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RESEARCH FLIGHT SIMULATION OF FUTURE AUTONOMOUS AIRCRAFT OPERATIONS

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ABSTRACT

A key element in the development and innovation of future aviation concepts and systems is research flight simulation. Research flight simulation is applied when the performance and perception of human pilots is a key measure of the overall assessment. This paper will give an overview of the research simulation set-up of the National Aerospace Laboratory (NLR), Amsterdam, the Netherlands, which is used for the human-in-the-loop evaluation of future operational concepts. Special attention is given to the research topic of Airborne Separation Assurance; often referred to as Free Flight. The presented set-up has proven to be a flexible evaluation tool for assessing human-in-the-loop performance when operating in a simulated future autonomous aircraft environment.

1 INTRODUCTION

Simulation is a useful tool for aviation research. Simulation has evolved and matured over the last forty years in equal pace with developments in the aerospace industry. One particular fascinating application of simulation for aviation research is real-time flight simulation. Real-time flight simulation allows pilots to fly in simulated conditions, without the costs and safety issues that go with performing real flight.

When flight simulation and research are combined, the objective is to measure the human performance in the simulated environment. Research will pose certain requirements on the simulation hardware and software used; it requires generic tools that can be adjusted to the evolving insight in topics. This implies that flight simulators (hardware) and simulation models (software) used for research will often be a compromise between realism and flexibility (Hoekstra 1995). This is completely contrary to the philosophy applied in training simulators for which realism is the most important objective and highly dependent on predefined standards. The compromise between realism and flexibility makes the research flight simulator the ideal platform for prototyping of new concepts, procedures and systems. This implies that generic systems in the research flight simulator can ultimately influence real aircraft development and thus also training simulators.

Over the last decades the continuous global growth of air traffic has led to increasing problems with respect to airspace capacity and delays. This situation has initiated the research for new operational concepts and aircraft systems that aim for more independent aircraft operations in so-called Free Flight traffic environment. In order to aid this research, flight simulation is often applied to probe the human factors of pilots when operating in simulated Free Flight environments using new avionics installed in the simulated aircraft. The discussion in this paper will be based on the research experiences of the authors at the National Aerospace Laboratory (NLR), Amsterdam, the Netherlands.

This paper will discuss research flight simulation and how it can contribute to the future of aviation, particularly the way aircraft are operated in a future air traffic system. The next section will discuss in more detail the research for autonomous aircraft operations. Subsequently, a state-of-the-art simulation set-up will be described that has been used for recent "Free Flight" projects at NLR. Important components of the set-up will be described on a high-level.

2 AUTONOMOUS AIRCRAFT OPERATIONS

Due to the continuous growth of air traffic over the last decades, the current Air Traffic Control (ATC) system is approaching its capacity limits. The capacity limit of the traffic system is highly dependent on the way ATC guides aircraft to its destinations. Present day ATC is organized with a fixed airway structure that enables human traffic controllers to detect conflicts between aircraft and perform resolutions by guiding the traffic via radio communicated commands. This rigid "highway" structure poses constraints on the flexibility of aircraft operations. Moreover, the capacity of an airspace sector is dependent upon the workload of the human controllers on the ground that are responsible for separating and guiding all traffic.

2.1 Free Flight with Airborne Separation Assurance

It has been argued that removal of constraints could enable more efficient user-preferred routing, and that removal of all constraints may eventually lead to the realization of a Free Flight traffic environment (RTCA 1995). Free Flight has been proposed as a new concept for a future ATC system that could relieve the growing congestion of the current system and, moreover, would have the potential to offer great economic benefits (Valenti Clari et. al., 2001). Figure 1 below illustrates the traffic environment of an airspace with ATC routes and an airspace in which traffic is free to select their routes.

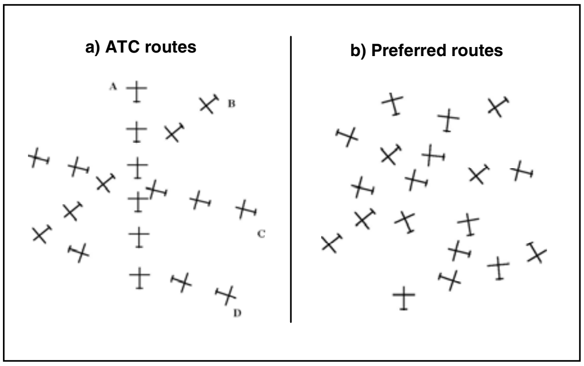

Figure 1: ATC Traffic Compared to Free Flight traffic

It is clear from the picture that user-preferred routing will result in a chaotic traffic environment, especially when observed by a single traffic controller. This controller will probably have problems with guiding the traffic, because the traffic pattern is unpredictable from a ground perspective. However, this is not true when observing the traffic situation from an aircraft perspective. This is why the most ultimate form of Free Flight assumes that the removal of current ATC constraints will also imply a complete shift of the separation assurance responsibility from the ground to the cockpit, resulting in a decentralized traffic control environment. In such a system, pilots will not only be allowed to freely select and fly their routes, but will also have an additional task and responsibility related to separation assurance; this is often referred to as Free Flight with Airborne Separation Assurance. The shift of responsibility implies a change in tasks of pilots, and also a change of the onboard systems requirements. International research is still ongoing with the purpose of defining in detail the concept, procedures and system requirements.

2.2 Airborne Separation Assurance System

With Airborne Separation Assurance pilots will operate the aircraft autonomously without depending on guidance of a ground-based air traffic controller. It is foreseen that the new task will imply a revolutionary change of ATC system, but more importantly, a new cockpit system will have to be developed, tested, and certified.

This Airborne Separation Assurance System (ASAS) will be an essential onboard system that will upgrade the flight deck into a free flight deck. The future system will encompass all the tools that pilots require for their new procedures in autonomous airspace, such as traffic monitoring, conflict detection, conflict resolution, and conflict prevention.

When subdividing ASAS, one can identify at least the following subsystems (ICAO, 2000):

1. Airborne Surveillance and Separation Assurance Processing (ASSAP) system
2. Cockpit Display of Traffic Information (CDTI) system
3. Alerting system

The CDTI and the Alerting system form the Human Machine Interface of ASAS to the pilots. Examples of CDTI will be presented at the end of the next section. The remainder of this section will discuss in more detail some modules in the ASSAP that contains the logic for conflict detection, resolution and prevention.

2.2.1 Conflict Detection Module

A conflict is defined as an actual or potential intrusion of a protected zone in the near future. The protected zone is a circular zone of 5 nautical mile radius and a height of 2000 ft at the altitude from 1000 ft below to 1000 ft above an aircraft; as shown in Figure 2.

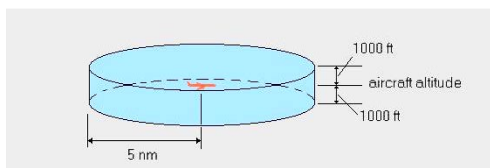

Figure 2: Protected Zone

As part of the aircraft's ASSAP system, the conflict detection module detects only conflicts with aircraft for which an intrusion of the protected zone takes place within a predetermined look-ahead time. This potential intrusion, or conflict, can be detected based on two basic aircraft trajectory prediction methods, which are:

1. State-based conflict detection, and,
2. Intent-based conflict detection

For the state-based method, the conflict detection module uses the aircraft current position and a trend vector (ground speed, track and vertical speed) to detect conflicts. This method has often been used in experiments with a look-ahead time of about five minutes.

The intent-based method uses the aircraft active flight plan as a basis for trajectory prediction and conflict detection. This method is better applied to the more strategic domain for operating aircraft, beyond five minutes look-ahead time. A detailed discussion of both methods is beyond the scope of this paper. Nevertheless, the differentiation of the two methods is important, because they pose different requirements on the aircraft onboard systems. Moreover, research on how both methods can be applied best for various circumstances, is still ongoing (INTENT Consortium, 2001).

A new conflict is detected when an intrusion of the protected zone is predicted, and the time of this intrusion is within the look-ahead time. The conflict information from the detection module can be presented graphically to the flight crew by using the CDTI. The next step is presenting the crew with options to resolve the detected conflict

2.2.2 Conflict Resolution Module

The conflict resolution module is a sub system of the ASSAP that is responsible for calculating resolutions for all detected conflicts. Over the years various methods for resolving conflict situations have been proposed. Some methods use force field techniques, others use genetic algorithms, rule-based methods, or optimization techniques; an overview of numerous approaches to conflict detection and resolution is given in (Kuchar and Yang 1997). A subdivision of methods could also be made by taking into account the conflict detection method. For example, a state-based conflict could be resolved by means of changing the aircraft state until the conflict disappears. An intent-based conflict could be resolved by changing the aircraft's active flight plan. This implies that calculated resolution advisories must match the character of the detected conflict.

2.2.2.1 State-Based Conflict Resolution

For state-based conflicts NLR has developed the Modified Voltage Potential concept (Hoekstra 2001), a method based on force field algorithms (Eby 1994) which use the values shown in Figure 3.

When the conflict detection module predicts a conflict with other traffic, the resolution module determines the predicted future positions of the current aircraft (ownship) and the obstacle aircraft (intruder) at the moment of minimum distance. The *minimum distance vector* is the vector from the predicted position of the intruder to the predicted position of the ownship at the closest point of approach.

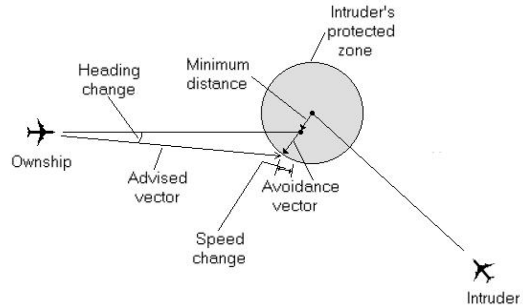

Figure 3: Modified Voltage Potential Method

The *avoidance vector* is calculated as the vector starting at the future position of the ownship and ending at the edge of the intruder's protected zone, in the direction of the minimum distance vector. The length of the avoidance vector is the amount of intrusion of the ownship in the intruder's protected zone and reflects the severity of the conflict. It is also the shortest path out of the protected zone.

The ownship should try to accomplish this displacement in the time remaining until the conflict start time. Dividing the avoidance vector by the time-to-conflict yields a speed vector that should be summed to the current speed vector. The result is an advised track and ground speed. Using the three-dimensional vector, an advised vertical speed is also calculated.

The state-based resolution determines maneuver advisories that resolve the detected conflict without considering the long-term goals of the aircraft of following a route from origin to destination. In some cases, such as with altitude changes, this is not necessary. However, with horizontal resolution of a conflict the crew must plan a recovery maneuver that will take the aircraft back on track to the destination. One way of dealing with this weak point of a state-based resolution is adding an extra functionality that enables pilots to anticipate and monitor potential conflicts. This conflict prevention functionality will be discussed in section 2.3.3.

2.2.2.2 Intent-Based Conflict Resolution

Another way to tackle the problem of the recovery maneuver, is to take the aircraft flight plan into account when calculating conflict resolution advisories. Hence, the conflict resolution should be calculated and presented as an amendment to the active route. This flight plan-based resolution is best applied to the intent-based conflicts that are also detected using the aircraft routes.

Figure 4 shows a conflict situation between two aircraft in which the ownship has detected a conflict using the intent-based conflict detection method. It is clear from the conflict position (i.e., the highlighted loss of separation) that the method has taken into account the intent (flight plans) of both aircraft, which has been shared via a data link system. Based on the conflict geometry and the air-

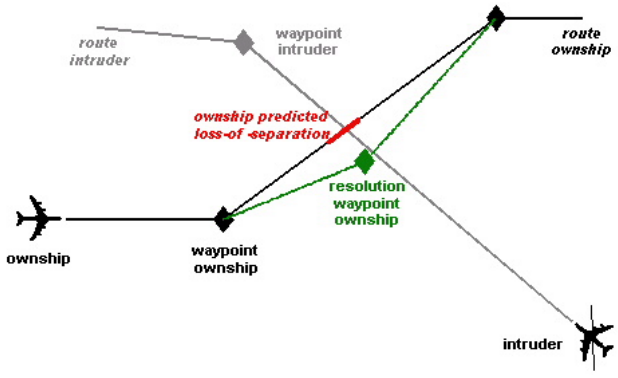

Figure 4: Flight Plan-based Conflict Resolutions

craft flight plans, the resolution module can now determine a route change that will resolve the conflict. The figure illustrates how the addition of a resolution waypoint will resolve the conflict in the horizontal plane. This horizontal resolution has automatically a recovery maneuver, represented by the leg after passing the resolution waypoint. Another option of resolving this conflict would have been a cruise altitude change to the flight plan of the ownship, taking it over/under the intruder trajectory.

The advantage of a flight-plan based conflict resolution, besides the incorporation of a recovery maneuver, is that route optimization techniques can be taken into account for time-efficient resolution maneuvers. Moreover, it is expected that the method is best applied in the strategic operational domain of the aircraft, whereas, state-based resolution is more a tactical resolution method for near-term conflicts. The solution can probably be found in a combination of both. Current research projects are addressing this issue (INTENT consortium, 2001).

2.2.3 Conflict Prevention Module

The purpose of conflict prevention is to provide pilots with additional situation awareness with respect to potential conflicts. This is done by determining if maneuvers are conflict free. Conflict prevention indication can be shown on the cockpit displays, and can be applied to both aircraft state changes as to flight plan changes.

Simulator trials have proven that the additional awareness is of vital importance for recovery maneuvers after resolving conflicts ("is it safe to turn back now?"), but also for standard maneuvering ("what if…?"). Examples of the presentation of conflict prevention functionality will be give in the next section, when discussing cockpit displays.

3 RESEARCH FLIGHT SIMULATION OF AUTONOMOUS AIRCRAFT OPERATIONS

The NLR has various flight simulation facilities that cover the fidelity range from desktop simulation applications to high-fidelity motion base simulators. This paper will only discuss the Research Flight Simulator (RFS), and will focus on developments that enable autonomous aircraft research.

3.1 Overview

The RFS, shown in Figure 5, is a four degree-of-freedom motion-base simulator that is mainly used for civil aircraft simulation studies. The RFS cockpit consists of generic hardware for simulation of several civil aircraft types. The cockpit is equipped with four large Liquid Crystal Displays (LCDs) and four Cathode Ray Tube displays (CRTs) for avionics displays, control-loaded flight controls, throttle levers and several essential cockpit panels. The RFS has a two channel collimated visual system that can be used with an image generator. The generic hardware can be operated with various aircraft simulation models.

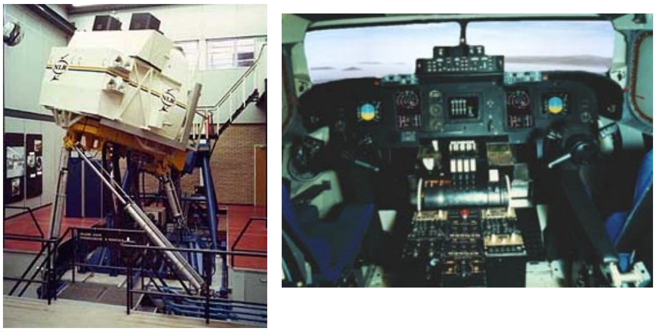

Figure 5: NLR Research Flight Simulator

3.2 Architecture

As discussed in the introduction, flexibility implies a compromise regarding the realism of the simulated aircraft. Nevertheless, this compromise should not have significant impact on the research results. The philosophy applied is called the "Smart Software - Simple hardware" concept (Hoekstra 1995), and can best be explained using the RFS architecture as a high level overview; see Figure 6.

The figure illustrates that the simulator consists of several networked systems, that are connected to a central host computer. This host computer, a Silicon Graphics Challenge L computer, is used for real-time execution of all real-time simulation tasks, such as the basic aircraft and environment simulation. Moreover, the host computer provides the user-interface for managing scenarios, events and data recording. The simulator hardware can be subdivided in three groups:

1. Dedicated simulator hardware
2. Generic simulator hardware
3. Generic cockpit hardware

The dedicated simulator hardware is rigid hardware with a specific dedicated task; such as the 4-degree of freedom

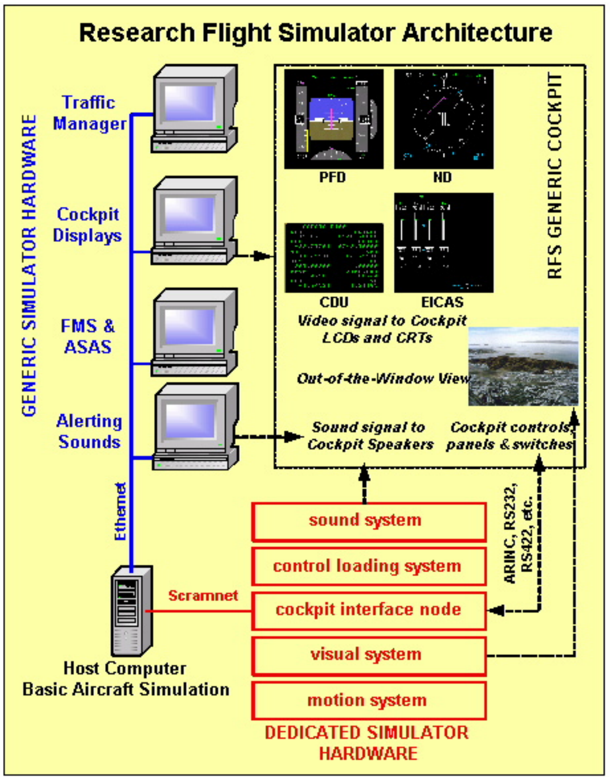

Figure 6: RFS Architecture

motion system or the visual system. A particularly important dedicated hardware system is the cockpit interface node that interfaces the cockpit panels and switches to the host computer aircraft simulation and other networked systems. All of the dedicated hardware systems are connected to the host computer in a Scramnet reflective memory network, essential for the real-time exchange of data.

The second network is an Ethernet network, which is also directly connected to the host computer. All the workstations on this network have generic tasks. They form the "playing field" when it comes to prototyping new cockpit systems. The most important components, when focussing on autonomous aircraft simulation, are:

1. Traffic and Experiment Manager (TMX)
2. Research Flight Management System (RFMS) and Airborne Separation Assurance System (ASAS) module
3. Cockpit Displays
4. Alerting Sounds

All of these components are simulation applications that are used for the replication of future aircraft system and environment behavior. The mentioned components will be discussed in more detail in the next sections.

Finally, the generic cockpit is the platform of all simple hardware devices that enable the pilots to interact with smart software simulated aircraft systems. None of the generic cockpit hardware contains relevant embedded logic (as in the real aircraft), because all interpretation of functionality is done in software applications. This allows maximum flexibility regarding functionality of the simulated aircraft, which is essential for research flight simulation.

3.3 Traffic and Experiment Manager

Traffic environment simulation is one of the key components for autonomous aircraft research. In a typical experimental scenario the autonomous aircraft (RFS) will fly through a Free Flight airspace with the additional responsibility of self separation with the surrounding traffic. The subject pilots will monitor the traffic environment by means of the CDTI and sometimes in the Out-of-the-Window View, generated by the visual system.

In the RFS architecture the traffic simulation is performed by the TMX. This desktop simulation application runs on a Windows workstation and is interfaced to all other applications via the Ethernet network. The TMX has a dual purpose. First of all, the TMX is the central traffic environment simulation application. With the TMX it is possible to generate a traffic environment with various aircraft types, which can be both automatic pilot models and interactively controlled by user input and scenario scripts. The TMX also provides a graphical user interface, shown in Figure 7, for the experiment manager to monitor the overall scenario and to trigger pre-defined events for the RFS simulated aircraft (e.g., engine failures).

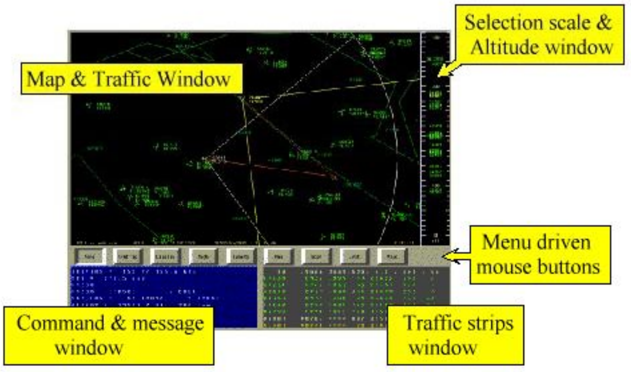

Figure 7: TMX Graphical User Interface

3.3.1 Autonomous Traffic Simulation

For the simulation of the autonomous traffic the TMX uses six-degrees-of-freedom models containing auto-pilot and auto-throttle functionality, route guidance functionality and a pilot model. The Eurocontrol Base-of-Aircraft Data is used as data base for the simulation of different aircraft types (Bos 1997). Besides the basic aircraft simulation model, traffic can be simulated as conventional ATC traffic or autonomous Free Flight traffic.

Conventional traffic flies along predefined routes comparable to the present-day situation. Autonomous aircraft flies direct user-preferred routes from origin to destination. In order to separate the traffic, additional modules can be activated that enable airborne separation assurance of these aircraft. This implies that interaction between autonomous aircraft can be simulated in a chaotic traffic environment. Aircraft will detect and resolve conflicts depending on the implemented conflict detection and conflict resolution algorithms in the ASAS module. It is also possible to create a so-called mixed-equipped traffic environment, by simulating both groups at the same time in the same airspace.

For more pilot-like behavior, the TMX pilot model includes a delayed reaction to conflict resolution advisories and a delayed resuming of navigation to the aircraft's destination, once a conflict is solved. The ASAS module is discussed in more detail in section 3.4.2.

3.3.2 Data Link Simulation

The ASAS functionality of an autonomous aircraft must be based on complete and accurate data of the surrounding traffic. This implies that data sharing between aircraft is of crucial importance in order to enable aircraft to see and avoid each other by using the available tools. One of the most promising inter-aircraft data link systems is called Automatic Dependent Surveillance Broadcast (ADS-B), for which standards are still under development. It is clear that ADS-B will be one of the key enablers for autonomous aircraft operations and that the performance of the data link system will have an impact on the technical feasibility of airborne separation assurance.

It is not difficult to realize actual data sharing within one application that simulates all traffic. Nevertheless, for realistic traffic environment simulation, TMX can simulate performance issues of future aircraft datalink systems (e.g., update rate, range effects, transponder and/or receiver failures). Moreover, when simulating a traffic environment around the RFS, the Ethernet network will form the medium for datalink between RFS and the Traffic Manager aircraft. This is comparable to future datalink systems, such as ADS-B.

3.4 Research Flight Management System (RFMS) and ASAS Module

In an aircraft, the Flight Management System consists of the Flight Management Computer (FMC) and Control Display Units (CDUs). The FMC is the central computer system comprising most functionality regarding navigation, communication and trajectory optimization. The most important functionality is the aircraft route guidance, when the aircraft flies with the auto-flight system engaged to the FMS. The CDU is the primary interface unit for the crew to interact and monitor the functionality of the FMC. Via the CDU, the crew can manage the flight on a strategic level.

This central role of the FMS in the modern cockpit makes it an interesting system for research. Moreover, from an ATM perspective the FMS is interesting because it holds the aircraft intent, which could be used by ASAS.

3.4.1 Generic Simulation Tool

The Research Flight Management System (RFMS) is an NLR-developed generic simulation of an aircraft FMS that can be configured for various aircraft. The RFMS features common functionality, such as route implementation and editing, aircraft datalink functionality, aircraft progress monitoring and trajectory guidance. Beside these standard FMS functionalities the RFMS software has additional research functionality such as the ASAS module, discussed in the next section.

The RFMS software can be used in combination with hardware CDUs, of which two are fitted in the RFS cockpit. This hardware-in-the-loop simulation is often used for experiments with real pilots operating the system. It should be emphasized that once again the smart software - simple hardware concept is applicable, because none of RFMS logic runs within the hardware CDU. The hardware CDU is only used to simulate the actual look-and-feel for the pilots. The RFMS software responds to pilot inputs on the CDU. Changes to the CDU displays are shown as an output of the cockpit display simulation, discussed in the next section.

Another option is to use the RFMS in combination with a software CDU, which is an interactive GUI running on a PC or UNIX workstation. Both the hardware and the software CDU are shown in Figure 8.

Figure 8: Hardware and Software Control Display Unit

3.4.2 ASAS Module

The ASAS algorithms for conflict detection, resolution and prevention for the RFS are contained in a separate module within the RFMS simulation application. As described in section 2.2 an autonomous aircraft will have various systems that are all part of ASAS. The conflict detection, resolution and prevention functionality will make the RFS capable of Free Flight. The ASAS algorithms will require data regarding aircraft state, flight plan of both the ownship and the surrounding traffic. Hence a datalink between the ownship and the surrounding traffic is required.

Figure 6 illustrates that the RFMS and ASAS simulation is connected to the Ethernet network which can transmit and receive data from other simulation applications. The RFMS will send data to the aircraft simulation on the host computer for guidance of auto flight system. In return the host computer will relay back aircraft sensor data (e.g., aircraft position and speeds) and status information of other aircraft systems.

The ASAS module will receive from TMX state and intent information from the surrounding traffic. This is analogous to ADS-B data link. In return the ASAS module and RFMS will broadcast aircraft state and intent to the surrounding traffic simulated by TMX. Another important flow of information is from the RFMS and ASAS module to the cockpit displays and alerting sound system. The required data regarding the aircraft route and ASAS system functionality are broadcast on the Ethernet so that these applications can use it.

3.5 Cockpit Displays

The development of affordable high fidelity display systems over the last decade have resulted in the advance of the glass-cockpit concept. This advance is a blessing for the flight simulation research community, because in modern aircraft the analog avionics have been almost completely been replaced by digital multifunction displays. This implies that the modern glass cockpit is becoming closer to that of a research flight simulator using the same display techniques.

A difference between research and actual cockpits will remain, but will be well hidden from the pilots' eye. In a real aircraft, each instrument is driven by one or more avionics systems. In the RFS, pilots will operate the aircraft using the glass-cockpit avionics that have exactly the same look. The presented displays are generated by dedicated desktop simulation applications, which replicate all real aircraft instruments plus additional functionality. The crew will not perceive the difference between the real aircraft hardware devices or the simulated functionality presented on commercial-of-the-shelf LCDs and CRTs.

3.5.1 Display Development

The smart software - simple hardware concept allows maximum flexibility, without the crew noticing the difference with the real aircraft. To allow a flexible prototyping of the used displays, NLR has developed a desktop tool called NLR Avionics Display Development and Evaluation System (NADDES).

NADDES facilitates the rapid development and evaluation of avionics display formats throughout the complete human engineering and development stage. Display formats can be created and tested using a customizable development environment on a standard desktop computer, which is highly accessible to all human engineering and software development experts. Figure 9 below is an example of Boeing 747-400 Primary Flight Display (PFD) that has been made using NADDES.

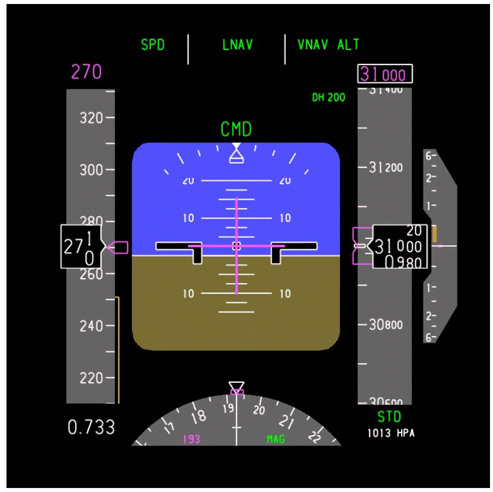

Figure 9: Boeing 747-400 Primary Flight Display

3.5.2 Cockpit Display of Traffic Information

In an autonomous aircraft environment the pilot will require information on the position of the surrounding traffic, and the functionality of the ASAS tools. The detection and resolution of conflicts with intruder aircraft must be presented clearly, and the conflict prevention provides additional awareness for potential conflicts. It is very likely that in the future cockpit all ASAS functionality will be integrated in the current Navigation Display (ND), making it a CDTI. Figure 10 below gives an example how this integration can be realized with a Boeing 747-400 ND.

The Navigation Display is split into a horizontal display, which shows the ownship aircraft position as a triangle comparable as in the real display. Below the horizontal display an additional vertical display has been added. This vertical display gives a side view of the airspace in the horizontal display.

The presented situation shows a conflict detected with an intruder inbound from the left on the same altitude. The state-based detection module has determined the closest point of approach of the intruder, which is shown as a dashed red circle and rectangle around the intruder's protected zone; the protected zone of the ownship is a solid

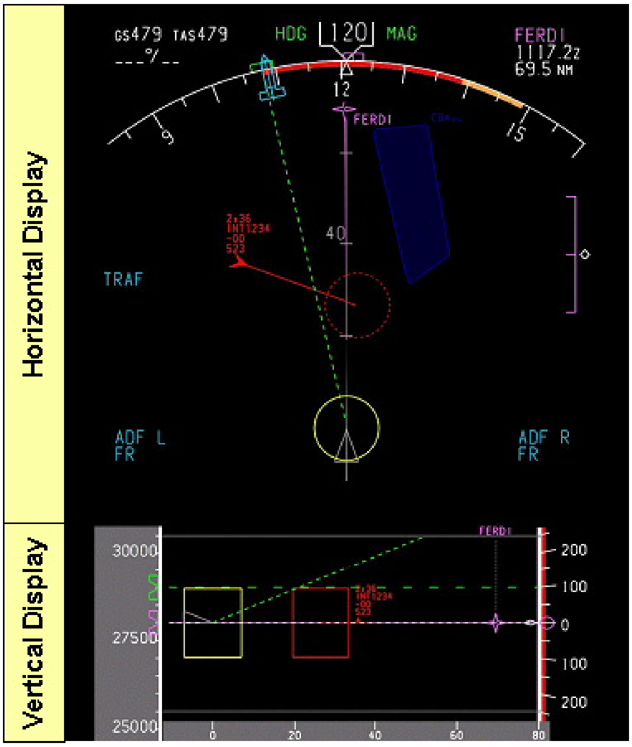

Figure 10: CDTI Integrated in a Boeing 747-400 ND

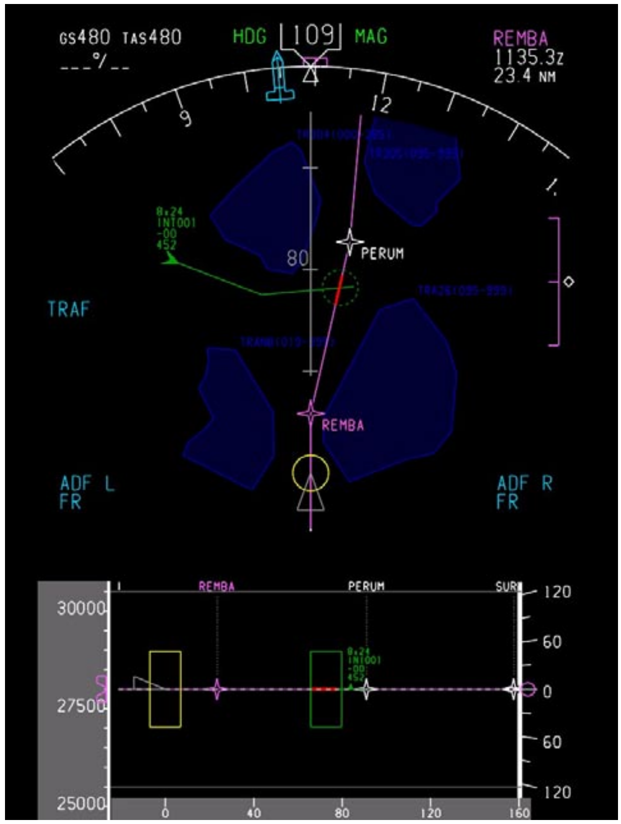

Figure 11: “Green” Intent-based Conflict

yellow circle and rectangle. The conflict resolution module has determined a state-based resolution presented as a heading change advisory and a vertical path advisory, which are both marked as green dashed lines in the horizontal and vertical displays, respectively.

Finally, the conflict prevention module provides the pilots with no-go bands on the horizontal heading scale and vertical speed scale. The no-go bands indicate which maneuver will result in a conflict. The bands are also integrated in the PFD. Figure 9 shows a different scenario than Figure 10, with a small amber band on the vertical speed scale. This band indicates that an conflict will occur if the aircraft climbs with that particular vertical speed. The color-coding of display of the additional functionality is chosen such that urgent conflicts (0 – 3 minutes) are marked red, medium urgent conflict (3 – 5 minutes) are marked amber and low urgent conflicts (beyond 5 minutes) are marked green. The green conflicts can only occur with look-ahead times beyond 5 minutes. An example of a “green” intent-based conflict is shown in Figure 11. This picture also shows that the intent-based conflict detection has taken into account the intent (active flight plan implemented into the FMS) of both the ownship and the intruder.

4 CONCLUSION

This concludes the overview of the simulation set-up used for autonomous aircraft operations research. The aim of this paper was to give an overview of the architecture and functionality of important components. Examples have been given how the smart software – simple hardware concept has been successfully applied.

It can be concluded that NLR operates a powerful research flight simulation facility which has shown to be capable of testing all future autonomous aircraft operational concepts as demonstrated in various past and ongoing international projects in which NLR participates.

The scalability of the research facility from desktop flight simulation, full flight simulation, and even flight testing with the exact same hardware and software components and architecture, is a promising set-up for efficient and effective research into autonomous aircraft operations.

AKNOWLEDGMENTS

The presented set-up and the insight into the subject of Airborne Separation Assurance is a result of years of research, prototyping and development in various international research projects. Mentioning all people involved would be too much. Nevertheless, the authors would like to acknowledge Dr. Jacco Hoekstra, (NLR/NASA Free Flight project leader) and Frank Bussink (NASA, former NLR), who have both had a major influence on the presented set-up and have always been advocates of the smart software – simple hardware concept.

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