# DESIGN PHILOSOPHIES OF THE BASIC RESEARCH SIMULATOR

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## Abstract

A new flight simulation research facility is being developed, a system designed to investigate certain issues related to vehicle simulation in three specific areas of interest. These are:

- The dynamic behaviour of motion platforms.
- The performance of vehicle simulations in a ground-based environment.
- The human factors of vehicle operation.

The dynamic behaviour of a motion platform can be improved by minimizing the mass of the moving components and by placing the centre of gravity in a low vertical location. In practice, metal-fibre laminates (hybrid materials) will form the primary structure of the Basic Research Simulator in order to minimize its weight. To lower the centre of gravity, the cockpit floor will be attached beneath the primary load-bearing frame of the moving platform and below its gimbals. Further improvements to the dynamic properties will be achieved through the application of multi-variable control techniques to drive the six-degrees-of-freedom motion system.

A motion system with favourable dynamic properties can serve as a tool for conducting basic research into vehicle simulation and into the human factors related to the operation of vehicles. Parasitic motion signal noise, or displacements in the non-driven directions, can be virtually cancelled by proper design and control techniques. The provision for flexible cockpit and instrument arrangements supports research into man-machine interfaces in the cockpit.

This paper will discuss the principles applied to the design of the Basic Research Simulator and in further detail the proposed applications of the facility.

## 1. INTRODUCTION

Flight simulators play a very large and growing role in the aerospace industry as technology becomes increasingly capable of recreating the flight-deck environment. This has resulted in using simulators as cost-effective flight crew training tools, and as invaluable facilities for aerospace research and development. With further technological improvements, and the growing capacity to implement these concepts into hardware, the next generation of flight simulators will provide improved cue realism for pilots at a minimum operating cost in the training and research environments.

The Basic Research Simulator will aid in these developments, by merging many new technologies from the aerospace, mechanical, and electrical disciplines to create a simulator which is notably different from present-day devices.

Several features of the Basic Research Simulator configuration have stemmed from the requirements to investigate specific areas of interest which are or will be of merit to the next generation of vehicle simulators. The design principles are described in this report. Section 2 describes the existing simulation research facility at the Delft University of Technology and the work accomplished to date with it. Then, the Basic Research Simulator is introduced: Section 3 suggests how a motion-based simulator can be optimized. Section 4 describes the Basic Research Simulator hardware and its design, while Section 5 provides an overview of the proposed applications and their projected benefits.

## 2. BACKGROUND

The Basic Research Simulator Programme is the continuation of research activities in the areas of flight simulation and human factors sciences in the Faculty of Aerospace Engineering. The equipment used to date and the research conducted are described in this section.

The TU Delft has been operating a three-degrees-of-freedom research flight simulator since 1969, see Figure 1. This system has served as a research tool for the development of simulation technology such as hydrostatic bearings and motion drive laws,[1] and the development of several aerodynamic models for research and commercial purposes.[2] Additionally, man-machine systems research related to motion perception[3] and cockpit systems have also been investigated.[4] This system is currently being used for the development and preliminary evaluation of future cockpit displays including those which use four-dimensional navigation systems.

In continuation of the research goals in the areas mentioned above and beyond, a new facility is planned, the Basic Research Simulator. The development of this multi-purpose facility requires considerable design effort in order to maximize the system performance, to permit the various applications to be carried out, and to be safe, reliable and rugged. These considerations and other design input parameters are now discussed.

## 3. MOTION SYSTEM AND FLIGHT-DECK PLATFORM

### 3.1 Importance of a Motion System

During the manual operation of a vehicle, the human controller receives important information from motion, visual, and aural cues through his sensory devices. The motion sensations can serve to close the loop by providing a control feedback to the pilot, thereby improving the performance of the whole system.

It is thought that humans most readily sense specific forces and angular accelerations,[5] so these must therefore be presented most reasonably, with minimal false cues.

Furthermore, experience indicates that good motion cues with minimum time delays in the simulator environment significantly reduce pilot-induced oscillations, and also the possibility of simulator sickness. Based on these findings, it is clear that motion cues are essential to the controlling of vehicles, both real, and simulated.

### 3.2 Fidelity of Motion Cue Generation

The fidelity of simulator motion, apart from the mathematical model of the vehicle, depends on three factors. These are:

A. Motion filters

Various motion drive algorithms have been developed for use in six-degrees-of-freedom simulations.[6] Exact one-to-one simulation is rarely possible due to the hardware constraints of the motion system. While a vehicle may move freely, the simulator remains fixed to the floor. Therefore, the transfer functions generated by the aircraft mathematical model must be modified by washout filters. These filters are usually tuned subjectively with the help of an experienced pilot in order to optimize the match between the motion system and the aircraft characteristics.

B. Fidelity of the motion system mechanical hardware

The responsiveness of a simulator depends considerably on the ability of the motion system to produce smooth and accurate movements representative of the shape desired by the controlling algorithms. Because the human motion detection systems are very sensitive, the bandwidth, phase, and noise properties of the motion base hardware play an important role in simulation realism. The quality of the hydraulic actuators and of the valves which control these is of particular importance.

C. Inertial properties of the moving platform

The inertial properties of the motion platform can influence the desired behaviour of the mechanical system by introducing phase lags. Considering that a modern flight simulator cockpit may weigh in the order of twelve tonnes, and that the translational and rotational acceleration limits may reach 10 $m/s^2$ and 400 $deg/s^2$, substantial dynamic loads associated with this system are transmitted to the hydraulic actuators. The interactive behaviour of the closed-loop system is thus affected by the combined mass and inertial properties of the motion system/cockpit platform and considerable compensation is thus required.

### 3.3 Improving the Motion System Dynamics

The realism of flight simulation depends on the software controlling the mechanical motion system, as well as the properties of the hardware. Since motion drive laws are not the focus of this paper, attention will now be turned to the hardware of the motion system.

In order to improve the realism of simulation, it is necessary to accurately represent flight through turbulence, the aeroelastic modes of an aircraft, and other high-frequency characteristics of flying. It is in general desirable to increase the bandwidth of flight simulator motion systems while minimizing errors resulting from dynamic lag. This is among the major challenges in the development of any modern motion-based flight simulator.

The dynamic behaviour of a motion platform is an indicator of its quality. AGARD Report AR-144 specifies the dynamic requirements for six-degree-of-freedom flight simulator motion platforms.[7] The FAA Level D (Phase III) standard requires the time lags of all simulator systems, including motion, visual and instruments, to be within 150 milliseconds.[8]

Despite the abilities of the motion system manufacturers to produce motion systems with excellent dynamic properties which meet the above standard, the overall performance of such systems is directly affected by the mass properties of the flight deck payload. As the mass increases, the system's natural frequencies decrease. More hydraulic power is necessary to provide the required dynamic compensations, yielding also higher leakage flows in the actuator hydrostatic bearings and servo valves.

Therefore, in order to provide optimum dynamic performance of a motion system for moderate power requirements, three design factors must be considered: The mass of the platform, the location of the mass centre, and the distribution of this mass.

A. Minimizing the mass of the moving platform

The principal means by which the mass of a motion platform can be reduced are listed:

- ☐ Minimize the floor space to what is needed for the required simulation missions.

- Produce a structure which incorporates light weight materials, such as modern composites, while meeting critical fatigue life-cycle requirements.
- Integrate the structure so that the cockpit walls and roof are also load-bearing.
- Minimize the amount of heavy equipment on board the moving platform. For example, computer hardware and associated power supplies can be placed on the ground. Electronic signals can be multiplexed onto fewer cables and modern high-speed communication protocols used.

B. Lowering the platform centre of gravity position

The vertical location of the platform centre of gravity in a motion system directly affects the loading on the actuators. High centre of gravity configurations tend to increase these loads during motions that are not symmetrical about the vertical axis. Also, in extreme cases of pitch and roll, very large restoring forces may be needed if the centre of gravity is significantly higher than the platform centroid and, in general, high loads translate to higher compensation requirements by the actuators.

During motions of the platform, each of the six actuators moves a virtual or "reflected" mass, which depends on the mass and moments of inertia of the platform, and its motion state. Thus, the total "reflected" load on an actuator is that due to the instantaneous geometry of the system.[9] Parasitic motions (those in the non-driven degrees-of-freedom) can also be substantial when the centre of gravity does not coincide with the geometric centroid of the moving platform. It is important that the parasitic motions and other motion-related noise are not detected by the simulator pilot(s). Parasitic noises are proportional to the vertical centre of gravity offset.[10] The threshold limits of human motion perception can be compared.[11] A motion system must therefore be controlled by a high frequency feedback system which compensates for the potential discrepancies. The compensation requirements, however, depend considerably on the magnitude of the centre of gravity offset and can thus be reduced in the design stage by optimizing the platform geometry as described above.

In practice, the vertical centre of gravity location can be lowered by the following procedures:

- Place the floor inside the triangular load frame, thereby locating the floor surface beneath the gimbal plane. To accommodate the cockpit layout, the load frame becomes semi-triangular as shown in Figure 2.
- Place the flight deck equipment (computer hardware, etc.) in the lowest possible locations. Heavy equipment which is position independent can be mounted beneath the floor, which also improves ease of inspection and maintenance.

In general, by reducing the level of compensation that is required, the inevitable errors are reduced. Whatever compensation that is still required is for much smaller effects. In the case of the Basic Research Simulator, this compensation will be with virtually perfect mathematical tools and advanced control concepts.

C. Optimizing the mass distribution of the platform

The mass moment of inertia plays an important role in the dynamics of rigid body motion. The inertia increases with the square of the radius from the rotational centre of a given mass. In the case of a motion platform, this suggests that the mass should be placed close to the centroid, the kinematic centre. As well, the mass should be balanced about the primary axes of motion so that the reflected load is minimized and, hence, parasitic motions are reduced. Then, the required performance can be achieved for a minimum of power consumption.

A small platform with a nearly symmetrical mass distribution will result in low mass moments of inertia of the moving platform. When the payload is centered, the coupling between symmetrical and asymmetric dynamics is also small, thereby reducing the compensation necessary. This is a design goal in the Basic Research Simulator.

## 4. BASIC RESEARCH SIMULATOR HARDWARE

The Basic Research Simulator will be based in the laboratory space of the Disciplinary Group of Stability and Control of the Faculty of Aerospace Engineering. It is shown in Figure 3.

### 4.1 Motion System

A. Hydrostatic actuators

The motion system is driven by six linear hydraulic actuators and their related hardware. The actuators have a stroke of 1.25 metres with .05 metre excursion limitation buffers at each end. The operating stroke thus becomes 1.15 metres. In the event of a control signal failure, the buffers would serve to cushion the load of an uncontrolled actuator before metal-to-metal contact occurs.

The type of actuators to be used were originally developed for the very large motion system of the new National Simulation Facility of the National Aerospace Laboratory (NLR). They incorporate friction-free hydrostatic bearings to virtually eliminate undesirable motion noise resulting from their movement. Figure 4 shows that these actuators utilize a double-concentric piston design which effectively forms a symmetrical extension/contraction surface area. This means that the servo valves may also be of a symmetric critical centre design, making their precision control straightforward and size compact. This arrangement also makes the kinematic efficiency (the ratio of total stroke to the minimum length of the jack) considerably large.

A stroke of 1.25 metres was chosen since this would provide a sufficient lateral stiffness and could be produced without difficulty. A prototype actuator with a stroke of 1.0 metre will be tested before the six longer stroke devices are produced.

B. Kinematic geometry of the motion system

The optimization of the motion system geometry was based on providing a reasonable balance of various degrees-of-freedom for the proposed uses of the simulator. Since this is not only a pure transport aircraft "flight" simulator (the realistic simulation of road vehicles and rotorcraft is also necessary), the optimization was not limited to maximizing the pitch and roll degrees-of-freedom; these provide the essential cues in the performance of tracking tasks. Pitch and roll motions also yield the specific forces in the x and y directions which create the effect of sustained linear accelerations along these axes.[5] Vertical Takeoff and Landing vehicles have characteristic motions such as high frequency dutch roll in which yaw dominates, and other motions which introduce themselves in surge. Periodic motions in surge are also significant. The vertical accelerations of rotorcraft, primarily due to the application of collective pitch inputs, can be reproduced by motion base heave. Vertical linear accelerations cannot be sustained however, although these are not essential in a control task.

The simulation of sustained longitudinal (x-direction) accelerations in flight simulators makes use of specific force vectors and is accomplished by rotating the platform to an angle at which the gravity vector corresponds to the net acceleration vector so that at least the sense of the acceleration and its onset are accurately represented. This rotation is performed at an angular rate that is below the human vestibular system thresholds. Lateral (y-direction) accelerations are initially represented in the same way, with the roll angle used to derive the lateral specific force. If the turn is coordinated so that the side force is small, the roll angle of the cockpit subsequently reduced. Although the aircraft remains in a constant rolled attitude during the turn, the simulator motion platform is kept level since there is no sustained side force (tilt coordination).

For the accurate simulations of road vehicles such as cars or aircraft in contact with the ground, however, it is necessary to produce large high frequency longitudinal and lateral accelerations. Since there are often large lateral accelerations during a turn in a ground vehicle, it is difficult to deceive the human sensory system by replacing the sustained accelerations with a specific force simply by rotating the platform. Similarly, acceleration and braking can be characterized by large and frequent changes in longitudinal forces. The onset of these must be quick, and cannot be attenuated by the limiters which prevent the perception of roll or pitch. The best way in which to represent the sustained longitudinal and lateral forces is to actually accelerate the platform in these directions, a condition which is obviously limited by the hardware of a motion system.

From the foregoing discussion, it is clear that the specification of a multi-purpose simulator motion system is a difficult task which involves mathematical optimization, as well as intelligent judgement since not all parameters can be simultaneously optimized. In order to provide a reasonable balance between all of these requirements, the configuration shown in Figure 5 has been selected.[12] The attachment points of the gimbals will be located on 3.10 metre (lower) and 3.20 metre (upper) diameter circles.

C. Gimbal forces

The upper and lower gimbals are designed to minimize the forces on their bearings. The upper gimbals have also been oriented in such a way that the platform floor is 16 cm below their centroid (Figure 6) which helps to lower the platform center of gravity. The lower (ground frame) gimbals are angled so that the horizontal axial load is minimized. A dynamic analysis of the motion system indicates the mean force vector of the actuators, and the lower gimbals are oriented perpendicular to this vector.

## 4.2 Flight-deck Motion Platform

The flight-deck motion platform of the Basic Research Simulator is notably different from the layered platform frame/cabin arrangements found on most commercially-produced flight simulators. The cockpit hardware is generic and can be configured to represent various types of vehicles, rather than a particular model. Generally only the vehicle-dependent sections of the software are changed. The size of the cockpit has been selected so that both a two-seat side-by-side transport aircraft can be represented in the front, or a single place workstation in the rear.

The motion platform frame shown in Figure 7 is to be built from an aluminum-polymeric material, either ARALL (Aramid-reinforced Aluminum Laminate), or GLARE, which uses glass fibres. Selection from the possible grades of each material will follow in the platform detail design and analysis. Preliminary design estimates show that a beam section of 10 centimetres width and 30 centimetres depth all around will be necessary. The resulting weight and mass moments of inertia of the platform frame will be less than one third of the same for a conventional steel frame.

Table 1 compares the mass moments of inertia of the Basic Research Simulator motion platform when steel, aluminum, and GLARE are used as the primary material. The fatigue tolerant properties of GLARE, which far exceed those of aluminum, make it a very favourable candidate.

The two-axis gimbals will be attached to the semi-triangular frame in pairs, located equilaterally. The frame will also provide attachment points for the upper portion of the flight-deck, which will support the visual systems, overhead cockpit displays and control panels, and the cockpit roof structure. When assembled, the integrated platform is designed to have no natural frequencies below 20 Hertz, and to withstand a minimum load factor of 4.0 g in any translational direction, and 400 deg/sec$^2$ in pitch, roll, and yaw.

Preliminary motion system specifications are given in Table 2. A finite element program is used to analyze the structural properties of the system and to achieve these constraints. In the past, this software package has been used to investigate the structural properties of several motion base platforms on a contract basis.

## 4.3 Flight-deck Hardware

Three configuration possibilities exist:

- ☐ Transport aircraft simulation station
- ☐ Single-seat multiple simulation station
- ☐ Motion perception research workstation

### A. Transport aircraft simulation station

Figure 8 shows the general arrangement of the forward cockpit. Two aircraft seats on adjustable rails will be mounted to the floor of the flight deck. Two removable and mechanically independent control yokes will be installed. These will be driven by rotary hydraulic actuators. Rudder pedals will be hydraulically active, as well as two throttle quadrants in the central console. The console will be attached to the floor by a quick-release mechanism for ease of reconfigurability. Sidesticks will be incorporated as well to permit a wider range of applications.

A three-channel visual display system will permit operation from either or both of the pilot stations. Either a collimating projection or a monitor-based system will be installed. The minimum field-of-view will be 75° horizontally and 30° vertically for each pilot station. The monitors (or projectors) will be selected so that each pixel subtends an angle less than 1 arc minute when viewed from the pilots eye positions.

The transport aircraft configuration will be operated with a programmable Electronic Flight Instrumentation System (EFIS), presented on five screens abreast. The basic software used to define the display format has been developed.[13] The high resolution monitors will have a display size of at least 8 X 8 inches (20.32 X 20.32 cm), and a maximum pixel spacing of .25 mm. They will be either cathode ray tube (CRT), or liquid crystal displays (LCDs). The outermost pairs will generate the primary flight display (PFD) and navigation displays (NDs), while the centre screen will provide status information on engine settings, landing gear status, aircraft system failures, etc.

A digital hydraulic control loading system will provide a realistic force-feel in the primary controls. There will be four active channels in each pilot station: the aileron, elevator, rudder pedals, and brakes, all activated by rotary hydrostatic actuators similar to the type which will be used in the servo-controlled sidesticks, as shown in Figure 9. The compact rotary actuators, applied to each control column will permit mechanically-independent removable control yokes. This reduces the overall weight while enabling quick change possibilities within the flight deck.

### B. Single-seat Multi-purpose Rear Workstation

A removable floor panel in the rear of the flight deck will permit the installation of interchangeable workstations. By installing the controls of a particular vehicle type, the simulation of various vehicle examples in the same facility becomes feasible. Only the floor panel needs to be changed, and electrical and hydraulic lines connected as necessary. A helicopter workstation is shown in Figure 10, and a car driving station in Figure 11.

The visual display system of the rear workstation will be different from that of the forward two-place configuration. Only the image generating computer will be commonly shared. The outside display will provide up to 60 degrees vertical and 140 degrees horizontal field-of-view due to such needs in rotorcraft simulation.

### C. Motion Perception Research Station

All of the aforementioned workstations will also be used to investigate the human factors and man-machine interactions associated with the operation of a vehicle. It is also intended to improve the understanding of the motion and visual perception processes of human beings. This research, for example, can be used to optimize the motion drive laws of flight simulators. Furthermore, it is essential to identify the factors which cause motion sickness. The development of such models would contribute not only to the design of simulators and aerospace vehicles, but also to the general understanding of human sensory organs from a physiological point of view.

The motion envelope of the six-degrees-of-freedom synergistic motion system can be extended by installing a seat on low-friction sliding rails. This workstation, shown in Figure 12, would be driven by a separate hydraulic actuator with a stroke of 100 centimetres to produce the fore and aft motion. This motion, in conjunction with that of the main motion system, would permit large displacements in the x-z plane as linear, or rotational motion, permitting specialized human perception studies to identify the characteristics of the visual-vestibular interaction in the motion perception process.

It is important to recognize that although the six-degrees-of-freedom motion system will be fully capable of providing simultaneous linear motions in the x-z plane (surge/heave), it is also valuable to increase the kinematic envelope of these motions. The sliding seat can also be used to add a seventh degree-of-freedom.

The layout of this system is such that the subject's head is nominally located very close to the centroid of the motion platform, with the following offsets:

X-offset: 0 cm (moving seat in neutral position)
Y-offset: 0 cm
Z-offset: 65 cm maximum

## 4.4 Computer Systems and Interconnections

A network of digital computer equipment will link the Basic Research Simulator in its real-time environment. The total system will be flexible and reliable to allow the user easy access to the facility in any configuration.[14] The primary goals of the digital system are:

- ☐ To perform the necessary computations in the specialized research environment
- ☐ To provide the necessary cues in the simulator in a real-time environment
- ☐ To monitor and control the experiments from the ground

and from the simulator cab
- To provide a user-friendly development environment with multiple terminals

## 5. APPLICATIONS OF THE BASIC RESEARCH SIMULATOR FACILITY

### 5.1 Advances in Hydraulic Systems

Through the design of the mechanical and electrical systems of the Basic Research Simulator hardware, and in its subsequent use as a testbed for improving and evaluating the technology in:

A. Hydraulic motion systems:
- Improving the dynamic performance of motion systems by non-standard control strategies
- Compensation of parasitic effects through modern multi-variable and robust control theories
- Evaluations of different inner-loop control concepts for position, velocity, and acceleration control
- Compensation of time delays through prediction
- Modelling the system dynamic behaviour in order to estimate dynamic forces
- Design principles for low-cost motion systems that require minimal power consumption through the optimization of mass distribution and by weight minimization
- Capability of frequent system self-diagnostics through identification

B. Hydraulic actuators:
- Improved actuator buffering
- Efficient designs for low manufacturing and operating cost
- The design of light-weight rotary actuators, such as those developed for sidesticks

### 5.2 Motion Drive Research

The application of modern control techniques to the motion system will be investigated, including:
- Multi-variable robust control
- Predictive control
- Adaptive control

Inner loop control is another subject to be considered. Different concepts such as acceleration, feed-forward velocity, and position control will be evaluated and be improved upon by using the new control theories.

The platform will be monitored using precise mathematical models and parameter identification techniques, with the aim to support on-line supervision of the motion system properties. Whereas the electronic interfaces of motion systems are usually tuned on a semi-annual basis, the Basic Research Simulator would be capable of frequent self-monitoring.

Furthermore, objective tuning of motion drive laws based on the responses during "flight critical maneuvers" will be developed.

In summary, the Basic Research Simulator, with its favourable dynamic properties, will be ideally suited as a testbed through which advanced control concepts will be exhaustively studied. The contribution of optimized structural design, advanced electrohydraulic servo actuators, and several modern control theories are expected to set new standards in motion-based simulation, and to reduce and eventually *virtually eiminate motion signal time delays.*

### 5.3 The Improvement of Vehicle Simulation Models

The realism of a simulation depends considerably on the accuracy of the mathematical model, along with the ability of the hardware to recreate the cues in the flight deck environment in real-time. The system models can be either based on empirical relations, or on values determined by identification of the system parameters.[2] Research will focus on the following:
- aeroelastic models which take into account all of the structural flexibilities in an aircraft.
- The modelling of non-homogeneous atmospheric phenomena in a real-time simulation environment. Wake turbulence, atmospheric disturbances and wind shear can be modelled with reasonable accuracy, however much improvement is needed in order to present truly realistic responses to these effects in the flight simulator. Interactions between the turbulence models and the flexibility of the simulated aircraft also need investigation.

The models of these phenomena will be evaluated with the simulator as well as by comparison with actual high-precision recordings from several aircraft types. New parameter identification techniques will allow the merging of Datcom and other apriori information with data derived from stationary and dynamic flight tests.

Further attention shall be devoted to the following:
- Ground-effect modelling of aircraft in proximity of ground
- Ground contact modelling for aircraft landing gear simulation, and for road vehicle driving simulation
- Rotorcraft simulation to improve the modelling of main-rotor/body/tail-rotor interactions.
- Hydrodynamic models of submerged and surface vessels.

### 5.4 Aircraft Systems Research

A. Research into advanced cockpit environments:
- Evaluation of four-dimensional navigation systems
- Application of active sidesticks using hydrostatic bearing rotary actuators[4]
- Evaluation of head-up displays for commercial applications
- Evaluation of expert (knowledge-based) systems for cockpit systems management

B. Integration of radio-navigation systems into the simulation:

- Optimum tracking loop design in radio navaids for maneuvering aircraft
- Pilot reactions to infrequent, yet large and realistic navigation errors
- Multi-path effects on position with GPS and MLS and attitude determination with gps in the approach phase[15]
- The verification of approach dynamics limits for given radio-navaid dynamic tracking specifications

The operational aspects of the systems, as well as the man-machine interfaces associated with these will be investigated.

### 5.5 Human Factors Research

The fundamentals of human perception, visual and vestibular system characteristics, and the man-machine interactions during vehicle operation are of considerable scientific interest. These topics require specialized materials with which to conduct experiments and monitor the subject. The Basic Research Simulator will provide an ideal tool with which to investigate several topics due to the multi-purpose, flexible, and high fidelity nature of the system, namely:

- Six-degrees-of-freedom motion system with favourable and identified dynamic properties, driven by modern control theories to eliminate motion signal noise
- The ability to change between helicopter, transport aircraft, and road vehicle simulations
- Availability of conventional yoke, and servo-controlled sidesticks to investigate specific tasks using these manipulators
- Programmable and reconfigurable Electronic Flight Instrument System displays to manipulate the display scene as required
- High-resolution outside world visual display systems allowing complete control over scene content and definition, combined with flexible visual scene data-bases

Two kinds of human factors research which require, and will benefit from the use of a six-degrees-of-freedom research simulator facility:

A. Basic research into human factors sciences:

- Vestibular and Visual Perception Models including:
  - Identification of vestibular system dynamics
  - Directional sensation of linear motion
  - Development of models for Space Adaptation Syndrome (SAS) and simulator motion sickness
  - Visual-vestibular interactions in self-motion perception
  - Disorientation
- Research into Sidesticks
- Basic research into display presentation formats
- Evaluation of foveal vision models in a piloted task
- Perception of pilots during the landing phase

B. Applied human factors research:

- Evaluation of approaches using 4D navigation displays
- Evaluation of man-machine interfaces in digital flight control systems
- Evaluation of navigation systems in the cockpit
- Design of the advanced cockpit environment
- Evaluation of Traffic Collision Avoidance Systems (TCAS) in new ATC environments
- Evaluation of Take-off Performance Monitoring Systems (TOPMS)
- Evaluation of various experimental Flight Management Systems (FMS)
- Evaluation of Global Positioning System (GPS) assisted approaches to unprepared landing sites with helicopters

## 6.0 CONCLUDING REMARKS

Designed for cost-effective research, the Basic Research Simulator will provide a nucleus for new developments in:

- hydraulic systems design
- motion drive laws
- real-time simulation software and hardware
- specifications for man-machine interfaces
- human perception models
- simulator motion platform design

It will also serve as a testbed and demonstration platform for new hardware/software, a multi-purpose research facility, capable of simulating virtually all vehicle types, and a facility for aircraft systems and human factors research.

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Table 1. Total mass moments of inertia of the Basic Research Simulator Platform structural frame for three material types

| Moment of Inertia ($kg \cdot m^2$): | **STEEL** (7830 $kg/m^3$) | **ALUMINUM** (2690 $kg/m^3$) | **GLARE** (2500 $kg/m^3$) |
|---|---|---|---|
| $I_{xx}$ | 2628 | 903 | 839 |
| $I_{yy}$ | 3722 | 1279 | 1188 |
| $I_{zz}$ | 6279 | 2157 | 2004 |

Table 2. Motion excursion limits of the Basic Research Simulator

| ANGULAR MOTIONS: | PITCH | ROLL | YAW |
|---|---|---|---|
| ANGLE (deg) | + 25, -24 | ± 27 | ± 43 |
| VELOCITY (deg/s) | ± 35 | ± 35 | ± 35 |
| ACCELERATION ($deg/s^2$) | ± 400 | ± 400 | ± 400 |

| LINEAR MOTIONS: | HEAVE (VERTICAL) | SWAY (LATERAL) | SURGE (LONGITUDINAL) |
|---|---|---|---|
| DISPLACEMENT (m) | 1.34 | 2.04 | 2.24 [2.84]* |
| VELOCITY (m/s) | 0.8 | 0.8 | 0.8 |
| ACCELERATION ($m/s^2$) | 10 | 10 | 10 |

* denotes extended longitudinal motion when sliding-seat motion perception station is installed.

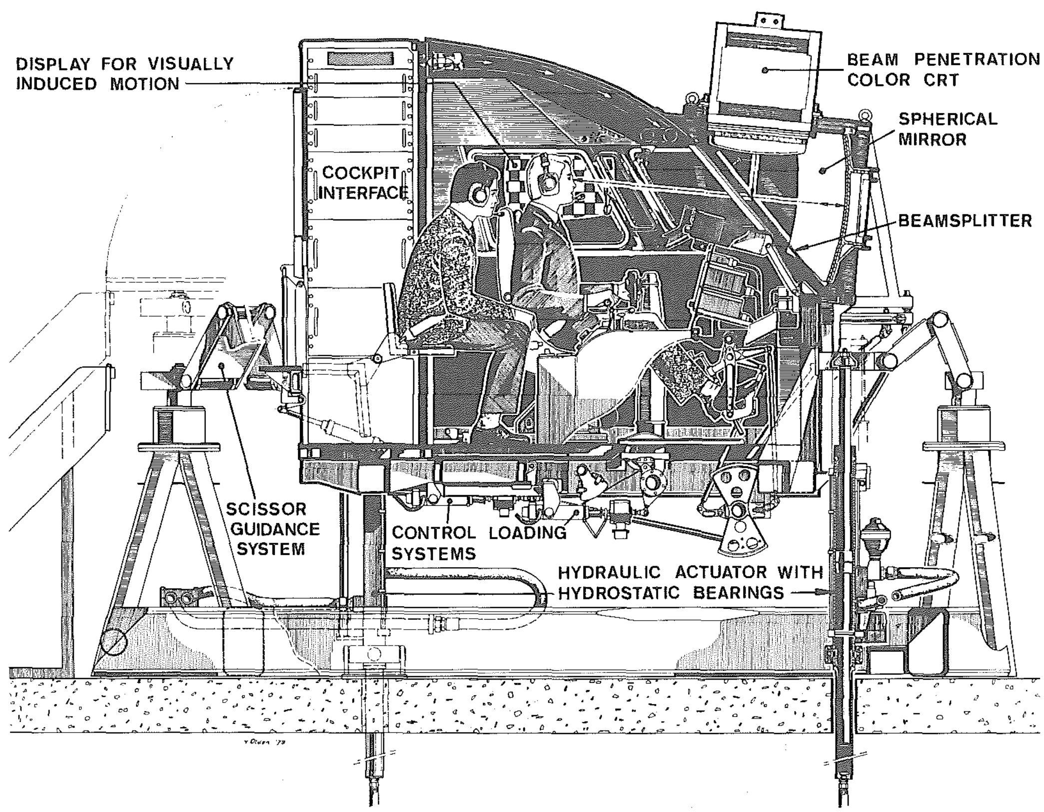


Figure 1. Three-degrees-of-freedom flight research simulator

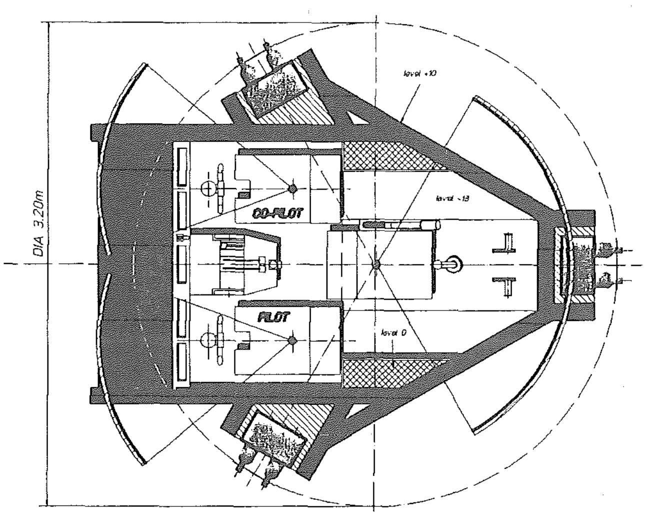


Figure 2. Cockpit floor layout

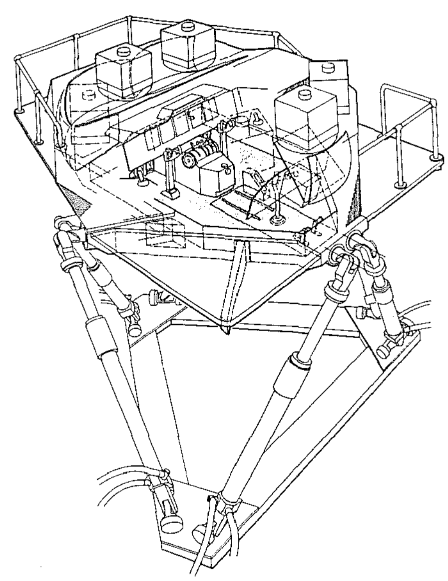

Figure 3. General arrangement of Basic Research Simulator

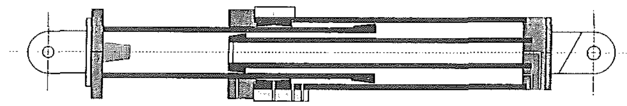

Figure 4. Symmetrical piston hydraulic actuator in cross section

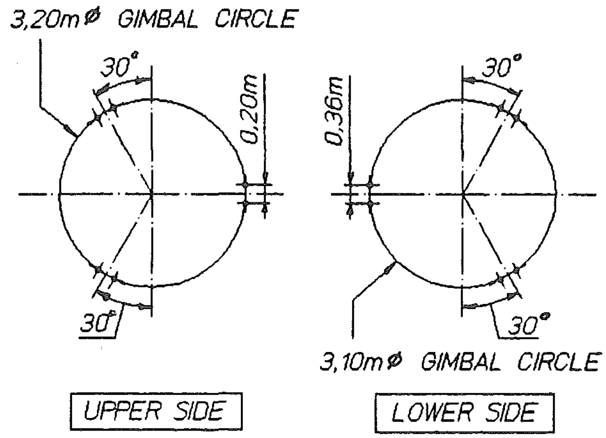


Figure 5. Motion system kinematic geometry

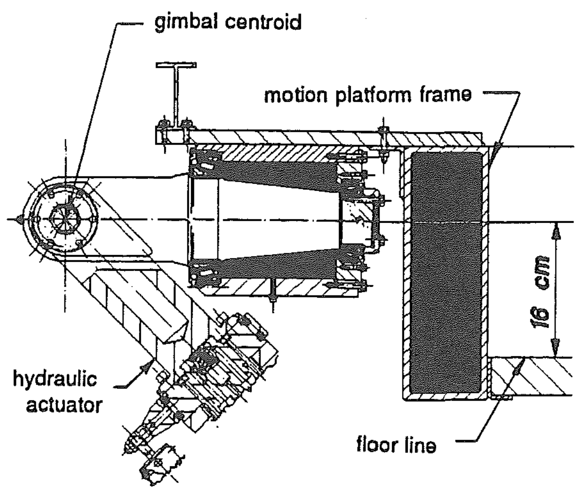


Figure 6. Motion platform gimbal geometry

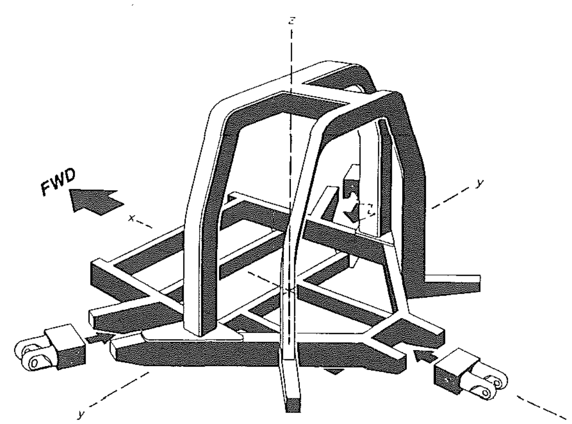


Figure 7. Composite materials platform frame

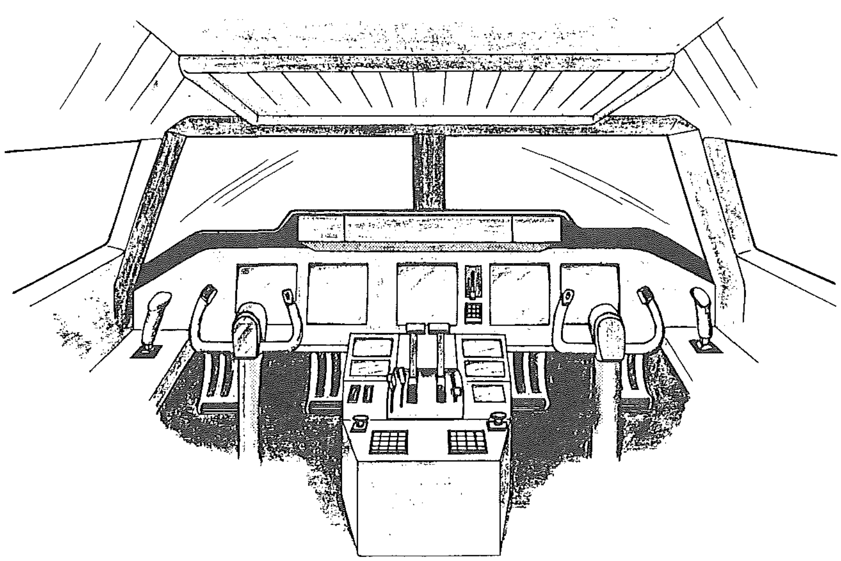

Figure 8. Transport aircraft cockpit

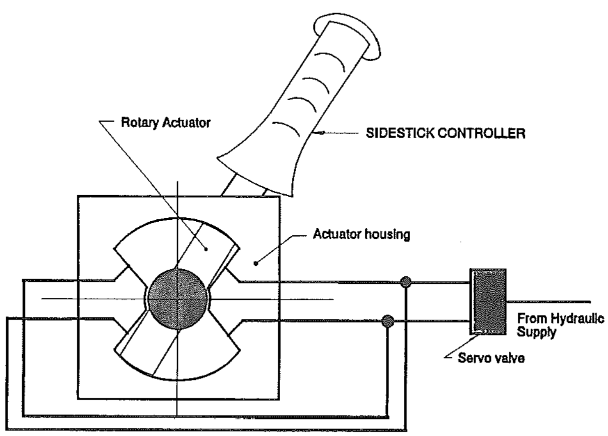


Figure 9. Rotary hydrostatic actuator in sidestick application

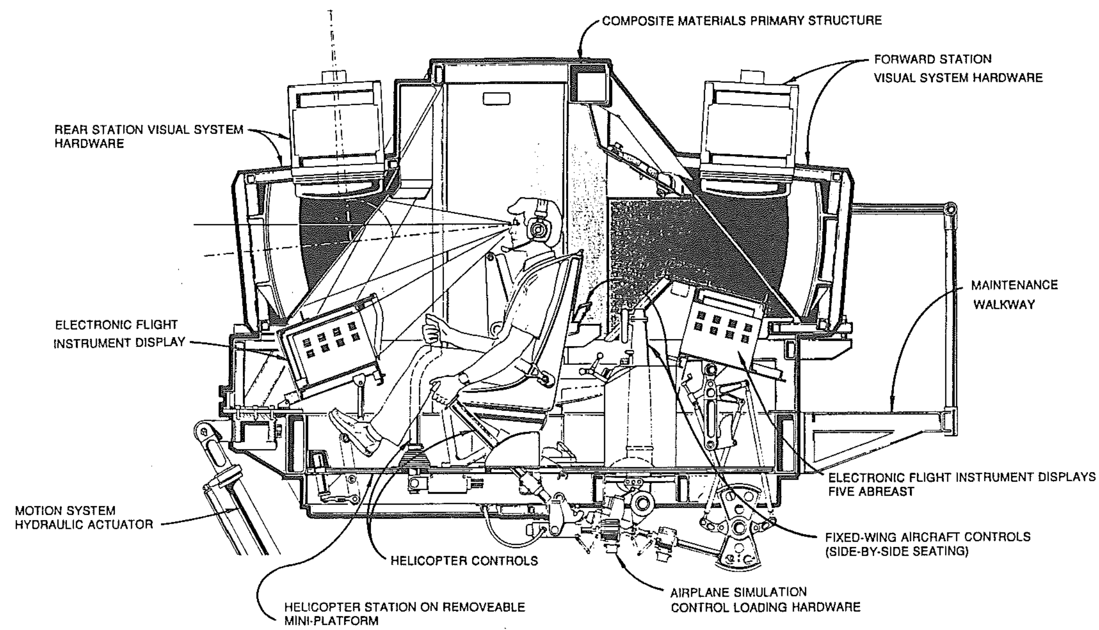


Figure 10. Helicopter configuration

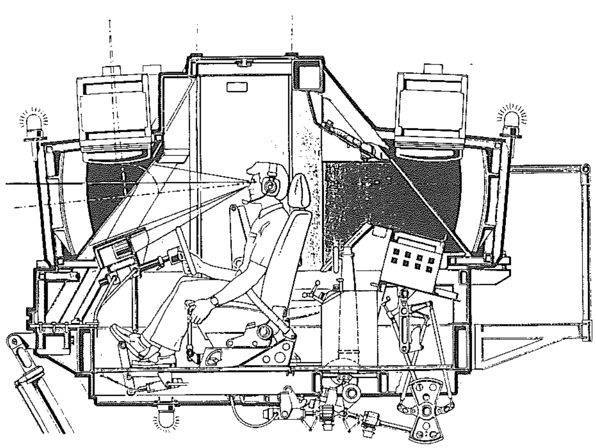

Figure 11. Automobile configuration

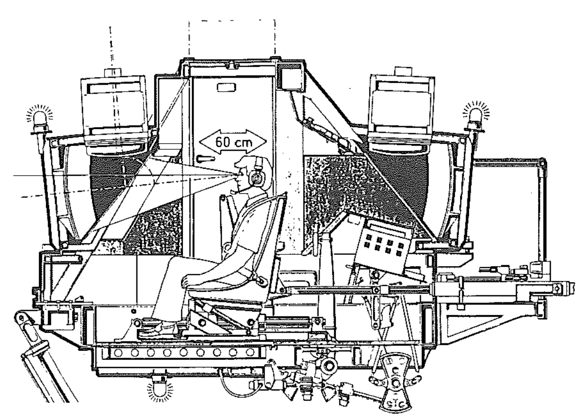


Figure 12. Motion perception research configuration