

Human Factors Aspects of Air-to-Air Refuelling of Civil Aircraft - A Human-in-the-loop study

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Keywords: Air-to-Air Refuelling, Cruiser-Feeder, Simulation, HMI, DIS

Abstract

This paper discusses the research into the feasibility of air-to-air refuelling of civil transport aircraft as a cruiser-feeder concept for the near future. The focus of this research is on the human factors aspects of operating the cruiser and feeder aircraft during the complete air-to-air refuelling manoeuvre. Two series of human-in-the-loop experiments are executed on two research flight simulators to study the human factors aspects. With these experiments we will test the hypothesis that the presented cruiser-feeder concept can be operated by pilots with an acceptable increase of their workload compared to present-day oceanic operations while maintaining the required safety level for civil aviation. To include both the point of view from the cruiser aircraft and the feeder aircraft, two research flight simulators are interconnected with each other. The pilots in both these simulators can interact with each other while they take part in the same experiment scenario. The results of the first series of experiments are used to improve the human-machine interface and the involved procedures. These improvements will be evaluated in the second series of experiments. The participating pilots all stated that they were convinced that the presented concept for air-to-air refuelling of civil aircraft can be operated with an acceptable workload while maintaining the required safety level.

1 Introduction

This paper discusses the research into the feasibility of air-to-air refuelling of civil transport aircraft as a cruiser-feeder concept for the near future. The focus of this research is on the Human Factors (HF) aspects of operating the cruiser and feeder aircraft during the complete air-to-air refuelling manoeuvre. This research is part of the RECREATE [1] (REsearch on a CRuiser Enabled Air Transport Environment) project which is about the introduction and airworthiness of cruiser-feeder operations for civil aircraft. Cruiser-feeder operations are investigated as a promising pioneering idea for the air transport of the future. The RECREATE project has received funding from the European Union Seventh Framework Programme. The different work packages study different aspects of cruiser-feeder operations. The main aspects are: possible cruiser-feeder concepts, safety and certification, potential benefits, aircraft design, automatic flight control and HF aspects. This specific research is dedicated to the HF aspects of operating the cruiser and feeder aircraft during the complete air-to-air refuelling manoeuvre. In this cruiser-feeder concept the feeder aircraft is a tanker aircraft providing air-to-air refuelling to the cruiser aircraft. Air-to-air refuelling has been selected as cruiser-feeder concept for studying the HF aspects, because it is a concept which can be implemented in the near future based on current generation aircraft. Using the class of aircraft that pilots who participate are used to operate, makes it easier for them to compare between present-day operation and the operation of the cruiser-feeder concept. The cockpit layout will also be based on an existing aircraft and only the specific systems for the air-to-air refuelling will be added. During the experiment the pilots can focus their attention on these specific systems.

2 Objective of this human-in-the-loop study

The objective of this study is to evaluate the proposed cruiser-feeder concept for air-to-air refuelling. The hypothesis of this study states that the presented cruiser-feeder concept can be operated by the crew of both the cruiser and the feeder aircraft with an acceptable increase of their workload compared to present-day oceanic operations while maintaining the required safety level for civil aviation. In order to study the HF aspects and test this hypothesis, the proposed cruiser-feeder concept has been implemented on two research flight simulators. These are the GRACE [2] (Generic Research Aircraft Cockpit Environment) research flight simulator (Fig. 1) of the NLR located in Amsterdam the Netherlands and the GECO (Generic Experimental COckpit) research flight simulator (Fig. 2) of DLR located in Braunschweig Germany. These two simulators are interconnected over the internet using the Distributed Interactive Simulation (DIS) protocol to exchange all data needed for the interaction between the two simulators. Using two interconnected research flight simulators enables to evaluate the air-to-air refuelling procedures from both the cruiser and the feeder aircraft point of view. Performing scenarios with interaction from the cruiser pilots and the feeder pilots makes the simulation very realistic. This level of realism is important for the evaluation of the concept. It generates a certain mind-set when the pilots know that the other aircraft is operated by real pilots. Other aspects that add to the realism are the presentation of the feeder aircraft in the visual system, the information provided on the Human-Machine Interface (HMI) and the realism of the simulation models representing the physics and aerodynamics involved. A high level of realism will provide an experiment environment where the pilots will experience the presented concept as if they are really flying the air-to-air refuelling manoeuvre. In this situation the participating pilots will generate the most valuable feedback.



Figure 1 - GRACE cockpit at NLR Amsterdam



Figure 2 - GECO cockpit at DLR Braunschweig

3 Defining the cruiser-feeder concept

Air-to-air refuelling is standard operation for the military. In order to implement air-to-air refuelling for civil aircraft some changes have to be implemented to make this feasible. To attain the required safety level for operation under civil aircraft regulations, the air-to-air refuelling must be executed fully automated under control of the automatic flight control systems. In the automatic flight control work package [3] of the RECREATE project, the required sensors, autopilot and autothrottle systems were developed and implemented in simulation models. Special attention was given to the selection of different types of sensors which could complement each other in deriving the best possible relative position information [4]. This resulted in the use of Inertial Navigation System (INS), Global Positioning System (GPS), Electro Optical (EO) sensors and Radio Frequency (RF) ranging equipment. Each sensor system uses dual or triple sensors for redundancy. Combining the position information from all available sensors results in an accuracy of the relative position determination with a maximum error of less than a couple of centimetres with both aircraft in position for refuelling. Besides the highly automated flight control system the concept also needs to define the operational procedure and additional systems. Since Controller-Pilot

Data Link Communications (CPDLC) is currently already used to request and provide clearances during oceanic operations, it is convenient to use this also for the air-to-air refuelling clearances. Before the cruiser aircraft will start its approach to the feeder aircraft the crew needs to receive clearance from Air Traffic Control (ATC) to do so. When the clearance is received from ATC the crew of the feeder and the cruiser aircraft are responsible for the separation of both aircraft. Only after completion of the air-to-air refuelling manoeuvre or after an abort manoeuvre, will the responsibility for separation be returned to ATC. Furthermore, the operational conditions were defined. The air-to-air refuelling will take place at flight level 260 at Mach 0.73. This flight condition is selected to keep the manoeuvring margin large enough and with respect to the required performance for flying in trail of the feeder aircraft. Also the geometry of the approach path was defined. The cruiser will start 1000 feet below and about 1/3 of a nautical mile behind the feeder aircraft. It will approach the feeder aircraft on a relative climb path of some 30°. The following phases are defined from initial approach up to departure after completion of the refuelling:

1. Pre-Approach
2. Approach
3. Astern hold
4. Rendezvous
5. Station keeping (Refuelling)
6. Departure

These phases are illustrated in Fig. 3. The automatic flight control system will guide the cruiser aircraft through these different phases.

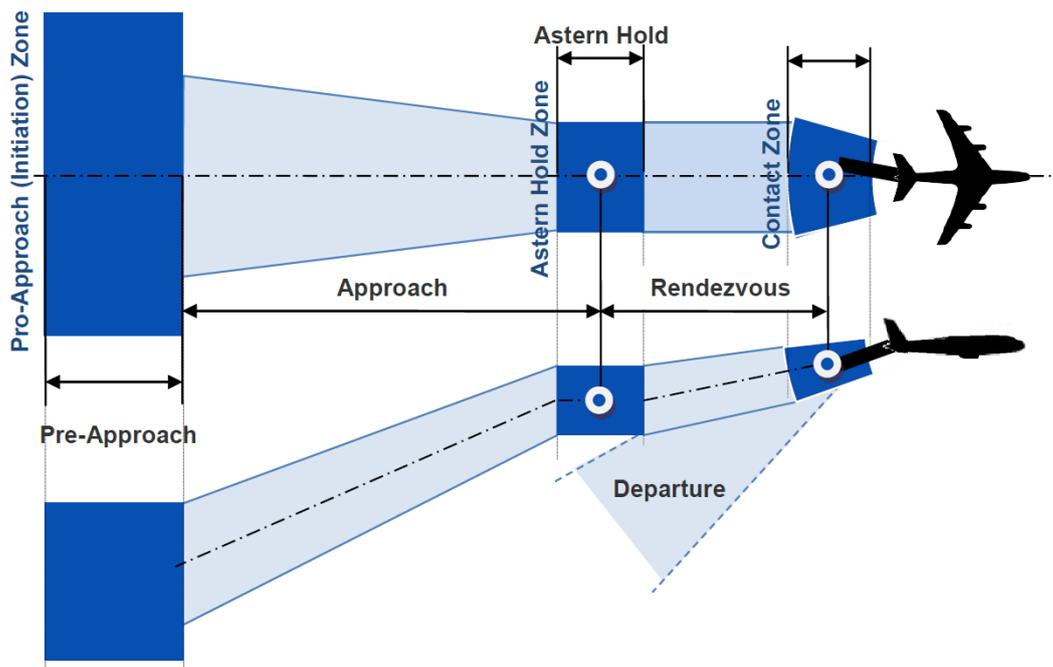


Figure 3 - The different phases during the automated refuelling procedure

4 Design of the HMI

The HMI is very important for the monitoring and controlling task of the pilots during the refuelling operation. Therefore, it is a very important part of the simulation. A special RECREATE HMI has been developed in the RECREATE project that presents the relative position of both aircraft in all phases of the refuelling manoeuvre. This is called the Manoeuvre Progress Display (MPD) which is shown in Fig. 4. It indicates the active phase and the status of the refuelling boom. The pilots can monitor the progress of the manoeuvre and check if their relative position is within the safety margins and if all required systems are

operating correctly. If the pilots identify a potential hazardous situation they can activate an automated abort manoeuvre or perform a pilot controlled abort manoeuvre.

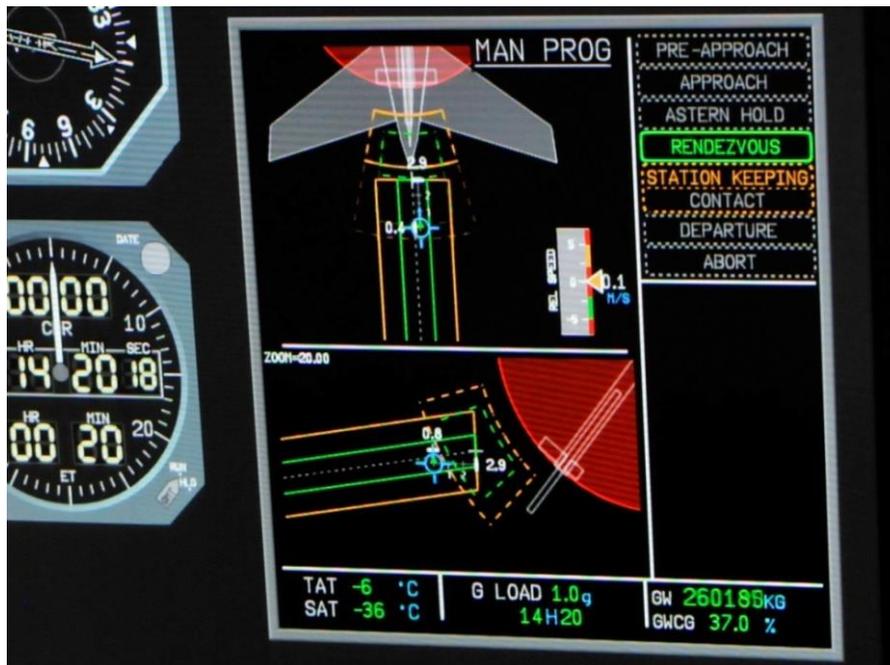


Figure 4 - Manoeuvre Progress Display (MPD)

The feeder aircraft is also equipped with a second HMI called the Boom Status Display (BSD) and is shown in Fig. 5. This display provides detailed information on the position of the refuelling boom, its control surfaces and the corresponding actuators.

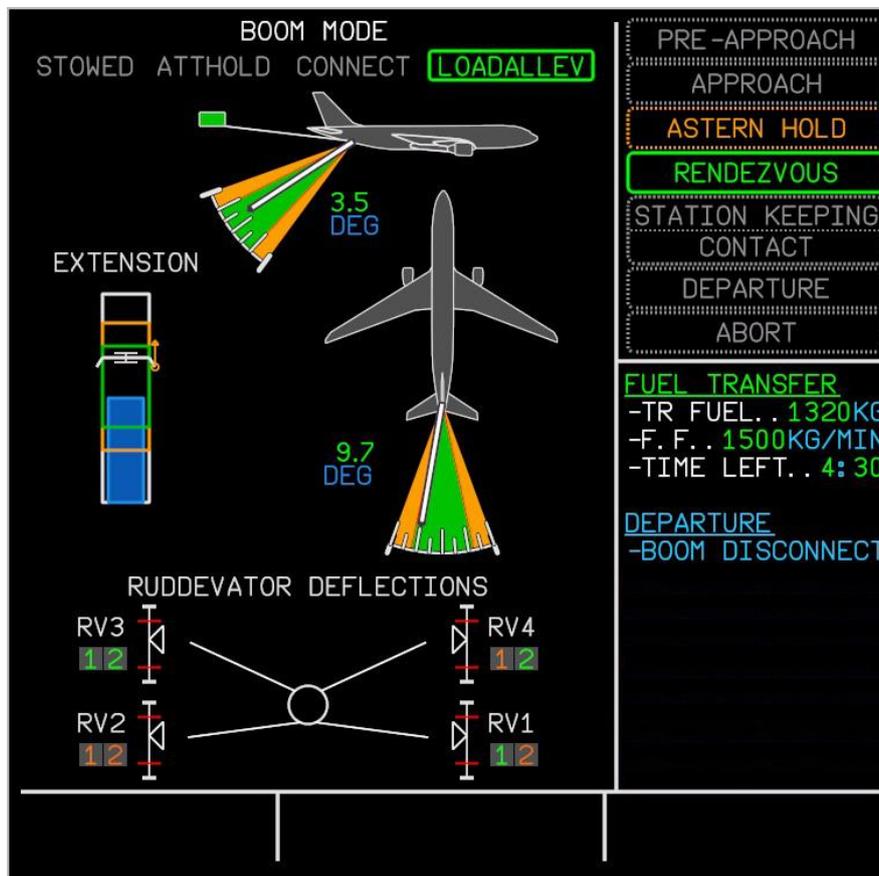


Figure 5 - Boom Status Display (BSD)

5 Creating the experiment environment

A specific simulation environment was constructed by the Technical University Munich (TUM) in MATLAB/Simulink with accurate models of both aircraft, the refuelling boom, including aerodynamic and mechanical forces, the sensor systems and the automatic flight control systems. A 3D model of the feeder aircraft including the refuelling boom was implemented in the visual system. This refuelling boom was specifically designed for this cruiser-feeder concept in the RECREATE project. Besides the 3D geometry also the aerodynamic characteristics were derived and implemented in the simulation model [5]. The cruiser aircraft can observe the feeder aircraft and the boom position during their approach and experience the sensation of flying in close formation with the feeder aircraft. This turned out to be an impressive sensation for pilots that are not used to fly in close formation.



Figure 6 - Close formation flying during the experiment

The GRACE cockpit has been configured as an AIRBUS A330 cockpit to reflect a present-day fly-by-wire (FBW) aircraft. The GECO cockpit reflects an AIRBUS A350 cockpit. The RECREATE HMI has been integrated into the AIRBUS System Display (SD) of the Electronic Centralised Aircraft Monitor (ECAM) system. This is the lower ECAM display in the middle of the instrument panel. With the realistic simulation models running on both the GRACE and the GECO simulators, the RECREATE HMI presented on the cockpit displays and the 3D model of the feeder aircraft visible in the out the window view, the perfect environment is created to put this cruiser-feeder concept to the test. Airline pilots were invited to participate in the phase 1 human-in-the-loop experiments. During the experiment both GRACE and GECO were piloted by a two pilot crew to reflect standard present-day operation. The experiment consisted of performing a couple of refuelling manoeuvres going through the procedures and all the manoeuvre phases. The pilots were asked to give their feedback and remarks on the concept, the operational procedures, the operation of the systems, the presentation of information on the HMI and their perspective on the safety of the operation. The feedback and remarks are used to improve the concept, the operational concept, the systems and the HMI. The improved concept and systems will be evaluated in the phase 2 experiments.

6 Distributing the simulation

The RECREATE simulation environment was implemented on the GRACE and GECO research flight simulators for the human-in-the-loop experiments. A special implementation of this simulation environment was needed to cope with the fact that the simulation will be split between the two simulators located at different locations. In the design of the control systems it was decided that the flight control system of the feeder would not only control the feeder aircraft but also the cruiser aircraft via a special datalink between both flight control systems. Because of this high interaction between the flight control systems of the feeder and the cruiser aircraft a special configuration was implemented where the feeder aircraft could be simulated on both sides of the internet connection and switch control of the active simulation depending on the mode of the automatic flight control systems.

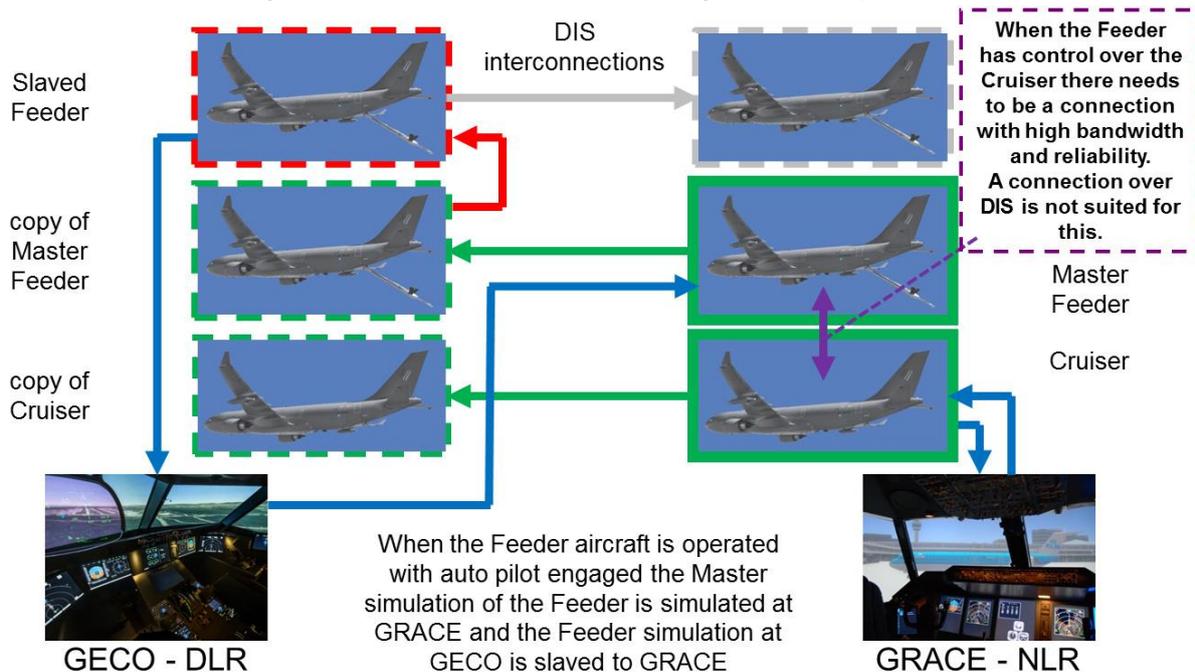


Figure 7 - Special distribution of simulation models between GRACE and GECO

7 Execution of the experiments

The human-in-the-loop simulation experiments are executed on both the GRACE and the GECO research flight simulators. They are interconnected using the DIS protocol over an internet connection. GRACE was selected to simulate the cruiser aircraft because the cruiser aircraft will encounter more turbulent conditions flying behind the feeder aircraft and its flight control system will have to react on the movements of the feeder aircraft. These kinds of movements will be experienced much better in a motion base simulator like GRACE. The fixed base GECO was used to simulate the feeder aircraft. Both the cockpit crews in GRACE and GECO could interact with each other while they observed and controlled the refuelling manoeuvre from their cockpit. Two series of human-in-the-loop experiments are executed to study the HF aspects. The phase 1 experiments have taken place in August 2013 and the phase 2 experiments will take place in September and October 2014. The participating pilots will be asked to fill out questionnaires and they will be interviewed during the simulator session debrief to capture as much as possible feedback and comments. During the experiments the pilots will be observed and rated on recognising potential hazardous conditions and acting on time to prevent contact between both aircraft. The test days start with a familiarisation run to get the pilots familiar with the procedures and the operation of the new systems. The experiment scenarios provide some critical situations that sometimes require action from the pilots. Critical situations include engine failure, highly turbulent conditions and sudden gusts.

8 Results

The main outcomes of the phase 1 experiments are that most pilots who participated are convinced that the presented cruiser-feeder concept can be implemented and will provide the required level of safety. With the highly automated operation of the refuelling manoeuvre the pilots rate the workload to be comparable with present-day operations. There was a notable difference between pilots with and without experience with air-to-air refuelling. Pilots who had flown air-to-air refuelling missions with military aircraft were very comfortable flying in close vicinity of the feeder aircraft. The pilots without air-to-air refuelling experience got pretty nervous the first time they approached the feeder aircraft, even though they were in a simulator. This is clearly a situation that needs to be trained and takes getting used to.

9 Improvements to the concept

Based on the results from the phase 1 experiments the most important improvements to the cruiser-feeder concept that have been identified are concerned with the RECREATE HMI. All pilots pointed out that the HMI should be located in the primary field of view of the pilots. The initial position of the HMI on the SD of the ECAM system, makes the scanning cycle between the Primary Flight Display (PFD) and the HMI for the pilot flying difficult to perform and tiresome. A much better position would be the position of the Navigation Display (ND) so the pilot flying can monitor both the PFD and the HMI with more ease. The pilots also advised to duplicate the indication of the deviation from the approach path and the final station keeping position on the PFD. Also the active manoeuvre phase should be indicated on the Flight Mode Annunciation (FMA) so it directly reflects which mode is the active mode of the automatic flight control system. The MPD provided a closure rate indicator that turned out to be difficult to interpret. To provide the pilots with a more intuitive indicator, an estimated safety margin indicator was designed as shown in Fig. 8. This indicator shows the calculated estimated safety margin which is derived from:

1. Margin to the envelope limit
2. Rate of the margin to the envelope limit
3. The navigation performance
4. The control performance

The navigation performance takes the availability of all sensors into account. The control performance includes the effect of external influences like turbulence. This margin is calculated for all three dimensions of movement. The lowest of these three numbers is used as a global safety margin and displayed on the HMI. The indicator has a green, a yellow and a red zone and shows how close the aircraft is to the abort condition. Green is well within limits. Yellow indicates that the system is getting closer to the abort condition which starts at the red zone. Certainly during turbulent conditions, when both aircraft are bouncing around, the pilot can use this indicator to get an idea of how close to the abort condition the automatic flight control system is operating.



Figure 8 - Estimated Safety Margin Indicator

10 Work in progress

Currently the preparations for the phase 2 experiments are being performed. All the proposed improvements are being implemented and tested. Also the full functional automatic flight control system is now available and will be integrated into the research flight simulators. These improvements will be evaluated during the phase 2 experiments. The phase 2 experiments are now scheduled for September and October 2014. There will be 8 test days. On each test day both GRACE and GECO will be piloted by a two pilot crew. The results of the phase 2 experiment will be reported and published on the official RECREATE website [6].

11 Conclusions

- Most of the pilots who participated in the phase 1 experiment stated that they are convinced that the presented cruiser-feeder concept can be operated in real life with an acceptable workload for the pilots while maintaining the required safety level for civil aviation.
- The HMI presented in the phase 1 experiment can be improved on a number of items. Improvements to the HMI will be evaluated during the phase 2 experiments.
- For pilots who do not have experience with air-to-air refuelling it takes time to get used to operating an aircraft in close vicinity of another aircraft.
- It has been demonstrated that with a special distribution of the simulation models it is possible to simulate the cruiser and the feeder aircraft on different locations while still providing highly dynamic interaction.

Nomenclature

BSD	Boom Status Display
CPDLC	Controller-Pilot Data Link Communications
DIS	Distributed Interactive Simulation
DLR	German Aerospace Centre
ECAM	Electronic Centralised Aircraft Monitor
EO	Electro Optical
FBW	Fly-By-Wire
FMA	Flight Mode Annunciator
GECO	Generic Experimental COckpit
GPS	Global Positioning System
GRACE	Generic Research Aircraft Cockpit Environment
HF	Human Factors
HMI	Human-Machine Interface
INS	Inertial Navigation System
MPD	Manoeuvre Progress Display
ND	Navigation Display
NLR	National Aerospace Laboratory of the Netherlands
PFD	Primary Flight Display
RF	Radio Frequency
SD	System Display
TUM	Technical University Munich

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