laptop PC, Tablet or i-Pad may be all that is needed. Connections 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, a training solution based on FTD/PTT, backed up by use of the real equipment in a training mode, will increase the wear-and tear on the equipment itself and will have a higher overall cost than funding a Full Mission Simulator with network connections.

20 **Cue Conflicts and"Simulator Sickness"**. Pilots fly thousands of hours in real aircraft and the brain becomes used to receiving aircraft-based visual and motion cues in real world situations (more detail is in para 5 and annexes B and C). In simulators with wide-angle visual but no motion, a "Vestibular Mismatch" [15] may occur after a period of time because the brain subconsciously senses an unfamiliar situation and eventually causes symptoms of so-called "Simulator Sickness" that can vary from a feeling of disorientation to actually being sick. The time period after which the brain signals a Cue Conflict compared to the real world situation varies with the individual and with the magnitude of the difference in cueing. Another factor is the level of familiarity with the real world situation, and crew in the initial training process may have different reactions compared to highly experienced crew who are used to real-world cues.

20.1 Mis-matched motion and visual cues. A cue mismatch can also occur in a motion-based simulator if the motion and visual cues do not occur in the real-world sequence. Older, less responsive motion platforms had long reaction times that led to motion cues being sensed ***after*** the related changes in the visual scene, the opposite of what happens in the real world. Modern motion platforms do not suffer from this, particularly if the simulator systems continuously monitor reaction times of motion and visual systems.

20.2 Simulator Sickness. The author started testing simulators in the 1980s and the cases of "Simulator Sickness" that he has experienced have all been in simulations with wide visuals but no motion platform. Symptoms included nausea, the "leans" (a strong feeling of false pitch and roll attitudes), and post-simulation disorientation. These effects were not experienced when motion and visual cues were sequenced as in the real world, in which motion cues are processed by the brain before changes of the visual scene.

[15] Dr Helen Hoar, lecture at the Royal Aeronautical Society, October 2015

20.3 Visual Scene Distortion. Another type of cue conflict is where the visual scene is distorted compared to the real world. This can be critical when accurate visual imagery is needed, such as targets, other aircraft and objects, and so forth. For the correct perspective of objects at difference distances, the simulator subject needs to be at the Design Eye-Point (DEP) of the visual display system. In a multi-crew simulator this is not possible for all of the crew if the outside-world display is on screens a few feet ahead. On page 12 of the Annexes there is more detail on how imagery viewed by crew members in different positions is changed by being displaced from the DEP. It should be noted that a distant focus "Collimated" display system avoids this situation. Because of the "distant focus" of the imagery, the crew see essentially the same perspective although they view it from different locations (see the diagrams in para 5.2.2, page 6).

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 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.

21.1 Stop and Start. For vehicles that often stop and start, cueing for longitudinal acceleration and deceleration ("surge") can be improved by using a motion platform designed specifically for this and having particularly large "throw" in surge.

Alternatively, a conventional 6-axis platform can be mounted on a base that can move horizontally, giving extra motion cues. Examples include the US National Advanced Driving Simulator at the University of Iowa (picture on the right), Toyota's driving simulator at their Higashifuji Technical Centre, and a smaller version at Leeds University in the UK that the author has experienced.

21.2 Noise and Vibration. Cues of noise and vibration may be particularly important in some vehicles, and these cues can easily be produced in a simulator (see para 9.3).

21.3 Ship simulators. The case for real motion in ship's bridge simulators is not as strong as for aircraft because of the longer time-period of ship motion. Sea swells and responses to ship control movements have a time-constant of several seconds rather than the milliseconds that apply to control activity and air turbulence effects in aircraft. The author has experienced a fixed-based ship's bridge simulator with a wide-angle visual system that was realistic enough for a number of subjects to be "holding on" to objects in the simulator as the ship pitched and rolled, even though the simulator could not move. However, on leaving the simulator, adverse motion effects (spatial disorientation) were felt for some time afterwards. This may be a reaction to visual motion not being backed up with cues of real displacement as in the real world, or it could be a reaction to normal ship motion (sea-sickness).

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 Life-Cycle Costs, 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. With the costs of flying complex aircraft such as Eurofighter Typhoon, F-22 Raptor and F-35 JSF Lightning II, the cost ratio will always be very favourable to good quality simulation . 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. See also 17.4.1 and 17.4.2 about the costs of conversion to military aircraft such as the C-17 and Multi-Role Tanker/Transport (MRTT).

23.2 Vehicles other than Aircraft. A cost ratio of 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 really "big one" in cost is the possibility of extending the service life of the vehicle fleet by judicious use of simulation, compared to fatiguing the vehicle itself by over-using it for training. The reverse is having to retire the real vehicle early. In the past, this happened to the very capable F-14 Tomcat naval fighter aircraft which had been subject to a substantial amount of high-G training in the aircraft itself, and less use of simulation.

SUMMARY AND CONCLUSIONS

23 Visual Cues

Computer-generated Imagery (CGI) closely matches the real world in resolution and image content.

Simulators are therefore able to give similar visual cues to those in the real world.

23.1 Imagery. Realistic real-world visual scenes are created by computer-based Image Generation (IG). For simulators, large-area databases can be stored and the relevant data can be "paged up" into active memory for use in visual display. 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

These are cues as a result of real movement, not due to changes in the visual scene.

The principle of "acceleration-onset cueing" in simulators matches the way that the motion sensors of the human body work, because they also sense acceleration rather than steady, unaccelerated movement.
This can be replicated in the accelerations produced by a simulator motion platform.
Crew members of the real equipment are used to real world cues, and when in a simulator the brain will expect similar cues.

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 have limited fields-of view. In the real world, after a displacement has occurred, the brain processes acceleration cues quickly, followed 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 systems must be set-up carefully and their operation synchronised correctly with visual displays and instrument indications.

24.2 Cueing for G. For 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. **Conclusions**

25.1 Versatility. 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 the use of simulation. Training for conditions that are too hazardous to train in the real vehicle can also be covered, and training can include exercises with different organisations including other services and nations.

25.2 Cost savings. Savings are particularly large 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 be 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. Cost savings with other aircraft, ships and land vehicles are also significant.

25.3 Military Uses. In the military, where real vehicles and weapons are used for training, there are constraints in their use, including the hazards of training for 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 to train for hazardous situations or those that are simply not possible in live training in peacetime. Simulation can also include various possible reactions of a potential enemy and a number of counter-actions can be explored. For exercises, network links can be used for multi-role, multi-Service and multi-national exercises, and future scenarios can be explored.

25.4 Summary. Simulation is very capable, can train in more areas than the real vehicle, and can save money.

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. BAE Systems Hawk aircraft simulator - test results
G. Extracts from Simulator Test Reports
H. Cueing for G forces
I. References