Communications to SIMAI Congress,
ISSN 1827-9015, Vol. 2 (2007)
DOI: 10.1685/CSC06052

Flight Simulation Environment of The University of Naples and Recent Developments in Control Loading Reproduction

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This paper presents the work done by authors to set-up and test a real 6DOF flight simulation facility recently acquired. The whole system has been designed to be operated both as a driving simulator and as a flight simulator. The facility is a full scale simulator and includes a real aircraft cabin mock-up, a motion base, a large projection system, and force feedback modules. The authors have guided the specifications, the development and the final acceptance procedure of this simulation facility.

The aim of the flight simulator is twofold: serving as a tool for the investigation of flying qualities of light and ultra-light aircraft and offering a training options to the pilots of such airplanes. For these reasons the simulator cockpit has been conceived as a generic cabin of a small aircraft.

The facility is located in Naples, in one of the buildings belonging to Consiglio Nazionale delle Ricerche (National Research Council, CNR), Istituto Motori. The simulator main room is proportionate to the horizontal and vertical motion envelope of the cockpit and to three large fixed screens located in front of the cabin. Three static DLP projectors project a composite image of the virtual outside environment reproducing a horizontal field of view of 190 degrees. During the simulation the pilot is given a motion cue, which is obtained by animating the airplane mock-up with a six-degree-of-freedom motion base *Maxcue 610-450-16-12* by cueSim. The performance characteristics of this 1000 kg maximum payload motion platform are the following:

	min/max position	*peak velocity*	*peak acceleration*
Surge	$-491/+432$ mm	718 mm/s	$\pm$ 1,39 g
Sway	$-425/+425$ mm	712 mm/s	$\pm$ 1,2 g
Heave	$-247/+248$ mm	484 mm/s	$\pm$ 0,59 g
Roll	$-25/+25$ deg	50 deg/s	575 deg/s^2
Pitch	$-24/+25$ deg	48 deg/s	595 deg/s^2
Yaw	$-43/+43$ deg	82 deg/s	1100 deg/s^2

Inside the cockpit, a complete and customizable virtual instrument panel is reproduced by means of two tactile LCD screens. The flight controls are made up of a *Cirrus II Flight Console* from Precision Flight Inc., a yoke, and a pair of real rudder pedals. The yoke and the rudder pedals are connected to a force feedback system giving to the pilot an additional cue on the piloting effort.

The chosen software module, that guides the various components of the system, is based on *FlightGear* (Sehgal et al. 2002), a civilian open-source flight simulator comparable to Flight Simulator from Microsoft. The simulation of aircraft motion, the cockpit instrument panel and flight controls, and the outside scenery are all managed by a number of instances of FlightGear, running on dedicated computers, and talking to each other via net protocols. Moreover, the simulation is supported by two other software modules that control: (*i*) the motion platform, in conjunction with the external view generation module, in order to give a proper acceleration feel to the user, and (*ii*) a force reproduction system on the cockpit controls that adds realism to the pilot's task.

In order to reproduce realistic piloting efforts, particular care has been taken to implement hinge moment equations in the simulation software resulting in a reliable closed-loop force-feedback system on all aircraft commands. For the sake of example, the well known equation of motion of a conventional elevator (Etkin 1982), including the inertial coupling and hinge line eccentricity effects, is reported below

$$I_e\,\ddot{\delta}_e - \big(\,\dot{q} - p\,r\,\big)I_{ey} + \big(\,a_{G_z} - g_z\,\big)\,m_e\,e_e = \eta_H\,\bar{q}\,S_e\,\bar{c}_e\,C_{he} + F_{e,\mathrm{C}}/G_e \tag{0.1}$$

This model of longitudinal control dynamics is illustrated in fig. 0.1. The first term in eq. (0.1) is the typical inertial term, i.e. the moving surface angular acceleration multiplied by its moment of inertia I_e around the hinge line. The remaining terms are all torques acting on the elevator around the hinge as well. The term $H_{e,\mathrm{In}} \equiv (\dot{q} - p\,r)I_{ey} - (a_{G_z} - g_z)m_e e_e$ represents the moment 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). The term $H_{e,\mathrm{A}} \equiv \eta_H\,\bar{q}\,S_e\,\bar{c}_e\,C_{he}$ is the moment resulting from aerodynamic (A) actions on the elevator. Finally, $F_{e,\mathrm{C}}$ is the force applied by the pilot (C stands for commanded) to the yoke. It is reduced to a moment about the elevator hinge after dividing by the dimensional gearing ratio G_e. In stick-free condition this term is zero. Generally, in a commanded manoeuvre the pilot control force $F_{e,\mathrm{C}}$ is non-zero and is treated as an input in the model (0.1). The algorithm controlling the force cue to the pilot (*i*) measures the action actually exerted on the yoke, (*ii*) evaluates the inertial coupling and aerodynamic terms, being known from the current aircraft state the quantities $\dot{q}$, p, r, a_{G_z}, g_z, $\bar{q}$, and from the control surface data the values of I_e, I_{ey}, m_e, e_e, η_H, S_e, $\bar{c}_e$, C_{he}, G_e, and (*iii*) finally calculates the angular acceleration contained in the first term. The latter has the be reproduced by the actuators connected to the cockpit control. The static equilibrium condition: $G_e\,H_{e,\mathrm{A}} = F_{e,\mathrm{C}}$ is obviously a particular case of equation (0.1).

Simulation of a pilot-in-the-loop general manoeuvred flight requires the solution of the classical set of airplane equations of motions. This is done by *JSBSim*, *FlightGear*'s aircraft dynamic model. When the force-feedback system is matched with the aircraft equation solver, the cockpit control loads are computed from the known aircraft state at each simulated time step. Stick and pedal loads are controlled with a given frequency, typically higher than the simulation frequency, and properly reproduced. In the present simulator the definition of the aerodynamic control surfaces has been extended with respect to *FlightGear*'s original functionalities and implemented in *ForceGear*, a dedicated piece of software. The evaluation of the aerodynamic and inertial actions on all aerodynamic control surfaces is one of the main tasks of this code. Their equations of motion are solved within the control algorithm loop between two successive *FlightGear* time steps. This is also referred to as the "inner" integration loop while *FlightGear*'s job is then called the "outer" integration loop.

At the beginning of a generic control loop, the forces and torques actually exerted on the cockpit controls by the pilot are measured by dedicated load cells. The current yoke and pedal positions are sensed by a number of corresponding potentiometers and optical encoders. By evaluating the difference between the sensed actions and the calculated aerodynamic/inertial actions, the control loading module orders the yoke and pedals to move (accelerate) accordingly, giving the desired "feel" to the pilot. 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.

Two useful generalizations have been implemented in the inner loop model. The first includes the effect of the mechanical linkage dynamics on the control surface motion. The user is able to specify the equivalent reduced masses that model the motion and inertia of the actual command line of the simulated aircraft. The second generalization includes the effects on the control displacement due to the mechanical friction and to the presence of springs. The user can specify an appropriate friction damping coefficients and the stiffness of a springs possibly located along the command line.

The generality of the control loading module presented here permits the reproduction of force-free elevator or stabilator response in which the additional unknowns are the time histories of aerodynamic surface angular excursions: $\delta_a(t)$, $\delta_e(t)$, $\delta_r(t)$. The "stick-free" conditions are those particular situations in which the pilot actions on the cockpit controls are null and the aerodynamic control surfaces are free to float under the effect of external actions. These actions depend: (i) on the aircraft motion and acceleration, and (ii) on the characteristics of the mechanical linkage between the control column located in the cockpit and the tail plane moving parts. In all cases the excursions time rates are evaluated and used by the force feedback module.

The actuators and the rest of the hardware of the force feedback system have been chosen in order to reproduce a realistic amount of effort required to the subject pilot. The following are the main characteristics: Max. force on yoke $\pm$400N (push/pull), Max. torque on yoke $\pm$40 Nm (turn left/right), Max. force on each pedal 400 N. When needed, the force feedback can be easily disconnected.

There is a strong interconnection between the simulator operating characteristics and authors' past and current research in flight and wind tunnel testing. To carry out a flight simulation of a given aircraft one has to collect a number of data coming from: flight tests, wind tunnel experiments, and numerical or semi-empirical estimations. Experiences gained by the authors in these fields are reported in (Coiro et al. 1998, Giordano et al. 2001, Coiro, Nicolosi, De Marco 2002, Coiro, Nicolosi, De Marco, Genito 2002, Coiro 2003, Iscold 2004). In particular, the authors have worked at the certification process of the G97 ultra-light aircraft (Giordano et al. 2001). All aspects regarding JAR-VLA certification procedures have been object of research. Accurate and detailed analysis of flight test maneuvers have been performed and comparisons with numerical predictions have been done. All G97 performances have been measured. Particular attention has also been given to the parameters estimation for the complete aircraft aerodynamic and dynamic characterization. These data are properly structured in XML format according to the FlightGear configuration style and used in the present simulation facility.

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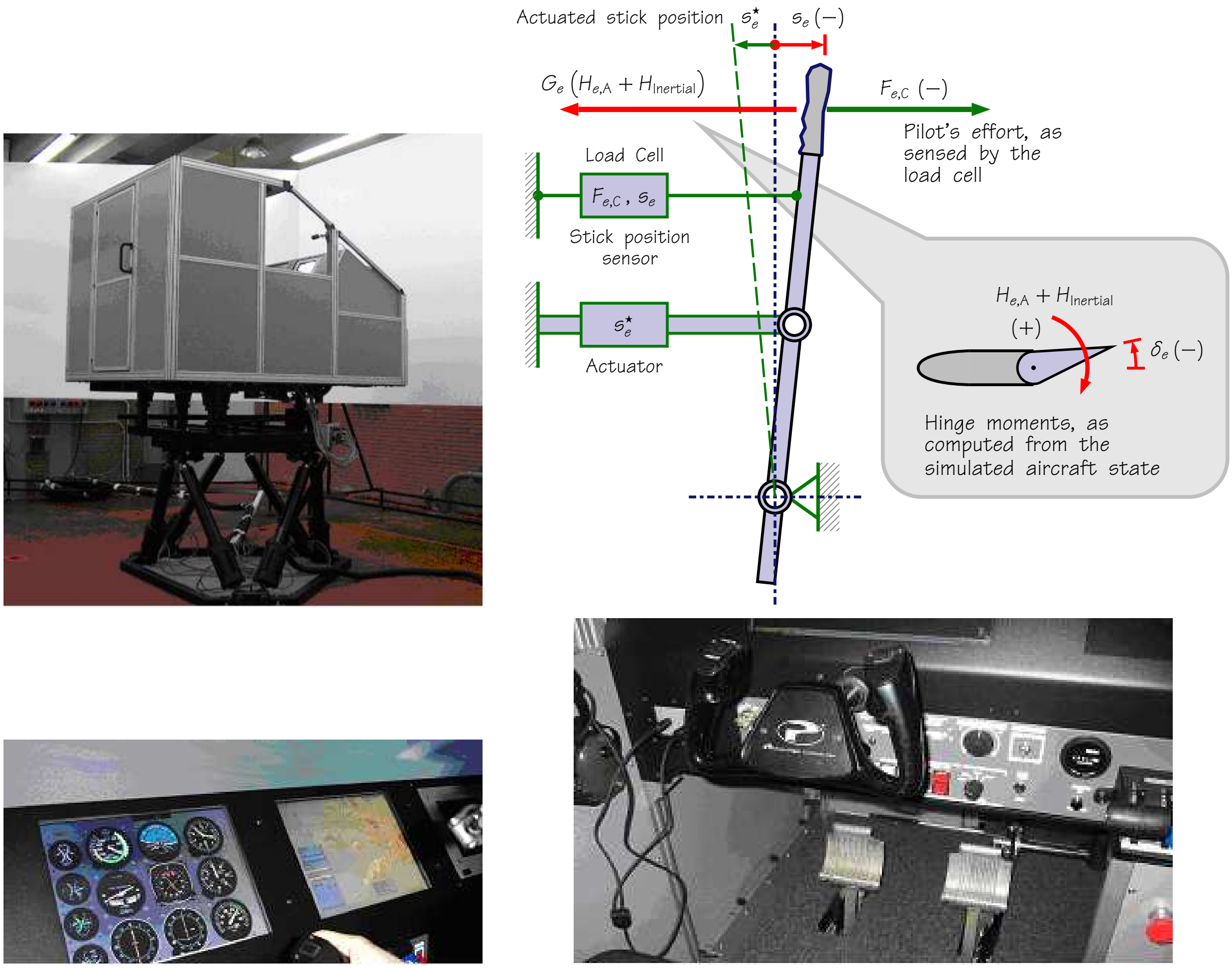

Figure 0.1: Pictures of the flight simulator and schematic of longitudinal control loading implemented in the force-feedback software.