A 6DOF Flight Simulation Environment for General Aviation Aircraft with Control Loading Reproduction

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Automotive/Flight Simulator

- We introduce a 6DOF flight simulation facility recently acquired.
- System designed to be operated both as a *driving* simulator and as a *flight* simulator.
- Full scale simulator,
  - real vehicle mock-ups,
  - a motion system, and
  - a large projection system.
- Car half-body and aircraft cockpit are exchangeable and easily installed on a motion platform.

Flight Simulator Purpose

- Authors have worked to the specifications, the development and final acceptance procedure of the simulation facility.

  (Manufacturer: *Oktal*, France, **www.oktal.fr**)

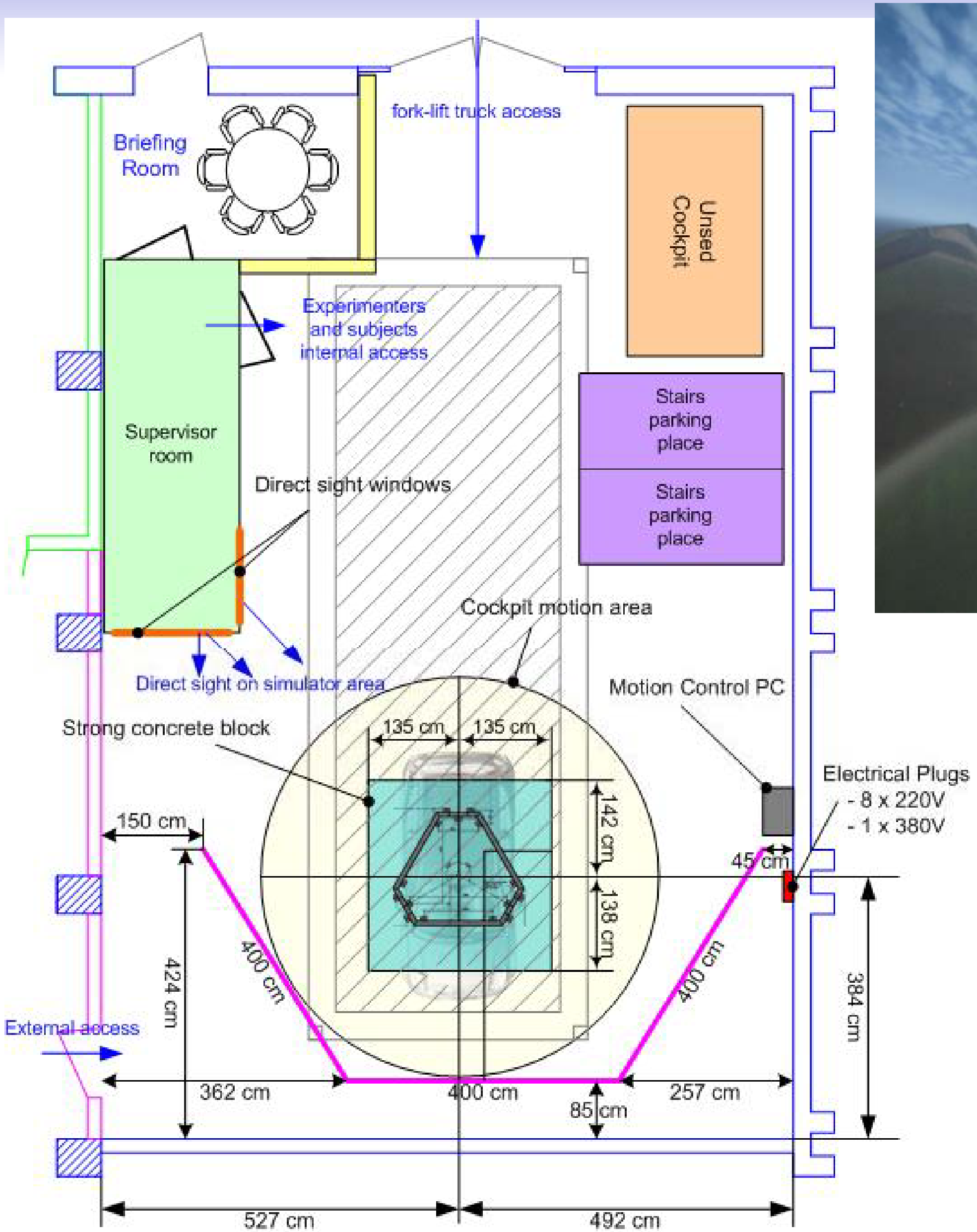
- Flight simulator cockpit conceived as a generic cabin of a small aircraft (*research simulator*).

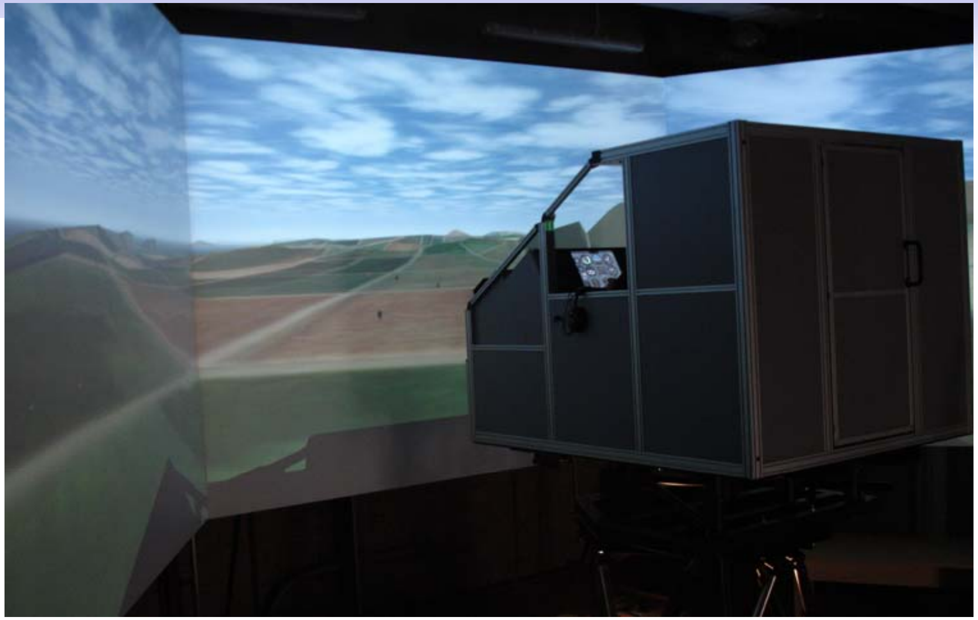
- Aims of this facility:
  - *investigations on flying qualities* of light and ultra-light aircraft,
  - *training* for pilots of such airplanes,
  - *teaching aid* in Aircraft Control & Stability courses.

Simulator Layout And Components

- **Three large screens, three DLP projectors *DS30* from *Christie Digital*; 3000 lumens, 1280×1024, SXVGA.**

- **The chosen projection system is preferred in car simulators and proved to be effective in the flight simulator presented here (190° field of view, horizontal).**


fork-lift truck access
Briefing Room
Unsed Cockpit
Experimenters and subjects internal access
Supervisor room
Stairs parking place
Stairs parking place
Direct sight windows
Cockpit motion area
Direct sight on simulator area
Motion Control PC
Strong concrete block
135 cm
135 cm
Electrical Plugs
- 8 x 220V
- 1 x 380V
150 cm
142 cm
45 cm
138 cm
400 cm
400 cm
424 cm
384 cm
External access
362 cm
400 cm
257 cm
85 cm
527 cm
492 cm



Simulator Layout And Components: Cockpits

- Two available cockpits (*car*/*airplane mock-up*) can be plugged on the motion platform.
- Each cockpit is mounted on an adaptor plate, which is designed to be firmly coupled with the motion base.
- The car and aircraft cockpits are switched using a fork-lift truck. The entire operation takes less than 30 min.

Simulator Layout And Components: Motion Base

- The user is given a motion cue during the simulation. Airplane mock-up animated by a six-degree-of-freedom motion platform.
- A "Stewart platform" by *cueSime*, mod. *Maxcue 610-450-16-12*
- Six high efficiency electric actuators driven by brushless servomotors with position feedback.
- Max. Payload of 1000 *kg*, cabin and pilot ≈600 *kg*.

Motion Base Characteristics

	Excursion range [*mm & deg*]	Peak Velocity [*mm/s & deg/s*]	*Peak Acceleration* [*g's & deg/s²*]
Surge (*z*)	**-491 / +432**	**718**	**±1.39**
Sway (*y*)	**-425 / +425**	**712**	**±1.2**
Heave (*x*)	**-247 / +248**	**484**	**±0.59**
Roll	**-25 / +25**	**50**	**575**
Pitch	**-24 / +25**	**48**	**595**
Yaw	**-43 / +43**	**82**	**1100**

(Max. payload 1000 *kg*)

- High-fidelity motion with low tracking errors.
- No belts or gearboxes in the drive system: smooth, quiet motion.
- Minimum maintenance.

Mode of Operation

- Simulation sessions managed by a supervisor in the control room.
- Emergency stop buttons (Pilot/Supervisor).
- The supervisor has a direct sight on the simulator area.
- A camera (audio/video) is installed inside the cockpit.
- The simulator motion area is protected.

Cockpit Layout

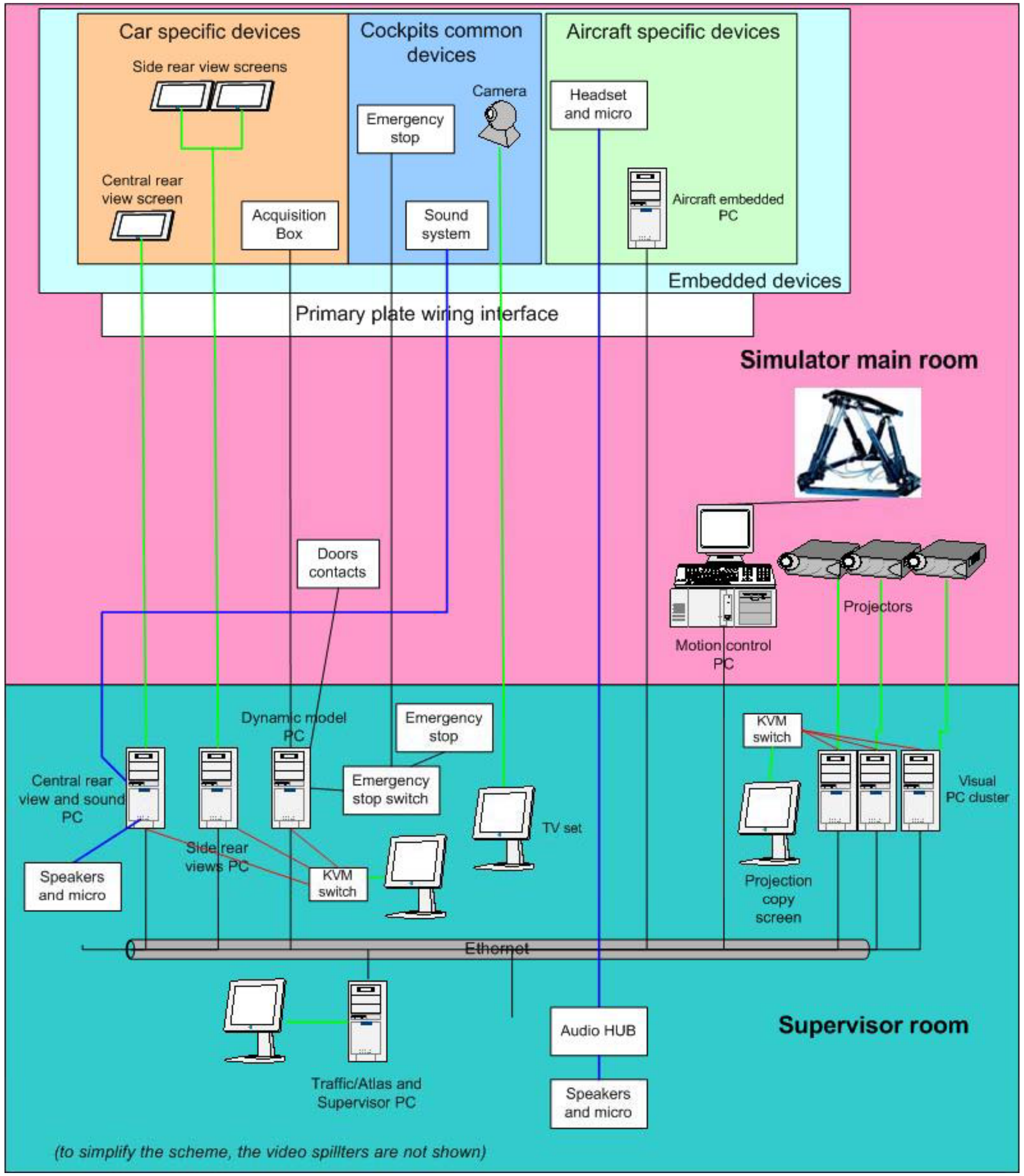
- The cockpit reproduces a generic cabin of a small aircraft.
- Main instrument panel, two tactile LCD screens:
  - virtual flight panel.
  - display of moving maps and flight parameter real-time plots.
- Flight controls:
  - *Cirrus II Flight Console* from *Precision Flight Inc.*,
  - modified yoke,
  - a pair of real rudder pedals.

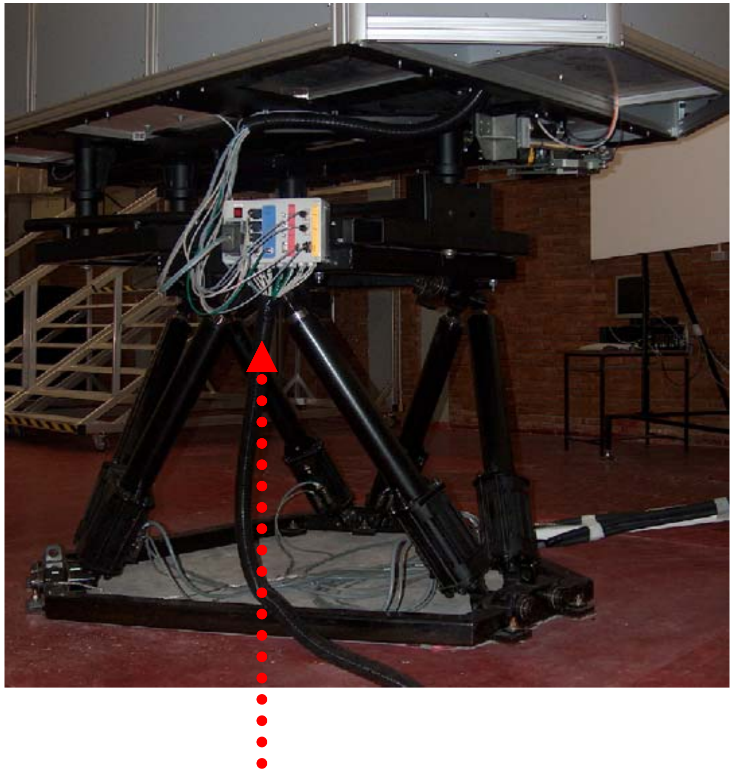
Detail of yoke loading leverages

Computer and Software Architecture

- The main software is ***FlightGear*** (FG), an open-source, multiplatform flight simulator (**`www.flightgear.org`**).
- Flight dynamics model (FDM) currently chosen is ***JSBSim*** (**`www.jsbsim.org`**).
- *FlightGear Scenery Designer*, a set of tools dedicated to the terrain generation, importing GIS data, DTM, etc.
- Simulation session wizard: configuration, FDM, hardware management, network connections, safety.

Computer and Software Architecture





Interface between cockpit internal hardware and external wiring

Simulation software management

- **A number of instances of FlightGear run at the same time on dedicated computers**:
  - Aircraft motion (Flight Dynamics Model, FDM),
  - Cockpit instrument panel and flight controls,
  - Outside scenery.

- **FG's instances talk to each other via net protocols**.

- The simulation is supported by two additional softwares:
  - a **motion platform cueing module**, coupled with FG's external view generation module,
  - a **force reproduction module (*ForceGear*),** driving the cockpit controls, and coupled with FG's FDM.

Control Force Feedback: Intro

- The "control loading" module reproduces the piloting efforts on yoke & pedals, according to the simulated flight conditions.
- The force-feedback system is matched with the aircraft equation solver.
- Cockpit control loads are computed from the known aircraft state at each simulated time step. Stick & pedal loads are controlled with a given frequency, higher than the simulation frequency.

Elevator Dynamics

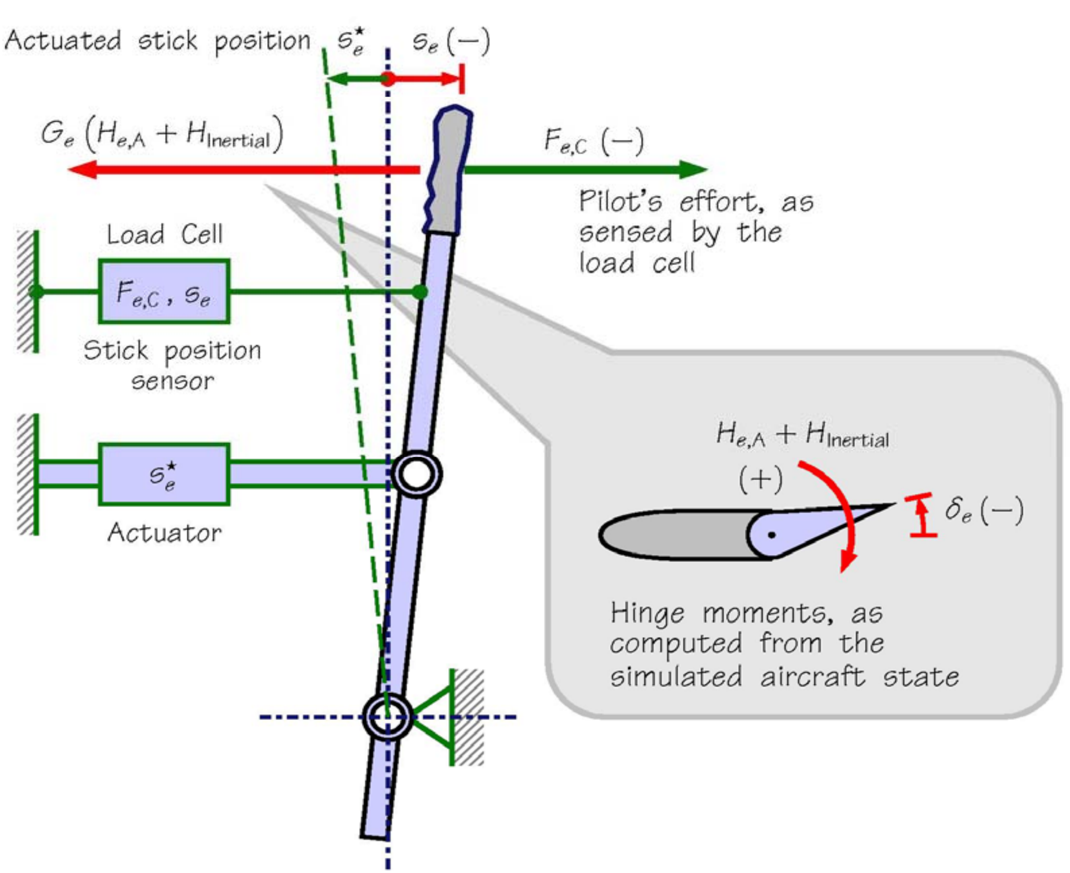
- Inertial coupling actions
- Typical inertial term

$$I_e\,\ddot{\delta}_e + \left(-H_{e,\mathrm{In.}}\right) = H_{e,\mathrm{A}} + \frac{F_{e,\mathrm{C}}}{G_e}$$

- Aerodynamic hinge moment
- Pilot's action

- **Typical inertial term**: moving surface angular acceleration times the surface moment of inertia $\boldsymbol{I_e}$.
- **Hinge moment $\boldsymbol{H_{e,\mathrm{In}}}$**: resulting from the inertial coupling actions (time-varying aircraft pitch rate and/or combination of non-zero roll and yaw rates about airplane center of gravity).
- **Hinge moment $\boldsymbol{H_{e,\mathrm{A}}}$**: resulting from aerodynamic actions on the elevator.
- **Pilot force, $\boldsymbol{F_{e,\mathrm{C}}}$**: applied on the command (C). It is reduced to a moment about the elevator hinge by the dimensional gearing ratio $\boldsymbol{G_e}$ (No force stick-free condition).
- The algorithm controlling the force cue to the pilot ***measures*** the action actually exerted on the yoke, ***evaluates*** the inertial coupling and aerodynamic terms, and ***reproduces*** the angular acceleration contained in the first term.

Control Loading Strategy



- *FG* loop: ~ 100 Hz
- Control Loading loop: ~ 500 Hz
- Control loop:
  forces and torques actually exerted on the cockpit controls by the pilot are measured by dedicated load cells.
  (Kalmann filtered)

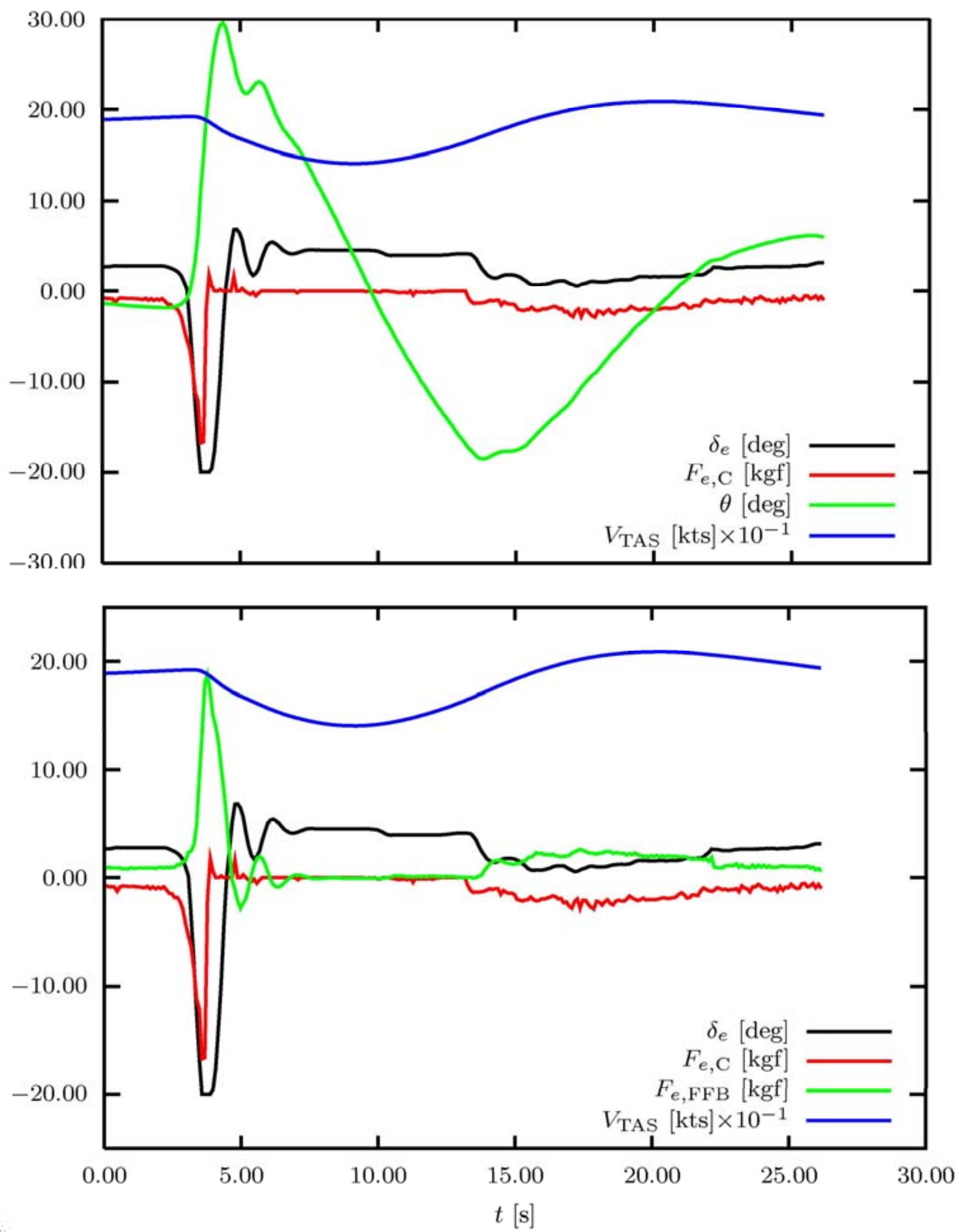
1. The current yoke and pedal positions are sensed by potentiometers.
2. The difference between the sensed actions and the calculated aerodynamic/inertial actions, is evaluated
3. Resulting acceleration is fed to the actuators.

Force Feedback Characteristics

- ***FG-like*** generalizations have been implemented in the inner loop model to avoid hard-coding: ***XML configuration files***.
  - **Geometric**, **mass**, **inertia** characteristics of each control surface and the **hinge moment coefficients** specified by configuration files (tabular data allowed),
  - Effect of **mechanical linkage dynamics** on the control surface motion. User can specify equivalent **reduced masses** that model the motion and inertia of the actual command line of the simulated aircraft.
  - Effects on the control displacement due to the mechanical **friction** and to the presence of **springs**. User can specify an appropriate friction damping coefficients and the stiffness of a springs possibly located along the command line.

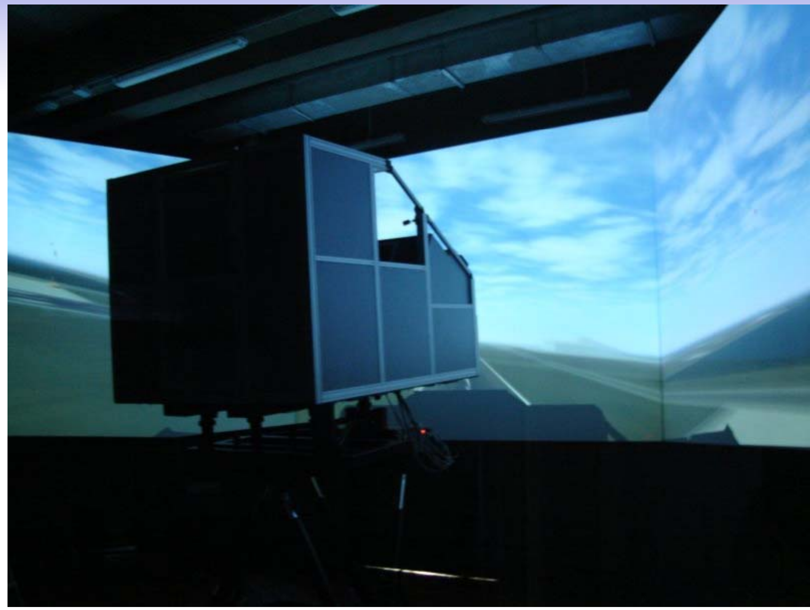
Force Feedback Characteristics

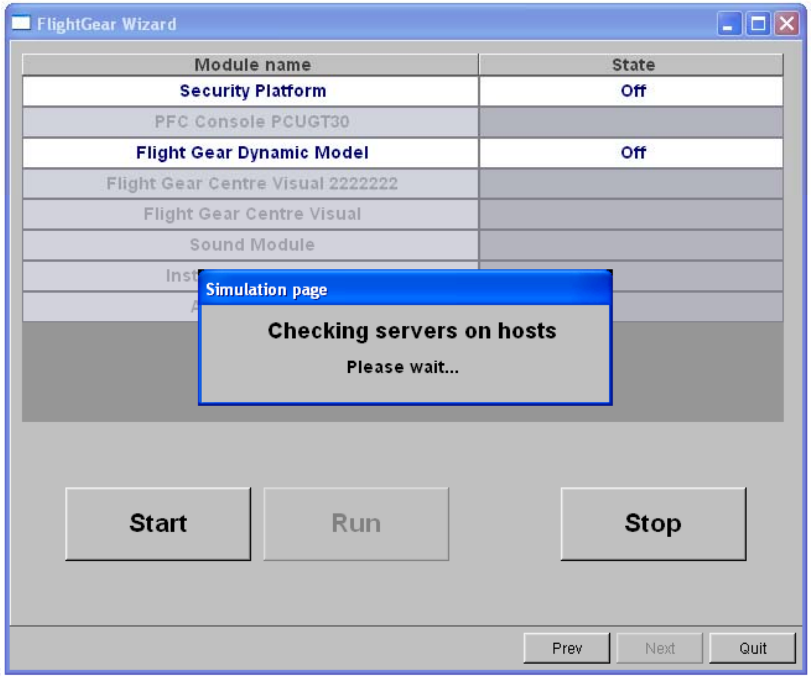
- Electro-dynamic actuators reproduce a realistic amount of effort required to the subject pilot.
- The following are the main characteristics:
  - Max. force on yoke ±400N (push/pull)
  - Max. torque on yoke ± 40Nm (turn left/right)
  - Max. force on each pedal 400N

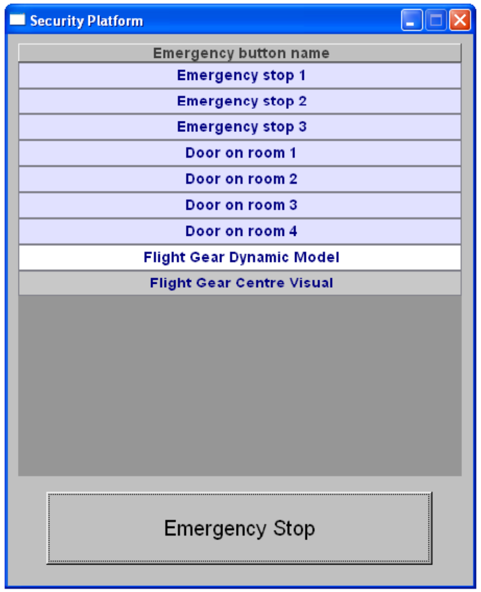


Conclusions

- A 6DOF flight simulation facility has been presented.
- The open-source projects ***FlightGear*** and ***JSBSim*** are two important building blocks of this research simulator.
- Main features:
  - ***low cost***,
  - ***controllable*** and easily customizable for special needs, in our case open-source
  - ***highly configurable*** especially in terms of flight model definition, i.e. one of the most valuable features of JSBSim/FG.
- An *ad-hoc* force feedback system has been developed. The companion software ***ForceGear*** based on ***JSBSim's*** philosophy has been written and tested for the acceptance procedure.
- This is the first application that makes use of ***FlightGear*** together with:
  - a 6DOF motion base,
  - a 3-screen projection system, and
  - flight control force feedback.




FlightGear Wizard
Module name
State
Security Platform
Off
PFC Console PCUGT30
Flight Gear Dynamic Model
Off
Flight Gear Centre Visual 2222222
Flight Gear Centre Visual
Sound Module
Simulation page
Checking servers on hosts
Please wait...
Start
Run
Stop
Prev
Next
Quit


Security Platform
Emergency button name
Emergency stop 1
Emergency stop 2
Emergency stop 3
Door on room 1
Door on room 2
Door on room 3
Door on room 4
Flight Gear Dynamic Model
Flight Gear Centre Visual
Emergency Stop

FlightGear & JSBSim

- ***JSBSim*** was conceived in 1996 as a batch simulation application aimed at modeling flight dynamics and control for aircraft.

- It was accepted that such a tool could be useful in an academic setting as a freely available aid in aircraft design and controls courses. In 1998, the author began working with the ***FlightGear*** project.

- ***FlightGear*** is a sophisticated, full-featured, desktop flight simulator framework
  - for use in research or academic environments,
    - for the development and pursuit of interesting flight simulation ideas,
    - and as an end-user application.

FlightGear & JSBSim

- In ***JSBSim*** specific aircraft are *defined in data files*, and *no new program code is required to model any arbitrary aircraft*. Additional characteristics of such a framework include:
  - Employs object-oriented design principles (**C++**).
  - Compiles across common platforms and compilers.
  - Readily available as an open source application.
  - Is self-documenting.
- ***JSBSim*** was integrated with ***FlightGear*** in 1999, and is today the default flight model. ***JSBSim*** retains the capability to run in a batch mode. The volunteer development team has grown over the years, and vigorous development continues.
- ***JSBSim*** is provided and developed under the GNU General Public License, and is available for use in other simulation projects with few restrictions.

Control Force Feedback: Details

- Simulation of aerosurfaces has been extended, with respect to *FlightGear*'s functionalities, and implemented in a dedicated piece of software: *ForceGear*.

- The evaluation of the aerodynamic and inertial actions on the aerodynamic control surfaces is one of the main tasks of *ForceGear*.

- Control surfaces equations of motion are solved within the control algorithm loop between two successive *FlightGear* time steps ("outer"/"inner" integration loops)

- In the general case of simulated *stick-free manoeuvred flight* the additional unknowns are the time histories of surface angular excursions: $\delta_a(t)$ (right aileron), $\delta_e(t)$ (elevator or stabilator), $\delta_r(t)$ (rudder).

- In all cases the excursions time rates are evaluated and used by the force feedback module.

Control Loading Strategy II

- ***If pilot's action is adequate to react to the feedback*** and keep the yoke/pedal position stationary, the flight conditions remain *stick-fixed*, or nearly so.

- ***If not***, the unbalance between the force actually exerted on the control and the one calculated by the force-feedback system from simulated flight data results in a general manoeuvred flight with a varying excursion of one or possibly all the aerodynamic control surfaces.

- The actual amounts of the excursions, in terms of yoke and pedal displacements, are fed back to *FlightGear* and used in the successive outer integration step.

Related Research Activities