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GRACE – a Versatile Simulator Architecture Making Simulation of Multiple Complex Aircraft Simple

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Versatility is an essential asset of any research flight simulator but at the same time a high level of realism is needed to create the right experimental environment. How can a research flight simulator combine both efficiently and become the ultimate research platform? The answer to this question lies in the design of the architecture of the research flight simulator and the software techniques used to enhance its versatility. Each research project poses its specific requirements on the research flight simulator. Different projects require different aircraft types to address specific operational issues. To cope with these ever changing requirements a research flight simulator must be modular not only in software but also in hardware. Flight training simulators need a high level of realism because it's essential for the quality of flight training to create a cockpit environment that closely matches the real live cockpit. For a research flight simulator the focus of attention is aimed at the research objective and the changes it brings to the flight deck. In order to produce a high level of realism for a number of aircraft types, as in the case of a research flight simulator, the simulator must be reconfigurable to represent these aircraft types. A cost-efficient solution is one cockpit which can be reconfigured to represent different aircraft types by exchanging hardware components. To combine both versatility and a high level of realism in a research flight simulator a special versatile modular architecture is needed that facilitates both. The National Aerospace Laboratory (NLR) has developed such an architecture and has implemented this architecture with the construction of its new research flight simulator called Generic Research Aircraft Cockpit Environment (GRACE). Both the hardware and the software used for GRACE are constructed to fit in this versatile modular structure. To make it easy to exchange components of the simulator the interfaces between the components must be designed to be generic. Generic in this sense means that the interfaces can support the superset of signals that any module may use. Special attention is needed to control the configuration of the simulator. Flexible configuration of the communication interfaces is the key to easy introduction of new and research specific modules to the architecture. Another technique applied to increase versatility is the use of adaptive software modules. The described versatile modular architecture and all the applied techniques to enhance this architecture are successfully demonstrated for the first time ever in the GRACE research flight simulator. In the most recent research projects GRACE was operated in four different aircraft configurations consisting of Fokker F100, Boeing B747-400, Airbus A320 and A330. A lot of research specific software and hardware was integrated into GRACE with low effort and in a short time span. Its unique architecture has made GRACE the most versatile research flight simulator in the world today.

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I. Introduction

THIS paper describes the versatile architecture of the Generic Research Aircraft Cockpit Environment (GRACE) research flight simulator, developed and operated by the National Aerospace Laboratory NLR at the Amsterdam site in the Netherlands (Fig. 1). After some 25 years of operation NLR's first motion based flight simulator, the Research Flight Simulator (RFS) (Fig. 2), was finally ready for its retirement and needed to be replaced. With the growing need for a more realistic cockpit environment and at the same time a desire to simulate multiple aircraft types, this was the opportunity to make a completely new design that would meet these new challenges.

The biggest challenge for this new design was finding a way to incorporate both a high level of realism and high flexibility, which in principle are conflicting features. Flight training simulators need a very high level of realism in order to qualify for flight training certification. In these simulators the cockpit must be a complete copy of the real cockpit in terms of functionality and geometry. It's not possible to change anything without losing its training certification. A research flight simulator is almost the complete opposite on this point because there's a need to change just about anything for research purposes. With the GRACE design the NLR combined the best of both worlds; high realism and versatility.

If financial resources and storing space were no limiting factor, the easiest solution for the design is to build a separate one-on-one copy simulator cockpit for each aircraft type that needs to be simulated. In the real world the solution must be cost efficient and reconfiguration should be easy and quick. The best solution for this is one cockpit that's reconfigurable to represent multiple aircraft types. Such a cockpit needs a modular setup of the cockpit hardware, where aircraft type specific hardware can be replaced to match the real cockpit. To be cost efficient, cockpit hardware is designed to be common for different aircraft types. This reduces the number of hardware components needed to represent different aircraft types.

Not only the hardware needs a special design, the software is also specially designed to facilitate easy reconfiguration. The software must be adaptable to any changes in the hardware configuration. On top of this the software also must facilitate simulating aircraft types that differ from the cockpit hardware configuration. This is essential for testing of different aircraft simulations without changing cockpit hardware. During the parallel preparation and testing phase of simulator experiments, there's no time to swap back and forth between cockpit configurations. The use of common software components for different aircraft types makes software development efficient and reconfiguration very easy.

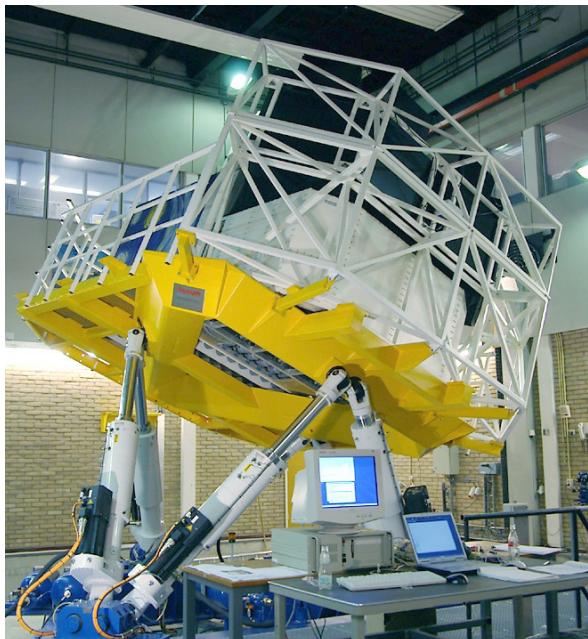


Figure 1. NLR GRACE flight simulator..
Generic Research Aircraft Cockpit Environment



Figure 2. NLR RFS flight simulator.
Research Flight Simulator

II. The Concept of the GRACE Architecture

The concept of the GRACE architecture is based on a modular approach with high compatibility. This means that the different variants of a module are designed to be compatible and therefore can easily be exchanged for each other. This makes it possible to configure a complete simulator out of any collection of modules. Each research project can construct its own tailor made simulator by selecting one of the variants for each module.

In order to meet the high level of realism the design of GRACE incorporates two basic configurations representing each an aircraft type from the two biggest civil aircraft manufacturers, Boeing and Airbus. Many research projects request aircraft simulations of widely used aircraft types. One practical advantage of simulating a widely used aircraft type is that it's easier to get pilots for the experiments with a current type rating on that aircraft. It's important that pilots can focus on the experimental issues and therefore they must feel at home in the simulator cockpit.

The B747-400 was selected as the basic Boeing configuration. The A340 was selected as the basic Airbus configuration. One of the reasons for the selection of these two aircraft types is the fact that they both have four engines. This implies that both the basic configurations must support four engine operation and that they in principle can share engine related hardware. The major reason for selecting the four engine configuration as the basic configuration is that it's the largest number of engines that will be supported and fewer engines can be simulated with the same hardware or by removing one or more of the engine control segments. To be able to reduce the number of engines, the engine control hardware is constructed out of separate segments per engine which can be removed individually. In practice this makes configurations possible with four, three and two engines. For each cockpit module a selection was made based on the required level of realism. The required level of realism is determined by the importance of a module for the operation of the aircraft. Controls and instrumentation which are part of the primary interface between pilot and aircraft must be of the highest level. Secondary cockpit systems require a lower level because slight differences in the operation of these systems are acceptable as long as this doesn't increase the workload of the flight crew. Cockpit systems that are seldom used or only in very specific situations, only require a low level of realism and may differ substantially from the real cockpit. This classification also applies to the software modules. Based on the required level of realism for each module it was determined if a type specific version, a type similar version or just a generic version was needed. The result of this classification can

Table 1. Hardware and Software Module Compatibility Matrix.

		[Basic Config A]		[Basic Config B]					
		Airbus A340-300	Airbus A330-200	Airbus A320-200	Airbus Generic	Boeing B747-400	Boeing Generic	Fokker F100	Citation C550
Hardware		Universal							
		Universal							
Motion	Visual	A340 Mask	A340 Mask	A340 Mask	Generic Port.	B747 Mask	Generic Port.	F100 Mask	F100 Mask
Displays	Controls	Airbus Side Stick	Airbus Side Stick	Airbus Side Stick	Airbus Side Stick	B747 Column	B747 Column	B747 Column	B747 Column
Control Loading	Airbus	Airbus	Airbus	Airbus	Airbus	B747	B747	F100	C550
Throttles Box	A340 4 Throt.	A340 2 Throt.	A340 2 Throt.	A340 X Throt.	B747 4 Throt.	B747 X Throt.	B747 2 Throt.	B747 2 Throt.	
Landing Gear	A340	A340	A340	A340	A340	A340	A340	A340	A340
Glare Shield	A340 FCU/EFIS	A340 FCU/EFIS	A340 FCU/EFIS	A340 FCU/EFIS	B747 MCP/EFIS	B747 MCP/EFIS	B747 MCP/EFIS	B747 MCP/EFIS	B747 MCP/EFIS
MCDU	A340	A340	A340	A340	B747	B747	B747	B747	B747
RMP	A340	A340	A340	A340	A340	A340	A340	A340	A340
ACP	A340	A340	A340	A340	A340	A340	A340	A340	A340
ATC/TCAS	A340	A340	A340	A340	A340	A340	A340	A340	A340
WXR	A340	A340	A340	A340	A340	A340	A340	A340	A340
O/H Panel	A340	A340 2 Eng.	A340 2 Eng.	A340	A340	A340	A340 2 Eng.	A340 2 Eng.	A340 2 Eng.
GCP / XSW					Universal				
Software									
Aero Model	A340	A330	A320	A330	B747	B747	F100	C550	
Engine Model	CFM56-5C	CF6-80E1	CFM56-5A1	CF6-80E1	CF6-80C2	CF6-80C2	TAY650	JT15D-4	
L/G Model					Multi Functional				
Displays	A340	A330	A330	A330	B747	B747	F100	F100	
FBW							N/A		
Auto Pilot					Multi Functional				
Auto Throttle							Multi Functional		
FMS							Multi Functional		
NAV Radios							Universal		
FWC							Multi Functional		
GPWS							Multi Functional		
TCAS							Universal		
Sound Gen.							Multi Functional		
Traffic Gen.							Universal		

Legend : Complete Compatibility
Reduced Compatibility
Limited Compatibility

be seen in Table 1, the hardware and software module compatibility matrix. This matrix shows the level of compatibility of each module in the different aircraft type simulator configuration. For the basic configuration "A", the Airbus A340, the complete set of modules are completely compatible. For the other Airbus types some secondary modules are not completely compatible. For the basic configuration "B", the Boeing 747-400, some more secondary and lower systems are shared with basic configuration "A". The only module with limited compatibility is the overhead panel, because in real live these panels are completely different. The choice was made to have only one type of overhead panel for both the Airbus and Boeing configurations. This was driven by the fact that the role of the overhead panel in most simulator experiments is limited and therefore this module is classified as not essential. Of course in future upgrades of GRACE there will be opportunities to add more type specific modules.

The compatibility matrix (Table 1) also clearly shows that the software modules are almost all completely compatible in all configurations. The flexibility of software makes it much easier to represent different aircraft types. The main aircraft simulation model and the cockpit displays are very type specific. They are essential for a realistic simulation. Other software modules can often be designed to be universal or multi functional. Universal modules are completely general and therefore can be used for any configuration. Multi functional modules have a common core which contains the basic functions of the module. On top of that they have sets of aircraft type specific functions which can be activated through simulator configuration control. In this way these software modules can automatically adapt to configuration change.

The interface software between simulator hardware and simulation models software has a special function in the GRACE concept. It's referred to as the hardware/software interface layer. It not only must pass on signals back and forth, it also must resolve mismatches in simulator hardware configuration and simulator software configuration. In other words it must cope with situations were a certain aircraft simulation must be performed with a conflicting cockpit hardware configuration. Like for instance performing a B747 simulation with an A330 cockpit configuration. This interface software must present to the simulation model the signals it expects, derived from the signals it has available from the cockpit and vice versa..

Figure 3 shows the architecture of GRACE with its hardware and software modules. The host computer forms the heart of the simulator and contains the main simulation software modules. The host runs the main aircraft simulation model which consists of the aerodynamics, the engines and the landing gear. Some closely linked modules like atmosphere, auto pilot and auto throttle, run also on the host. Other software modules are run on

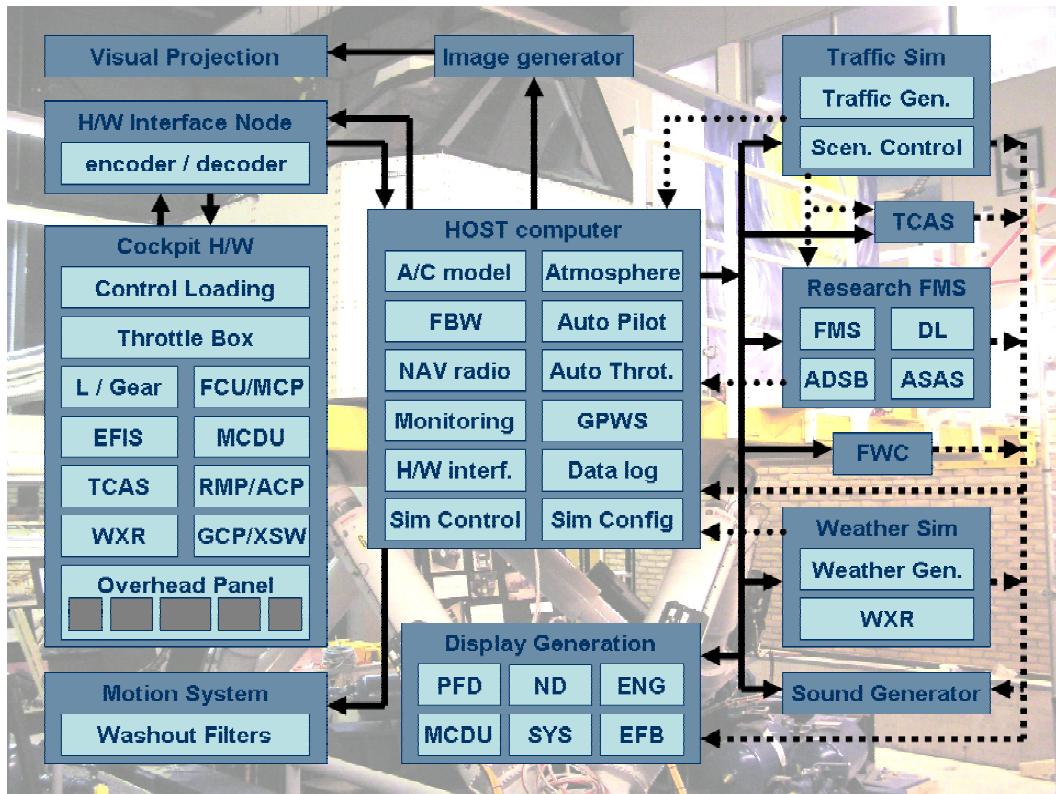


Figure 3. GRACE Modular Architecture. Hardware and software modules

separate machines. In the past there was a trend to distribute simulation modules over many computers. This was driven by the limited computing power of computer hardware. With the computing power of today's PC's it is in principle possible to run all the modules on one machine. In the GRACE architecture the decision to place a module on a separate machine, is based on more practical advantages. One of the main practical advantages is the possibility to run stand alone simulations which makes testing and debugging easier. In many cases starting up a whole simulation with all modules is not needed and therefore not efficient. Besides that some of the simulation modules can be used as stand alone simulation tools. NLR's Traffic Manager¹ (TMX) is part of the GRACE architecture but can also be used as a stand alone traffic simulator for fast time studies. One other big advantage is the portability of the software modules. Software modules like the Research Flight Management System (RFMS) or the TMX which run on a separate PC can easily be installed on board of a test aircraft for in-flight simulation experiments. This was for instance demonstrated in the MFF project² where two NLR test aircraft were equipped with the RFMS, the TMX and experimental cockpit displays.

III. Versatile Simulator Hardware

The GRACE simulator is equipped with a six degrees of freedom electric powered motion platform. Because of building constraints, the current visual projection system consists of four Wide Area Collimated (WAC) displays, two front view, one left and one right view. In the near future when the GRACE simulator will be relocated in a new building, this system will be replaced by a wide view dome with five projectors which will enable cross cockpit viewing. The cockpit has two side by side pilot seats and two observer seats with workstations in the aft station. Basically all cockpit equipment can be exchanged or adapted to the needs of the simulator experiment. The following paragraphs will focus on the exchangeable hardware components and how they can be configured to represent different aircraft types.



Figure 4. GRACE Cockpit Layout. Mixed configuration: Airbus A330 with generic instrument mask, two columns and one side-stick. Also two additional cursor control devices in front of the MCDU's.

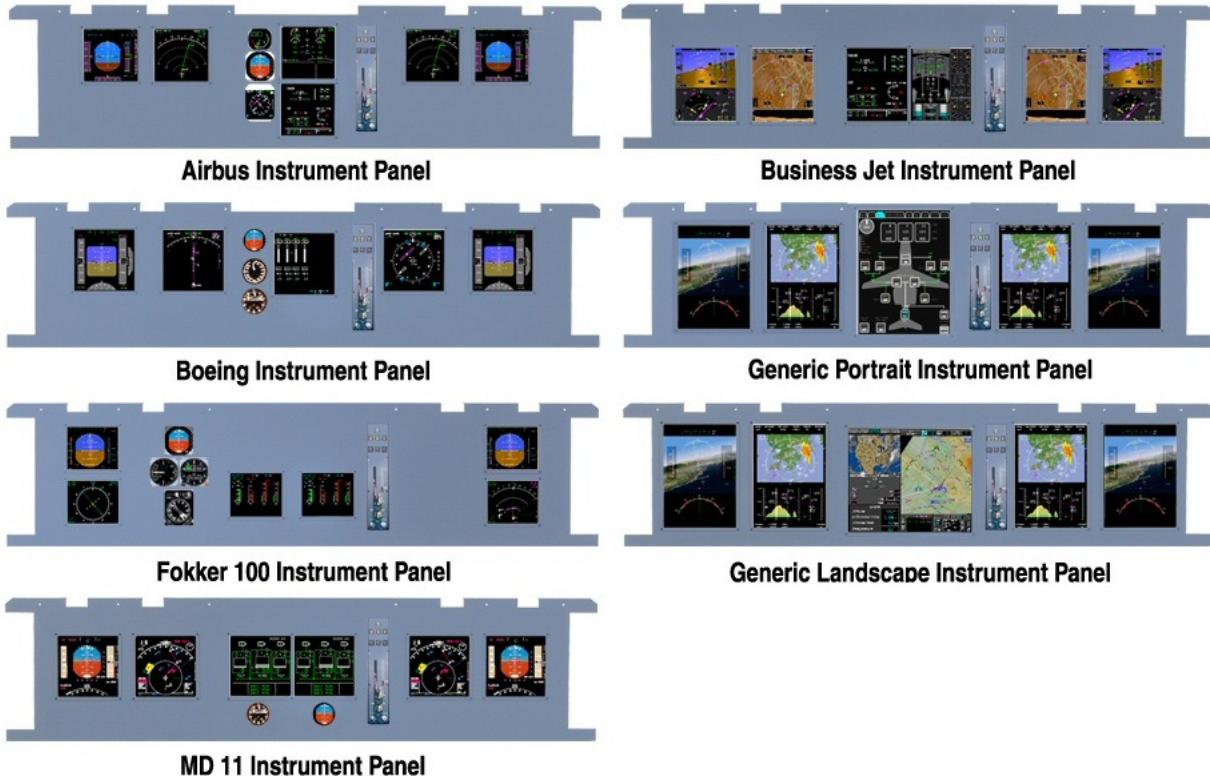


Figure 5. Instrument Panel Masks.

Current available instrument panel masks for representing different aircraft type layouts.

A. Instrument Panel and Displays

The main part of the instrument panel consists of five large LCD screens. Two 15" screens for both captain and first officer and one 17" in the center (Fig. 4). With the use of metal masks the location and the dimensions of the visible area of the LCD screens can be adapted to match the geometry of the display screens in the real cockpit.

As shown in Fig. 5, currently available instrument panel masks include:

1. Airbus A330/A340
2. Boeing 747-400
3. Fokker 100
4. McDonnell Douglas - MD11
5. Business Jet
6. Generic - Portrait
7. Generic - Landscape

The instrument panel also contains a generic landing gear and auto brake panel based on the A340 panel, which can be used for all aircraft types. In the design of GRACE this panel is considered as a "not aircraft specific" system and therefore a generic implementation of this panel is sufficient for realistic operation. During the design process the decision was made for each hardware component if a generic implementation was sufficient. Due to budget limitations it was necessary to make a prioritization of the most essential cockpit components for creating a highly realistic cockpit environment. Components which initially could only be implemented as a generic or basic component can be replaced with aircraft type specific ones in a later stage if desired.

B. Glare Shield Panel

The glare shield panel is available in an A340 and a B747 variant (Fig. 6). The A340 glare shield consists of the Flight Control Unit (FCU) and two EFIS control panels. These panels are practically the same for most Airbus Fly By Wire (FBW) aircraft, and therefore the same glare shield panel can be used to simulate these aircraft. The B747 equivalent consists of the Mode Control Panel (MCP) and two matching EFIS control panels. This glare shield panel is specific for the B747 and differs more from other Boeing aircraft. Since the functionality provided by the B747

panel is common to other Boeing aircraft and even to aircraft from other manufacturers, it still can be used to simulate these other aircraft, but with reduced compatibility. In other words pilots may need some extra familiarization time to get used to the different operation. For experiments where MCP operation is not critical this is acceptable.

C. Pilot Controls

The different hardware options for the pilot controls include a side-stick with Airbus grip or generic grip, a column with wheel and even a center stick (Fig. 7). With these options virtually any transport cockpit can be simulated realistically. It's even possible to combine two control columns with one additional side-stick. The electric control loading system which drives the forces on the pilot controls, can simulate any control forces to match the real cockpit controls.

D. Pedestal

The throttle section of the pedestal is available in the A340 and B747 configuration (Fig. 8). Besides the basic four engine layout, both these modules can be reconfigured for two or three engine operation. Each throttle can be removed individually. Besides the throttle section, the mid pedestal also contains corresponding flap, speed brake, engine master/fuel and parking brake panels.

The aft part of the pedestal is shared between Airbus and Boeing configuration. It contains two Radio Management Panels (RMP), two Audio Control Panels (ACP), the weather radar panel, the ATC/TCAS panel, the rudder trim panel and the aileron trim panel (Fig. 9). The panels have the A340 layout but their functionality and operation are practically the same as with the B747 panels. The small differences in the operation of these panels are considered to be acceptable for research simulation of Boeing and other types of aircraft.

To make the two sections of the pedestal more modular some of the A340 panels are relocated from the original A340 layout. The flap, speed brake and parking brake panels are moved to the mid pedestal. And in return the two RMP's and ACP's are moved to the aft pedestal. In this way all the Airbus and Boeing specific panels are contained in the mid pedestal. So for changing between Airbus and Boeing pedestal configurations, only the mid pedestal has to be exchanged.

The extra free space on the Airbus mid pedestal can be used for experimental and future control panels. For a number of research experiments this space was used to fit Cursor Control Devices (CCD), as can be seen in figure 4 and 8.

E. Overhead Panel

As previously noted the overhead panel is only available in Airbus configuration (Fig. 10). Because of the limited role of the overhead panel in most simulator experiments, it's considered to provide sufficient functionality. Simulator experiments that require realistic operation of the overhead panel should select the A340 simulator configuration.



Figure 6. Glare Shield Panel Options.

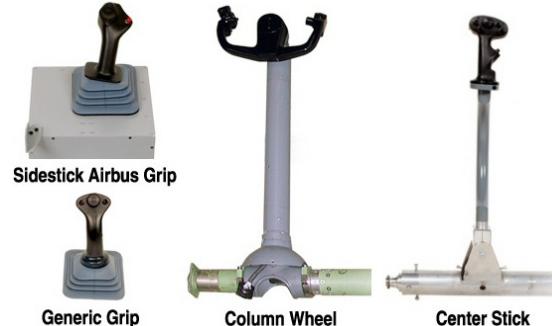


Figure 7. GRACE Flight Controls Options

A340 Throttle Section



B747 Throttle Section

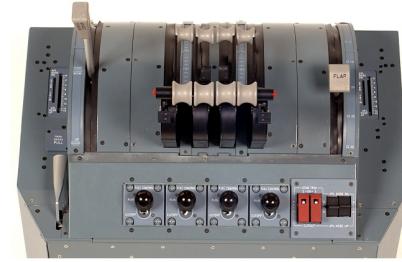


Figure 8. GRACE Throttle Section Options

Basically all parts of the overhead panel that are related to engine control, like the hydraulic, the fuel, the electric and the fire panel, can also be configured for two engine layout. Individual switches can be removed and the faceplates can be replaced by a faceplate with matching holes and inscriptions. In this way aircraft types like the A330 and A320 can be simulated realistically.

F. Generic Control Panel and Experiment Switches

The Generic Control Panel (GCP) and the EXperiment SWitches (XSW) are special features of GRACE introduced to have auxiliary control panel inputs and indications which can be used to configure and control experimental applications. These are essential and very useful functions of a research flight simulator. They are used in most simulator experiments. The logic behind the GCP and XSW can easily be adapted to any experiment needs by editing data files or if needed changing the software logic. This offers a flexible way of introducing experimental functionality to the cockpit without any hardware modification.

Two GCP's can be located in the center of the aft pedestal. Figure 9 shows one GCP in the aft pedestal. The XSW panels are located under the glare shield on the outside for each pilot (Fig. 11).

G. Electronic Flight Bag

The latest addition to the GRACE cockpit equipment are two sets of Electronic Flight Bags (EFB). One set for the Airbus configurations and one set for the Boeing and other configurations. The EFB's are equipped with 11" LCD screens with a touch screen overlay. In the Airbus configurations the EFB's fold down from underneath the glare shield in front of the pilots (Fig. 11). In this configuration the EFB's are mounted in landscape orientation. There was no room below the cockpit displays to install the original A340 stowaway table with integrated EFB. For the Boeing and other configurations the EFB's have to be located on the outboard side of the pilots in front of the instrument panel. The EFB can't be used in front of the pilot in the Boeing configuration because this would interfere with the control column. The EFB is relatively new technology in the present day cockpits and still in development. That's why the EFB is an important feature of the research flight simulator.



Figure 9. GRACE Aft Pedestal



Figure 10. GRACE Overhead Panel

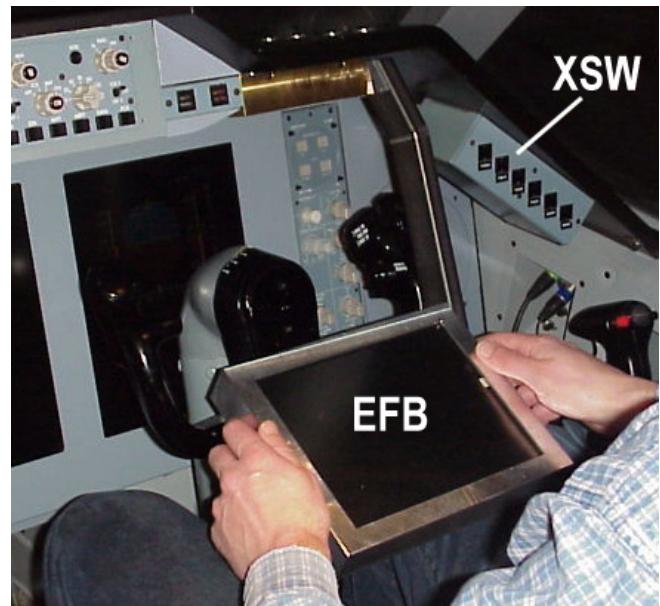


Figure 11. GRACE EFB and XSW

IV. Versatile Simulator Software

The simulator software brings the simulator hardware to life. The hardware is the direct interface between pilot and simulator but the software defines the interaction with the simulator. Not only the cockpit hardware must resemble the real cockpit, the software must also resemble the real interaction and behavior. The software must also be reconfigurable to simulate the different aircraft types. Some of the simulation modules are universal and can be used to simulate any of the aircraft types. These modules may need some aircraft type specific data files. The multi functional software modules need to be configured in order to activate the aircraft type specific functions and set the corresponding parameters.

The adaptive software modules will automatically reconfigure to the host simulation configuration. The aircraft type configuration of the host simulation is transmitted to all other applications through the aircraft type specifier. Based on this specifier other modules or applications can select the appropriate configuration and data files.

A. Aircraft Models

The heart of the complete simulation is the main aircraft simulation. The main aircraft model specifies the general behavior and performance of the simulated aircraft. The main aircraft model consists of the aerodynamic model, the engine or propulsion model, the landing gear or ground interaction model and the mass properties. With these four components all forces acting on the aircraft are determined and with the equations of motion the aircraft movements can be calculated. These four basic modules can be coded in Fortran or C, but they can also be developed using higher level methods like Matlab-Simulink. Matlab-Simulink is the choice for the development of new aircraft models because of its large tool set which makes testing and analyzing very easy. The NLR used this method for the development of their Airbus A330 simulation model³ and a number of derivatives.

The interfacing with the rest of the simulation modules is kept as general as possible to make the complete simulation aircraft type independent as much as possible. In fact any aircraft model can be integrated easily into the GRACE simulation. Some research projects provide their own aircraft simulation to be integrated and evaluated in the research simulator. One example of such a project was the ADFCS-II project⁴. For this project a complete aircraft model and fly-by-wire system designed in Matlab-Simulink was integrated into the simulator software.

B. Cockpit Displays

The cockpit displays form one of the most important interfaces with the pilots. Therefore a good replication of the cockpit displays is essential for the realistic simulation of an aircraft. For many simulator experiments the cockpit displays need to be modified to include new experimental features. The NLR has many years of experience in the field of designing and building cockpit displays for simulator experiments with the focus on human factors. With this experience the NLR has developed its own display prototyping tool. The first two versions of this tool were called NADDES (NLR Avionics Display Design and Evaluation System), but with the new version it has been renamed to Vincent^{5,6} after the famous Dutch painter van Gogh. Vincent stands for Visual Interface design of New Control concepts for Effective and Natural Task performance. With the Vincent tool it's easy to replicate real

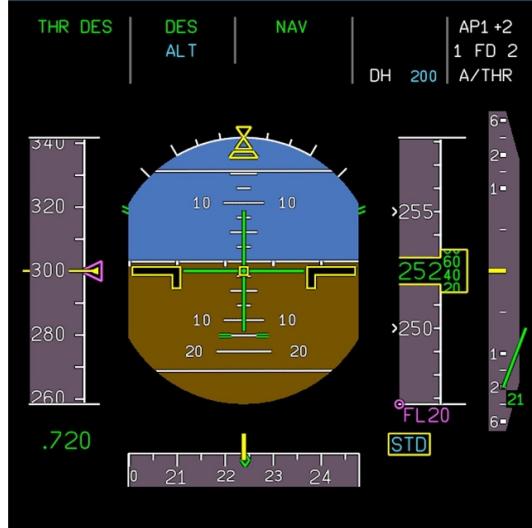


Figure 12. Vincent Airbus PFD

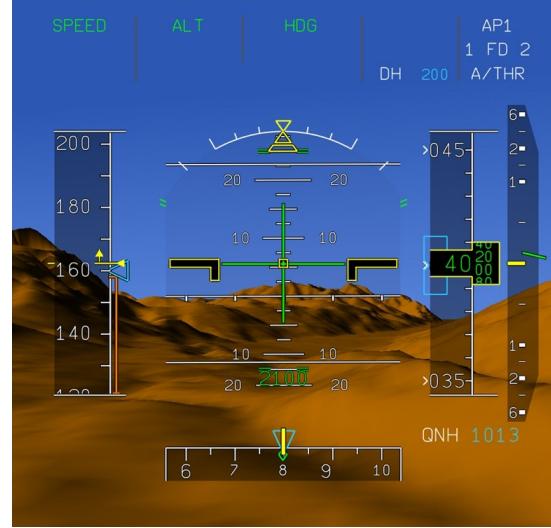


Figure 13. Vincent Synthetic Vision PFD

cockpit displays very accurately. Figure 12 shows an example of an Airbus PFD. Replicated displays build with Vincent are very hard to distinguish from the real cockpit displays. It's also easy to create new display concepts while reusing components of existing displays. An example of this is a synthetic vision display based on the Airbus PFD. This display is shown in figure 13. The displays are built up out of components, which makes it very easy to add new components with experimental functions and reuse components from existing displays. This versatile display software development tool is indispensable for the GRACE simulator.

C. Avionics

All the avionics simulation modules are universal or multi functional and can be used for any type of aircraft. Aircraft type specific parameters or functions are defined in configuration data files. The avionics systems generally provide the same functions onboard of all aircraft. Only special features may differ with aircraft type. The biggest difference between the Airbus and Boeing avionics is of course the fly-by-wire system. This system is only activated for the Airbus aircraft simulations. The RFMS can be used for both Airbus and Boeing aircraft. Its FMS core is common and is used for both configurations. The user interface and the special MCDU pages are contained in type specific modules within the RFMS. The Airbus or Boeing option selects which of these modules is active. In this way developments on the RFMS core are shared and available in both Airbus and Boeing configuration. Only the user interfaces have to be developed separately. For most of the other avionics modules and in general for all simulation modules the same philosophy is applied. Keeping the major part of the software modules common to all aircraft type makes development and maintenance efficient.

D. Traffic Simulation

A standard simulation module of grace is the Traffic Manager, TMX¹. Its first function is to generate traffic around the GRACE simulator. This is used to test systems which are concerned with traffic avoidance like the Traffic alert and Collision Avoidance System (TCAS) and Airborne Separation Assistance System (ASAS). The generation of a present day traffic picture around GRACE also adds to the realism of the simulation. Certainly during taxiing interaction with surrounding aircraft is part of every day operation. Simulated traffic can also be relayed from an external source like for instance NLR's NARSIM (NLR ATC Research SIMulator). This enables the combined simulation of the aircraft cockpit and the ATC ground stations. This is very useful for evaluating new ATC procedures or Data Link (DL) systems from the air and the ground side simultaneously.

The Traffic Manager can also be used to generate conflicts between GRACE and surrounding traffic. This is often a good way for forcing the pilots to take action and evaluate their responses. The Traffic Manager is also used as an experiment leader control station. The execution of the experiment scenario can be monitored and the experiment leader can interact with the scenario. Simulated traffic can be controlled instantly to force events, but also events acting on the host simulation can be commanded. For instance an engine failure or an avionics system failure can be introduced.

V. Communication and Interfacing

The communication and interfacing is the glue between all the hardware and software modules that makes them all work together as one. The interfacing also facilitates the interchangeability of the modules. With a good design of the interfaces it's easy to replace one module without any impact on the rest of the system. For good compatibility interfaces must be set up to be general of art. Using interfaces with a general or common definition makes the modules they connect highly compatible. Module specific signals must be avoided as much as possible. They require separate logic for processing which makes the software more complex and reduces interchangeability.

A. Hardware Interfacing

A very special interface is the hardware/software interface layer. This interface acts as an intermediary between the I/O signals from the cockpit and the I/O signals from the aircraft simulation. All cockpit hardware is connected to a so called "interface node". This is a VME (VERSA-Module Euroboard) rack computer system that translates analog, digital and RS485 signals to numbers and the other way around. The interface node communicates with the host computer via a high speed optical fiber (scram-net) connection. This makes all cockpit hardware I/O available on the host computer.

The primary function of the hardware/software interface layer is translating hardware values to flight simulation values. The second function is to resolve mismatches between aircraft simulation model and cockpit hardware. The best example is the simulation of the A340 with the cockpit in the A330 configuration. The A330 cockpit only has

two throttle handles but the A340 simulation needs four. The interface layer will apply a patch table to reproduce 4 throttles. Throttles #1 and #2 of the A340 model will be driven by the #1 throttle of the A330 cockpit, and throttle #3 and #4 of the A340 will be driven by the #2 throttle of the A330 cockpit. This is essential for simulating aircraft models that differ from the cockpit configuration. Parallel preparation of multiple simulator experiments often calls for fast switching between different aircraft simulations. That's why the simulator must support these mismatches between simulation model and cockpit configuration.

The hardware/software interface layer also makes the simulation models hardware independent. The simulation models connect only to the interface layer and don't interact with the hardware directly. In fact it doesn't matter to the simulation models what sort of hardware is connected to the interface layer. This not only makes it possible to simulate independently from the cockpit hardware configuration, but also provides for scalability of the simulation. The complete GRACE simulation software can also be used in a lower fidelity simulator like NLR's fixed base simulator called APERO, which is an acronym for Advanced Prototyping Environment. In this simulator a lot of the simulator hardware is replaced by so called "soft panels". These soft panels show an image of the control panels and allow the pilot to interact with them through a touch screen. The signals from these soft panels are fed into the interface layer and presented to the simulation models the same way as with the cockpit hardware.

B. Ethernet Communication

The communication between the host computer and all simulation applications running on separate PC's, is established over ethernet. The NLR developed an ethernet communication library⁷ for easy and flexible configuration of the ethernet interfaces. The interface of each ethernet connection or service is defined in a separate data file. These ethernet interface files simply list all variable names, their types and dimensions. The ethernet library places data in and retrieves data from the ethernet buffers by reference of these variable names. This makes it very easy to add new variables to the communication. New variables only need to be defined by the sending and receiving application. Other applications on the same ethernet service don't need to be changed but only need the new ethernet interface file at runtime. The ethernet services can be set up as UDP or TCP. UDP stands for User Datagram Protocol and TCP stands for Transmission Control Protocol. There are two big differences between these protocols. TCP has a mechanism for reliable packet delivery and will automatically resend data which didn't reach the receiving application. UDP doesn't support this. UDP on the other hand can be send as broadcast to multiple receiving applications, which resembles a sort of avionics data bus with multiple receivers. TCP can only be used to communicate one-on-one. In order to communicate with multiple receivers, a separate TCP service needs to be used for each receiver.

Most of the ethernet communication in the GRACE simulator is based on UDP broadcast. Every application that produces data which needs to be shared with other applications, transmits this data over an UDP ethernet service. Any application that wants to use this data can listen in on this service. The use of UDP also enables the use of an ethernet recorder that listens in on all ethernet traffic. It can play back all the ethernet traffic on a later time for debugging and analysis. Another benefit is the possibility to use an ethernet monitor which can be used to instantaneously show the data that's been transmitted over ethernet. This can be a command line monitor to quarry variable values or a plot monitor which shows time histories of selected signals. These tools have been developed by the NLR in support of the ethernet library and are very valuable during integration and testing of application in the GRACE simulator.

VI. Simulator Configuration Control and Management

Simulator configuration control facilitates easy reconfiguration of the simulator. First of all it is used to define the simulated aircraft type and the aircraft subsystems. It activates the corresponding functions of the multi functional simulation modules. For example the auto pilot is configured to activate the supported flight modes and mode switching logic. It loads the aircraft type specific data files for the configuration of the universal simulation modules. This for example concerns data like the aircraft geometry, mass properties and the control loading force characteristics. The adaptive simulation modules automatically configure themselves based on the aircraft type specifier. They load their own data files and select the corresponding functions. The RFMS for instance has this ability and will automatically adapt to the simulated aircraft type.

Besides the configuration of the simulated aircraft type, simulator configuration control is also used to define the current cockpit hardware configuration. The current cockpit configuration is defined with the installed variants of all the exchangeable cockpit hardware modules. A good example is the number of throttles that's installed in the cockpit. The hardware/software interface layer needs to know this number in order to set up the throttle patching



Figure 14. GRACE Control Desk

table. The throttle patching table is used to resolve any mismatch between the number of engines of the simulated aircraft and the number of throttles in the cockpit.

For some hardware modules the change in hardware configuration is automatically detected through a configuration parameter that is transmitted to the host computer. For instance the control loading system reports its current configuration with a configuration number. This number specifies the presence of the control column and the number of side-ticks. With this information the hardware/software interface layer can select the available signals and if needed convert side-stick inputs to column and wheel inputs and vice versa.

With the complete cockpit hardware configuration specification the hardware/software interface layer can translate all hardware signals to the general cockpit interface signals. Any simulated aircraft model can connect to this general cockpit interface which makes it possible to simulate any aircraft model independently from the cockpit hardware configuration. Of course this has its limitations. If a certain type specific function isn't available in a given cockpit hardware configuration and it can't be replaced through any other function, it simply will not be available with that cockpit configuration. This is acceptable because such a configuration will only be used for testing and preparation of simulator experiments.

Simulator configuration management is concerned with setting up and maintaining the different configurations. Default configurations are prepared for all the available aircraft simulation models and cockpit hardware configurations. These are stored in configuration data files. The simulator operator can simply select the desired aircraft model and load the current cockpit hardware configuration from the predefined configuration data files. The current cockpit hardware configuration data files must be updated after any cockpit reconfiguration. In this way the operator doesn't need to select the different parts of the cockpit hardware configuration data files, but simply selects the current configuration data files.

Startup of the cockpit display is done remotely from a workstation at the GRACE control desk (Fig. 14). Different scripts are available to startup the desired cockpit displays. These scripts contain the startup commands for each display which are distributed over ethernet to the display generating PC's. Default scripts are available for B747, F100, A340, A330 and A320. But many experiments have their own specific displays which can be started with tailor maid scripts.

VII. Conclusion

With its unique architecture of hardware and software the GRACE simulator can be used to simulate a large range of civil transport aircraft with a high level of realism. Different research projects require the simulation of different types of aircraft to test new systems and operations in an appropriate cockpit environment. The flexibility in the software architecture even makes it possible to simulate completely different aircraft with the same cockpit hardware configuration. This is essential for parallel preparations of multiple simulator experiments. It also makes the operation of the simulator very efficient because it reduces the number of times that the cockpit hardware configuration has to be changed.

In its first years of operation the GRACE simulator has proven to be very versatile in adapting to the requirements of many simulator experiments. In the most recent research projects GRACE was operated in four different aircraft configurations consisting of Fokker F100, Boeing B747-400, Airbus A320 and A330. A lot of research specific software and hardware was integrated into GRACE with low effort and in a short time span. Its unique architecture has made GRACE the most versatile research flight simulator in the world today.

Abbreviations / Acronyms

<i>ACP</i>	= Audio Control Panel
<i>ADFCs</i>	= Affordable Digital Flight Control System for Small Commercial Aircraft
<i>AERO</i>	= Aerodynamic
<i>APERo</i>	= Advanced Prototyping Environment
<i>ASAS</i>	= Airborne Separation Assistance System
<i>ATC</i>	= Air Traffic Control
<i>CCD</i>	= Cursor Control Device
<i>DL</i>	= Data Link
<i>EFB</i>	= Electronic Flight Bag
<i>EFIS</i>	= Electronic Flight Instrument System
<i>ENG</i>	= ENGine
<i>FBW</i>	= Fly By Wire
<i>FCU</i>	= Flight Control Unit
<i>FMS</i>	= Flight Management System
<i>FWC</i>	= Flight Warning Computer
<i>GCP</i>	= Generic Control Panel
<i>GPWS</i>	= Ground Proximity Warning System
<i>GRACE</i>	= Generic Research Aircraft Cockpit Environment
<i>I/O</i>	= Input / Output
<i>L/G</i>	= Landing Gear
<i>MCP</i>	= Mode Control Panel
<i>MCDU</i>	= Multifunction Control and Display Unit
<i>MFF</i>	= Mediterranean Free Flight
<i>NADDES</i>	= NLR Avionics Display Design and Evaluation System
<i>NARSIM</i>	= NLR ATC Research SIMulator
<i>NAV</i>	= Navigation
<i>ND</i>	= Navigation Display
<i>PFd</i>	= Primary Flight Display
<i>RFMS</i>	= Research Flight Management System
<i>RFS</i>	= Research Flight Simulator
<i>RMP</i>	= Radio Management Panel
<i>TCAS</i>	= Traffic alert and Collision Avoidance System
<i>TCP</i>	= Transmission Control Protocol
<i>TMX</i>	= Traffic and Event Manager, traffic simulator
<i>UDP</i>	= User Datagram Protocol
<i>VINCENT</i>	= Visual Interface design of New Control concepts for Effective and Natural Task performance
<i>WXR</i>	= Weather Radar
<i>XSW</i>	= eXperiment SWitches

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