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FLIGHT CREW SUPPORT FOR AUTOMATED NEGOTIATION OF DESCENT AND ARRIVAL CLEARANCES

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ABSTRACT

This paper focuses on the application of data link for communication between air traffic management and FMS-equipped aircraft. Based on requirements and guidelines for data link usage, a general philosophy for automated data exchange and the distribution of tasks between the human operators and the automation is presented. Many different areas are affected by the introduction of data link, including the role of the flight crew and the controllers as well as procedures and training requirements. In particular, the design of a flight crew interface providing for the necessary flight crew support is a crucial factor for data link efficiency. This paper introduces a concept addressing these areas and concludes with an outlook to upcoming experiments at NASA's research facilities that are aimed at validating the proposed concept. Ultimately, safety and cost-effectiveness of the air transport system should be significantly improved by exploiting the capabilities of automation tools like CTAS on the ground and the FMS in the aircraft through the utilization of digital data connections.

BACKGROUND

It is generally recognized that new kinds of automated systems like flight management systems and autoflight control systems tend to suffer from serious design and utilization problems with regard to human factors aspects. One problem is that often a philosophy is missing that could provide a general guideline for designing and using the automation. This lack of automation philosophy is accompanied by insufficient feedback to the operator about the state of the automation leading to strong and silent machines that cause significant situation awareness problems on flight decks (e.g. Sarter &Woods, 1993). There are clear indications that many of the aircraft accidents attributed to 'pilot error' are strongly related to this kind of human-automation interaction problem.

While these problems still exist with regard to 'conventional glass cockpits', the next revolution within aviation is on its way. Like an 'internet in the sky' data link will connect different air traffic control facilities, airline operational control centers, and modern aircraft. Studies indicate that this may lead to more cost-effective operations during all phases of flight (FAA, 1996, den Braven, 1992). On the other hand experiences, e.g. gained with the FANS data link connection for oceanic flights show that this application is far from being operationally acceptable as a general data link solution. Some of the reported problems became apparent in the study described subsequently.

In a full-mission experiment conducted in the NASA Ames Boeing 747-400 simulator, descent and arrival constraints were datalinked from the ground into the aircraft using FANS 1 data link. In this environment, handling an ATC message that can be loaded into the FMC requires that the flight crew press several buttons on the CDU, thereby executing the following actions:

- printing the message on the cockpit printer
- loading the data into the FMC
- responding to ATC and
- executing the flight plan.

[*] This work was performed while the author held a National Research Council-NASA Ames Research Associateship

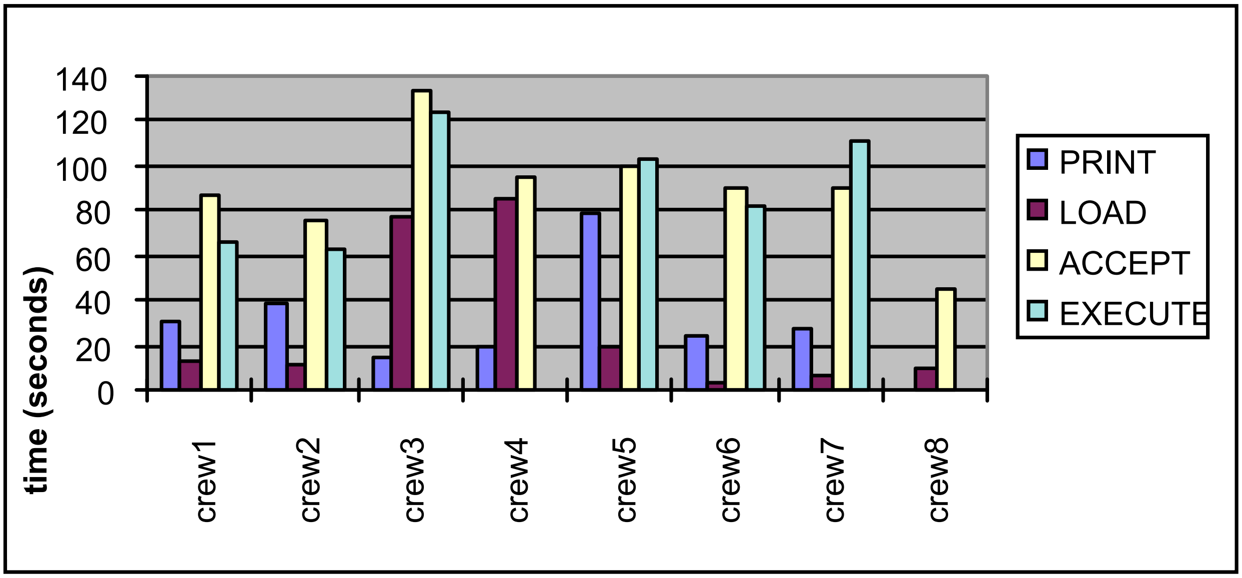

Figure 1: FANS 1 experiments with NASA's B747-400 simulator

Figure 1 shows the elapsed time for flight crews to perform each action after accessing the ATC-Uplink message. It took between 40 and 140 seconds from accessing the ATC page to responding to ATC. Since the air/ground transmission time and the time to access the ATC page must still be added, total transaction times for a ground initiated communication cycle of one to three minutes were typical for this application. Additionally, loading the route into the FMS usually led to route discontinuities and it took between one and seven more minutes to 'repair' the flight plan stored in the FMS. Therefore, with route uplink handling times of up to 10 minutes, this interface is unsuitable for high workload flight situations.

Another result was that the flight crews performed the required actions in different orders, because no clear procedures were defined and the pilots had only very little training in dealing with FANS data link. This was even true for pilots, who had already used this interface operationally in the oceanic environment. The results from this study are similar to other studies suggesting that the FANS1-CDU interface is cumbersome and research and development efforts are needed in order to improve or replace it.

It is important to note that all aspects of the air-ground-human-automation interaction are extremely interdependent. A redesigned pilot interface will affect the complete communication loop including the pilot procedures, training requirements, the capabilities of dealing with ATC-instructions and the controllers task. Thus, it is insufficient to design and research only certain parts of the overall system, before the philosophy of the overall system and the roles of the different agents -human and machine- have been clearly identified. This philosophy identification process must be based on the requirements for the system operation and guidelines for human automation interaction.

GUIDELINES AND REQUIREMENTS FOR DATA LINK USAGE

The digital connection between aircraft and air traffic management is one of the most significant automation steps in aviation. Therefore, the principles, guidelines and requirements for human-centered automation must be carefully regarded and applied. Given the premises that the pilot is responsible for safety of flight and the controller is responsible for traffic separation and safe traffic flow Billings (1996) states his first principles of human-centered aviation automation as follows:

- Pilots must remain in command of their flights
- Controllers must remain in command of air traffic

The corollaries to these principles requiring operator involvement and information as well as monitoring capabilities of human and automation build a fundamental basis for the data exchange concept proposed in this paper. In addition to the general principles for human-centered automation the main requirements concerning data link usage have been summarized in terms of recommendations in SAE (1996). These recommendations cover technical details as well as many human factors aspects regarding procedures, flight deck integration, and the human computer interface.

The following three requirements deal with the main human factors concerns underlying the subsequent concept definition:

- the air/ground communication procedures shall be consistent throughout all phases of flight and all kinds of communication environments
- the situation awareness of all operators shall be maintained or increased
- the communication transaction times shall be within acceptable limits for the respective flight situation

The requirements stated above must not be confused with the goals of the data link integration. Meeting these requirements only assures that the situation does not deteriorate , but it does not improve the air traffic situation per se. The only clearly defined goals that are associated with controller/pilot data link so far are to relieve the frequency congestion and to transmit messages with less transmission errors. A more recent safety and efficiency oriented goal is to integrate ground automation with airborne automation. This allows to load constraints (e.g. generated by CTAS) that are necessary for scheduling purposes directly from the ground into the aircraft Flight Management System to exactly follow the most cost-effective trajectory that meets these constraints.

THE ROLE OF THE AGENTS IN THE AIR-GROUND SYSTEM

The overall air ground system comprises several human and machine agents. Typically two flight crew members interact with the aircraft automation via manual input devices and displays. This automation is used for controlling and monitoring the aircraft behavior according to tactical or strategic reference values and trajectories. On the ground, one or more operators are controlling the aircraft that are flying in a certain area. The controllers use radar displays as well as automated tools that provide advisories for aircraft sequencing, runway assignment, and descent, arrival and approach instructions. Figure 2 compares the main agents and their interdependencies in a current (voice) environment, in a mixed datalink/voice environment, and in a data link only environment.

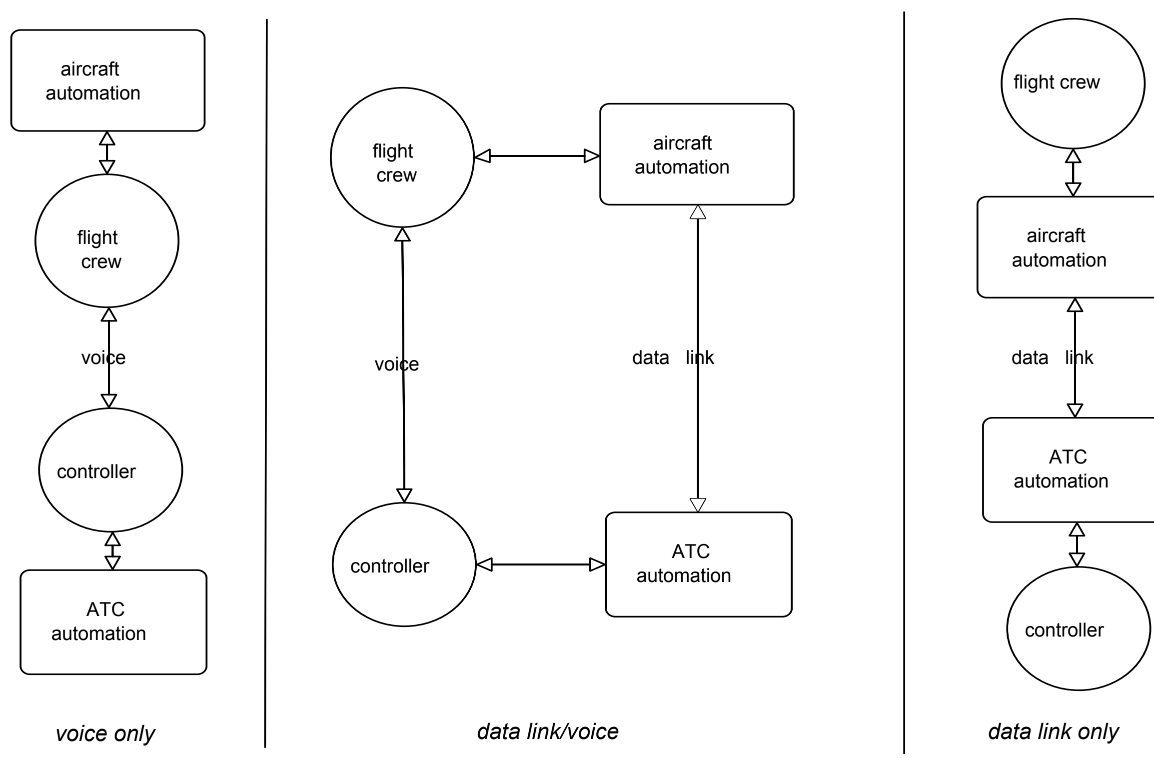

Figure 2: Interaction of flight crew, controllers and automation in different environments

Currently the flight crew members and air traffic controllers exchange information directly via voice, and modify their automatic systems accordingly. The humans talk about the modifications and adjustments they have to perform in order to meet each others constraints. Hence, the human operators are the active agents manipulating the air- and ground-based automation tools.

In a future data link environment, ground-based and airborne automation can directly exchange large amounts of information. In a mixed data link/voice environment, two independent channels can be utilized for data exchange. Depending on the extent to which voice is used, the machines may become the active agents and the human operators fulfill a passive monitoring role. Apparently, the transition of human operators from being an actively controlling agent to becoming a reactive monitor causes problems if too many automatic functions are hidden from the operators. The following principles shall contribute to avoiding this kind of feedback and interaction problem.

DATA EXCHANGE PRINCIPLES

The goal of automating functions in general is to let human operators perform tasks that would otherwise be more difficult or impossible to accomplish. Automatic functions should complement human capabilities. Regarding communication, humans are capable of exchanging reasonable (i.e. small in most cases) amounts of information in a known phraseology. If operators make changes immediately after receiving this kind of information, they are usually aware of what they have done and maintain the necessary 'short-term situation awareness' on a tactical level.

Machines are very good at exchanging and storing large amounts of information and executing given instructions very precisely. They can perform tasks on a strategic level and complement the human shortcomings in this area.

The parallel architecture as described in the mixed data link/voice environment in the center of figure 2 is the configuration which accounts best for this distribution of tasks. However, the humans do not have to communicate via voice, as long as only meaningful data is exchanged between the operators in a common standard phraseology. In certain instances data link will be the more suitable medium for communicating modifications depending on the required transaction time and the information contents (e.g. names vs. numbers).

We propose the following principles for data exchange in a data link environment:

- machines exchange descriptions of the situation (i.e. trajectories, performance, weather, etc.)
- humans exchange modifications (i.e. actions to be performed to alter the situation)
- humans are provided with enough independent information to verify the machine exchanged information

When the machines exchange information that describe the situation comprehensively, this information can be presented to the operators so that they can gain a complete understanding of the surrounding situation. In this case the operators only need to talk about certain adjustments in order to meet given constraints. The data exchange between the machines should not involve additional operator actions, as long as no modification is implied. However, it is important to provide the operators with independent information enabling them to evaluate the reasonableness of the computer-provided information and to detect errors in the passively exchanged data (Leveson, 1997). Whenever the automatic exchange of descriptions of the situation leads to a (significant) modification, the humans have to be made aware of this modification in a meaningful manner.

Thus, the overall air/ground communication can be described as follows: The automatic systems passively exchange information and alert the humans to significant changes in the environment. Independent cues are provided to the humans to enable a verification of the automatically exchanged data. Whenever necessary, the humans communicate meaningful modifications, either by voice or by data link. The medium depends on the particular kind of information and the required transaction time. Examples for modifications appropriate for voice would be immediate heading or speed corrections. Since the voice 'partyline' contributes to providing independent information to the flight crew, some reports may also be communicated via voice. Frequency changes or revised clearances for future phases of flight may be more suitable for data link communication.

The realization of this concept requires an automatic function on either side (ground and air) that manages the interaction between the human operators and the automatic systems in terms of data link activities. This function is introduced in the next section as the Data Link Manager (DLM).

MANAGING THE DATA EXCHANGE BETWEEN AIR AND GROUND AUTOMATION

The Data Link Manager (DLM) has access to the complete air/ground situation comprising aircraft state, active and modified FMS routes, ATC/CTAS constraints, weather, etc. It compares datalinked constraints or state data with current states in order to recognize significant modifications and highlight them to the operators.

A ground-based DLM can be used for assuring that FMS generated routes are within acceptable margins of scheduling constraints and for notifying the controllers of specific changes in the aircraft trajectory. In addition to this task, the DLM is used in the aircraft to make sure that the flight crew gets the appropriate feedback during the passive data transfer and that uplinked modifications are presented appropriately to the crew and directed to the respective system. Thus, flight plan data that can be loaded are directed to the Flight Management System. Figure 3 depicts an air/ground architecture including the Data Link Manager.

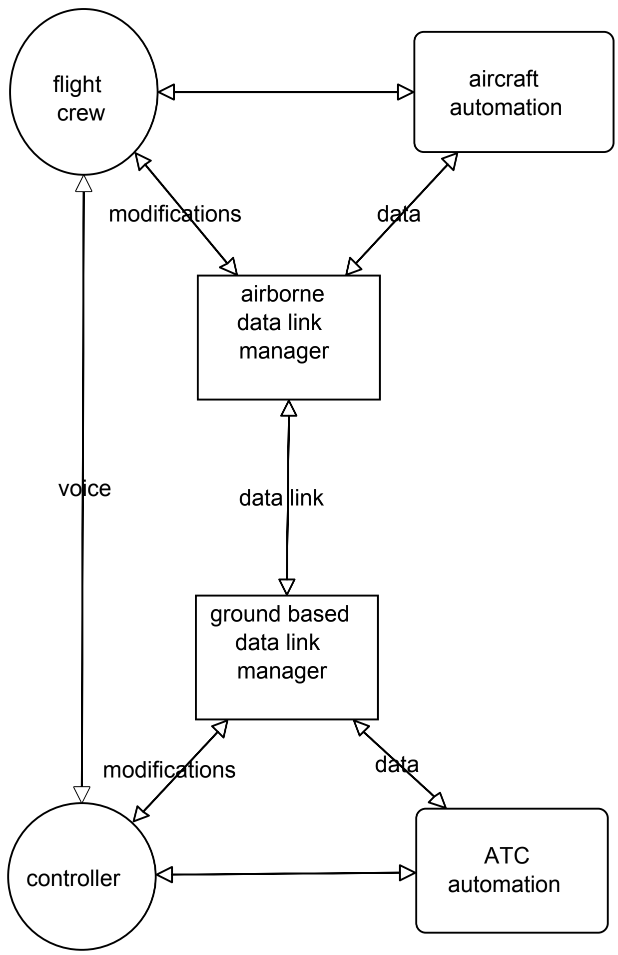

Figure 3: Air/ground architecture with Data Link Manager

The DLM can be considered a crew assistant system for a restricted problem space. The basic requirements and design considerations for this subsystem are similar to those of more comprehensive systems like the Cockpit Assistant System CASSY (Prevot & Onken, 1996). The DLM could be extended towards an advisory system, e.g. to give assistance on accepting or rejecting clearances. An activity tracking system like GT-CATS (Callantine et al., 1997) could be connected to the DLM for on-line operator tracking purposes in order to make sure that all necessary actions for dealing with the air/ground interaction are performed in a reasonable manner.

The systems which enable the functionality of the DLM are the strategic planning and navigation devices. Thus, the ground-based DLM needs to be connected to the scheduling and spacing tools (CTAS in this case), and the air-based DLM needs to be connected to the Flight Management System. Additionally, the DLM must be integrated with communication management units providing for the low level data link communication functions according to the selected data link type and protocol (ACARS, ADS, ATN, etc.). Since the Data Link Manager controls the information flow between the operators and the automated systems, its effectiveness strongly depends on the number and quality of interface resources it can access. Further considerations regarding the ATC interface can be taken from den Braven (1992) and FAA (1996). The following section discusses the flight crew interface in more detail.

FLIGHT CREW INTERFACE FOR DATA LINK MANAGEMENT

Presently, many different kinds of data link implementation on the flight deck are being investigated or are already in use by several research institutions, aircraft and avionics manufacturers, aviation authorities and airlines. While the flight crew interface for Airline Operations Control - Pilot Data Link Communication (AOCPDLC) has been established on the Control and Display Unit CDU of the FMS, the flight crew interface for Controller Pilot Data Link Communication (CPDLC) is very unclear. The range of different flight crew interfaces for data link interaction covers a large variety of cockpit systems: The alphanumeric Control and Display Unit, interactive multi function displays, interactive navigation displays and graphical Control and Display Units are some of them.

Most of the interface implementations are designed for one specific task and try to keep the data link interaction in one designated cockpit space. Which cockpit interface is modified at what level of sophistication basically depends on the time frame at which an operational use is expected. Therefore, naturally the first operational data link interface is the Control and Display Unit (CDU). Because of its non-flight critical status, the CDU is easier to modify and certify than other systems. Unfortunately operational experiences and empirical studies show that this interface is hardly useful especially in other than oceanic environments, because of the complicated interaction provisions and the long communication transaction times. On the other hand, the time period to wait for a sufficient development and certification of highly sophisticated interfaces, like interactive navigation displays, as well as the cost factor associated with retrofitting existing aircraft would very probably delay the utilization of data link far too long. In order to progress with the data link integration while at the same time regarding the basic human factors aspects, a trade-off has to be made between what is operationally feasible and affordable and what is desirable from a human factors standpoint.

The first step is to investigate how the operators needs for performing the revised tasks can be met appropriately by exploiting all currently available cockpit resources. If the basic human factors requirements can be met with the current cockpit interfaces, reasonable resources can be added or modified in order to provide the complete range of required functionality.

The interface design that is being proposed in this paper and prototyped at NASA’s Ames Research Center follows these principles. One general principle underlying this design is that all provisions for human automation interaction are located at the most appropriate display or input device.

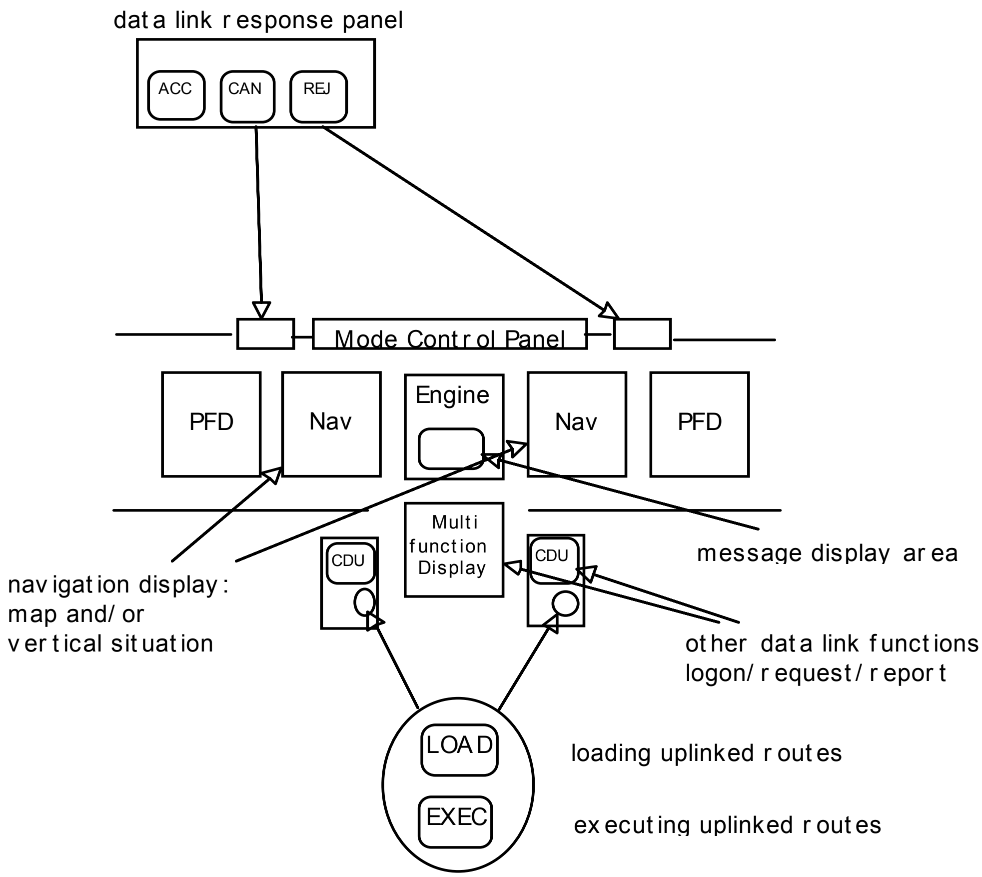

Figure 4: Proposed flight crew interface

Figure 4 shows a schematic view of the resulting interface in a typical (Boeing 777- like) cockpit configuration. The main components of this interface are:

- A data link response panel in front of each pilot (already part of B 777, to be added in other cockpits)
- A designated datalink message display area on the center display
- An additional 'LOAD' hardkey on both CDUs
- An integrated presentation of modifications on the navigation displays (a vertical situation display has been added)
- A page-oriented means for performing data link tasks that are only necessary and applicable in low workload situations. They can either be part of the CDU or of a multi function display.

In a data link transaction the meaningful message contents are indicated in a designated area of the center display, which is easily accessible for both crew members. The pilot not-flying can read the message text loud. In addition to this the data link manager determines the basic modifications associated with the new information and highlights them on the navigation display. Whenever the message contains information that is directly loadable into the Flight Management Computer, a 'LOAD' button added to the CDU is illuminated and the pilots can load the information into the FMC by one button press without leaving the page they have up for the current phase of flight. This will load the uplinked data into the modified route and the 'EXECUTE' button will illuminate. At this point the modified route can be reviewed by the crew and checked by the data link manager in order to make sure all ATC constraints are met. If this is the case, the uplink can be accepted and the flight plan can be executed.

The overall data link concept requires that each major flight plan modification results in a downlink of the new trajectory to the ground. Thus, when the flight plan is executed, the trajectory is transferred to the ground and can be checked again for being within acceptable margins of the clearance. Additionally the controller can access the active aircraft trajectory or important parts of it at any time.

EXPERIMENTAL VALIDATION OF THE CONCEPT

Although the proposed concept is based on results of previous experiments and line operations, there is currently no empirical support that the proposed data exchange philosophy or the flight deck interface fulfill the relevant requirements and contribute to the overall goal of increasing safety and airspace capacity. Several experiments are scheduled in the pursuit of these objectives. Currently, the flight deck interface prototype is implemented into a part-task simulator at NASA Ames. This flight simulator is connected to the Center TRACON Automation System CTAS, so that the complete air/ground loop can be simulated. Initial experiments with airline pilots are scheduled for spring this year. Depending on the results of this study, the next simulation experiment could involve a full mission simulation at Ames' Advanced Concepts Flight Simulator. Furthermore, joint experiments with simulation facilities at NASA Langley are scheduled. The experiments will concentrate on the arrival and approach phases of flight, where traffic advisories are generated from the CTAS components Descent Advisor (DA) and Final Approach Spacing Tool (FAST), which are currently operationally evaluated at the Denver and Dallas ATC facilities.

CONCLUSION

The wide variety of data link related research, development and operations indicate that there is a need for defining a general concept for the digital air/ground integration and a useful flight crew interface. The concept proposed in this paper can be investigated and realized with few modifications to the current avionics system. It is aimed at exploiting the current aircraft automation as much as possible by integrating the different subsystems and controlling the information flow in a reasonable manner, thus providing the operators with the necessary feedback and tools for performing their tasks.

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