8 Cognitive Cockpit Engineering: Coupling Functional State Assessment, Task Knowledge Management, and Decision Support for Context-Sensitive Aiding

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ABSTRACT

The UK Ministry of Defence (MOD) in conjunction with the Defence Evaluation Research Agency (DERA) have established a program of applied research concerned with the development of cockpit adaptive automation and decision aiding for military fast-jet pilots. The operational requirement for this *cognitive cockpit* project arises from the possibility of a highly automated future offensive air system, involving a mix of manned and uninhabited air vehicles. In complex, rapidly changing military environments, increased dependencies on automation present significant challenges to maintaining effective human cognitive involvement in systems functioning. A human-centered approach to system design is needed that is based on human cognitive requirements for the control of system functional purpose, decision-making usability, and effectiveness in context of use. Technology is needed to assist rather than replace the future aircrew in cognitive work with systems involving high levels of task automation. Support will be needed that is adaptive and context-sensitive, to be responsive to changing mission requirements, in particular for in-flight situation assessment and mission replanning, in other words, decision support to provide the right information, in the right way, and at the right time. Technology needs to consider the aircrew's physiological and behavioral state, adaptively responding to an individual's indications of overload, distraction, and incapacitation. This chapter describes a program of research in cognitive systems engineering that seeks to couple pilot functional state assessment, knowledge-based systems for situation assessment and decision support, with concepts and technologies for adaptive automation and cockpit adaptive interfaces. The intention is to provide a scientific quantitative assessment of a broad range of options for intelligent pilot-aiding. This is to be based on sound cognitive systems engineering principles for system cognitive control, which keeps the pilot in control of the system, rather than the system controlling the pilot.

8.1 INTRODUCTION

8.1.1 Cognitive Design Requirements

Cognitive systems engineering seeks to bring together consideration of the environment, artifacts, and agents (human and machine) in a system of systems approach to design (Hollnagel & Woods, 1983; Rasmussen, 1986; Norman 1986). It tries to make sense of the mutual interactions between people and their environments under a variety of changing conditions (McNeese, 1995). This supports a much needed human-centered, rather than technology-centered, approach to systems design, with a strong understanding of the role of artifacts—machines, tools, computers (i.e., things that make us smart or dumb)—and the requirements of the context of use and of system functional purpose. The need for this approach has arisen generally from human problems of working with automation and computers, and from considerations of human error and safety, in addition to efficiency and productivity. This has led to a focus on analysis of cognitive work and environmental constraints, and ideas such as context of use, cognitive control, situated cognition, and other ecological issues (Hollnagel 1993; Rasmussen, Pejtersen, & Goodstein, 1994; Vicente, 1999). These ideas and approaches are particularly relevant to the implementation of intelligent aiding systems in complex environments such as military aviation.

In aviation, computer-based cockpit automation has been designed generally to replace rather than to support human functions. Implementation of conventional automation, particularly in civil aviation, has sought to reduce or simplify crew tasks, so as to enable cost savings from reductions in crew complements, human error, and training. However, in the military aviation environment, human involvement is needed in systems control to govern the system's functional purpose, and particularly to provide the strategic guidance and tactical flexibility needed in rapidly changing, complex military operations. In the environment of use, the complexity of military aviation task domains is such that without considerable computerized assistance the aircrew would not be able to cope with the very large number of potentially relevant features and a vast number of possible responses. Perceiving and interpreting all of the relevant features and choosing an appropriate response within the tight temporal constraints of the domain will challenge any intelligent agent—whether human or machine.

One method of reducing the task and cognitive load on aircrew, enabling the pilot to concentrate unique cognitive skills on critical tasks, is the provision of intelligent knowledge-based aiding systems with the context sensitivity needed to provide the right information, in the right way, at the right time (Eggleston, 1993). Providing an aircrew with usability aiding makes the crew station easier to use and—determines when and how to deliver proposals and notifications. The introduction of intelligent aiding systems requires cockpit systems engineering to consider the cognitive requirements in the specification and design of cockpit processes, in addition to the basic system physical design (Eggleston, 1993; Taylor, MacLeod, & Haugh, 1995). Eggleston redefines cognitive design requirements as "all the system factors that are essential for it to behave at a conceptual (symbolic and abstract) level of understanding and engage in a knowledge level discourse with the user." He notes that conventional cockpits, aimed at providing information delivery and a control system, have cognitive requirements imbedded in their basic design, captured through mission, task, information, and workload analyzes. In contrast, intelligent cockpits aimed at mission task and usability-aiding, through interagent, knowledge-based, conceptual, mixed initiative transactions, have the additional cognitive design requirements of the design of the knowledge base and reasoning processes that need to be embedded in the system process architecture.

Validated psychological methods and techniques are needed to capture cognitive requirements of the essential high-level internal processes of user's mental models. The methods available for cognitive systems engineering are becoming increasingly diverse and mature and are available for use as a systematic practice, such as the Work Domain Analysis (WDA) Workbench (Sanderson, Eggleston, Skilton, & Cameron, 1999). They include cognitive modeling, Cognitive Work Analysis (CWA), functional decomposition, Cognitive Task Analysis (CTA), control task analysis, concept mapping, Knowledge Acquisition (KA), knowledge modeling, Ecological Interface Design (EID), and prototype story boarding. Some of the methods available for understanding user mental models are illustrated in Figure 8.1 (adapted from McNeese, 1995). For the purposes of providing intelligent knowledge-based aiding, a key development has been the evolution of the CommonKADS knowledge engineering methodology (Schreiber et al., 1999). This provides a structured approach to knowledge modeling, with a comprehensive approach to the aiding context distinguishing the requirements of the organization, task, and agent.

Significant progress has been made towards the provision of intelligent knowledge-based aiding systems in a variety of application environments, sufficient to warrant their serious consideration for the next generation of military

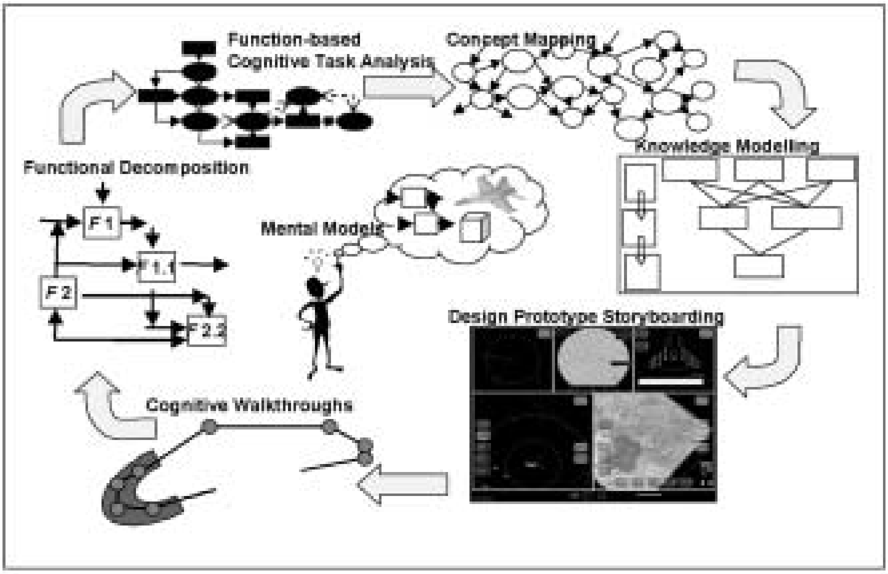

Figure 8.1: Cognitive engineering methods. (Adapted from McNeese, 1995)

aircraft, both manned and uninhabited, and controlled from the ground. Recently, DERA has been tasked with investigating cognitive technologies and cognitive design requirements and with providing proof-of-concept technical demonstration of options and benefits for future envisioned air systems MOD procurements (currently Future Offensive Air System [FOAS], Future Carrier-Borne Aircraft [FCBA], and Eurofighter Upgrade). The resultant DERA Cognitive Cockpit (COGPIT) program provides research on intelligent aiding systems in which the relationship between the pilot and the system is flexible and context-dependent to support adaptiveness (Taylor, Howells, & Watson, 2000). This flexibility is derived from a functional architecture that couples on-line monitoring of the pilot's functional state, and on-line task knowledge management and decision support for context-sensitive aiding, deriving information to mediate the timing, saliency, and autonomy of the aiding. The potential system benefits include the following:

- Real-time pilot functional state assessment for cockpit task adaptation
- Real-time support for situation assessment, task prioritization and decision making
- Real-time idiosyncratic and bespoke cockpit ergonomics, and
- Real-time safety net, with potential to recover to base an incapacitated pilot.

8.1.2 Background—The Development of Intelligent Pilot-Aiding Systems

Historically, the aircraft pilot and cockpit systems have had a master-slave relationship, with full pilot authority for aircraft control functions. This relationship changed with the introduction of computer control technology, with the pilot acquiring systems monitoring and supervisory roles. In the late 1970s, ideas arose for more intelligent cockpit systems, with an interactive and synergistic pilot-system relationship, providing cooperative rather than conflicting advice and control (Reising, 1979; Rouse, 1976, 1988). The crew-adaptive cockpit proposed sensors for monitoring the pilot's state, Artificial Intelligence (AI) software enabling the computer to learn, and pictorial displays allowing efficient presentation of cockpit information. This developed into a form of "R2D2" intelligent agent cooperating with the pilot as a Human-Electronic Crewmember (HEC) team, raising issues of human-computer teamwork, trust, technology capability maturity, cognitive requirements, and architectures (Emerson, Reinecke, Reising, & Taylor, 1988; Reising, Taylor, & Onken, 1999; Taylor & Reising, 1994).

Developments in advanced computer technology now make intelligent pilot-aiding through an HEC team realizable, including real-time data acquisition, fusion and processing, and computer modeling and AI-inferencing techniques, such as expert systems, Knowledge-Based Systems (KBS), and neural nets (for a recent review, see Taylor & Reising, 1998). Beginning with the U.S. Air Force/Defense Advanced Research Projects Agency (DARPA) Pilot's Associate (PA) program (1985–1992), expert systems showed the potential of AI to support the pilot's problem analysis and solution generation. PA research identified human factors issues of adaptive automation, dynamic function allocation, levels of system autonomy and trust, and introduced goal-plan tracking for inferencing pilot intent. The U.S. Air Force Small Business Innovation/Research (SBIR) Hazard Monitor provided a real-time KBS for supporting system malfunction management in transport aircraft. Now, the U.S. Army's Rotorcraft PA (RPA) provides a *cognitive decision aiding system* and *cockpit information manager* (Miller, Guerlain, & Hannen, 1999).

In Europe in the 1990s, AI efforts on pilot-aiding have centered on the French Co-pilote Electronique (CE), and on the German civil and military Cockpit Assistant Systems. In contrast to PA, the CE program focused on AI support for problem recognition and situation assessment. The German CASSY project provided flight test of flight management KBS for rerouting of civil aircraft. Situation assessment modules provided perception, diagnosis, decisions and communication management, with pilot intent and error recognition functions. CAMMA has extended this application of KBS to military missions (for detailed technical information on CE, and CASSY/CAMMA, see Reising, Taylor, & Onken, 1999).

In the UK in the late 1980s, the joint Industry/MOD Mission Management Aid (MMA) project applied conventional computer techniques to sensor fusion, situation assessment, and dynamic planning. Using deterministic, rule-based, event-driven logic, MMA found positioning (rerouting) and EW functions more difficult to assist and automate reliably than fuel and time-management tasks. Lessons-learned have been applied to Eurofighter to reduce pilot workload. MMA identified the need for context-sensitive prioritization of interrupts in high workload phases. Subsequently, industry research has used AI model-based reasoning with multiple-goals to provide context-sensitive prioritization for intelligent warning systems for civil cockpit applications. Applying KBS to safety critical functions poses certification problems. At Farnborough in the 1990s, MOD Navy sponsored AI research by DERA Aircraft Sector focusing on KBS for aiding aircrew mission decision-making in helicopter antisurface warfare and airborne early warning (Zanconato & Davies, 1999). This has led to the development of real-time multi-agent KBS software, and new methodologies for knowledge acquisition and management (Martin & Howells, 1995).

Other MOD RAF-sponsored human factors research at DERA/Center for Human Sciences (CHS) focused on the cognitive issues in HEC teamwork, in particular situation awareness, trust, and cognitive compatibility (Taylor & Selcon, 1993; Taylor, Shadrake, Haugh, & Bunting, 1996). It was followed by work on cognitive engineering issues, associated interfaces, and the operation of adaptive automation and decision support (Taylor, Finnie, & Hoy, 1997; Taylor, Shadrake, & Haugh, 1995). The results highlighted the risks of poor awareness of functioning with dynamically changing automation and the problems of cognitive bias associated with acceptance of automation advice. This work generally raised concern with the problems of maintaining effective human control of critical decisions and complex system functions with high levels of automation. It identified the need for further cognitive-engineering work on cognitive control issues and on supporting adaptiveness.

8.1.3 Cognitive Systems Engineering Challenges—Supporting Adaptiveness

To assist future pilots perform their critical cognitive tasks, technology is needed for automation and decision support that is context-sensitive and adaptive, in other words, responsive to changes in the operating environment, mission requirement, and operator capability. Adaptiveness can be considered as the ability of the human-machine system to perform in an appropriate, context-sensitive manner in different situations (Miller & Goldman, 1999). Adaptiveness is needed to support in-flight situation assessment, retasking, and replanning, and increasingly to avoid casualties, fratricide, and collateral damage. Adaptiveness and context sensitivity in use have traditionally been provided by the pilot knowing when and how to change the plan. To support and enhance adaptiveness, technology needs to respond to context divisions with sensitivity that is both precise and accurate (i.e., supports handling of critical events, in the appropriate manner and at the appropriate time.) This increased adaptiveness needs to be achieved without increasing crew workload and without the unpredictability often associated with the action of conventional automation (Miller & Goldman, 1999; Miller, Pelican, & Goldman, 1999).

Decision aids in particular need adaptiveness, ideally to both individual user characteristics and to changing task situations, to be useful in complex, dynamic problem-solving environments (Rouse & Rouse, 1983). Currently, intelligent knowledge-based aiding systems are available that are capable of responding to changes in the aircraft and the environment. Technology under development seeks to monitor and respond adaptively to changes in the mission plan, and to provide inferencing of pilot intent. Cognitive technology is also needed that is influenced by the aircrew's physiological and behavioral state, adaptively responding to an individual's indications of overload, distraction, and incapacitation. Integration and implementation of these cognitive technologies will need to be based on sound cognitive engineering principles. Cognitive technologies and architectures are needed that support the required levels of human control over critical system functions, and that keep the crew in control of the system, rather than the system in control of the crew.

Early research on adaptive decision-aiding (Rouse & Rouse, 1983) considered the form of adaptation (user or task), the locus or mode of adaptation (designer, user, or aid), the method of adaptation (task allocation, partitioning, or transformation), and the communication of information (implicit or explicit). Recently, the focus has shifted towards the nature of the knowledge underlying the task adaptation. Intelligent aiding systems previously attempted, or currently under development, can be distinguished in terms of the tasks and roles that they perform, and the knowledge that they manipulate, indicating levels of capability maturity (Geddes, 1997):

- Assistant—Performs specific tasks when instructed by the operator, using basic task and situation knowledge. For example, such a system could provide the pilot with an assessment of a threatening aircraft when asked
- Associate—Automatically recognizes that the operator requires assistance (using complex task and situation knowledge, and basic user knowledge), and provides some level of support. For example, such a system could recognize a threatening situation and automatically provide the pilot with all threat information
- Coach—Using complex task, situation, and user knowledge, these systems are capable of recognizing the need for automation to achieve a mission objective, and providing instructions to the operator on how to achieve it. For example, the pilot is presented with the most threatening aircraft first, in accordance with the higher-level goal of maximizing own-ship survivability.

In this analysis, the drivers for aiding capability maturity are the complexity of task, situation, and user knowledge managed by the system. Technological advances in both artificial intelligence and the physiological monitoring of human performance have the potential to provide complex task, situation, and user knowledge, sufficient to allow these higher levels of intelligent aiding to be realized. Thus, in the future, intelligent aiding systems will be considered more as fully integrated, intelligent cockpits that take on agent-like properties, rather than as traditional cockpits with a discrete automation control center. Intelligent aiding systems have the potential to provide the following capabilities (Eggleston, 1997):

- Respond intelligently to operator commands, and provide pertinent information to operator requests
- Provide knowledge-based state assessments
- Provide execution assistance when authorized
- Engage in dialogue with the operator, either explicitly or implicitly, at

a conceptual level of communication and understanding, and
- Provide the operator with a more usable and nonintrusive interface by managing the presentation of information in a manner appropriate to the content of the mission.

The requirement to provide support in the appropriate internal and external "context" can be realized through a functional architecture with the following attributes (Taylor & Reising, 1998):

- A model of human decision-making and control abilities
- The ability to monitor pilot performance and workload through behavioral and physiological indices, and
- The ability to predict pilot expectations and intentions with reference to embedded knowledge of mission plans and goals.

Experience with conventional automation has highlighted the need for the state of highly complex avionics systems to be readily *comprehensible* to operators. Cockpit displays and controls for interacting with intelligent aiding systems must be particularly easy to understand and to operate, since their benefits arise only in use, and not automatically. Principles of cognitive compatibility and efficiency, such as simplicity and consistency, need to be design drivers so as to reduce rather than to increase workload from using cognitive aids. However, this requirement may be at odds with the ability of the automated system to remain *flexible.* Billings (1997) argues that there is an inverse relationship between system comprehensibility and system flexibility, especially when such systems exploit adaptive-aiding technologies. This corollary is unfortunate given that system comprehensibility and system flexibility are both important design drivers for adaptive aiding. Miller and Goldman (1999) and Miller, Pelican, and Goldman (1999) argue that the implication of this corollary is that, for any increase in system flexibility or adaptiveness, there must be an accompanying increase in either operator workload (i.e., the amount of cognitive effort required to operate the system), or in unpredictability for the operator (i.e., the inability of the human to know what the automation will do at any given time) (see Figure 8.2). Allowing operators to choose various levels of interaction for the tasks they are required to conduct can mitigate this problem.

The use of intelligent aiding within the cockpit requires aiding and interaction in real time. In real-time operations the correctness of the system is dependent not only on the correctness of its result, but also on meeting stringent timing requirements. The deadlines for tasks that a real-time system must perform can be characterized as *hard, firm, or soft.* Failure to meet a firm deadline means that the results of the computation have no utility. This is in contrast to soft deadlines where the results of the computation are still useful after the deadline has elapsed, but have decreasing utility as a function of the time

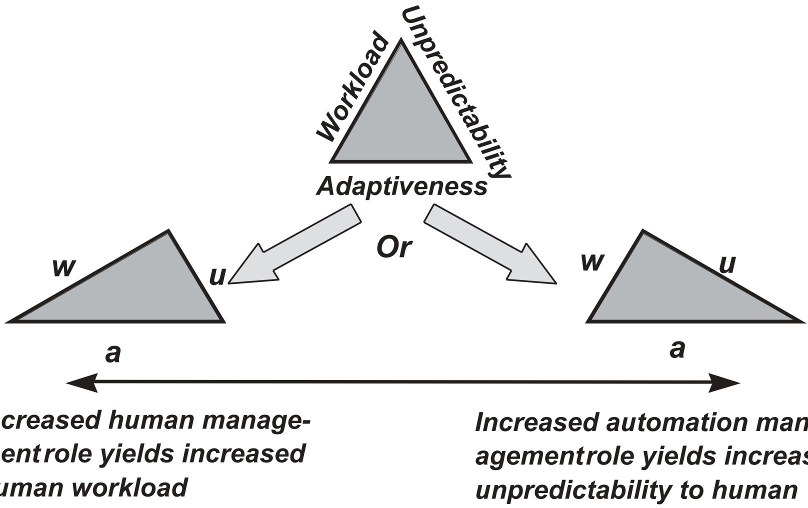

Figure 8.2: Relationship between system adaptiveness, human workload, and predictability. (From C. A. Miller, M. Pelican, & R. Goldman, Tasking interfaces for flexible interaction with automation: Keeping the operator in control, *Proceedings of the International Conference on Intelligent User Interfaces*, Association for Computing Machinery [ACM], 1999. Reprinted with permission.)

elapsed (Hayes-Roth 1991). For knowledge-based tasks, systems may be useful that can produce aiding at *anytime,* such as through progressive reasoning, providing the best advice immediately available when called upon to provide support. Some of the requirements for the real-time operation of intelligent aiding systems, identified by Hayes-Roth (1991) include the following:

Cognitive Versatility

- Multifaceted expertise—The system should be able to perform different types of reasoning tasks in an attempt to solve problems in a variety of domains utilizing a number of problem-solving techniques
- Concurrent reasoning activities—The system must be capable of simultaneous reasoning about a number of concurrent activities
- Incremental reasoning—The system must be able to integrate information over time to produce an accurate assessment of the current situation
- Explanation—The system should be able to explain all aspects of its behavior in the time available.

Management of Integration

- Functional asynchrony and parallelism—The system must be able not only to investigate anomalies, but also perform routine actions within specified time limits
- Continuous operation—The system must be capable of functioning over extended time periods
- Functional Integration—The system should be able to perform accurate reasoning even where certain conditions affect normal output of the reasoning process (e.g., recommendations may differ as a function of weapons fit).

Management of Complexity

- Selective attention—The system may encounter situations in which it cannot process all the data in real time. Therefore, the system must be able to make choices about which data are the most important and disregard extraneous data. However, it is imperative that the system still be alert to new data that might be critical to the current task
- Automatic performance—The system must be able to deal with complex anomalies or situations while performing important routine activities in a timely manner
- Focused reasoning—The system must be able to control its reasoning such that it can achieve specific goals. The system will face more "problems" than it can solve in real time, and so it is important that the system must be able to choose the most urgent problem(s) to solve first.

Real-Time Performance

- Guaranteed interoperation latencies—The system must be able to guarantee that it can achieve certain goals within the prescribed timeframes
- Time-stress responsivity—The system should be able to respond to increased pressure on time resources by decreasing its response latency
- Graceful degradation—The system must be able to reduce response latency as a function of time stress by compromising precision and confidence in a graduated manner
- Speed-knowledge independence—The system must be able to produce consistent response latencies despite the inclusion of new knowledge.

8.2 THE COGNITIVE COCKPIT

8.2.1 Assisting Cognitive Work

Arising from DERA CHS human factors work on cognitive issues in HEC teamwork, adaptive automation, and decision support, the need was identified for crew-centered, cognitive engineering research on cognitive control issues in supporting adaptiveness. It was envisioned that there was a need to provide a *cognitive cockpit.* This would be a form of electronic crew-member or cockpit cognitive assistant, constructed using cognitive engineering principles and methods. It would provide a principled implementation of cognitive technologies that use knowledge about how people perceive, think, and act adaptively, such as knowledge-based systems (Taylor, 1997; Taylor & Finnie, 1999). Figure 8.3 illustrates some of the initial concepts for a prototype DERA cognitive cockpit (from Taylor & Finnie, 1999).

In this early COGnitive cockPIT (COGPIT) conceptualization, potential threat locations are shown as cued adaptively (visual and 3D audio) off boresight, in the helmet-mounted display, with the form guided by head/eye location monitoring. Pilot health monitoring is operating in the background, showing no unexpected indications (customized functional abstraction/decomposition available on pilot request). The pilot has a "panic" button to provide inputs on subjective status and load. Systems health shows normal status using an adaptively reduced, iconic information "stamp." A rerouting proposal (best-calculated computer plan) is presented for pilot critiquing, in response to an identified air threat, using an adaptively enlarged Situation Awareness (SA) panel. This SA panel is provided with a background attitude indicator for spatial orientation SA, with accept, reject, and explanation key options for computer proposals. The intended automatic maneuver (with pilot interrupt, if required) is shown using a head-up, pathway-in-the-sky and pictorial aircraft velocity cue. A summary indication (functional abstraction/decomposition available on pilot request) of the mission effectiveness, based on mission plan and goal tracking, is shown in the form of a mission "goal ball." The internal diameter indicates the level of effectiveness, and the degree of risk. The operating status of three aiding agents—skill (coach, with flight path control), rule (three R2D2s, two currently active) and knowledge-based (Odin, advising tactical reroute)—is shown by pictorial adaptive icons with a summary of the allocated control authority or "balance."

Coupled with the confidence-building DERA KBS work, and encouraging DERA CHS Corporate Research Programme work on monitoring cognitive load, these ideas led in 1998 to an enhanced MOD Royal Air Force (RAF) Applied Research Programme project on a technical demonstrator for auto-

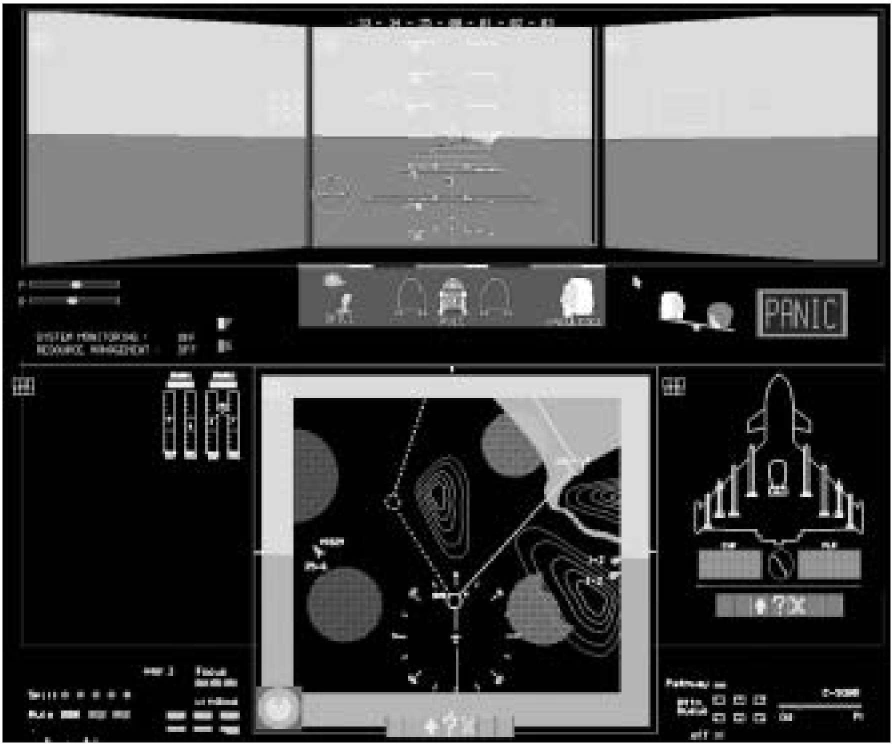

Figure 8.3: Initial conceptual prototype for the DERA cognitive cockpit.

mated decision support, known as the DERA Cognitive Cockpit (Taylor, Howells, & Watson 2000). This program seeks to provide a human-centered contribution to a system-of-systems approach, with an overall focus on system functional purpose, usability and affordability, and cost-effectiveness in use. The operational aim is to allow the pilot, in control of the aircraft or an Unmanned Air Vehicle (UAV) "to concentrate his skills towards the relevant critical mission event, at the appropriate time, to the appropriate level." The project is originally scoped as a three-year program, led by CHS, with multidisciplinary internal DERA (CHS and Aircraft Sector) and significant external contractor involvement (Epistemics Ltd., University of Southampton, University of Bristol, Honeywell Technology Center). The DERA COGPIT work is conducted with international collaboration through The Technical Cooperation Program (TTCP) HUM Technical Panel 7, Human Factors in Aircraft Environments, and under bilateral agreements. This includes the U.S. Air Force Research Laboratory (USAFRL), Human Effectiveness Directorate, the Defence and Civil Institute of Environmental Medicine (DCIEM), Canada, and the Defence Science and Technology Organisation (DSTO), Air Operations Division (AOD), Australia. European bilateral collaboration is with Sweden FOA, under Project Longboat (Linde & Berggrund, 1999), and recently with The Netherlands, National Aerospace Laboratory (NLR), through Project Nightwatch. Collaboration with the USAFRL began with work on virtually augmented and adaptive cockpit interfaces (Hettinger, Cross, Brickman, & Haas, 1996; Haas et al. 1997), and continues with the USAFRL current real-time human engineering program. Banbury, Bonner, Dickson, Howells, and Taylor, (1999) provide a detailed technical review of the COGPIT program, covering the first two years of work.

The DERA Cognitive Cockpit program, while broadly aimed at supporting future MOD air systems procurements needing intelligent aiding, is focused initially on the single-seat, fast jet role, and in particular the Future Offensive Air System (FOAS) pilot. The complexity, time-pressure, and rapidly changing uncertainties of the single-seat, fast jet environment provide a major cognitive engineering challenge for implementing intelligent knowledge-based pilot aiding systems. Figure 8.4 illustrates the major functions of the offensive air role using a WDA abstraction-decomposition breakdown (Vicente, 1999).

The military aviation domain is characterised by being uncertain and having shifting goals, dynamic evolution, time stress, action feedback loops, high stakes, and multiple players. While operators may wish to remain in charge, and it is critical that they do so, today's complex systems no longer permit them to be fully in charge of all system operations at all times as in earlier cockpits and workstations (Miller, Guerlain, & Hanner, 1999; Miller, Pelican, & Goldman, 1999). Cockpit automation has been, and will continue to grow more intelligent and more sensitive to context and mission objectives. But no one seriously believes that cockpit automation and decision aids can or should replace pilot control. Instead, they must free up pilot resources to concentrate on the most important tasks and must create in the pilot a situation awareness that allows him/her to make decisions correctly and very quickly.

To handle the kinds of unpredictable events experienced in the military environment, the functions in Figure 8.4 have to be accomplished by a combination of planning and reacting, with various degrees of human involvement. Many of these functions can be aided by computer-based systems and automated to a greater or lesser degree, depending on their simplicity and complexity and the maturity of the relevant technology, and on the predictability or uncertainty of factors governing their performance, and hence the need for involving human judgment. In human systems generally, the operator sets the goals and functional purpose of the behavior, and through the use of aids, automation, and other artifacts (things that make the user smart or dumb) provides the coordination and adaptation directed at coping with the complexity and uncertainty in the world. The military pilot needs to be involved in critical decisions affecting the safety of the aircraft, and the effectiveness of the mission. The pilot needs to be able to concentrate his cognitive skills "on the critical mission event, at the appropriate time, to the appropriate level." In addi-

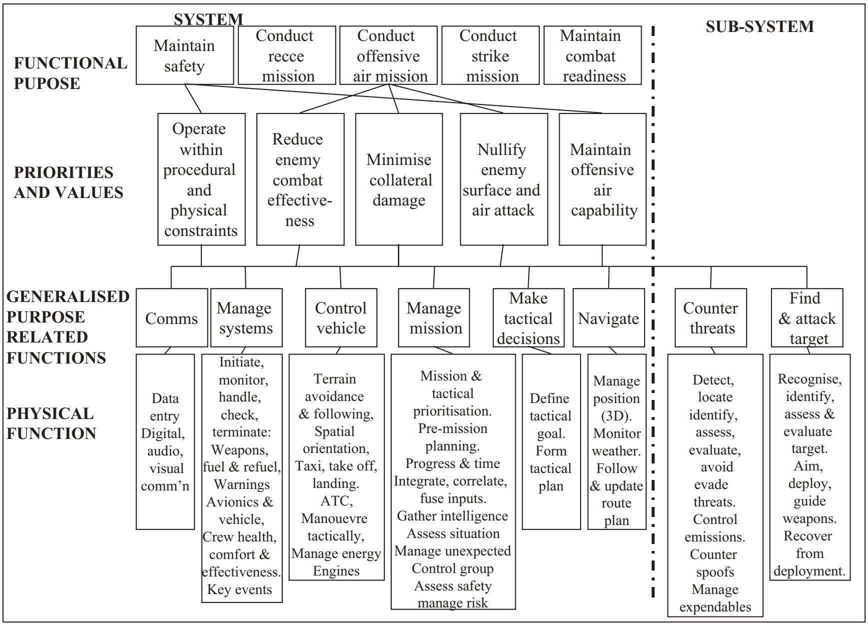

Figure 8.4: Offensive air functions.

tion to the goal setting and high-level control functions, the pilot's expert knowledge and adaptive, pattern recognition and decision-making cognitive skills in uncertain situations are difficult to emulate, and remain key capabilities for computer-aided support.

8.2.3 Functional Integration and Cognitive Control

The emerging situation with automation capability begs questions about the appropriate roles for pilot and smart automation in future military aircraft. It is becoming increasingly apparent that the dedicated and limited roles of today's automation systems (e.g., one system devoted to collision avoidance, another completely separate system devoted to route planning, etc.) cannot sustain the requirements for advanced missions. This is because such systems leave the most complicated task, that of integration and holistic decision making, to the human. By contrast, functional integration is an important characteristic of advanced intelligent aiding systems, in that the required behavior can be shared across many functional components, including the user (Geddes, 1997). That is, several functional components can collectively perform many of the same behaviors as the pilot—because they are aware of each other, capable of sharing information, aware of overall mission goals, and capable of integrating their behaviors in the same way the pilot would. Functional integration of cockpit duties provides for a more robust and flexible integrated system when compared to systems based upon more strict function allocation to individual and unique components. It is expected that future intelligent aiding systems will be considered more as fully integrated, intelligent cockpits that take on agent-like properties, rather than as traditional cockpits with a discrete automation control center.

Adaptive automation occurs when the control decisions concerning the onset, the offset, and the degrees of automation are shared between the operator and machine. Within such a system the human operator remains "in-the-loop" and the automation intervenes only when the operator requires support to meet operational requirements—but it does not require explicit human instructions to do so. At the highest level of capability maturity, adaptive automation systems seek to augment and enhance human judgment and responsibility "intelligently," while mitigating against their limitations, by adapting to the changing requirements of both the operator and the external situation. These systems can be considered as "intelligent" insofar as they exhibit behaviors that are consistent with human-like characteristics (Taylor & Reising, 1998).

The requirements for command, control, and communication with conventional "intelligent" and hybrid computer systems are of particular interest. The use of intelligent and adaptive automation technology allows both the human and the machine components to influence and jointly support cognitive functioning, providing joint cognitive control (Hollnagel, 1996, 1997). Hollnagel illustrates how in a joint cognitive system, the decisions required can be considered a task net, through which some particular path can be taken, and where the tasks can be flexibly assigned to either human or computer performance. The specific elements can be performed by the human, by the automation, or alternatively by both, say if insufficient information may or may not be available for the automation to work (Figure 8.5).

Such joint cognitive systems require new levels of human-computer interaction, such as cooperative teamwork between human and electronic crewmembers, with dynamic allocation of functions responding to changing aircrew and mission requirements. This will require an adaptive interface that is aware of, and continually responds, to such changes.

To provide a principled development of intelligent aiding with the required levels of pilot control, we have established a systematic approach to cognitive control to guide the COGPIT program (Taylor 1997; Taylor & Finnie, 1999). This framework is based on the concepts and implications of Perceptual Control Theory (PCT) (Farrell & Chery, 1998; Powers, 1973; Taylor, 1992) and on the theory of cognitive control of complex systems (Brehmer, 1992; Hollnagel, 1997; Rasmussen, 1986). The work is influenced by a recent theory of Information Processing (IP) load under time pressure (Hendy, Liao, & Milgram, 1997) and with DERA/University of Cardiff work on a theory of

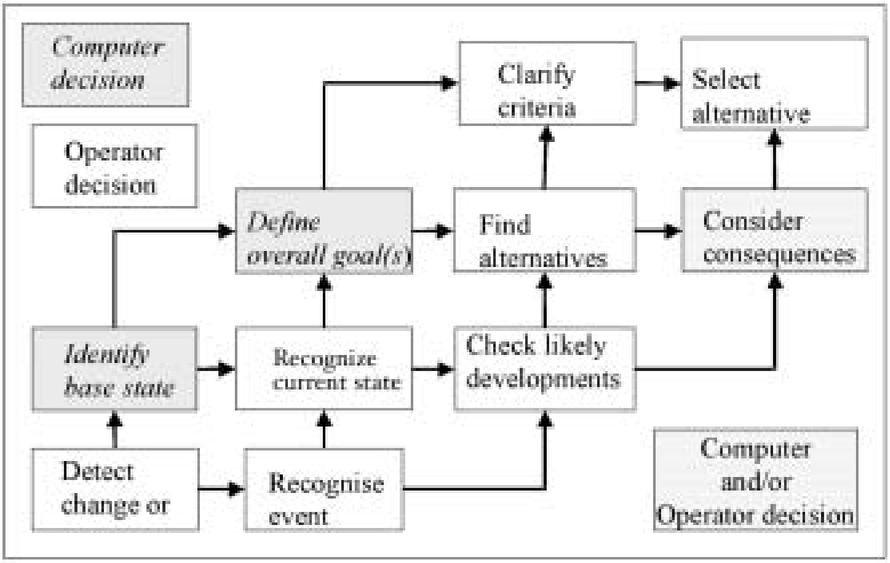

Figure 8.5: Task net of decision making. (Adapted from E. Hollnagel, Decision support and task nets, in S. A. Robertson [Ed.], *Contemporary ergonomics 1996*, Taylor & Francis, 1996. Reprinted with permission.)

cognitive streaming, emphasizing the importance of conflict of process, rather than content (Banbury, 1999; Tremblay & Emery, 2000). The general approach highlights the importance of functional integration, rather than partitioning and allocation, and of joint cognitive control, between the pilot and the intelligent aiding systems. In this way, a more direct and systematic consideration of the cognitive engineering and control issues can be achieved. For example:

- The incorporation into intelligent aiding systems of the ability to track the operator's goals and plans (e.g., the difference between current and desired states) and to infer the intent of the operator
- The use of abstraction hierarchies and system aggregation methods during task decomposition to determine important interactions and emergent properties within the knowledge base
- The importance of information utility in the design process (e.g., a focus on the information used, rather than the resultant action)
- The importance of error diagnosis and rectification
- The enhancement of system stability through the balance of feedback (i.e., reactive) and feed-forward (i.e., proactive) control information (Brehmer, 1992)
- The recognition of differences in cognitive control strategies between Skill, Rule, and Knowledge-based (SRK) levels of performance

(Rasmussen, 1986)

- The incorporation of planning horizons (e.g., scrambled, opportunistic, tactical and strategic) into cognitive control strategies (Hollnagel, 1997), and
- The use of intelligent aiding to critique operator performance and prevent cognitive bias and other forms of human error.

Using Rasmussen's SRK taxonomy (Rasmussen, 1986), the broad aim is to provide support for the pilot's knowledge-based behavior, in handling complex, unpredictable situations, where new procedures need to be formulated, reducing the pilot's cognitive decision-making load through the provision of KBS advice and assistance with knowledge management. Furthermore, the intention is to provide automation of rule—and skill-based behavior, if feasible and as required, for application in simple, predictable situations, where successful procedures are known to work, enabling the pilot to concentrate on critical strategic and tactical decisions. Broadly, for simple problems, the aim is to provide computer-based solutions where successful procedures are known (rule-based processing), and when procedures need to be formulated (knowledge-based processing). For complex problems, the intention is to provide computer-based support where known procedures are probably applicable (rule-based processing), and when new procedures need to be developed (knowledge-based processing). Support decision-making where the outcome is unpredictable;

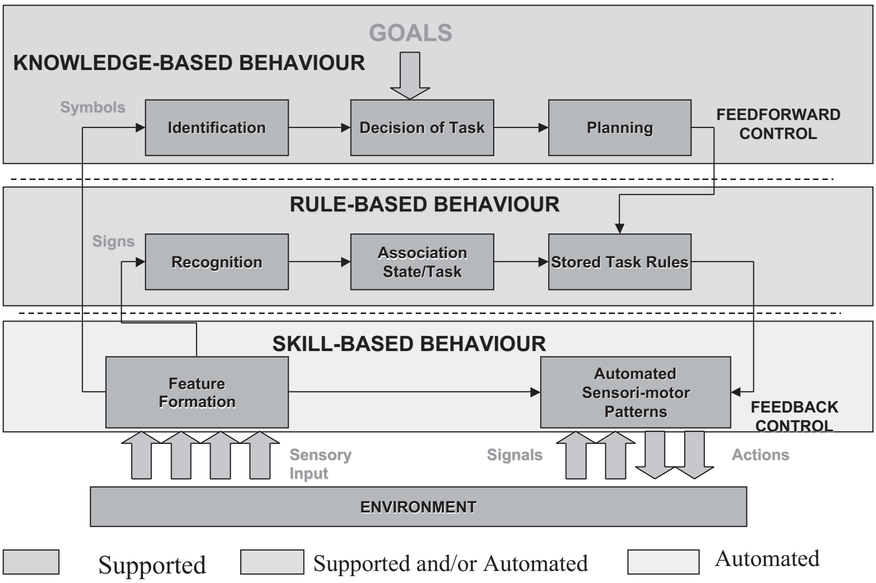

Figure 8.6: Strategy for aiding skill-, rule-, and knowledge-based behavior.

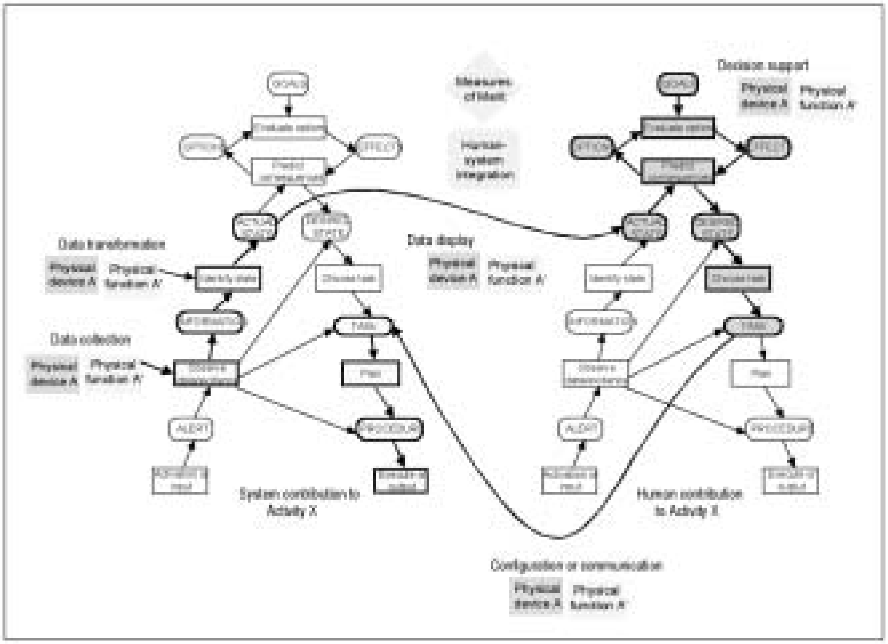

Figure 8.7: Decision ladders for control task analysis.
(From Sanderson, 1999, personal communication)

automate decision-making where the outcome is predictable. Figure 8.6 illustrates the strategy for aiding through automation and/or support in relation to skill, rule, and knowledge-based levels of behavior.

A typical aiding configuration is illustrated in Figure 8.7, using the SRK decision ladder modeling tool (Rasmussen, 1976; Vicente, 1999). Any given activity can comprise a combination of skill-, rule-, and knowledge-based process, and the information processing steps can be represented as a decision ladder. Combinations of decision ladders can be used to model collaborative work between agents. Decision ladders have been used in CWA for CIA to identify levels of human-system integration in Royal Austrian Air Force (RAAF) airborne early warning and control (Sanderson, Naikar, Lintern, & Goss, 1999). In Figure 8.7, provided by Sanderson (personal communication), two decision ladders are linked together to show different human and computer contributions in computer-assisted decision-making. This might apply to a complex problem, with automation of the relatively simple aspects of situation assessment and plan execution, and with KBS support for the more complex options evaluation. The computer is responsible for data collection and transformation and for communicating the actual state (i.e., computer situation assessment). The human is then responsible for interpreting the consequences for system goals, for identifying the required state, and the task to be performed to achieve the desired state. These decisions require formulation of new procedures, which could be assisted by KBS decision support, but they are too complex for the computer alone to provide a successful solution. The computer is then responsible for analyzing the identified task, formulating the plan of procedures, and executing the plan. Other combinations are possible, with different computer and human decision roles and responsibilities. This form of cognitive activity analysis is useful since it allows the analyst to understand the human operator's goals in performing activity, it helps identify possible sources for competition of operator's attention, and it describes the forms of collaborative work and aiding that will be essential for mission effectiveness.

In summary, the significant technical challenges for the COGPIT program are as follows:

- Improving adaptiveness without increases in workload or unpredictable automation
- Providing real-time, context-sensitive aiding with accuracy and precision to be useful and trustworthy, with tracking of operator's goals and plans to infer intent
- Building an integrated KBS for prioritizing pilot tasks and aiding decisions
- Supporting adaptiveness in skill-, rule-, and knowledge-based levels of performance, critiquing performance, preventing cognitive bias, and aiding error rectification
- Providing useful functional state information for task adaptations and interruptions
- Providing quantitative, scientific assessment of a broad set of aiding options using measures of effectiveness based on mission task performance.
- Providing a blend of automation levels and pilot cognitive control strategies with:
    - Pilot executive authority for controlling the system
    - Stability through feedback (reactive) and feed-forward (proactive) control
    - Strategically planned pilot control at the knowledge-based level (feed-forward), and
    - Automation of reactive skill and rule-based responses (feed-back).
- Focusing system design on functional purpose, control allocation and information utility using cognitive work analysis methodologies.

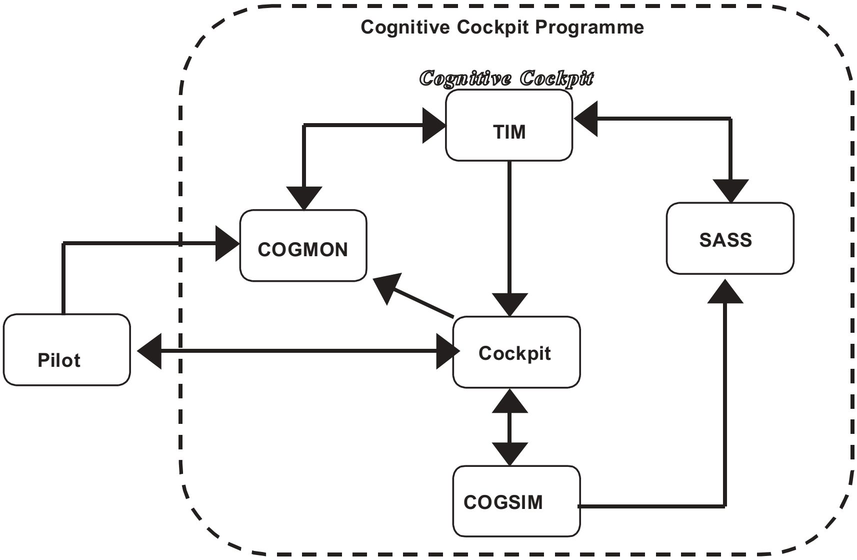

Figure 8.8: COGPIT agents architecture.

8.2.4 Functional Architecture—Agents, Communication, and Tasks

The COGPIT systems under development involve the interacting agents and communications shown in Figure 8.8. A simplified activity diagram, representing the processes performed by these agents, in support of updating the mission plan, is shown in Figure 8.9. Ultimately, the aim is to increase system adaptiveness by enabling changes in the mission plan in response to changes in the situation. To achieve this, the COGPIT will monitor three aspects of the situation: *the pilot* to take account of his physiological and cognitive state; *the environment,* both external to the aircraft and the aircraft systems; and *the mission plan* to indicate current and future pilot actions (Tennison, 1999). Four agents with different tasks can be distinguished as comprising the COGPIT system:

Cognition Monitor (COGMON)—a module that monitors the pilot's physiology and behaviour to provide an estimation of pilot state. This module is concerned with on-line analysis of the psychological, physiological, and behavioral state of the pilot. Primary system functions include continuous monitoring of workload, and inferences about current attentional focus, ongoing cognition and intentions. It also seeks to detect dangerously high and low levels of arousal. Overall, this system provides information about the objective and subjective state of the pilot within a mission context. This information is used to optimize pilot performance and safety and provides a basis for the implementation of pilot-aiding (Pleydell-Pearce & Dickson, 2000).

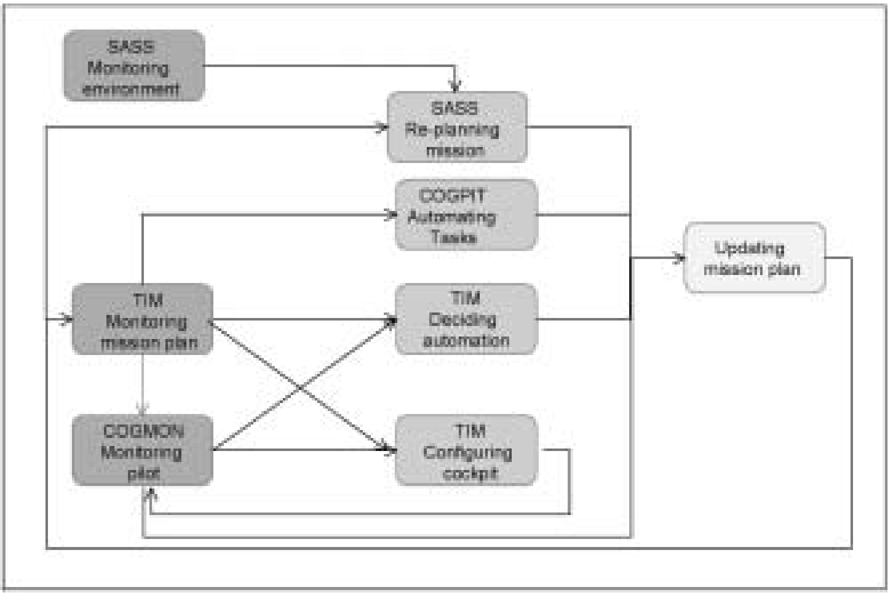

Figure 8.9: COGPIT agents, processes, and tasks.

Situation Assessment Support System (SASS)—a module that monitors the status of the aircraft situation and the outside environment and recommends actions. This module is concerned with on-line mission analysis, aiding, and support provided by real-time, multi-agent KBS software. This system is privy to the current mission, aircraft (e.g., heading, altitude, and threat) and environmental status, and is also invested with extensive a priori tactical, operational, and situational knowledge. Overall, this system provides information about the objective state of the aircraft within a mission context and uses extensive KBS to aid and support pilot decisions (Shadbolt, Tennison, Milton, & Howells, 2000).

Tasking Interface Manager (TIM)—a module that monitors the mission plan and manages the interface presented to the pilot. This module is concerned with on-line analysis of higher-order outputs from COGMON and SASS and other aircraft systems. A central function for this system is maximization of the goodness of fit between aircraft status, pilot state, and tactical assessments provided by the SASS. These integrative functions enable this system to influence the prioritization of tasks and, at a logical level, to determine the means by which pilot information is communicated. Overall, this system allows pilots to manage their interaction with the cockpit automation by context-sensitive control over the allocation of tasks to the automated systems (Bonner, Taylor, & Miller, 2000).

COGPIT Simulation Test Environment—COGSIM is concerned with the specification and provision of a proof-of-concept, Technical Demonstrator, simulation test environment for pilot-aiding. This includes the form and function of a cockpit that interprets and initiates display and automation modifications upon request, and in which the COGPIT modules will be implemented, tested, and validated. The cockpit will use adaptive interface technologies for multimodal communication. It will use aiding taxonomies and existing HF analysis methods and human-computer interaction guidelines. Computer application tools are used for prototyping, simulation, and scenario management (VAPS, VEGA, Stage).

8.3 MONITORING THE PILOT—COGNITION MONITOR

The COGMON is a COGPIT system designed to provide real-time information about the cognitive-affective state of a pilot. It derives data from four principal sources: physiology, behavior, context, and subjective states. Data from these sources are combined to update a real-time model of pilot state. This model can then be used as a basis for optimizing pilot performance, enhancing safety, and for the implementation of various on-board cockpit-aiding systems. The structure of COGMON is shown in Figure 8.10. This section provides an overview of the architecture of COGMON, its underlying theoretical basis, and ends with a discussion of the nature and uses of its outputs.

8.3.1 COGMON Functions—Pilot State Assessment

One of the basic principles underlying COGMON is the view that the term "workload" is too limited and should be replaced by the more embracing concept of "operator state." With regard to aircraft environments we view "pilot state" as a multidimensional concept. It includes, for example, levels of stress and alertness, current physical and mental demand, current locus of attention, nature of cognitive activity, current context as well as higher-order concepts such as pilot intent and situation awareness. At present there is no single measure that even remotely provides information about these various aspects of pilot state. For this reason, COGMON continuously samples a range of variables to provide a real-time model of pilot state. The data sources upon which COGMON relies can be divided into four general classes and these are now discussed in turn.

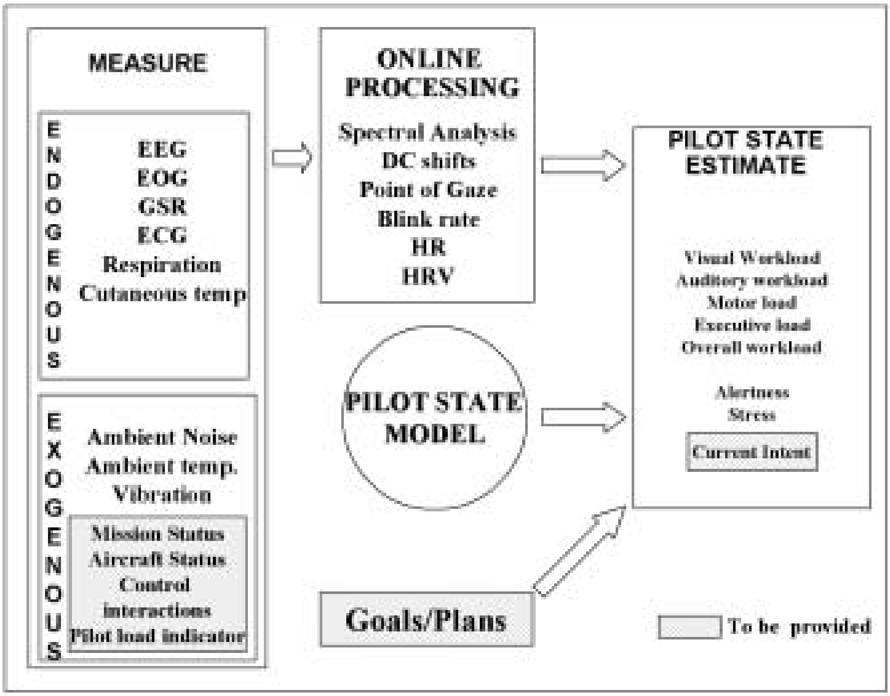

Figure 8.10: COGMON structure.

8.3.2 COGMON Measures

8.3.2.1 Physiological Measures. A full review of COGMON physiological recording and analytical facilities is beyond the present scope. However, the system includes measurement of heart rate, respiration rate, electromyogram, electrodermal activity, skin temperature, electro-oculogram, and electroencephalographic (EEG) activity. These measures provide information concerning levels of autonomic reactivity (e.g., stress) as well as information about current levels of alertness. Measurements of eye-movement activity and blink rate provide an index of visual workload, and recent improvements in biosensor technology and signal processing have allowed a dramatic improvement in locus-of-gaze detection (when head position is known). However, an optical solution to gaze location is presently seen as most promising. Recordings of brain electrical activity from the scalp also provide information about workload. For example, COGMON is capable of recording slow cortical potentials within the EEG which have been shown to be sensitive to fluctuations in cognitive demand (e.g., Pleydell-Pearce, McCallume, & Curry, 1995) and capable of differentiating load imposed upon distinct cognitive systems (e.g., Pleydell-Pearce, 1994). COGMON also employs spectral decomposition and coherence analysis of EEG to differentiate levels of cognitive load.

It is worth noting that many physiological measures are correlated. For example, heart rate and electrodermal activity are both influenced by respiration rate (e.g., Bernston et al., 1997) and many biosensors are sensitive to thermal and vibratory artifact. For this reason, COGMON uses various mathematical tools aimed at uncoupling correlations between its incoming physiological variables. Finally, physiological sensors can be time-consuming to apply. So, the development of COGMON includes the design of fast-fit biosensors including helmet-mounted nonpolarising EEG electrodes.

8.3.2.2 Behavioral Measures. While physiological measures provide a wide range of useful information, they are presently poor at providing fine-grained information about specific forms (i.e., contents) of cognitive activity. For this reason, behavioral data, and in particular, interactions with cockpit controls, provide a rich database, which can be used to make inferences about cognitive state. Interactions with controls are monitored by COGMON for two general purposes. First, such measures permit strong inferences about the nature of ongoing cognitive activity. For example, manual interaction with a visually guided cockpit control that uses an on-screen cursor typically indicates visuo-spatial workload and permits the inference that visual, somatosensory, and motoric attention are invested in that task. A second major aspect of COGMON is based on the view that a great deal of pilot behavior can be decomposed into separate largely encapsulated procedures or algorithms. A crucial aspect of COGMON function is therefore the facility to recognize when these specific procedures/algorithms are being performed. Such inferences rely heavily upon interpretation of interactions with aircraft controls, although other measures taken by COGMON can supply additional information.

COGMON refers to a database to detect the onset and track the progress of specific procedures. When a particular procedure is detected, COGMON uses a stored functional taxonomy to provide information about affective and cognitive states such as stress and workload that are likely to accompany the procedure. This kind of information derives in part from a priori subjective measures (see ahead). It also depends upon a deconstruction of procedures into components based upon logical analyzes. The database can also indicate many other factors such as whether the procedure is one which when started must be taken rapidly towards completion or can be left to "idle" in the background. The database also contains information about which distinct procedures can be combined without mutual interference on both logical and empirical grounds. Novel or unusual procedures adopted by pilots may not be correctly recognized. Under such circumstances, COGMON can still gain some information based upon lower-level monitoring of interactions with controls. For example, COGMON monitors all vocalizations from, as well as auditory inputs to, pilots. While this information may not be analyzed to the level of meaning, it does provide useful information about ongoing cognitive processes.

Specific combinations of particular procedures indicate more global goals and permit inferences about pilot intent. At this more macroscopic level, COGMON attempts to infer pilot intent using a pre-existing database in which the probable significance of particular procedural combinations is stored. Analysis at this level may also be guided by pertinent contextual information (see ahead). However, at this level, novel or unusual combinations of particular procedures may be enacted in the pursuit of complex unknown goals. Finally, the interpretation of some interactions with controls can be ambiguous. However, such sources of ambiguity can be minimized in carefully designed cockpits.

8.3.2.3 Subjective Measures. Subjective measures of pilot state are those provided by the pilot. In conventional settings these are often paper and pencil tasks (e.g., the NASA Task Load Index, Hart & Staveland, 1988). COGMON makes use of two kinds of subjective measure. "Prospective" measures can be signaled by the pilot to COGMON at any time and include communications such as "I am—drowsy, bored, stressed, or experiencing high levels of workload." We call this system the *Pilot Load Indicator* (PLI). Communication is currently made via pushbuttons. The direct communication of subjective states to COGMON provides useful additional information although the use of this system is currently seen as an issue of pilot preference. Under conditions of high stress and high workload the PLI could constitute an extra source of load although it does have a single prominent "emergency" button to signal such states. Furthermore, incorporating such measures within COGMON gives the pilot a direct link with on-board flight systems and does not therefore treat the individual as passive and "out-of-the-loop." For similar reasons we are considering the possibility of providing direct though simplified pilot feedback concerning current levels of pilot state inferred by COGMON.

A priori subjective measures are those that have been collected on the basis of interviews with pilots. Identifiable algorithms and procedures (defined above) are rated in terms of factors such as probable degrees of accompanying workload and stress. Thus when any actual task is detected, COGMON can make use of this existing knowledge. Furthermore, pilots can supply a priori information about the ease with which various separate tasks can be combined and the kinds of load that are associated with tasks and their components (e.g., visual/auditory/somatosensory, spatial/verbal or estimates of task time pressure). Finally, information concerning the stress and workload consequences of failures of various cockpit systems as well as influences of contextual measures (next) is contained within the database.

8.3.2.4 Contextual Measures. Context provides a powerful basis for interpreting pilot state data. COGMON has access to contextual information, which includes factors such as altitude, speed, levels of threat, and whether aircraft controls are functioning normally. This provides COGMON with a context for interpreting incoming data. COGMON also collects low-level contextual information as well. Examples of this include ambient noise, luminance, vibration and temperature, which are all factors known to influence pilot performance, and outputs from biosensors.

8.3.3 COGMON Implementation

8.3.3.1 Customized Systems. A characteristic feature of human performance is that there are widespread differences in behavioral and physiological responses to similar situations. This means that conclusions based upon average findings from a group of individuals may only correlate weakly with the behavior of a particular individual. However, scientific approaches to problems such as mental workload are usually based upon data averaged across subjects. In contrast, less research has attempted to identify unique but reproducible changes within single individuals. A major feature of COGMON is that it is designed to learn about the behavior of individuals and to look for predictable regularities in their particular responses to changing patterns of workload. This means that COGMON holds a database for each pilot that is activated when that pilot is identified. This is seen as a supplement to other aspects of COGMON, because in the absence of such a database, it would rely upon its noncustomized systems.

8.3.3.2 Convergent Processing. The previous sections indicate that COGMON processes a large amount of data. Although the various forms of data can be treated as separate variables, the relationships between different data sources will contain valuable information. For example, the absence of an arousal reaction to a mild threat, such as a low-altitude warning, may indicate that the pilot is confident and in control. However, it might instead indicate a loss of situation awareness caused by dangerously low levels of arousal. In recognition of the importance of convergent processing, COGMON is capable of performing complex on- and off-line multivariate analysis to improve inferences about pilot state. These routines include the facility to look for redundancy within measures. In other words, if two COGMON measures provide near identical information, then it makes sense to select the measure that is easiest to collect and process. A further benefit of convergent processing is that hidden predictive trends can often be discovered in the relations between data sets that cannot be obtained from either dataset alone. COGMON research has also employed artificial neural networks to search for “hidden” patterns within data.

8.3.3.3 A Model of Pilot State. Broadly speaking, COGMON provides an estimate of sleep-wakefulness, relaxation-stress, cognitive load (including an assessment of load imposed upon distinct modalities), an index of currently active procedures (algorithms), and an assessment of current intents and some specification of longer-term goals. COGMON outputs may also permit some estimates of situation awareness. For example, failure to have performed any (or recent) actions that might signal awareness of a particular threat would constitute grounds for inferring a deficit in situation awareness. Similarly, sustained focus of attention on a single task serves to warn that situation awareness may have decreased. Taken together, these various goals of COGMON processing constitute our multidimensional model of pilot state.

8.3.3.4 The Nature and Uses of COGMON Outputs. At present, COGMON is one component of a program aimed at the production of a cockpit that can monitor pilot state and implement automization and various forms of aiding as and when appropriate. In this system various aspects of aircraft control can be taken over by the SASS, for example, when the pilot is heavily overloaded. Decisions about which tasks will be automated are taken by the TIM, which is supplied with a constantly updated model of pilot state by COGMON. The TIM system uses this information to maintain pilot performance at optimal levels. For example, which task(s) might benefit from automation or how and where warning should be displayed? Similarly, COGMON can warn TIM if the pilot is dysfunctionally stressed, overloaded, or even underloaded and drowsy.

Another function of COGMON is its capacity to store data for later offline analysis. This allows it to examine patterns of performance in detail, improve prediction on future flights, and update the precision of its bespoke analyzes. This facility also provides a useful tool for flight training, debriefing, and a basis for improving various aspects of flight management. More generally, COGMON architecture employs computational principles that mean its individual components can function in isolation from the whole. This is even true of the systems that interpret interventions with cockpit controls, which will work in conjunction with any suitably specified functional taxonomy. For this reason the system can be easily adapted to other platforms (in part or in entirety) and also constitutes a stand-alone research tool.

8.4 MONITORING THE ENVIRONMENT—SITUATION ASSESSOR SUPPORT SYSTEM

The Situation Assessment Support System seeks to demonstrate a COGPIT knowledge-based subsystem that will provide a dynamic assessment of the operational context and generate recommendations to support tactical decision-making. Knowledge-based decision support systems are becoming a recognized technology in the defense industry, with situation assessment and awareness recognized as a key capability in military decision-support systems. This section describes the current state of development for the knowledge-based system component of the COGPIT program, including how the SASS fits into the COGPIT and the structured methodology used to develop it. First, some background is given by describing work on other knowledge-based decision support systems involving situation assessment.

8.4.1 The Development of Knowledge-Based Systems

Previous collaborations between DERA and Epistemics Ltd have included two projects which developed real-time knowledge-based systems with a major emphasis on situation assessment. These projects were Helicopter Aircrew Decision Support (HADS) and Future Organic Airborne Early Warning (FOAEW).

8.4.1.1. Helicopter Aircrew Decision Support. In collaboration with Cambridge Consultants Ltd., this project developed a helicopter-based decision-support system for antisurface warfare. The system provides automated support for the key decisions in the principal mission tasks. It interprets available sensor data to determine the identity of each surface vessel, then plans optimum routes for helicopters to move closer to vessels to confirm their identity and analyze any threat that they may pose. Route planning takes into account the speed and direction of vessels, while prioritizing according to their possible threat.

A knowledge-based approach allowed the informal reasoning involved in the task to be described and used in a flexible manner. In such tasks, no conclusions can be certain, and they depend upon other information that is similarly uncertain. The known features of a particular contact are matched with typical descriptions of certain types of vessel: for example, a contact with a high speed is likely to be a warship or merchant ship, rather than a fishing vessel. In this application, a knowledge-based system provides an extra level of support and supervision to increase operational efficiency. The underpinning real-time, multi-agent software required for the HADS system is described by Martin and Howells (1995).

8.4.1.2 Future Organic Airborne Early Warning. This project successfully demonstrated the feasibility of a knowledge-based decision support system to aid a helicopter-based Airborne Early Warning (AEW) crew in detecting and eliminating enemy aircraft. The system performs such key tasks as placement of the helicopter barrier, identification of hostile aircraft, management of Combat Air

Patrol (CAP) aircraft, and fuel/position management. Without such a system, it is expected that future AEW operator workload will increase to levels likely to have a detrimental effect on the performance of AEW operations.

Epistemics Ltd. performed all knowledge acquisition for the system using the PC PACK software toolkit (Schreiber et al., 1999, Chapter 8), and facilitated the implementation carried out by Cambridge Consultants Ltd. The structure of the knowledge models constructed in PC PACK was replicated in the system architecture to aid in the validation, upgrading, and maintenance of future systems (Zanconato & Davies, 1999). During KA sessions, extensive use was made of generic, reusable models of problem solving, which are supported within the GDM tool in PC PACK. A full description of the GDM tool and the use of this method are given in O'Hara, Shadbolt, and Van Heijst (1998).

As Zanconato and Davies (1999) point out, the system developed was not intended as an autonomous system with which the FOAEW operator has minimal interaction. Instead, it was required to be a cooperative system in which the system and operator are able to utilize the skills most appropriate to their capabilities. As such, the design of the Man-Machine Interface (MMI) was crucial to successful operation. Hence, the system was designed to interface with the Royal Navy's latest AEW MMI. Using this system configuration in a concept demonstrator, operator's confidence in the accuracy and reliability of the advice provided increased significantly. The dynamic filtering of information coupled with the MMI displays implemented was felt to provide temporal and consistency gains in achieving overall situation assessment (Davies, 1999).

8.4.2 SASS Functions—Situation Assessment and Tactical-Decision Making

Part of the COGPIT Technical Demonstrator will be a knowledge-based decision support system, termed the SASS. The COGPIT Technical Demonstrator is intended to showcase the role of future cognitive technologies within the cockpit, with an initial focus on the FOAS (and FCBA) role. A summary of the functions of FOAS under consideration, differentiated at levels of abstraction and system decomposition, is shown in Figure 8.4. SASS is currently scoped to support offensive air mission functions, in particular monitoring the situation and recommending actions to support tactical decision-making.

As with previous approaches to situation assessment, the SASS handles situation assessment on a task-by-task basis with no separate module or agent performing situation assessment. It is believed that this integrated approach is best suited to such applications, since the knowledge used by human operators when performing situation assessment is best acquired and modeled within the context of the task being performed. In other words, expert human operators conceptualize situation assessment in a task-specific way and not as a separate activity (Klein, 1995). This approach still allows specific information on situation assessment to be requested from the knowledge-based decision support system, for example for explanation to the human operator or use in another automated module, without the need for a specific situation-assessment module.

8.4.3 SASS Methodology

By exploiting software and toolkits developed under MOD Corporate Research Programme funding, the work seeks to define, design, and construct a decision support subsystem prototype to operate in scenarios associated with the target aircraft (FOAS and FCBA), using real-time multi-agent software. The development of the SASS follows the CommonKADS model for the development of knowledge-based systems (Schreiber et al., 1999). CommonKADS is a development methodology that is the result of a number of research and applied projects on knowledge engineering over the past 16 years and has been used in a wide variety of business contexts.

CommonKADS describes a number of knowledge-level models that should be developed prior to the implementation of a KBS. These models are:

- Organizational model—organizational analysis to identify the opportunities for knowledge-intensive systems within it
- Task model—identification of the major tasks involved within the organization
- Agent model—modeling of the agents (humans, information systems, and other entities) that carry out tasks within the organization
- Knowledge model—an implementation-independent description of the knowledge components involved in carrying out a task
- Communication model—a description of the interactions between the various agents involved in a task
- Design model—a technical system specification that indicates how the knowledge model and communication model will be implemented within a specific environment.

Figure 8.11 shows how the CommonKADS models are combined: the organizational, task, and agent models provide information for the knowledge and communication models, which themselves provide information for the design model. The resulting models are then implemented according to structure preserving design principles: the implemented code should retain the organization and structure of the antecedent models (knowledge model, communication model, etc.).

The development of the organizational model used a structured approach to examine the organization and assess the feasibility of knowledge-based solutions for the problems that are identified. The assessment of feasibility of

1. For more information, see http://www.epistemics.co.uk/products/

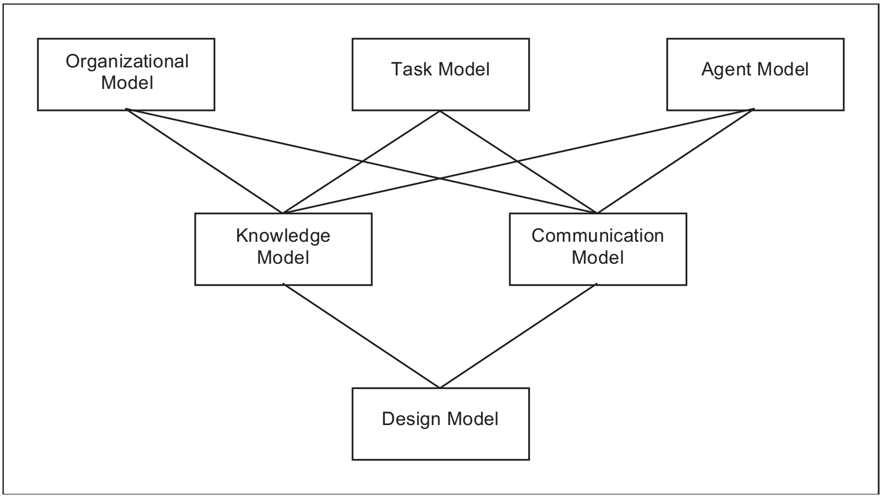

Figure 8.11: The CommonKADS models.

potential for knowledge-based solutions is summarized in Table 8.1. This scoping procedure uncovered four main areas that could benefit from knowledge-based decision support: plan assessment, system health checks, the attack phase of the mission, and the Defensive Aids Suite (DAS)/reroute task.

Extensive KA and validation have been undertaken with appropriate RAF and RN aircrew subject-matter experts (SMEs) over four vignettes on each of these task areas, leading to the production of the knowledge-base document. The individual task decompositions and detailed knowledge captured during this phase provide the basis for future architectural and software-design processes. This encapsulates all relevant expertise, for integration and aiding pilot tactical decision-making in the proposed COGPIT simulation test environment. For the purpose of the COGPIT Technical Demonstrator, current work focuses on the DAS/reroute task, which involves the use of the DAS and rerouting to counter problems caused by threats and weather.

The development of the knowledge model was substantially aided through the reuse of models, structure, and content used in the development of decision-support systems for HADS and FOAEW as described earlier. While those systems were used within helicopters, and with different tasks, a number of concepts could be reused due to the fact they were all systems to be deployed in a military airborne context.

The KA involved in the development of the CommonKADS models for the SASS has utilised a number of KA techniques, including structured interviews, laddering, repertory grid analysis, card sorts, and 20 questions. The KA was conducted in parallel with knowledge modeling, in consultation with the experts, which improves the validity of the models. The PC PACK and MetaPACK

Table 8.1: Prioritized Areas of SASS Support and Assessed Case of Supply

	Easy for Supplier	Medium for Supplier	Difficult for Supplier
Higher Priority for User	Advise on need for DAS Advise on need to route	Aid in target detection, target ID & designation Aid pilot in confidence to make weapon release	Reprioritize SA tasks Assess impact of pop-up threats & possible actions Advise on possible DAS actions Advise on optimal rerouting Advise on actions if events not occur in time
Medium Priority for User	Advise on possible actions if marshaling problems Aid in preparastion of sensor & weapon Highlight weapon/ platform/sensor system problems & possible actions Check crucial mission events occur on time	Generate and update prioritized “to do” list Aid classification of pop-up threat Use alternative means to monitor platforms if no data-link	Filter incoming information
Lower Priority for User	Highlight COMMS/ navigation system problems & possible actions Advise on EMCON	Control of automation level Anticipate/plan response to loss of INT updates Advise on sensor management	Control interaction with pilot Assess impact based on DAS information

toolsets, developed by Epistemics Ltd, have been essential in supporting the acquisition and modeling processes. The results of the KA are (1) a number of scenarios in which the SASS, and the COGPIT as a whole, can be demonstrated and evaluated, and (2) knowledge documents giving implementation-independent

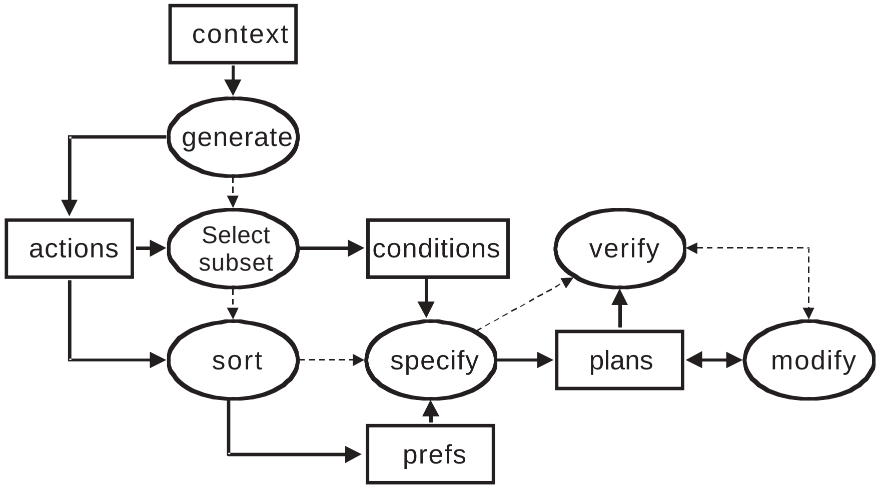

Figure 8.12: SASS replanning task process.

models of the knowledge involved in the relevant tasks. As an example, Figure 8.12 illustrates the SASS replanning task process based on CommonKADS "planning" and "rescheduling" templates that is adaptable to other tasks (e.g., plan assessment, target attack phase), and other mission support systems.

8.4.4 SASS Implementation

The implementation of the SASS will involve three stages. The first stage is a conceptual implementation, using the CLIPS expert-system shell, in which SASS will give advice on the best course of action given static situations. The second stage involves the integration of the SASS with the other modules of the COGPIT, involving the dynamic exchange of information between them. The final stage will involve the implementation of decision support for the other tasks.

The approach seeks to establish the power and utility of an incremental and structured knowledge-oriented development methodology. This improves the efficiency of KA, a classic bottleneck in system development. Moreover, this leads to substantial reuse of knowledge that has been elicited at great cost in previous projects. Finally, it is possible to demonstrate the enhanced maintainability of systems developed in this way. Together, these developments should decrease the risk associated with knowledge-intensive system development.

8.5 MONITORING THE MISSION PLAN AND CONFIGURING THE COCKPIT—TASKING INTERFACE MANAGER

The Tasking Interface Manager seeks to demonstrate real-time adaptive automation and real-time task, interface, and timeline management to support pilot operations in the COGPIT. The intended TIM application is to enable the pilot to concentrate his/her cognitive capabilities on the tactical aspects of the mission and off-load the routine activities to automation. Ideally, this would allow the pilot to remain in a planned feed-forward activity, while most, if not all reactive feedback requirements are met by decision aiding and automation. More specifically, the function of the TIM is to track goals and plans and to manage the pilot/vehicle interface and system automation. The TIM utilizes output from the SASS and the COGMON to adaptively present information and adaptively automate tasks according to the situation context and the pilot's internal state. The main features of a tasking interface are a shared mental model, the ability to track goals, plans and tasks, and the ability to communicate intent about the mission plan. This section describes the current state of development of a tasking interface component of the COGPIT program, that allows the aircrew to retain executive control of aircraft and mission parameters, while benefiting from such computerized assistance.

8.5.1 TIM Functions—Task, Timeline, Interface, and Automation Management

Among other things, as the integrated automation systems in an adaptive cockpit become more aware and capable of augmenting or even replacing pilot activities in some cases, new forms of interaction between human and automation become both possible and necessary. Our goal is the creation of an adaptive or "tasking" interface that allows an aircrew to pose a task for automation in the same way that they would task another skilled crewmember. It affords aircrew the ability to retain executive control of tasks while delegating their execution to the automation. A tasking interface will necessitate the development of a cockpit control/display interface that allows the pilot to change the level of automation in accordance with mission situation, pilot requirements, and/or pilot capabilities. It is necessary that both the pilot and the system operate from a shared task model, affording the communication of tasking instructions in the form of desired goals, tasks, partial plans, or constraints that accord with the task structures defined in the shared task model.

The function of TIM is to track goals and plans and to manage the pilot/vehicle interface and system automation. The central feature of the COGPIT Technical Demonstrator is to afford the pilot the capability to concentrate his skills towards the relevant critical mission event, at the appropriate time and to the appropriate level. This does not necessarily imply the exclusion of all other data from the pilot; rather mission-critical information will be of primary focus and other temporally noncritical but mission important data will be presented at a lower level of salience.

The work exploits the lessons learned from the U.S. Army's Rotorcraft Pilot's Associate program (Miller & Goldman, 1999; Miller, Guerlain, & Hannen, 1999; Miller, Pelican, & Goldman, 1999) through consultancy with the U.S. developer of the tasking approach. Operators allowed to choose various levels of interaction for the tasks they are required to conduct can mitigate the problem of unpredictability of automation. This notion can be described in terms of a "tasking interface" that allows delegating a task to automation in the same way one might task an intelligent, knowledgeable subordinate. The aim is to produce a tasking interface solution tailored to the requirements of the COGPIT project that is compatible with the outputs of the SASS and CM work. TIM will utilize the monitoring and analysis of the mission tasks provided by the SASS combined with the pilot state monitoring of the COGMON to afford adaptive automation, adaptive information presentation, and task and timeline management.

Honeywell Technology Center is developing the functional requirements for the TIM. The overall architecture of an adaptive cockpit we are working with involves 12 functions, with a natural flow of information and control across the functions as loosely illustrated by Figure 8.13 and described below.

Assess pilot state information and actions. Tracking the pilot's physiological and/or cognitive state should serve as one of two broad inputs for allocating automation and configuring information presentations; the other is the needed information and task performance as dictated by the mission. This function is performed by the COGMON in our architecture.

Assess aircraft and world states and events. Tracking the state of the aircraft and the world serves as one of two broad inputs for allocating automation and configuring information presentations; the other is the pilot state. It is important to maintain this information separate from pilot actions to be able to discriminate intended states from ones that happen serendipitously. This is a function of the Situation Assessor Support System in our architecture.

Store goals and plans. This GP repository is a database of the goals, plans, and tasks that relate to the mission plan. This includes the tasks that the aircrew and aircraft system are capable of doing (possible tasks), those that relate to the specific mission plan (planned tasks) and those that are currently active (current tasks). TIM will maintain this repository in our architecture.

Interpretation of pilot and world state into intended or actual goals and plans. This function takes the outputs of the pilot state and action information described above, along with auxiliary information as needed, and includes a set of pilot-intended and actual goals and plans. These are then written into the "active" task layer of the goals and plans repository. The interpretation of pilot state and actions into pilot intended plans is a function performed by TIM in our architecture.

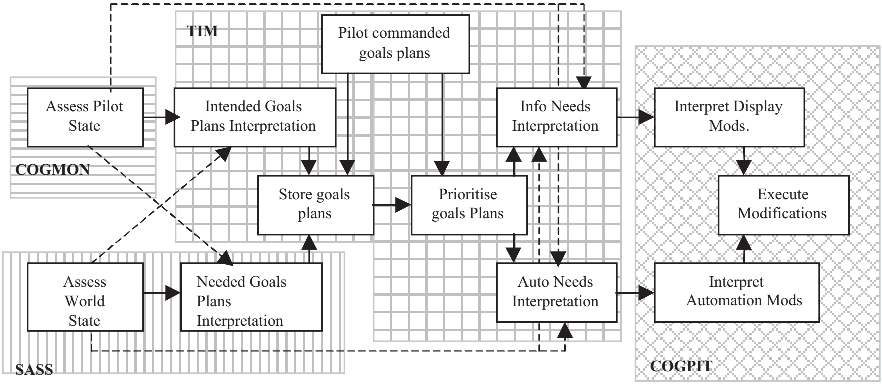

Figure 8.13: Flow of information across functions
(⟶ primary - - - -> secondary).

Interpretation of pilot and world state into needed goals and plans. This function is intended to provide a parallel view of what tasks need to be performed, not necessarily those that the pilot wants to be or is performing. These are then written into the "active" task layer of the GP repository, though they should be flagged as having a different status than tasks the pilot is actually working on. This task is performed by the SASS in our architecture.

Capture of pilot statements/commands about goals and plans. This function is intended to represent explicit pilot inputs (as opposed to implicit or inferred ones) about his/her goals and plans. These are also written to the "active" or "planned" layers of the GP repository, though they should be flagged as having a different status that the other tasks in those layers. The capture, storage, and integration of these commands are a function of the TIM.

Prioritization of goals and plans. This function is responsible for asserting some degree of importance or priority on the tasks that exist in the active layer of the GP repository. This will implement some prioritization policy defined by designers and modified by pilots. The prioritization of goals is a TIM function.

Interpretation of pilot state, world state, and goals and plans into information needs. This function is responsible for determining an aggregate set of information needs from what can be determined about the pilot and world state. The function may reduce to determining the set of information needs associated with those active tasks the pilot is doing or going to do. The interpretation of pilot state, world state, and goals and plans into information needs is a TIM function.

Interpretation of pilot state, world state, and goals and plans into automation needs. This function is responsible for determining an aggregate set of tasks that are and need to be performed at the current time, then, based on reasoning about pilot capabilities, preferences and automation authorizations, for developing a set of tasks for automation to perform. The interpretation of pilot state, world state, and goals and plans into automation needs is a TIM function.

Interpretation of information needs to display modifications. Given the information needs determined above, the role of this function is to determine how to best meet those information needs in the current cockpit and the mission context. This function will take the current information display, information on the pilot's attentional state, and cognitive and perceptual resources and the environmental context to determine display modifications. This is a function performed by the cockpit automation and control/display systems, in accordance with the TIM interpretation of need.

Interpretation of automation needs to control modifications. The role of this function is to take the automation needs already determined and determine how best to meet them in the current context. This function will take the currently invoked automation, the pilot's attentional state, cognitive and physical resources, and the mission context to determine control modifications. This is a function performed by the cockpit automation and control/display systems, in accordance with the TIM interpretation of need.

Execution of display and automation modifications. Once the display and automation modification requirements are known, this function is responsible for actually implementing them in the aircraft by placing a demand to the cockpit for their activation. This is a function performed by the cockpit automation and control/display systems, in accordance with the TIM interpretation of need.

8.5.2 TIM Implementation

8.5.2.1 Shared Task Model. To develop a tasking interface, it is essential to be able to code, track, and dynamically modify user's goals and plans. The use of a "task model" format shared by both the operator and the knowledge-based planning system affords a high level of coordination between the human and the supporting system (Miller, Guerlain, & Hannen, 1999; Miller, Pelican, & Goldman, 1999). Figure 8.14 shows the general architecture for tasking interfaces. This includes a Graphic User Interface (GUI) in the form of a "Playbook" and a mission analysis component, which are based on, and communicate with each other, through a shared mental model.

The development of the shared task model for the TIM will be based upon the analytical studies that have been conducted to develop a mission description and concomitant information requirement for an offensive air mission. The knowledge elicitation utilized to develop these documents included a number of KA techniques, structured interviews, laddering, and verbal protocols based on the Goals, Means Task Analysis methodology of Roth and Mumaw (1995). The mission description and information requirement documents were

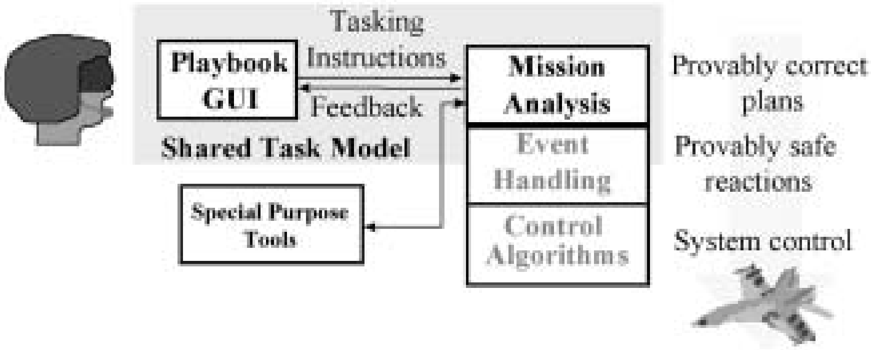

Figure 8.14: General architecture for tasking interfaces. (From C. A. Miller, M. Pelican, & R. Goldman, Tasking interfaces for flexible interaction with automation: Keeping the operator in control, *Proceedings of the International Conference on Intelligent User Interfaces*, Association for Computing Machinery [ACM], 1999. Reprinted with permission.)

developed using Jaguar SMEs and validated across Tornado ground attack and air intercept variants.

To support a tasking interface, a task model must be organized via functional decomposition, wherein there are alternative methods to achieve each task or goal. These tasks must be representative of the way pilots think of their domain and use operator-based labeling conventions (Miller, Guerlain, & Hannen, 1999; Miller, Pelican, & Goldman, 1999). The task model used for the COGPIT uses three task categories: generic tasks that are constant for a particular task for any mission, mission specific tasks that are constant for a particular task within a particular mission, and specific tasks that differ for each instance of a particular task.

8.5.2.2 TIM's Task-Tracking Capabilities. The Goal Plan Tracking (GPT) system is intended to take the form of a three-pass assessment. The first pass takes cockpit manipulation and interface information to infer a goal, a plan/objective, and a task (for example pilot stick inputs might imply SAM avoidance or acceptance of a new target or need to abort the mission). The second pass would use contextual information provided by the SASS to disambiguate the first pass (e.g., a SAM site in search mode has been located 20° on the right at approximately 20km). The final pass, which is pilot direct input, would only be used if the assessment were incorrect (for example in this situation the pilot would agree with the assessment and the TIM would then act upon this assessment to request interface modifications and automation requirements from the cockpit). The initial TIM build will be to provide a Mission Plan Tracking (MPT) capability, with later expansion to a full GPT system.

8.5.2.3 Communication About Intent. One of the goals of TIM is to allow the pilot to interact with advanced automation *flexibly* at a variety of levels. This allows the pilot to smoothly vary the "amount" of automation used depending on such variables as time available, workload, criticality of the decision, degree of trust, etc.—variables known to influence human willingness and accuracy in automation use (Riley, 1996). It further allows the human to flexibly act within the limitations imposed by the capabilities and constraints of the equipment and the world—a strategy shown to produce superior aviation plans and superior human understanding of plan considerations (Layton, Smith, & McCoy, 1994).

There are three primary challenges involved in the construction of a tasking interface:

- A shared vocabulary must be developed, through which the operator can flexibly pose tasks to the automation and the automation can report how it intends to perform those tasks. This challenge was discussed above
- Sufficient knowledge must be built into the interface to enable making intelligent choices within the tasking constraints imposed by the user. This is the role of the information and automation needs interpreters
- One or more interfaces must be developed which will permit inspection and manipulation of the tasking vocabulary to pose tasks and review task elaborations in a rapid and easy fashion.

This final challenge is one that will have to be undertaken for the FOAS fighter domain. The goal is to allow the human operator to communicate tasking instructions in the form of desired goals, tasks, partial plans, or constraints in accordance with the task structures defined in the shared task model. These are, in fact, the methods used to communicate commander's intent in current training approaches for U.S. battalion-level commanders (Shattuck, 1995). One of the authors (Miller, Guerlain, & Hannen, 1999; Miller, Pelican, & Goldman, 1999) has developed prototype tasking interfaces based on a playbook metaphor wherein the set of available plans can be described and visualized in a comparatively limited vocabulary of previously defined "plays" that can then be adapted rapidly to the current context. Figure 8.15 is an example of a prototype ground-based GUI for a tasking interface used to control unmanned combat air vehicles.

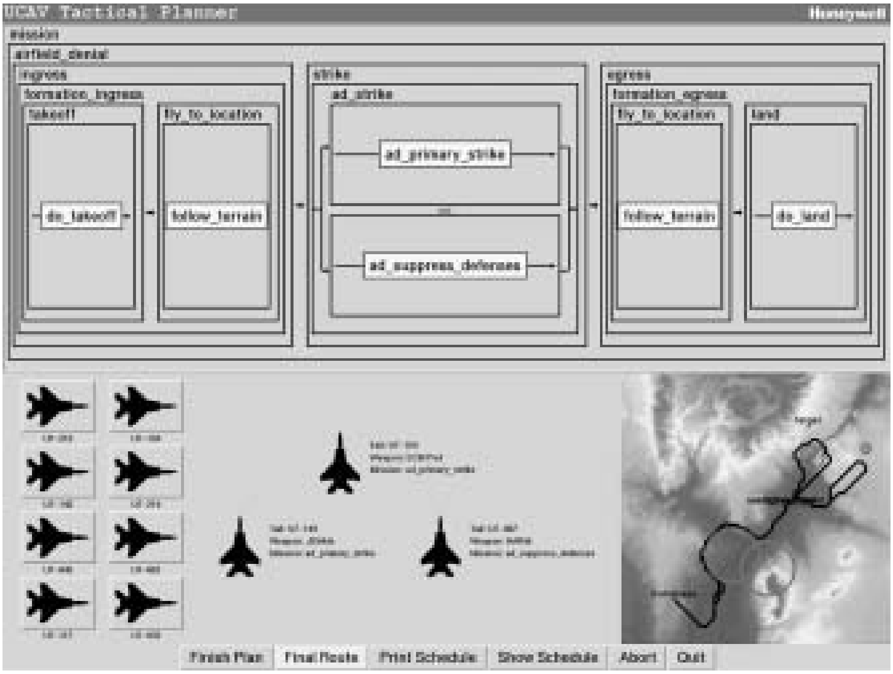

Figure 8.15: Prototype tasking interface GUI. (From C. A. Miller, M. Pelican, & R. Goldman, Tasking interfaces for flexible interaction with automation: Keeping the operator in control, *Proceedings of the International Conference on Intelligent User Interfaces*, Association for Computing Machinery [ACM], 1999. Reprinted with permission.)

8.6 PROTOTYPING, SIMULATION, AND TESTING INTELLIGENT AIDING

The COGPIT simulation and test environment is intended to provide a proof-of-concept cockpit technical demonstration of intelligent pilot-aiding (including COGMON, SASS, and TIM functions), enabling comparison of a broad set of options and providing quantifiable assessment of aiding benefit. COGSIM provides the form and function of a cockpit that interprets and initiates display and automation modifications upon request, and in which the COGPIT Technical Demonstrator modules will be implemented, tested, and validated. It will use aiding taxonomies and existing cognitive engineering and human factors analysis methods and human-computer interaction guidelines (Banbury et al., 1999).

8.6.1 COGSIM Functions—Specification, Analysis, Development, and Test

The development of the COGPIT Technical Demonstrator environment is guided by a taxonomic approach. The tenet of this approach is to scope what mission-related cockpit tasks are appropriate for machine assistance, the degree of such assistance, and the cockpit interfaces through which this interaction is likely to occur. The organization of this work is shown in Figure 8.16.

The construction of the COGPIT demonstration environment reflects an iterative approach in that the initial specification and development are followed by experimental trials, the results of which are then used to modify the environment's displays and formats. Thus, the work undertaken will include:

- Prototyping and demonstration of the cockpit and cognitive implications of intelligent aiding concepts, with appropriate human factors studies and analyzes
- Development of human-centered cockpit design principles and human-system interface guidance for automated decision support
- Provision of practical findings for cockpit design.

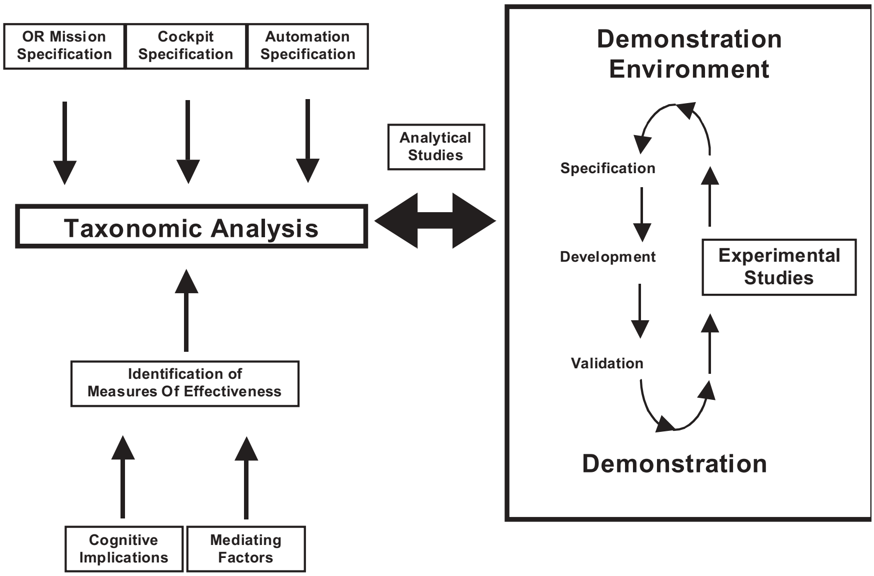

Figure 8.16: Structure of the COGPIT analytical and test work.

8.6.2 COGSIM Methodology

8.6.2.1 Measures of Effectiveness. For evaluation of COGPIT options and benefit, Measures Of Effectiveness (MOE) will be identified to provide task and mission performance metrics in the subsequent empirical evaluation. Each MOE must be mindful of the cognitive implications (i.e., capabilities and limitations of human information processing) and mediating factors (i.e., situation and environmental constraints) that exist. Mission-based MOEs provide monitoring of specific performance parameters in relation to phases of specific missions. Early work under the RPA program has shown that identification of MOEs for measuring the effects of decision aiding is a complex problem. Traditional measures of mission effectiveness, such as mission completion, arrival accuracy, and threat exposure, may not be sensitive to the effects of aiding manipulations (Casper, 1997). Linkage of MOEs to systems functions is needed to assess and analyze the benefits of specific forms of aiding. It is intended to use system functional abstraction/decomposition as a framework for developing a top-down, Function-based MOE (FMOE) system for the assessment of COGPIT intelligent aiding at the functional level. An FMOE system is also a potential source of high-level pilot feedback information, such as the “goal balls” idea for supporting the pilot’s mission situation awareness, as illustrated in Figure 8.3 (Taylor & Finnie, 1999). A program of empirical validation testing is planned, with collaboration on assessment methodologies from the USAF Adaptive Interfaces program, in particular the Global Implicit Measures (GIM) approach to assessing aiding of situation awareness (Vidulich & McMillan, 2000).

8.6.2.2 Human Performance Modeling. In addition to human-in-the-loop testing, it is intended to develop a pilot cognitive model to support testing. The pilot cognitive model will be developed using the Cognitive Network of Tasks (COGNET) cognitive task analysis tool, and the iGEN software modeling environment. COGNET is particularly suited to modeling real-time operations with multitask demands on attention. The intention is to develop an executable entity model for insertion into the COGSIM scenario management tool (STAGE), for the purposes of capability and scenario development. Furthermore, the aim is to develop a COGNET model of human performance, from the mission description and task analysis data, for incorporation into COGSIM for assessment of decision aiding and automation tasks.

8.6.2.3 Aiding Taxonomy. An initial Decision Aiding Taxonomy (DAT) has been produced to provide a development framework for the suite of intelligent

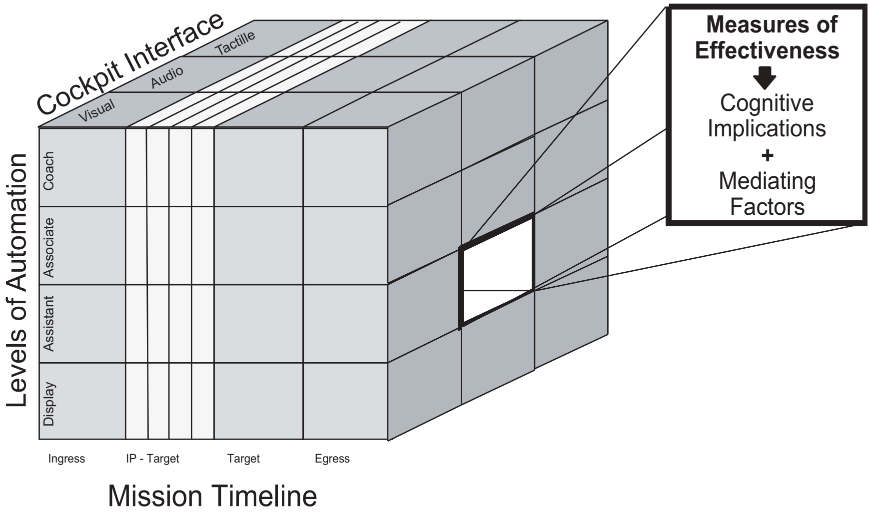

Figure 8.17: Generic format of initial decision-aiding taxonomy.

decision aids that will comprise the Cognitive Cockpit and to allow assessment of the progress of the research (see Figure 8.17). To achieve these ends, the DAT scoped a number of areas:

- The role of the human
- The role of the decision aid
- The level of automation possible
- The number of behavioral and cognitive functions possible
- The operational requirements of the scenario in which both the human and decision-aid were expected to operate, and
- The cockpit interface technologies through which this interaction can occur.

In doing so, the approach allows responsibilities to be allocated between the human and automated system, for a given mission segment, and through a specific cockpit interface (Banbury et al., 1999).

8.6.3 COGSIM Implementation

The COGSIM's main function is to provide a medium-low fidelity simulation of the out-the-window view, head-down displays, cockpit controls and displays, while also being responsible for modeling and controling the scenario and all the entities in the simulation (ground, air, and sea). The following commercially available software applications were selected for use:

- Virtual Application Prototyping Software (VAPS) which provides a rapid development environment specifically for avionics interfaces and systems
- Scenario Toolkit and Generation Engine (STAGE) which drives the simulator scenario and handles all entities and allows some degree of entity scripting, map importing, and distributed interactive simulation broadcasting
- Flight Simulation (FLSim) which provides a medium fidelity aerodynamic aircraft model which will be used for "ownship"
- MultiGen which is a modeling and simulation suite of software tools and modules
- VEGA which provides an out-the-window scene with the capability of handling large terrain databases.

The current state of development of the COGPIT program is summarized in Table 8.2, using the WDA abstraction-decomposition framework. The architecture of the COGPIT is being developed to include an XML-server approach to communications with other modules in the assignment. XML was chosen as an ideal means of rapid and reliable distribution of data and integration of modules developed on different machines, operating systems and networks, because the HTTP protocol and internet-based technology has been well proven. Due to the performance-cost ratio and recent rapid advancement in PC technology, PCs where chosen over other platforms such as SGIs for this assignment.

8.6.3.1 Baseline Cockpit. The interface technologies selected for inclusion in the cockpit simulation were chosen from an analysis of the maturity of candidate technologies for implementation in FOAS time-scales (Table 8.3). The intention is to provide comparison of the baseline cockpit (Eurofighter/F22 interface standard) with candidate cockpit configurations with TIM adaptive interfaces supported by COGMON and SASS. Consideration will be given to investigating the support for adaptiveness afforded by flexible, large area head-down displays, and multimodal display techniques for head-up, out-of-the-cockpit operations, in particular, the use of a Helmet-Mounted Visual Display (HMD) coupled with voice and 3D audio cueing.

8.6.3.2 Information Requirements Analysis. Information requirement analysis performed with the project SME pilot on the mission scenario description and storyboard, has identified the preferred modality, saliency, and method of dis-

Table 8.2: Summarized COGPIT Functional Decomposition

Abstraction Level	Functional Decomposition
Functional purpose and constraints	Help demonstrate pilot aiding benefit; Support development of plot aiding functionality; Support growth of DERA cognitive engineering capability
Abstract functions, priorities and values	Human-system performance assessment; Systen emulation, simulation; Pilot T&E; System design; Development; Research tool; Requirements analysis
Generalized purpose related functions	STAGE Entity management; VEGA/VAPS Responding to pilot interaction; VAPS/FLSim Providing cockpit system options; SASS/TIM Adaptation and pilot aiding; COGSIM Monitoring performance parameters; MultiGen/VEGA Providing realism; COGMON Assessing pilot functional state
Physical functions	COGMON Monitoring pilot parameters; SASS Monitoring environment, Replanning mission; TIM Configuring cockpit, Deciding automation, Monitoring & updating mission plan; COGSIM/Cockpit Automating tasks, Entity representation, Gathering mission, contact & pilot interaction data, Exchange information, Display warnings, interrupts, status & tasks
Physical forms and systems	DVI/DVO, 3-D sound, Radio voice links, Data links, HOTAS, Touch screen, Visually coupled HMD; Geo data base, Map; RWR, MAWS, Radar, DASS, ECM Chaff/flares; Warning system, Automatic FCS, Mission planning & re-planning systems; SASS Tactical KBS; TIM GPT system; COGMON biosensors, amplifiers; HTTP server, blackboard

play information for the baseline cockpit, and indicated the need for prioritization of the saliency of TIM advice (Taylor, Abdi, Dru-Drury, & Bonner, 2000). Mission analysis indicates that the primary display requirement is to

Table 8.3: Baseline Cockpit Interface Technologies

Display Technologies	Control Technologies
• Helmet Mounted Display	• Direct Voice Input
• Large Head-Down Display	• Active Throttle and Stick Control
• Direct Voice Output	• Hands-On Throttle And Stick (HOTAS)
• 3D Audio	• Helmet Tracking
	• Eye Tracking (pilot-state monitoring)
	• Hard Keys/X-Y Controller
	• Touch Screen

support head-up, eyes-out of the cockpit operation. The work has examined requirements for information at five levels of saliency, namely:

- Background—information
- Hinting—messages
- Influencing—suggestions
- Directing—warnings
- Compelling—alerts

SME analysis has indicated the need for TIM information to be managed, organized, and easily digested, so as not to unduly add to pilot workload. Direct voice input/output (DVI/DVO) is the preferred primary modality for TIM dialogues. Initial analysis has identified the need to provide a distinction between feed-forward primary information, and feedback secondary information, with appropriate levels of saliency in display, for example, center HMD location for feed-forward, and peripheral HMD location for feedback.

8.6.3.3 Control Requirements Analysis. In addition, consideration will be given to examining options for supporting adaptation using alternative control technologies, in particular coupling Hands-On-Throttle-And-Stick (HOTAS) operations with DVI and head-tracking (Hudgins et al., 1998). Eye-tracking is to be considered initially only for pilot-state monitoring, rather than for controlling systems, because of limitations on aiming accuracy with current technology. Allocation of control functions to HOTAS is guided by the requirements for speed of learning, ease of use and simplicity of operation. HOTAS is a primary mode of control for many critical functions, but it is intended to provide only a back-up to DVI and soft keys for TIM input. Particular attention is being given in the design of DVI protocols to control task information requirements and the design of feedback (Dru-Drury, Farrell, & Taylor, 2001). This is to provide an implementation of DVI consistent with principles of PCT (Powers, 1973; Taylor, 1992). Specifically, this is to allow the operator to flexibly pose tasks to the automation and for the automation to report on its intended action.

8.6.3.4 Control of Tasks. Recent analysis of the operator requirement for pilot authorizing and control of levels of automation, with the envisioned TIM support, has led to the development of the COGPIT PACT system (Bonner, Taylor, Fletcher, & Miller, 2000). The PACT system uses military terminology (Under Command, At Call, Advisory, In Support, Direct Support, Automatic) to distinguish realistic operational relationships for five aiding levels, with progressive pilot authority and computer autonomy supporting situation assessment, decision making, and action (Table 8.4). These are a reduced, practical set of levels, with clear engineering and interface consequences, derived from the ten levels of automation for human-computer decision-making proposed by Sheridan and VerPlanck (1978). The PACT terminology and selection of levels are based on operational considerations that are consistent with theory to afford usability and compatibility with military user cognitive schemas and models. It is envisaged that mission functions and tasks, at different levels of abstraction, will be allocated to these levels. The operator could control this allocation in a number of ways:

- Preset operator preferred defaults
- Operator selection during pre-flight planning
- Changed by the operator during in-flight replanning, and
- Automatically changed according to operator agreed, context-senstive adaptive rules.

8.6.4 COGSIM Demonstration and Test

8.6.4.1 Test Functions. The intended COGPIT application is to enable the pilot to concentrate his/her cognitive capabilities on the tactical aspects of the mission (knowledge-based) and off-load the routine (rule-based and skill-based) activities to automation. In effect, this will allow the pilot to remain in a feed-forward loop while, most, if not all, feedback requirements are met through decision aiding and automation. The principal functions that will need to be tested are as follows:

- That the SASS provides useful rule-based decision-aiding informa-

Table 8.4: PACT System for Pilot Authorization of Control of Tasks

Levels	Operational Relationship	Computer Autonomy	Pilot Authority	Adaptation	Information on Performance
5	**Automatic**	Full	Interrupt	Computer monitored by pilot	On/off Failure warnings Performance only if required
4	**Direct Support**	Action unless revoked	Revoking action	Computer backed up by pilot	Feedback on action. Alerts and warnings on failure of action
3	**In Support**	Advice, and if authorised, action	Acceptance of advice and authorizing action	Pilot backed up by the computer	Feed-forward advice and feedback on action; Alerts and warnings on failure of authorised action
2	**Advisory**	Advice	Acceptance of advice	Pilot assisted by computer	Feed-forward advice
1	**At Call**	Advice only if requested	Full	Pilot, assisted by computer only when requested	Feed-forward advice, only on request
0	**Under Command**	None	Full	Pilot	None, performance is transparent

tion, according to the situational context. For example, progressively providing avoid, evade, and defeat action requirements against ground and air threats as the scenario develops

- That the COGMON provides useful pilot-state information (cognitive capability) according to the pilot's physiological condition. For example, providing the TIM with the information that the pilot is high on visual and cognitive workload coupled with a high alertness and high arousal but low activity
- That the TIM affords the ability to adaptively provide information

according to the situational context and either selectively (pilot controlled) or adaptively (TIM-controlled) offload tasks to automation in accordance with the mission plan. For example, the TIM could adaptively increase the automation level on aspects of the DAS and aircraft defensive maneuvre to allow the pilot to concentrate on the ramifications of the threat avoidance to mission completion.

The basic experimental test design is illustrated in Table 8.5. In this design, the independent variables are the classes of cockpit and types of aiding. The classes of cockpit comprise conventional (i.e., baseline) and candidate (i.e., with adaptive aiding and adaptive automation). The types of aiding comprise, none (control condition), COGMON, SASS, and COGMON working together with SASS. TIM provides the integration of COGMON and SASS in the candidate cockpit, with adaptive aiding and adaptive automation. Function-based MOEs will provide a large choice of dependent variables to measure performance. The selection of the dependent variables is related to two factors: (1) the external validity of the measure in terms of its relevance to the real world; and (2) the internal validity of the measure in terms of its suitability to measure a particular aspect of performance.

Table 8.5: Basic Experimental Test Design

Between Subjects	**Conventional**				**Candidate**			
Within Subjects	None	COG-MON	SASS	COG-MON + SASS	None	COG-MON	SASS	COG-MON + SASS

8.6.4.2 Usage Scenario. The design of the COGPIT and its Technical Demonstration are based upon MOD customer-agreed scenarios and missions. Based on a NATO Studies Advisory Group European scenario and mission, three individual scenarios have been derived for technical demonstration of DAS/Rerouting (weather, threat update, SA–8 pop-up threat). These have different mission plans, timelines, and priorities and provide variations or tweaks to exercise specific functionality (known threat, loss of data link and RAP, loss of GPS, hostile AA, chaff failure, fuel leak, two missiles, ambiguous RWR tracks). The scenarios were originally developed as aids to the SASS knowledge acquisition to give contexts for the processes involved in the FOAS mission. In addition, the scenarios were chosen to show key situations where the COGPIT should aid the pilot. They are therefore selected to be challenging (e.g., flying over unfamiliar terrain, for extended duration and therefore fatiguing, and able to defeat the baseline cockpit), to demonstrate added value of aiding, and to show the COGPIT concept of operation.

8.6.4.3 Mission Story-Boards. Mission descriptions have been captured as mission timelines and analyzed by pilot SME to provide decomposition into goals, functions and tasks, systems operations, control inputs, and information display requirements. The methodology is derived from role-playing narrative procedures used to identify technologies and cueing for air-to-ground fighter integration (Boucek et al., 1996; Montecalvo, Redden, Rolek, Orr, & Barbato, 1994). The mission descriptions cover all potential tasks within a mission. They will be used to develop MOEs and to analyze automation and adaptive aiding requirements, in accordance with the DAT and PACT frameworks. Mission storyboards providing detailed, scripted tactical vignettes have been created in accordance with strategic factors in the high-level scenario and used successfully for the purposes of technical demonstration. The method of demonstration used to date has been a coupling of real-time simulated flight involving some automated actions (DAS, not auto-pilot) together with cognitive walk-through. The approach used is similar to the decision-centered approach to story-boarding used under the U.S. Navy TADMUS program by Miller, Wolf, Thorndsen, and Klein (1992) to provide focus on the situational dynamics. The mission storyboards are intended to drive the detailed COGSIM development to demonstrate COGPIT functionality. The priorities for COGPIT story-board development were the need to follow the mission description development, to allow each COGPIT component to demonstrate its functions, and that they should be based on KA with pilot SMEs, and not developed arbitrarily.

During demonstration, the simulation paused at selected decision points to provide explanation of SASS provided plans and to describe TIM automation of aircraft systems and presentation of information to pilots. COGMON operation has been demonstrated stand-alone with a simulated cockpit (F22) computer-game flying task. This showed significant sensitivity to types of physical activity, input and output modalities, and to changing levels of concentration, arousal, and cognitive load. Future work will seek to provide a real-time demonstration of the integrated functioning of COGMON and SASS working through TIM in the COGSIM cockpit.

8.7 CONCLUSIONS

The work has exercised a wide range of cognitive systems engineering methods in bringing together cognitive technologies for intelligent knowledge-based pilot-aiding. These cognitive technologies include pilot functional state monitoring—in its infancy in providing on-line measurement and interpretation for task adaptation—and task knowledge management and decision support for context sensitive aiding—applying relatively mature knowledge engineering techniques to support adaptiveness in real time. Considered in terms of the capability maturity levels suggested by Geddes (1997), the coupling of cognitive technologies proposed in the COGPIT project provides a capability at the level of "coach," using complex task, situation, and user knowledge. As proposed, the system will be capable of recognizing the need for automation to achieve a mission objective and of providing instructions to the operator on how to achieve it, and/or implement the required automation where necessary. A summary of the methods, tools, and techniques used on the COGPIT project in the phases of development of the COGPIT systems, including cognitive systems engineering, is shown in Table 8.6.

Functional analysis of cognitive work provides essentially the foundations for the successful development and implementation of cognitive technologies for pilot-aiding. Recent developments on cognitive work analysis seem particularly promising in providing a broad set of models and tools for human systems analysis, based on a high-level functional analysis (abstraction/decomposition framework), but they are not designed for ease of transfer into computer code. The CommonKADS methodology and PC PACK software toolkit for knowledge engineering seem particularly useful for implementing knowledge-based systems. However, there is sufficient commonality in the CWA and CommonKADS approaches, to afford validation of either.

Work to date has provided mission-based functional decomposition, cognitive task analyzes, knowledge acquisition and modeling, interface prototyping, initial proof-of-concept simulation, and cognitive story-board evaluation. The analysis is based on assumptions concerning future capabilities and technical developments, which require SMEs to extrapolate from their knowledge base. This poses considerable problems in validation. A particularly difficult area is the analysis of cognitive requirements of future automation capabilities.

A baseline conventional EF22 cockpit has been built, with initial scenario scripting for a partial prototype proof-of-concept demonstration. The idea that the scenario should be sufficiently difficult, so as to defeat the baseline cockpit, is an important scenario and COGPIT design driver. The validity of the scenario and the missions needs to be checked and maintained to ensure the validity of the findings for the intended, platform-specific application. However, the basic aiding concepts and technologies are likely to be generalizable to other applications and domains.

Table 8.6: Summary of COGPIT Engineering Methods, Tools, and Techniques

Phase of Work	COGMON	SASS	TIM	COGSIM
Requirements	KA Custom profile Empirical analysis Structuralist interference model of performance limitation	KA PC Pack Meta Pack Knowledge documents	KA GMTA COGNET	KA GMTA WDA Control task analysis PCT Cognitive Streaming SRK taxonomy DAT taxonomy EID Aiding HCI Style Guide
Specification and Design	Modular redundant architecture Near real-time Interleaved processing Polynomial decomposition Spectral analysis Regression analysis Coherence analysis Slow wave detection Loss line detection Artifact rejection and correction Rule-based artificial intelligence Recursive artificial neural networks	CommonKADS Organisational model Task model Agent model Knowledge model Communication model Design model	CommonKADS based	Interface Design Document HTML Corba Sockets
Implementation	Ethernet protocol Risk PC C code ARM code Time critical assembly language Basic 5	CLIPS expert system shell Ethernet protocol	Ethernet protocol Visual C++ Blackboard-based mission plan tracker	VAPS VEGA MultiGen FLSim STAGE LADBM Ethernet protocol
Simulation	Acorn RISC PC RISC-OS	Microsoft NT	Microsoft NT	Microsoft NT iGEN
Test and Evaluation	Iterative empirical validation F22 Computer game FMOE	FMOE Prototype story board Cognitive walk-through	FMOE Prototype story board Cognitive walk-through	Aiding Test plan PC-based and COGSIM-based experiments Iterative empirical validation FMOE

There has been some initial development of the COGPIT modules. Work so far indicates that on-line pilot functional state assessment is feasible with current computing power, and looks like providing useful information for cockpit and task adaptation. In particular, the increased power of individual profiles for developing custom adaptations seems a highly promising development.

Knowledge engineering methodology can provide useful on-line knowledge-based systems to support for pilot replanning tasks, and this has the potential for wider application. The traditional KA bottleneck has been significantly reduced by the provision of a structured methodology and tool set (CommonKADS, PC Pack and Meta Pack). Demonstration has highlighted the criticality of the timing of KBS advice in context.

Useful assistance in the management of cockpit interfaces, tasks, and automation can be provided by a tasking interface system based on a shared task model. The development of an effective TIM, with which pilots can interact easily, will be critical for the successful integration and acceptance of the outputs of the COGMON and SASS subsystems. The technical specification of a tasking interface for this type of system is a major task, particularly as the functional components require iterative development, precluding early definition of inputs and outputs. While it is relatively easy to track tasks instantiated in a mission plan, it becomes very difficult to track and support tasks that deviate from the intended plan. Tracking deviations requires the system to infer likely pilot intent, which is inherently problematic.

Further work is needed to identify the precise methods for cockpit adaptation and their benefits and to determine the optimization of control/display interfaces, in particular for DVI/O dialogue and HMD ramifications. A function-based system for MOEs could provide useful information on mission confidence for on-line pilot feedback, and for analysis of the benefits of aiding options. Future work seems likely to extend the system functionality and scenarios, to provide integration of subsystems for evaluating candidate cockpit options, and to consider wider applications, such as supporting the control of multiple UAVs, and export to other work domains.

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