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ABSTRACT
This paper is based on results of Research Technology Project (RTP) 6.5 "Crew Assistant", a co-operation between The Netherlands (NLR), Germany (DASA), Italy (Alenia) and Turkey (Bogaziçi Üniversitesi) under the umbrella of EUCLID (European Co-operation for the Long term In Defence). A crew assistant is an on-board automated system that supports an aircraft crew in performing its tasks. This paper presents a generic functional architecture of a crew assistant based on the operational environment in which it will operate.

This functional architecture is modular in several dimensions and identifies:
- various separated crew assistant functional modules,
- different levels of data processing within each functional module,
- management modules which interface the crew assistant with crew and aircraft.

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A GENERIC ARCHITECTURE FOR CREW ASSISTANT SYSTEMS

by

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Summary

This paper is based on results of Research Technology Project (RTP) 6.5 "Crew Assistant", a co-operation between The Netherlands (NLR), Germany (DASA), Italy (Alenia) and Turkey (Bogaziçi Üniversitesi) under the umbrella of EUCLID (European Co-operation for the Long term In Defence). A crew assistant is an on-board automated system that supports an aircraft crew in performing its tasks. This paper presents a generic functional architecture of a crew assistant based on the operational environment in which it will operate. This functional architecture is modular in several dimensions and identifies:

- various separated crew assistant functional modules,
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Contents

(27 pages in total)

1 Introduction

A crew assistant is an on-board automated system that supports an aircraft crew in performing its tasks. Aircraft crews are currently confronted with numerous displays and complex controls in their cockpit. An overwhelming amount of multi-source data is offered while simultaneously control over the aircraft and its systems has to be maintained. This may lead to situations of high workload in which non-optimal decisions are made.

Crew assistant systems are planned to reduce this problem and hence improve efficiency and flight safety. They are expected to rely heavily on Advanced Information Processing (AIP) technologies to organise data and control flow in such a way that the crew is provided with concise and relevant information. At the same time the crew's control efforts will be considerably reduced. This will enable the crew to concentrate on essentials and to make decisions more effective.

Several developments exist in this area. Pioneer programmes are the US "Pilot's Associate"[1], the British "Mission Management Aid"[2], the French "Copilote Electronique"[3] and the German "Cockpit Assistant System"[4]. These programmes go by different names but all aim at the automation of routine tasks and the provision of effective aids to the crew in problem solving and task management. The architectures developed in these programmes have many elements in common but suggest a more generic architecture. Another common element of these programmes is that they consider AIP as key technology for their successful implementation. AIP provides technologies able to handle the complex interaction between crew, crew assistant, aircraft systems and sensors.

This paper focuses in particular on these two aspects: a generic crew assistant architecture and the application of AIP technology. In section 2 the operational environment is described in which a crew assistant is to be embedded. Section 3 introduces a generic crew assistant architecture which is independent of any type of aircraft or operation. Section 4 proposes the application of AIP in general and of multi-agent systems in particular as a key technology for successful implementation of a crew assistant. Throughout the paper, the crew assistant is illustrated by an application of a single-pilot military aircraft, but the concept is also relevant to multi-crew or civil aircraft.

2 Operational environment

2.1 Introduction of crew assistant

The main task of any aircraft crew is to operate its aircraft to attain its military mission or civil flight objectives. In the traditional situation, each aircraft system and sensor will interface directly with the crew through dedicated controls and displays in the cockpit. The crew has to interpret multiple displays and has to operate multiple controls simultaneously in order to perform the functions that are related to its main task. In the non-assisted, traditional situation, the inter-pretation of all sensor information and the control of all systems remain with the crew. A typical example is an "oil pressure warning" on the cockpit system panel which may indicate an oil pressure malfunction. The crew has to confirm this hypothesis by considering oil pressures at a variety of engine power settings indicated in its checklist. Once this hypothesis is confirmed, the crew has to adjust the engine power to delay further system breakdown, search for the cause of the malfunction and meanwhile replan the routing to a recovery base in order to land as soon as practical.

The upward arrows in the traditional situation (left diagram in figure 1) illustrate the information flow from sensors to the displays, downward arrows illustrate the control flow to the systems. For reasons of functional consistency, the cockpit elements are divided into displays (inputs from sensors to the crew only) and controls (output from the crew to systems only). The aircraft elements are divided into sensors (output to displays only) and systems (input from controls only). In reality, most cockpit and aircraft systems will integrate these functional elements.

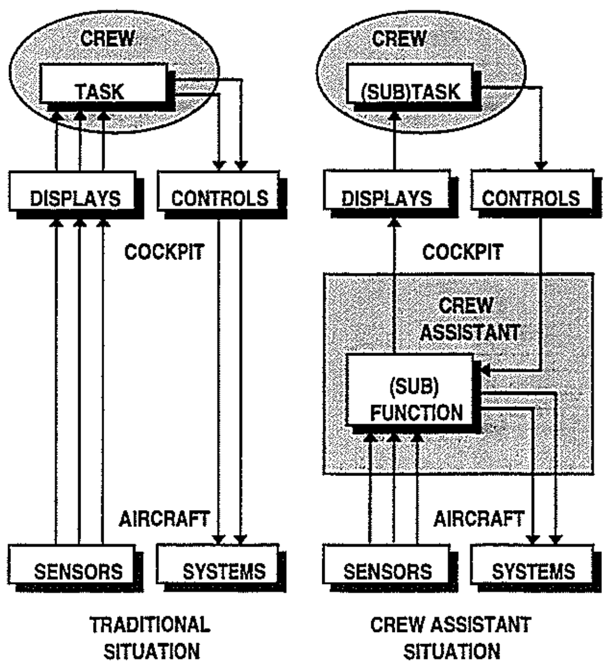

Figure 1 Crew assistant operational environment

The right diagram illustrates the situation when (a part of) a crew task is assigned to a crew assistant. The original task is then split into a (sub)function delegated to the crew assistant and a (sub)task that remains with the crew. Depending on how much of the original task is delegated to the crew assistant, this will result in a change in the amount of information offered to the crew and in a change in the amount of control required from the crew. In the "oil pressure warning" example, a crew assistant could confirm that the warning is indeed caused by an oil pressure malfunction and, depending on authorisation by the crew, the crew assistant could execute corrective actions. In addition the crew assistant could propose and prepare routing to the nearest recovery base.

Figure 1 is the basis for further discussion in this paper. The external elements (crew, tasks, cockpit and aircraft elements) will be described in this section and the crew assistant will be the subject of the next sections.

2.2 The crew

The number of cockpit crew members may vary from a single seat military fighter to 3-4 members of a commercial airliner crew. The situation of a single-seat fighter aircraft is considered to place the most severe requirements on a crew assistant. The situation of a multiple member aircrew (military transport or civil) is less demanding but may have additional and specific requirements. The commercial need in civil aviation for reduction of crew members has already led to the introduction of a number of operational crew assistant realisations. A typical example is the Electronic Centralised Aircraft Monitoring (ECAM) system on-board the Airbus-300 family of aircraft[6].

The difference between a military and a civil application will provide the designers of crew assistant system with an interesting design dilemma. It is essential for military operations, and especially for tasks that are related to tactics, that military pilots are trained to be "unpredictable". This implies that military crew assistant functions which require modelling or monitoring of pilot behaviour are difficult to define. In civil aviation, on the other hand, pilots behave more predictably and monitoring pilots behaviour is an attractive area for crew assistant research and applications[4].

2.3 The tasks

The aim of a crew assistant is to provide the crew with an improved system and situation awareness and to enable the crew to make the best possible decisions in any situation. When analysing different crew tasks to be supported by a crew assistant, it is attractive to decompose these tasks into several levels of hierarchy and complexity. The hierarchy between these levels is that the crew will only pay full attention to the next level once all tasks allocated with the

previous one are handled adequately. Going from one level to the next level, the attention span of the crew enlarges and the amount of information to be processed increases considerably. These tasks levels are:
the ***aviate*** level which includes all tasks related to handling the aircraft, to basic flying and manoeuvring, to monitoring system health and status, and to encountering system malfunctions and emergencies;
the ***navigate*** level which includes all tasks that keep the aircraft on the intended (navigational) mission or authorised (air traffic) flight plan;
the ***communicate*** level which includes the tasks that coordinate with all friendly elements that contribute to or may interfere with mission or flight intentions;
the ***operate*** level which includes the tasks that deal with all unfriendly entities that directly interact or will have effect on the successful mission completion.

The workload during a mission or flight is dependent on the amount of tasks at the highest level, which may be very different for a military mission and a civil flight. For a military mission the tasks at the "operate" level (eg. attack phase) represent the highest workload and will occur in the middle of the mission. For a civil flight the tasks at the "communicate" level, during approach and landing at the end of the flight, normally represent the flight phase with the highest workload.

The introduction of operational crew assistant systems will start with routine tasks at the “aviate” level. Traditional autopilots (altitude/heading/attitude-hold) were already introduced in the early-50s and can be considered first crew assistant systems that relate to the basic flying tasks of the “aviate” level[7]. Expansion of autopilot support to the “navigate” level was common on most civil airliners before 1980[8]. The research systems Assistant for Single Pilot IFR Operation (ASPIO, 1991) and Cockpit Assistant System (CASSY, 1995) monitored the execution of a civil flight-plan and apply to both the “navigate” and “communicate” level[9]. Typical military examples are the Joint Tactical Information Distribution System (JTIDS, first delivered in 1993) and the Multi-function Information Distribution System (MIDS, still under development and designed to fit smaller fighter aircraft). These systems provide secure voice communication and tactical digital information links, and apply to both the “communicate” and “operate” level[10]. Most complicated are military applications that are designed to support the “operate” level. Typical examples here are the self defence mission aids in development for the next generation fighters which aim to support electronic warfare tasks.

2.4 Cockpit displays and controls

When adding crew assistant to support different crew tasks, the interaction between crew and crew assistant depends heavily on the available display and control interfaces in the cockpit.

Contemporary cockpits reveal a blend of display and control technologies, ranging from conventional electro-mechanical dials to flat-panel colour displays and from mechanical switches to voice-controlled input devices.

By far the greatest majority of displays use vision although audio signals are used to provide alerts in danger or failure situations. Modern displays use fast computer processing and graphic symbol generators to convert sensor information into digital data for presentation on either head-down, head-up or helmet-mounted displays. Because these displays can be adapted to display almost any type of information, they became Multi Function Displays (MFD) which enables efficient use of cockpit space, especially in a front panel location.

Cockpits incorporate a variety of mostly manually operated controls. Recent developments might allow voice to be exploited for control purposes but recognition rate, response time and input error rates do not match those of manual keyboard entries. Visual controls and in particular helmet mounted pointing sights are operational in state-of-the-art Russian fighter aircraft. The field-of-view for target designation is much wider than conventional pointing devices and allows full exploitation of the off-boresight capability of modern guided weapons. Major disadvantages are the weight of the current generation sights and their unreliability at high g-load factors.

By far the greatest majority of controls are still manual and they can be located anywhere in the cockpit, provided the pilot can reach them. The hands-on-throttle-and-stick (HOTAS) concept that is pursued in almost all military fighters collocates important switches with the flight controls. Cockpit front panels, quarters panels and side consoles are traditionally crowded with singular switches, rocker switches, push buttons, rotary switches and joysticks. Each of these was originally assigned to a single system function. Multi-function controls are possible by adding arrays of push buttons to an MFD. A variety of controls are possible by displaying their active input function.

Because of their flexibility and capability to support complex (display and control) communication, MFDs are expected to play a major role in crew assistant applications. Some psychologists and human factors experts praise MFD's capability to present information and to reduce pilot's workload. Others expressed warnings of potential information overload eg.: "the F-18 cockpit has three cathode-ray tubes and a head-up display; there are 675 acronyms and 177 symbols which can appear in four different sizes on any of the three cathode-ray tubes; there are 73 threat, warning and caution indicators, 59 indicator lights, and 6 warning tones, 10 multi-function switches on the throttle, 7 on the stick, 19 controls on the panel underneath the head-up display, and 20 controls around the periphery of each of the three cathode-ray tubes, each of which has a multi-switch capability"[11].

2.5 Aircraft sensors and systems

The primary task of any aircraft crew is to operate its aircraft and to employ its sensors and systems in order to attain its mission (or flight) objectives. When considering a crew assistant to support the crew in performing this task, the aircraft sensors and systems that play a role can be divided according to the different task levels of section 2.3.

Sensors and systems to aviate. The aviate task is to keep the aircraft airborne and includes basic flying and system health monitoring. Main sensors and systems are the aircraft attitude (pitch-, roll-, and yaw-angle) sensors and the flight controls, closely linked with engine performance sensors and control. Current status of automation already provides basic autopilot functions and engine performance optimisation during different flight phases (take-off, climb, cruise). Additional systems included in the aviate task are flaps, slats, dive brakes, drag chute, landing gears, aircraft support systems (electrical power, fuel, hydraulics) and life support systems (oxygen, etc.). These systems are not expected to play a role in crew assistant applications because they are already self-contained and mostly fully automated.

Sensors and systems to navigate. Navigation comprises 3-dimensional routing and timing of an aircraft such that it reaches pre-defined positions at pre-defined times. This task can only be executed with sufficient knowledge of present position and existing restrictions as contained in air traffic control procedures and flight plan. Military operations are supplemented with a variety of time and position dependent restrictions. Various state-of-the-art automation supports navigation along a horizontal and vertical flight path (eg. autopilots for VOR interceptions or ILS landings), or are controlled by a Flight Management System (FMS). It is expected that, by the year 2000, satellite based navigation (GPS) will be the prime navigation aid for the en-route, terminal, non-precision and precision approach phases of flight. Present ground based navigation aids will be gradually phased out and GPS-INS embedded systems will provide a uniform concept with unprecedented accuracy for automated navigation support during the entire flight.

GPS is also a cornerstone technology of the free flight concept which envisaged that air traffic control systems would allow individual aircraft to utilise their own direct routing and air traffic separation. Both navigation and air traffic control are candidate areas for crew assistant developments.

Sensors and systems to communicate. Communication includes two-way verbal communication between aircraft crew and other entities, systems for identification (IFF/SIF), and tactical target and data links. The most suitable area for crew assistant support is verbal communication, especially during flight phases with a high workload (approaches under air traffic control) or during mission phases that are critical for successful mission accomplishment (ground controlled intercepts or ground directed attacks).

Sensors and systems to operate. The operate task refers to military roles. Aircraft sensors and systems that support these roles vary much dependent on the specific demands from their operational environment: eg. air-to-air defence, air-to-ground attack, defence suppression, airborne surveillance or airborne command and control. Consequently, candidate tasks for crew assistant support are manifold and range from target acquisition and weapon management to situation assessment and self defence.

3 Functional architecture

The previous section defined the operational environment of a crew assistant and described its complexity. A crew assistant will help the crew operate in this environment and will even hide some of the complexity from the crew. This section presents the functional architecture of a crew assistant and describes how the crew assistant will interface with this operational environment.

The functional architecture (see figure 2) is based on a modular, horizontal and vertical, decomposition. The crew assistant can be seen as a collection of relatively independent functions that assist the crew in different tasks and hence will require different capabilities. The crew assistant can also be seen as a data processing unit that processes low-level data in several stages from aircraft sensors up to easy-to-assess information to be displayed to the crew.

Coordination and interfacing between the crew assistant and the crew, and between the crew assistant and aircraft cockpit elements, will be allocated to four additional interface management modules.

3.1 Functions

The crew assistant functions directly support crew (sub)tasks. Ideally single crew assistant functions may correspond with single crew tasks. It is also possible that the crew assistant includes modules of multiple functions supporting strongly related (sub)tasks. This separation into functional modules will aim at a maximum internal coherence within one functional module and at a minimum interaction between different modules. The modules are at the same hierarchical level which results in the first (horizontal) decomposition of the architecture (see figure 2).

Typical military tasks to be supported by a crew assistant were identified during EUCLID RTP 6.5. Interviews were conducted with 33 pilots from air forces of the participating nations, flying the F-16, MRCA and AM/X. Reference missions (air-to-air and air-to-ground) were defined. Key criteria for task identification were their operational relevance, their impact on pilot workload and mission effectiveness and the expected applicability of AIP technologies[12]. The following typical tasks were identified:

System management: addresses monitoring of normal system performance (and in particular engine performance), trend analysis, and reporting of information on system status.

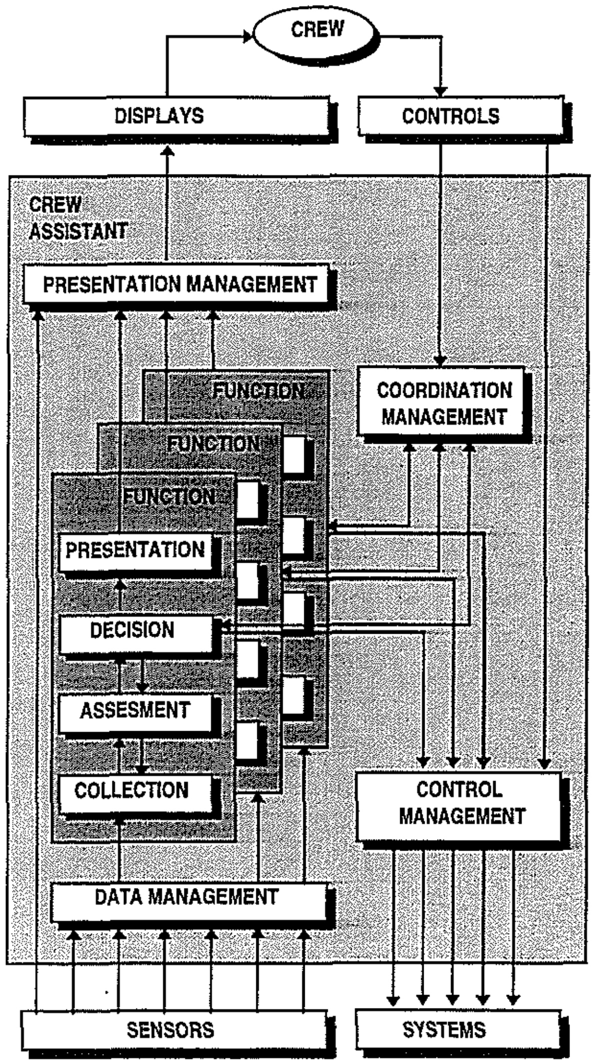

Figure 2 Functional architecture of crew assistant

Malfunction handling: relates to analysis of anomalies, to presentation of appropriate warnings, to (checklist) assistance in countering malfunctions, and (when authorised) to automatic execution of corrective actions.

Mission/flight planning: includes the capability to monitor mission/flight progress, to evaluate the impact of environmental entities (eg. adverse weather and enemy threats) on this plan and, if needed, to assist in or to perform an automatic (re)planning.

Situation awareness: relates to the capability to combine and interpret all available environmental data in order to derive an easy to assess situation picture of this environment; situation awareness may be limited to navigational information but, for military applications, includes all relevant strategic and tactical information.

Self defence: addresses management of self protection systems, assessment of sensor information, selection of available countermeasure options, and (automatic) execution of the selected tactics.

3.2 Data processing levels

For each crew assistant function, the basic flow of data is from the aircraft sensors to the cockpit displays. It is the goal of a crew assistant to direct this flow by processing aircraft sensor data into information for display. The main objective is to provide the crew with concise and relevant information. In this process, a number of steps can be distinguished, each representing a processing level at which data are combined with information, knowledge and procedures and interpreted into information for a next step. Four processing levels are distinguished (see figure 2): collection, assessment, decision and presentation.

At the ***collection*** level, data are collected and prepared for further assessment. This includes:

- the collection of data from sensors and other input devices on-board the aircraft,
- the transformation of these data into a format that can be read by the assessment level,
- the execution of complex operations in which data from different sensors are integrated into a standard data format (eg. by sensor data fusion),
- the preliminary filtering of data by rejecting irrelevant data or by giving priority to data that are urgently needed by higher processing levels.

At the ***assessment*** level, the collected data are assessed on normal or abnormal properties. This includes:

- the comparison of data from the collection level, mutually or by comparison with reference data (eg. threshold values),
- the execution of complex processing, eg. the analysis of system trends by examining a range of chronological data values and the prediction of values in order to anticipate future problems,
- the assessment of the aircraft environment on the basis of sensor data.

At the ***decision*** level, it is decided what has to be presented to the crew on the basis of inputs from the assessment level and possibly provide autonomous control. This includes:

- the filtering of data from the assessment level in order to prevent saturation of the crew's cognitive resources,
- the generation of advice on handling abnormal situations,
- if authorised, the execution of autonomous action, i.e. control the aircraft systems.

Finally, at the ***presentation*** level, it is decided how the information from the decision level is presented to the crew. This includes:

- an assessment of the available cockpit display resources and crew preferences,
- the presentation of information in such a way that the crew is directly cued and able to process the information efficiently and effectively.

Each processing level has a characteristic combination of type of data, information, knowledge and operations. These levels communicate with each other hierarchically and result in the second (vertical) decomposition of the architecture (see figure 2). Inputs from a higher level are intended for control or request for information. The lower level is obliged to act according to this input. Conversely, inputs from lower levels are intended to be information only. A higher level is free to process this input. The decision level is modelled to be the only level that receives external coordination from the crew and it is the only level that provides control to aircraft systems. Crew coordination includes preferences for display presentation and authorisation to the crew assistant to control aircraft systems.

The different levels of data processing within the crew assistant show similarity with the hierarchical model and processing levels proposed for C^3I data fusion[13]. The main difference is that the data fusion process specifically supports situation and threat assessment within a C^3I application while the crew assistant process will support a variety of crew tasks, including situation and threat assessment.

3.3 Interface management

Crew assistant externally interfaces with displays and controls in the cockpit and with sensors and systems on-board the aircraft. The crew assistant functional architecture adds capabilities to organise the corresponding data, information and control flows. These capabilities are organised in four interface management modules (see figure 2): coordination, control, data and presentation management. Different aspects of interface management will be discussed in the next sections.

3.3.1 Coordination management

Crew assistant authority. By delegating a task to the crew assistant, the crew inevitably has to specify the nature of its interaction and the authorisation for presentation and control. This delegated authority can be expressed in standard levels of automation (eg. stand-by, manual, semi-automatic and automatic). Full automation is outside the scope of the crew assistant and in the "automatic" mode the crew assistant should at least inform the crew on the status of its activities and should instantaneously accept a reset by the crew at any time. The crew should have a correct and complete understanding of the functioning of the crew assistant in all modes, in order to allow a smooth transition between different modes and to maintain consistency with manual (non crew assistant) operations. The crew remains in the loop and may regain control at any time.

Coordination between functions. When several tasks are delegated to crew assistant, interactions will take place which require coordination between the corresponding functional modules. This includes:

- translation and decomposition of the request for assistance by the crew into the activation of all needed functions within the crew assistant;
- prioritisation between crew assistant functions when simultaneous execution of crew assistant functions results in conflicts that are related to the crew (limited cognitive capabilities), to the aircraft (limited available cockpit displays or supporting sensors) or to other resources (computer memory, processing power or throughput capability);
- cooperation between crew assistant functions when some functions need specific results from another; this control (or request for data) is performed at the decision level though the actual exchange of data may remain at the assessment level.

3.3.2 Control management

Overruling by the crew. For each function that is delegated to the crew assistant, the crew shall be able to overrule the crew assistant. Overruling may cause sensors and systems to receive control inputs from both the crew and crew assistant which may be conflicting. This conflict is prevented within the design of the crew assistant by routing all control inputs through a control management module. Note that overruling of system control is basically different from de-selecting crew assistant.

Conflicting system control. A conflict in system control exists when the same aircraft system is employed simultaneously both by the crew and crew assistant while each performs a different task. This occurs when eg. the crew assistant performs a mission planning function and directs a radar in its ground mapping mode while simultaneously the crew selects that radar to operate in an air-to-air mode. Control management prioritises and solves such conflicts and, when required, informs the crew and requests additional guidance.

When multiple functions are assigned to the crew assistant, these may also conflict in controlling the same systems. This may occur when eg. (short term) self defence functions and (long term) mission planning functions simultaneously request the same sensor to provide information. Solving these conflicts has to match the way the crew would solve them.

Crew requested input. Occasionally, the crew assistant may not be able to collect all data required to perform a function, eg. because a sensor is malfunctioning or because there is no sensor available. Such data can be obtained by requesting the crew to provide them. Loading mission data via a crew inserted data cartridge is part of this capability.

Sensor management. When data collection requires activation or redirection of a sensor, this control is subject to crew authorisation and does not differ from control of other systems. Control management, therefore, should include sensor management.

3.3.3 Data management

Importing sensor data. Data management is responsible for importing and filtering all sensor data as required by the active crew assistant functions. One function might require data from multiple sensors while other functions might require data from the same sensor. Data management is responsible for correlation of filtered data with the crew assistant internal data. It is expected that data management and data collection will be closely integrated in the system design of a crew assistant.

Sensor data fusion. Data management is closely related to sensor data fusion, but the overall sensor data fusion problem should be resolved outside the crew assistant. The functional architecture assumes responsibility for correct data to remain with each sensor individually and the responsibility for correctly fused data with the involved sensors collectively.

3.3.4. Presentation management

Limited display resources. The crew assistant will be operational in a cockpit environment that is expected to rely heavily upon MFD technology. This implies that conflicting requirements in the presentation of information are likely to emerge when multiple crew assistant functions simultaneously require access to the same display. Solving these conflicts has to match the way the crew would solve them. Remaining conflicts should be prioritized and, when required, additional guidance should be requested from the crew.

The crew assistant may also be in conflict with a sensor not involved with crew assistant if both require the same display in the cockpit. Since such a conflict emerges by the introduction of a crew assistant, it should be solved by the crew assistant. The conflict could also be solved by displays that are dedicated only to the crew assistant.

4 Advanced Information Processing

The crew assistant architecture presented shows a modular approach in which various functional elements can be marked as knowledge intensive. It also shows that crew assistant interactions are complex and that these interactions should remain transparent to the crew at all times. Advanced Information Processing (AIP) provides technologies able to handle this complexity and support a sophisticated man-machine interaction by minimising the cognitive gap between man and machine. Candidate AIP technologies are:

- knowledge-based systems,
- natural language and speech understanding,
- perception, including advanced sensor data processing and fusion,
- planning, eg. for in-flight mission planning,
- learning to improve crew assistant capabilities,
- distributed problem solving.

This section will focus on how to realise a crew assistant system architecture. The features of AIP technologies that are required to provide a firm basis for a crew assistant system architecture are reviewed first. It is further argued that distributed problem solving, and in particular multi-agent systems, are proper AIP technologies for the crew assistant overall system architecture while other technologies might be applicable to specific elements within this system architecture.

4.1 Requirements for AIP applications

The AIP technologies that will be applied to develop the crew assistant functional architecture into a system architecture should have features that satisfy the following design requirements:

Modularity. The crew assistant shall be based on technologies that allow logical decomposition of the system into smaller components (modules) with well-defined interfaces. Modularity facilitates development, enables future upgrades and reduces life-cycle costs by improved maintenance.

Real-time performance. The crew assistant shall have guaranteed response times in a highly dynamic environment. It may be better to provide an acceptable response in time than to provide a response that is best, but too late. This can be extended with the requirement for a response being not too complex. Although a complex response is in time, its contents might be difficult to understand. Real-time performance is a critical factor in crew acceptance.

Reliability. The crew assistant shall have built-in hardware and software elements that are designed to reduce the risk of a complete system failure. The applied technologies should allow for a graceful performance degradation in case of failure.

Integration. The crew assistant includes many diverse functions needing different implementation methods and techniques. The technology used should support integration with conventional as well as advanced methodologies preserving modularity.

System engineering. The crew assistant shall be developed and maintained by a well-defined and widely-accepted system engineering methodology. The technology used should support such a methodology in order to reduce development and life-cycle costs.

Maturity. The crew assistant shall be based on mature and proven implementation technologies. This is expressed by the availability of tools, successful prototypes and operational applications.

4.2 Distributed Problem Solving

An emerging candidate technology for realisation of the crew assistant system architecture is Distributed Problem Solving (DPS)[14]. This technology provides a natural transition from the crew assistant functional architecture to a system architecture where the inherent distribution and modularity of functions is preserved in the functionally-distributed problem solving modules.

DPS technology considers two main approaches: distributed knowledge sources (often referred to as blackboard systems) and multi-agent systems. Both consist of multiple agents but they differ in structure at global architecture level and at agent level. A multi-agent system normally consists of heterogeneous agents that have a range of expertise or functionality (eg. a complete knowledge-based system performing a specific function such as mission planning or malfunction handling). These agents have the potential to function stand-alone but are also able to cooperate with other agents[15].

In a blackboard system, the agents are knowledge sources interacting through a shared memory: the blackboard[16]. Here, only knowledge is distributed, but data, information and control are central as compared to multi-agent systems. A common (shared) data structure for a complex crew assistant system with heterogeneous knowledge, data and functions is not likely to be obtained. A central blackboard system control will also be a bottleneck for real-time performance. Therefore the application of a blackboard system seems to be limited to single crew assistant functions only. In fact, the blackboard system concept provides a natural way to

Maturity of multi-agent systems is reflected by a growing list of development tools which in most cases have integrated a blackboard system technology. For crew-assistant applications it is recommended that specific arrangements are made to ensure:

- a relatively fixed agent organisation in order to map each crew assistant function on a specific agent, to reduce control complexity and non-determinism (which guarantees a consistent and predictable behaviour towards the crew) and to provide predictable load balancing of the limited computer resources in regard to data transfer bandwidth and processing power;
- a predictable conflict resolution where the agents opt for the same solutions (eg. selection of aircraft system modes) and the same use of resources (eg. choice of cockpit interfaces) to address consistently the limited cognitive capabilities of the crew.

5 Conclusions

A crew assistant is an on-board automated system which will support the crew in performing its task. It will enhance efficiency and flight safety in a demanding, complex operational environment. This is achieved by assigning (a part of) the crew task to the crew assistant. Depending on how much of the original task is delegated, the amount of information offered to the crew and the amount of control required of the crew will be significantly reduced. This will enable the crew to concentrate on essentials and make more effective decisions.

This paper presents a generic functional architecture of the crew assistant based on the operational environment in which it will operate. This functional architecture is modular in several dimensions and identifies:

- various separated crew assistant functional modules,
- different levels of data processing within each functional module,
- management modules which interface the crew assistant with crew and aircraft.

For crew assistant development, it is recommended to identify early in the design process the single or multiple functions supporting single or strongly related crew tasks. This will result in functional modules with a maximum of internal coherence and a minimum of interaction. Future modifications will also benefit from this modularity. When eg. a cockpit display has to be replaced, only the presentation module that addresses that display has to be adapted. The other modules remain unaffected.

The functional architecture includes various elements that are knowledge intensive. Advanced Information Processing provides technologies able to handle the complexity of the operational environment and to support sophisticated man-machine interaction.

This paper proposes Distributed Problem Solving technology in particular as a key technology to develop the functional architecture into a system architecture. The suggestion is to let a multi-agent system form the backbone of the architecture that includes coordination aspects and to apply blackboard system technology to local function-dependent problem solving. With respect to real-time operation, the multi-agent system architecture will be able to make a trade-off between agent communication and computation, and the agent's blackboard system is particularly suited to making problem-dependent trade-offs between quality and responsiveness.

Maturity of DPS development tools and existing realisations lead one to expect that next generation crew assistant applications will adopt widely the distributed problem solving and multi-agent technology. Specific arrangements are required to satisfy specific needs within a crew assistant application.

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