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Real-time Desktop Flying Qualities Evaluation Simulator

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ABSTRACT

This paper presents the application of model based design for the development of a real-time flying quality evaluation simulator named NALSim, built around Windows platform. NALSim is a novel rapid prototyping system based on Matlab^R, Simulink^R and the Real-Time-Windows Target^R, applicable for fighter, transport and unmanned air vehicles/micro air vehicles simulations. The simulator uses state of the art modeling and simulation technologies to validate various design and flying quality concepts. NALSim is developed such that it is scalable and low cost. The paper presents the simulator architecture and its application for flying qualities. A novel non linear Least Squares optimization based methodology is proposed for efficient handling quality studies.

Keywords: Desktop flight simulator, model based design, flying qualities, rapid prototyping, flight control, Tracking tasks

NOMENCLATURE

Ny	Lateral acceleration
Nz	Normal acceleration
p	Roll rate
q	Pitch rate
r	Yaw rate
α	Angle of attack
β	Angle of sideslip
φ	Aircraft roll angle
θ	Aircraft pitch angle
ψ	Aircraft yaw angle
θ_C	Pitch command for tracking task
ω_i	Frequency of sum of sines signal
θ_{bias}	Trim pitch angle
ϕ_C	Roll command for tracking task
ϕ_{bias}	Trim bank angle
$\varepsilon_{SP}, \varepsilon_{DR}$	Least squares cost function for short period and dutch roll characteristics
ω_{nSP}, ξ_{SP}	Desired short period characteristics
ω_{nDR}, ξ_{DR}	Desired dutch roll characteristics

1. INTRODUCTION

Flight simulator is an inevitable solution for flying quality evaluation of any developmental aircraft. Also test pilots can be trained for flight mechanics and flying qualities in such a platform. A modern simulator uses adequate fidelity models of the aircraft and its subsystems with high quality visuals to provide a realistic look and feel of the aircraft.

Development of a flight simulator is not a nascent field by itself and significant amount of work has been carried out in the related areas across the world and in India as well. Engineer-in-the-loop simulators are developed to carry out design, tuning of flight control laws and for handling quality evaluation[1]. Realistic flight training devices (FTD)[2,3] are built to provide pilot training and also to provide a platform to evaluate handling qualities for an aircraft. System level simulation tests can be performed in Iron bird[3]. The simulators use multiple/distributed processors to achieve their goals[1-3]. Also the underlying software for the flight dynamics and subsystem models are mostly coded in high level languages such as Fortran, C/C++. Hence they involve a lot of coding, networking and maintenance efforts. Development of hardware in-the-loop simulators (HILS) for micro air vehicles (MAVs) with flight dynamics model coded using MBD approach has been reported[4]. The present work aims to avoid extensive coding work and as well as multiple/distributed processors, yet achieved a cost effective desk top solution for handling/flying quality evaluations. Similar work named AIRSIM has been carried out at NLR, Netherlands which is also a PC based desktop simulator[5]. AIRSIM is specially developed for avionics development and testing, for air traffic control simulations and for aircraft incident/accident analysis. But, AIRSIM runs on UNIX Silicon Graphics workstations and the architecture is not based on MBD/Rapid prototyping.

The architecture implemented in the present work is novel as it encompasses real-time simulation using MBD approach on a single desktop named NALSim. In this kind of a simulator, users can work within the same environment from the requirement analysis to the flight simulation; controller design, implementation and validation to flying the aircraft model in real time. NALSim is a cost effective flight simulation technology as the whole application requires only a standard x86-based computing platform provided with Windows operating system using Mathwork's real-time Windows Target (RTWT$^{(R)}$) toolbox[6]. Also this simulator does not use any external data acquisition unit for data input/output (I/O). All interfaces are based on universal serial bus (USB).

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NALSim has been used for various applications such as handling quality evaluation in terms of damping factor and natural frequency, pilot tracking tasks, real-time autopilot tuning and engine failure studies. A novel least squares optimization based methodology is proposed for performing the handling quality studies. Results for all the above mentioned applications are presented in the paper.

2. STATUS OF CURRENT REAL-TIME FLIGHT SIMULATION TECHNOLOGIES

Some of the commercially off the shelf real-time simulation technologies currently available in the global market are discussed in [7-9]. Advantages of NALSim as compared to other traditional real-time simulation environment are discussed in Table 1.

3. NALSIM FRAMEWORK FOR FLIGHT SIMULATION

NALSim architecture consists of aircraft model, out of window visuals, avionics displays, data analysis tools and an instructor station application programmer's interface (API) housed in a single x86 based processor. Instructor station API is the heart of the architecture that controls all executions. The frame work of NALSim is shown in Fig. 1.

The aircraft model is built using the open source flight dynamics and control (FDC) toolbox in SIMULINK[10] with several customs made changes. The open loop aircraft model of NALSim consists of models for flight dynamics, aerodynamics, propulsion, landing gear, atmosphere and sensors. All models can be customized to feature transport, fighter and UAV/MAV simulations. In addition to the flight model, custom made trimming and linear model generation routines are also a part of NALSim. The autopilot features consists of basic modes such as pitch hold, roll hold, altitude select, altitude hold, heading hold, vertical speed hold, Nose up/down modes and soft ride modes. The closed loop model for NALSim is presented in Fig. 2. The simulator uses Mathworks's RTWT kernel to run auto code of the closed loop model in real time[6]. Pilot inputs are realised through USB based controllers.

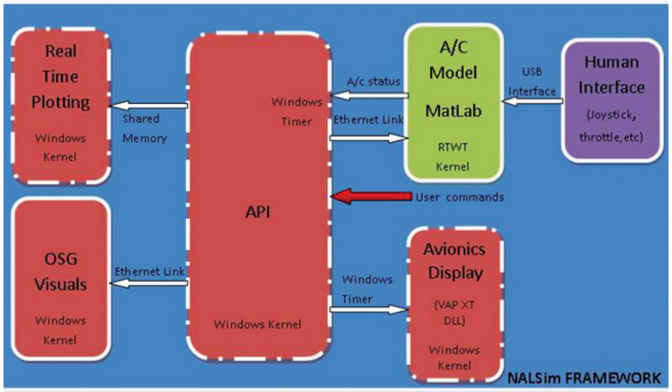

Figure 1. Framework for NALSim desktop flight simulator.

Out of the window visualization is realized using open source 3D rendering API, OpenSceneGraph (OSG)[11] based visualization software. The main advantage of using OSG is that it has minimal dependency on any specific platform or operating system. It requires only C++ and OpenGL software for programming. Head-up display (HUD) and head-down display (HDD) that are provided in NALSim are developed using VAPS XT. Features for data logging and real-time plotting are developed using VC++ application. Plotting is based on the bitmap-repainting concept, using picture box control.

Table 1. Current real time desktop based simulation technologies

Technology	Description	Merits of NALSim
Microsoft flight simulator and X plane	Most popular PC based entertainment simulators with windows/ Linux operating systems.	• Model based design for all aircraft subsystems. • Suitable for Research and Development. • Suitable for rapid prototyping applications. • Custom made user interfaces. • Ability to operate with custom made visuals, flight displays. • Scalable and reconfigurable.
Matlab based simulator using XPC target	Mostly used in hardware in the loop applications, requires minimum of two PCs- a host and a target. The operating system is provided by Mathworks.	• Requires no data acquisition cards. • Single desk top PC is sufficient. • Cost effective. • Custom made user interfaces. • Ability to operate with custom made visuals, flight displays.
NI VeriStand platform	Mostly used in hardware in the loop applications, requires minimum of two PCs- a host and a target. It can deploy LabView or MATLAB/Simulink models. Working knowledge of VeriStand is required.	
Opal-RT's RT-LAB platform	Mostly used in hardware in the loop applications, requires minimum of two PCs- a host and a target. It can deploy legacy code and MATLAB/Simulink models as well. Also supports distributed target configurations. Working knowledge of RT-LAB is required.	
dSPACE	Mostly used in hardware in the loop applications, requires minimum of 2 PCs - a host and a target. One can work on MATLAB/Simulink, with RTI block library.	

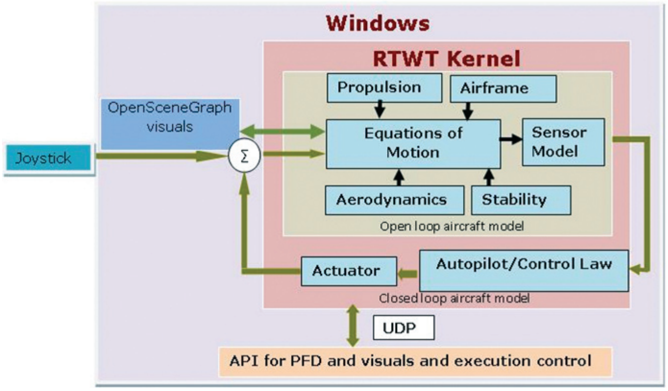

Figure 2. Closed loop model deployed in RTWT kernel.

Graphical user interface for instructor station is built using the microsoft foundation class (MFC) system framework of visual Studio. The VC++ application talks to the Matlab model using the Matlab 'engine' library. It then communicates the required flight parameters to visuals, avionics displays and for plotting using well defined interfaces. The key benefit of this kind of approach is that the system becomes modular and different kinds of aircraft can be simulated using a common user interface.

4. FLYING QUALITY EVALUATION

The proposed simulator architecture can be used for various flying quality evaluations. Results of important case studies are presented in the following subsections.

4.1 Handling Quality Studies

NALSim has in built capability for conducting studies on defining handling quality boundaries for a particular aircraft. Aircraft models are developed in the form of linear non dimensional derivatives across the flight envelope for a generic fighter and transport aircraft. By changing mass, inertia, geometry, aerodynamic derivatives and center of gravity (CG), designer can evaluate the handling qualities for the aircraft. This can also be a suitable tool for trainee pilots to learn flight mechanics and control at test pilot school.

4.1.1 *Variable Damping and Natural Frequency Characteristics*

User can vary suitable flight mechanics parameters displayed on the instructor station to study the effect of damping and natural frequency. For a learning test pilot, it is of interest to specify a particular damping ratio and natural frequency rather than tuning the corresponding flight mechanics parameters. The simulator offers a novel feature to achieve this for studying the short period and dutch roll characteristics as follows:

Aircraft is trimmed for wings level condition. Subsequently, linear models are generated numerically using central differences. From this linear model, short period and Dutch roll damping factor and natural frequencies are calculated and displayed on the instructor station. User now can change these values for the intended study. Once the desired values are entered by the user, a nonlinear least squares optimization is performed.

The short period natural frequency and damping ratio are as follows[12]

$$\omega_{nSP} = \sqrt{M_q \frac{Z_\alpha}{u_0} - M_\alpha} \text{ and } \xi_{SP} = -(M_q + M_{\dot{\alpha}} + \frac{Z_\alpha}{u_0})/2\omega_{nSP} \tag{1}$$

If a desired natural frequency/damping ratio is specified by the user then the short period parameter values should be such that the error functions should be minimum

$$\text{i.e., } \omega_{nSP_{desired}} - \sqrt{M_q \frac{Z_\alpha}{u_0} - M_\alpha} = 0 \text{ and}$$

$$\xi_{SP_{desired}} + (M_q + M_{\dot{\alpha}} + \frac{Z_\alpha}{u_0})/2\omega_{nSP_{desired}} = 0 \tag{2}$$

Dutch roll natural frequency and damping ratio are as follows[12]

$$\omega_{nDR} = \sqrt{\frac{Y_\beta N_r - N_\beta Y_r + u_0 N_\beta}{u_0}} \text{ and } \xi_{DR} = -(\frac{Y_\beta + u_0 N_r}{u_0})/2\omega_{nDR} \tag{3}$$

Similar to short period case, for Dutch roll

$$\omega_{nDR_{desired}} - \sqrt{\frac{Y_\beta N_r - N_\beta Y_r + u_0 N_\beta}{u_0}} = 0 \text{ and}$$

$$\xi_{DR_{desired}} + (\frac{Y_\beta + u_0 N_r}{u_0})/2\omega_{nDR_{desired}} = 0 \tag{4}$$

To perform the optimization, the LS cost functions from Eqns. (2) and (4) are as defined below

$$\varepsilon_{SP} = \left[\omega_{nSP_{desired}} - \sqrt{M_q \frac{Z_\alpha}{u_0} - M_\alpha}\right], \left[\xi_{SP_{desired}} + (M_q + M_{\dot{\alpha}} + \frac{Z_\alpha}{u_0})/2\omega_{nSP_{desired}}\right] \tag{5}$$

$$\varepsilon_{DR} = \left[\omega_{nDR_{desired}} - \sqrt{\frac{Y_\beta N_r - N_\beta Y_r + u_0 N_\beta}{u_0}}\right], \left[\xi_{DR_{desired}} + (\frac{Y_\beta + u_0 N_r}{u_0})/2\omega_{nDR_{desired}}\right] \tag{6}$$

where M_q, Z_α, M_α and $M_{\dot{\alpha}}$ are aircraft short period dimensional derivatives; Y_β, Y_r, N_β and N_r are aircraft Dutch roll dimensional derivatives; u_0 is Forward trim velocity. When optimization converges, the dimensional derivatives are converted into non dimensional derivatives that are suitable for the non linear simulation. The optimization meets the desired damping ratio and natural frequency with good accuracy in conformity with user entered values. It is a user friendly way of studying the effect of damping and natural frequency variations. In Fig. 3, the variation of damping factor for a same natural frequency short period characteristics are shown.

Figure 4 shows the variation of natural frequency for fixed damping short period characteristics.

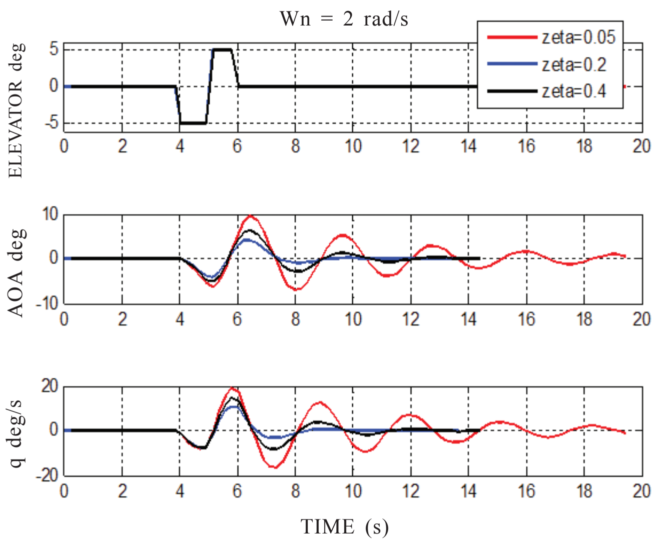

Figure 3. Short period characteristics for variable damping factor.

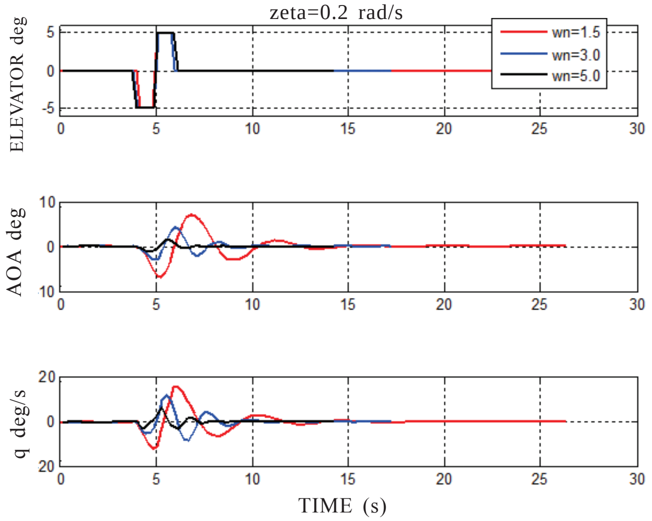

Figure 4. Short period characteristics for variable natural frequency.

This study is effectively executed using the proposed methodology. Otherwise it is a cumbersome task to choose the aircraft derivatives for keeping one parameter fixed and varying the other.

In Table 2, the variation of dominant short period parameters for a fixed damping and varying natural frequency and vice versa are presented. Similar results for dominant Dutch roll parameters are provided in Table 3.

4.2 Pilot Tracking Tasks

Tracking tasks are conducted to verify that the handling qualities of the vehicle are sufficient to perform its intended mission. They can also be given to a trainee pilot to evaluate the piloting skills. The types of tasks evaluated usually require some sort of precision control and can often be specified in terms of acceptable levels of performance in accomplishing the task. The results of these tests are in the form of pilot comments or an appropriate numerical pilot rating (Cooper Harper ratings).

Table 2. Optimization results on short period handling quality studies

Short period parameters	$\omega_{nSPdesired} = 2.0236$		
	$\xi_{SPdesired} = 0.05$	$\xi_{SPdesired} = 0.2$	$\xi_{SPdesired} = 0.4$
Cmα	-1.3937	-1.3443	-1.1826
Cmq	-1.2324	-11.6314	-25.6523
*CL*α	0.9689	3.0469	5.7958
		$\xi_{SPdesired} = 0.2$	
	$\omega_{nSPdesired} = 1.5$	$\omega_{nSPdesired} = 3$	$\omega_{nSPdesired} = 5$
Cmα	-0.8157	-2.9496	-8.1830
Cmq	7.41	-19.3673	-35.9632
*CL*α	4.6022	4.2332	6.5432

Table 3. Optimization results on Dutch roll handling quality studies

Dutch roll parameters	$\omega_{nDRdesired} = 2.0$		
	$\xi_{DRdesired} = 0.05$	$\xi_{DRdesired} = 0.2$	$\xi_{DRdesired} = 0.4$
*Cn*β	0.1020	0.0976	0.0873
*Cy*β	-0.8092	-2.4431	-4.8081
Cnr	-0.0319	-0.2427	-0.5449
		$\xi_{DRdesired} = 0.2$	
	$\omega_{nDRdesired} = 1.5$	$\omega_{nDRdesired} = 3$	$\omega_{nDRdesired} = 5$
*Cn*β	0.0559	0.2177	0.5990
*Cy*β	-2.0911	-3.4920	-6.6735
Cnr	-0.1733	-0.4388	-0.9110

Figure 5 shows the HUD symbology for the tracking tasks. The desired criteria for the pilot shall be to maintain the command bar at the tip of the watermark.

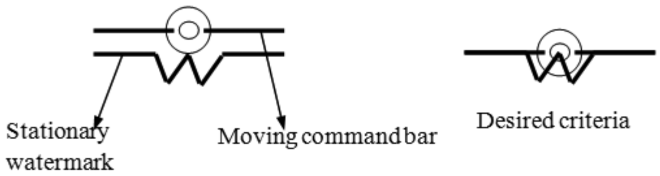

Figure 5. HUD symbology for tracking task.

The command bar shall behave as the pilot's target. The target shall be moved according to the user selected tracking task. NALSim GUI provides options to select any one of the following well established tracking tasks.

4.2.1 Sum of Sines Tracking Task

The purpose of sum of sines tracking task is to expose the phase lag. It is a pitch only task. The target's theta command shall be formed by summing 7 sine waves[12]. It shall have a random appearing frequency-based function computed using

$$\theta_C = k\sum_{i=1}^{n} A_i \sin(\omega_i t) \tag{7}$$

where n = 7 and $\omega_i = 2\pi\left(\frac{Ni}{63}\right)$ rad/s.

Table 4 provides the list of values for parameters in Eqn. (7). The task gain 'k' is set to achieve the desired task amplitude.

Pilot in the loop simulation is performed to track the moving command bar that is driven by θ_C. Figure 6 shows that the aircraft pitch angle tracks the target command. Since it is manual tracking, its accuracy depends on pilot's efficiency.

Table 4. Sum of sines parameters

i	A_i	N_i	ω_i
1	-1.0	2	0.1995
2	1.0	5	0.4987
3	1.0	9	0.8976
4	0.5	14	1.396
5	-0.2	24	2.394
6	0.2	42	4.189
7	-0.08	90	8.976

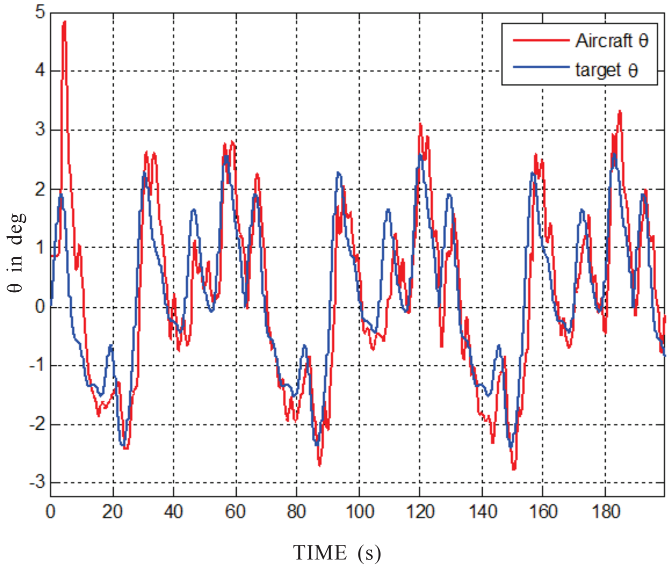

Figure 6. Tracking results for sum of sines task.

4.2.2 Discrete Tracking Task

Discrete task consists of a series of steps and ramps as given in Fig. 7. Both pitch and roll axes of command bar shall be driven by synchronized commands[13]. Pitch error is limited to ±3 degrees and roll error is limited to ± 70 degrees. The movement of command bar in pitch and roll axis is given by the following equations

The command bar on HUD is driven in pitch axis by

$$k(\theta_C - (\frac{\theta}{\cos(\psi)}) + \theta_{bias}) \qquad (8)$$

The command bar is driven in roll axis by

$$k(\phi - \phi_C + \phi_{bias}) \qquad (9)$$

where k is set to achieve the desired task amplitude and θ_C and ϕ_C are the pitch and roll command for the target; θ_{bias} and ϕ_{bias} are the aircraft's trim pitch and roll angles; θ and ϕ are the aircraft's pitch and roll angles respectively.

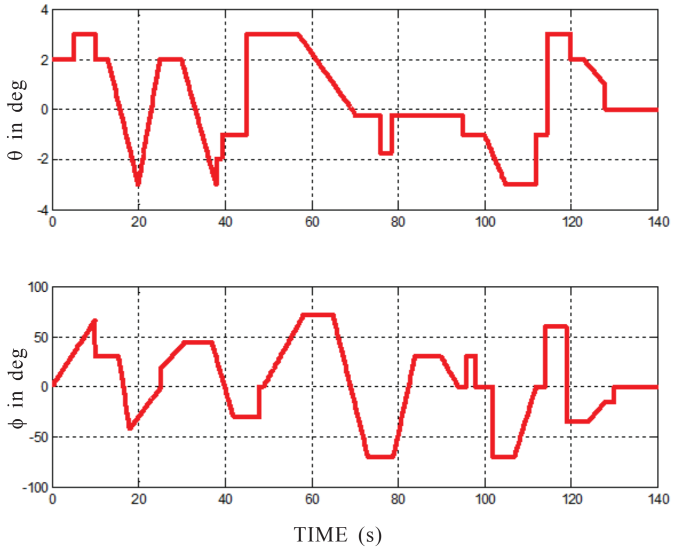

Figure 7. Pitch and roll commands for a discrete tracking task.

4.2.3 Disturbance Regulation Task

This task shall be computed in the same manner as the sum-of-sines task. But, instead of driving a command bar, command shall be added to the pilot's stick command. The pilot's objective during this task shall be to maintain wings level, zero pitch flight.

4.3 Real Time Autopilot Evaluation

NALSim provides following autopilot functionalities: Heading hold, altitude hold, altitude select and hold, speed hold, vertical speed hold, soft ride, nose up and nose down modes. The gains of the autopilot can be tuned in real-time to achieve the desired performance.

4.4 One Engine Failure Study for a Transport Aircraft

One engine failure study can be carried out to estimate the rudder power availability to compensate the asymmetry created by the engine failure. Also, the response of an aircraft for various atmospheric disturbances (wind) can be carried out to estimate the control power availability and the response time required to bring the aircraft back to the wings level state.

5. CONCLUSIONS

A novel cost effective desktop windows real-time flight simulation technology for flying quality evaluation is realized. The chief merits of the simulator are:

- NALSim does not require a target/ real-time simulator or any data acquisition hardware. The real-time application can be deployed in the host computer itself, where it is developed. Hence, a single workstation with high end graphics card can be used as a real-time simulator.
- The simulator uses commercially off the shelf USB

joystick.

- Open source tools such as FDC, OpenSceneGraph are exploited to make it cost effective.
- The benefits of MFC based VC++ programming are utilized to provide friendly interface and analysis tools for the user.
- Handling quality studies can be performed more efficiently, in a user friendly manner.

The results of case studies presented in the paper highlights the significance of NALSim. It is a potential platform for aircraft configuration design, studies on flight mechanics, algorithm development: such as guidance, control, autonomous navigation and human factor studies.

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