Single-Seat Cockpit-Based Management of Multiple UCAVs Using On-Board Cognitive Agents for Coordination in Manned-Unmanned Fighter Missions

Stefan Gangl, Benjamin Lettl, and Axel Schulte

Universität der Bundeswehr München (UBM), Department of Aerospace Engineering
Institute of Flight Systems (LRT-13), 85577 Neubiberg, Germany
{stefan.gangl,benjamin.lettl,axel.schulte}@unibw.de

Abstract. This article describes an automation concept, which enables the pilot of a single-seat fighter aircraft to manage more than one unmanned combat aerial vehicle (UCAV). The presented concept bases on the theory of cognitive and cooperative automation and suggests that unmanned aircraft are equipped with on-board artificial cognitive units (ACUs). By this, unmanned platforms are enabled to exhibit cooperative capabilities and rational behavior in the context of the mission. To accomplish efficient manned-unmanned cooperation the concept additionally proposes to support the pilot with an assistant system module for team coordination tasks and to provide a self-explanation capability to the unmanned aircraft. This concept has been realized as laboratory prototype and already been tested with operational personnel in our human-in-the-loop full scenario simulation environment. For the further evaluation of the concept an experimental design has been worked out.

Keywords: multi-UAV, multi-UCAV, mission planning, assistant system, manned-unmanned teaming, human-machine interaction, cognitive automation, cooperative automation, artificial intelligence, human-automation integration.

1 Introduction

Over the past years, unmanned combat aerial vehicles (UCAVs) have become increasingly important in the military field. Up till now they are mainly in single vehicle missions operated from ground control stations in use. At the same time, many multi-ship missions are still conducted by solely manned fighter teams. It is reasonable that in the upcoming years manned and unmanned forces become more and more integrated. This inevitably leads to increasingly complex information flows between manned and unmanned units. One possibility to encounter this concern on an organizational level is to guide UCAVs airborne on a high Level of Interoperability (LOI) [4], like LOI 4 or 5, as according to STANAG 4586. This means, that there are one or more highly automated unmanned aircraft under control of a manned platform including aircraft guidance and mission payload.

D. Harris (Ed.): EPCE/HCII 2013, Part II, LNAI 8020, pp. 115–124, 2013.

The introduction of highly complex automation aboard the UAV poses the serious challenge of supervising and monitoring of the automation to the human operator. Experiences with automation systems for manned aircraft show that complex automation can lead to automation induced errors [3][10] and may raise the human workload in situations where the workload is already at a critical level.

An automation concept to accomplish such a team configuration while avoiding potential issues in cooperation with complex automation has been developed at the Institute of Flight Systems at the University of the Bundeswehr Munich (UBM) and is presented in this article. Our work is based upon previous results [9][8] concerning unmanned cooperating fighters performing a SEAD mission. A major add-on in this study is the investigation of the role of the human operator.

Related work in this field has been reported in [1] and [2]. Those approaches are based on the guidance of intelligent unmanned capabilities on high level mission commands [2]. The operator, the pilot of the manned aircraft, passes specific mission tasks to a "pool" of co-operating UAVs. The unmanned systems self-organize and perform all of these tasks independently. Therefore, the unmanned vehicles are furnished with a multi-agent system (MAS), consisting of different types of software agents with various abilities. This concept was successfully tested in real flight tests (one manned fighter, one real and three simulated UAVs) in spring 2007 [1].

2 Cognitive and Cooperative Automation

2.1 Cognitive Automation

The automation design approach of cognitive automation was developed at the Institute of Flight Systems and is described in detail by Schulte & Onken [10]. In the following subsection a summary of the most important aspects with respect to this article is given.

In the domain of flight guidance up to now mainly what we call conventional automation is in operation. Operators supervising complex automated systems are exposed to several problems like "opacity", "literalism" or "brittleness" as stated by the well-known critics on aircraft automation by Billings [3]. These problems are even increased in the case of UAV flight guidance due to even more complex missions and automation. To overcome these shortcomings of conventional automation the cognitive automation approach proposes the usage of automation with cognitive capabilities like decision making, problem solving and planning.

Suchlike automation will, in our case, be implemented by so-called Artificial Cognitive Units (ACUs). These are basically artificial, knowledge-based agents, which are able to develop rational goal-directed behavior by processing knowledge.

The approach of cognitive automation suggests two possibilities for implementing this kind of automation in form of ACUs in a human-machine system design. These are called the "dual-modes" of cognitive automation [10] and will be explained by use of the work system framework. A work system consists of two basic components, there is an Operating force (OF) and there are Operating Supporting Means (OSMs). The OF, which is always represented by at least one human operator, understands and pursues the overall work objective. It generates a comprehensive understanding of the actual situation and knows the capabilities of the available OSMs. Based on this knowledge an OF is able to decide for the course of action to comply with the work objective by using the OSMs. In contrast to this, the OSMs do not know the overall mission objective, they only accomplish sub-tasks assigned by the OF. In the dual-mode cognitive automation concept an ACU can be either part of the OF or of the OSMs (Fig. 1). These ACUs are called Operating Cognitive Unit (OCU) and Supporting Cognitive Unit (SCU), respectively. From a human operator's point of view, an SCU is a subordinate system deployed in a supervisory control relationship whereas an OCU teams up with the human operator, both of which composing the OF. The relationship between the human operator and an OCU is of special interest in the context of this article and is therefore presented in more detail. This relationship can show different characteristics mainly depending on qualification and capabilities of the cooperating entities.

For example in a pilot/co-pilot relationship, both team mates have the same expertise. Therefore, takeover of tasks is possible and mutual understanding of each other behavior/misbehavior can be supposed. In a human-machine team with similar cooperative characteristics, the machine teammate acts as an OCU and is also called an assistant system in our notion. Such an assistant system can, as according to Onken & Schulte [10], appear in three different roles as cooperating partner in the OF, i.e. associative assistance, alerting assistance and/or (temporarily/permanently) substituting assistance. The micro-behavior of the assistant system is defined by the three basic requirements for human-automation co-action [10].

Like in human teams a specific kind of cooperative relationship can be found, which is of particular relevance for the concept, which will be described in chapter 3. Given e.g. a medical team consisting of a surgeon and an anesthetist doing a surgery. The team members of such a team have different abilities and qualifications. Therefore, they cannot be replaced by each other and takeover of tasks is only possible to a limited extend. Work-share and responsibilities are defined prior to assignment of a work objective. Both team members know the overall work objective and pursue it in cooperation with each other. The contribution of both team members is needed to comply with the work objective.

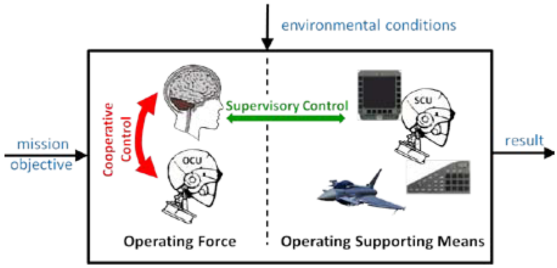

Fig. 1. Concept of Dual-Mode Cognitive Automation

Therefore, we propose to define a similar human-cognitive agent team in analogy to a solely human team. If we want to integrate a cognitive agent being part of such a team in a work system, as according to the dual-mode concept, this agent acts as an OCU in the permanently substituting role. To clearly distinguish this kind of OCU for the purpose of our work, it will be called "complementing OCU" in contrast to an "assisting OCU". Under consideration of a more general background of cooperation, the cooperative relation of such a man-machine team is discussed in the next section.

2.2 Cooperation

In this subsection guidelines are derived for the design of machine team members, which are supposed to cooperate with humans.
A general definition of cooperation on which is widely referred to origins from Deutsch [5] and states: *"Cooperation is the situation where the movement of one member towards the goal will to some extent facilitate the movement of other members towards the goal"*. According to this definition a cooperative situation is basically characterized by "the goal" and by "the movements" on which cooperating individuals interfere. Consequently two necessary conditions can be derived, which individuals have to fulfill to be part of a cooperative situation:

1. ***Strive towards complementary or identical goals****, if this is not the case team members are not in a cooperative but in a competitive situation.*
2. ***Capable to coordinate****, which means to be able to manage interdependencies or to do rational "movements".*

A human-machine team in which individuals comply with these conditions is able to process assigned tasks in a rational and effective way, but not mandatory. It can be assumed, that a human who cooperates with machine team members will find himself/herself in situations where he/she not understands what the teammates are doing or why they are doing what they do. This lack in understanding leads to instantaneous confusion, as well as lasting decline of trust in machine agents by the human. Moreover, even if the human team member is able to understand the observed behavior the process of reach understanding by interpretation of available information is a rather cognitively demanding one. The issues of lack of understanding of behavior, a low level of trust and the demanding process of generating understanding lead to potential rejection of cooperation by humans.

Consequently, the above-mentioned necessary conditions are extended by two sufficient conditions, which machine team members should fulfill at their best to finally yield good cooperative performance:

3. *Support the* ***generation of mutual understanding and acceptance*** *of behavioral pattern of the other.*
4. *Support the* ***development of trust*** *by team members toward own behavior.*

3 Automation Concept for a Manned-Unmanned Fighter Team

In this chapter the proposed automation design concept for a manned-unmanned fighter team is developed for a given application. In a first step a manned fighter team will be analyzed. Based on this analysis and under consideration of the theory of cognitive automation and cooperation as described in chapter 2, the concept is developed.

Finally, in the following subsections the most important parts of the concept are discussed in more detail.

Assuming a Close Air Support (CAS) mission with the objective to engage a by SAM-sites protected target with a laser guided bomb (LGB) is conducted by a manned team. One team member would have the expertise and resources to attack the target, maybe it is a pilot trained for interdiction strike missions (IDS). The other three team members form a sub team with the supporting ability to take photos, suppress SAM-sites or designate the target. They are maybe qualified for reconnaissance (RECCE) or suppression of enemy air defense missions (SEAD). Analyzing such a team set-up by the work system framework, results in a work system configuration as shown in Fig. 2 left. Every pilot is in a supervisory control relationship to his own aircraft and systems, as shown by the green arrows, and in a cooperative relationship to his team, as shown by the red arrow. In a next step we have a closer look to the cooperative relationship between the attack pilot and the supporting sub-team. Both cooperating individuals in this relationship know the overall work objective, work-share and responsibilities between them are defined with the assignment of a work objective and takeover of tasks is not possible because they are specialized experts. Consequently this relationship has similar characteristics as the one in the surgery team exemplarily mentioned in section 2.1.

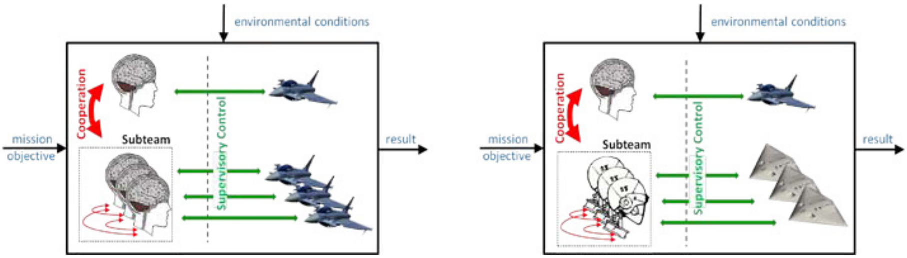

Fig. 2. Work systems of a manned (left) and a manned-unmanned fighter team (right)

Transferring such a team set-up to a human-machine team by use of cognitive agents, we end up in a work system configuration as shown in Fig. 2 right. The supporting pilots are substituted by complementing OCUs and consequently the manned platforms by unmanned ones. The control relationships from the attack aircraft pilot's point of view remain the same. This means the pilot supervises the own aircraft and systems and cooperates with the unmanned sub-team. In our case the unmanned sub-team members will not be tasked individually, but on the level of the whole team.

These OCUs must have the capability to utilize their individual platforms to implement decisions, to cooperate with the unmanned teammates, and last but not least to cooperate with the human in the context of the mission. These agents are implemented by use of the Cognitive System Architecture (COSA) [11]. The COSA framework offers the possibility to model domain knowledge subdivided into knowledge-packages with a rule-based syntax. To provide the required capabilities they are given knowledge on system management, the environment, the mission and cooperation, all of which implemented as so-called "knowledge packages" [8][9].

Assuming good team performance of this OCU-Team as such, the cooperative relationship between the unmanned team and the manned platform can be identified as the most important parameter with respect to overall performance of the work system. Therefore, an additional focus of this concept is to ensure efficient cooperation between the pilot and the unmanned team in all mission phases. To accomplish this, two additional system components are proposed. First of all we provide a Team-Coordination-Module (TCM) to the pilot. This module comprises different assisting system components with the goal to support the pilot by team coordination tasks. In addition it offers a communication interface to inform the team about mission objective and constraints. In subsection 3.2 the components of this module are described in detail. Secondly, we propose to expand the abilities of the OCUs with a Self-Explanation-Module (SEM), which enables them to provide explanation about own actions and decisions to the pilot. The purpose of this measure is to support understanding of behavioral patterns and to support development of trust towards machine behavior in line with the sufficient conditions for cooperation as derived in chapter 2.2. More specific aspects on this module are discussed in subsection 3.1. The whole assistant system composed of the core elements OCU-Team, Team-Coordination-Module and Self-Explanation-Capability is visualized in the work system in Fig. 3.

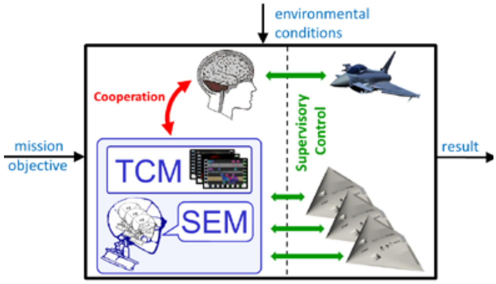

Fig. 3. Work system of proposed concept

3.1 Self-Explanation-Module

Due to communicational shortcomings, machine teammates accomplish the sufficient conditions for cooperation inadequately. To overcome this deficiency we suggest a self-explanation-module for cognitive agents, which enables them to provide causal information about own actions and decisions to human team mates.

The concept for this module proposes a self-explanation capability based on two modes of explanation as shown in Fig. 4. The first mode is called "continuous self-explanation" (SEC-Mode) and the second one "self-explanation on demand" (SED-Mode). By the SEC-Mode we understand the advanced capability of an agent to provide relevant situation adjusted explanations on own initiative. In contrast the SED-Mode provides the possibility to the operator to request an explanation. The SED-Mode is designed to complement the SEC-Mode. All explanations are presented to the pilot by verbal output generated by a speech synthesizer.

In order to enable the ACU to exhibit self-explaining behaviors, its knowledge base is extended by specialized knowledge packages (see dashed box of Fig. 4). The "Natural Language" package enables an ACU to provide explanations in morphological and syntactical correct language. With the "Own Status" knowledge package an

ACU is aware of own behavior and the cause for it. This enables the cognitive agent to provide at any time information which are of interest to answer question like "What am I doing?" and "Why am I doing this?". The knowledge package "Evaluation of the need for explanation" is only of relevance in the SEC-Mode. It permits an agent to reason about the necessity of an explanation and therefore initiates explanations in the SEC-Mode. In contrast, in the SED-Mode the pilot initiates an explanation by simply asking a question regarding the status of a cognitive agent. This request is processed by a speech recognition system and forwarded to the ACU.

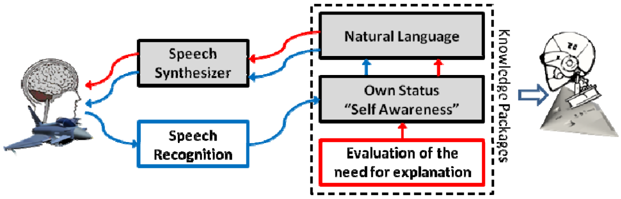

Fig. 4. Concept of a two mode self-explanation capability, SEC-Mode (red), SED-Mode (blue)

3.2 Team-Coordination-Module

The entire mission can be broken down into individual sub-tasks as mentioned before in section 3. These sub-tasks are distributed among all team members according to their capabilities. Mainly "prerequisite" and "simultaneity" dependencies exist between sub-tasks within the mission context. A typical prerequisite dependency is the flight of the manned fighter aircraft into hostile territory. The pilot should enter threatened areas only, if known threats are successfully suppressed. The attack of the mission target is an example for a simultaneity dependency. An unmanned team member needs to designate the target, while the manned fighter is deploying the ordnance. In order to enable suchlike coordination between the pilot and the unmanned sub-team we developed a team-coordination module (TCM) as part of the assistant system.

The TCM supports coordination in different roles of assistant systems [10]. Basically it works in the role of associative assistance and continuously provides necessary coordination information to the pilot. If the TCM identifies a problem between the coordination of sub-tasks, the TCM informs the pilot in the role of alerting assistance. If this warning is not handled in a specific time period, e.g. because the pilot may be overtaxed, the TCM takes over certain activities to cope with the situation. In this case the TCM works in the role of a temporarily substituting assistant.

The necessary coordination information including the pilot's sub-task dependencies within the team will be displayed on multifunctional head down displays (MHDD) in the cockpit. The visualization on the display can be either a spatial (Fig. 5, left) or a temporal (Fig. 5, right) representation. The left screen-shot shows a section of the advanced map display. The aircraft symbols and the appropriate icons on the map represent the position and the actual carried out sub-task of each team member. For example, the green team mate is designating the target. Furthermore the red circular lines mark the threatened area of hostile SAM-sites. If the SAM-site is suppressed the line is dashed otherwise it is continuous. The threat status is usually communicated by the unmanned team members as prerequisite coordination information. The two trapezoidal elements in the map support the coordination between the two different time-critical simultaneity sub-tasks, laser designation and weapon release. By the right figure a section of the onboard timeline display is illustrated. The upper timeline indicates the mission sequence of the manned aircraft and the bottom timeline that of the UAV-team in a temporal manner. Through the upper timeline the pilot is continuously informed when a mission relevant event for him will occur and when a specific sub-task has to be performed. The timeline at the bottom is primarily dedicated to increase the pilot's situation awareness. Therefore, all sub-tasks including estimated start times and execution durations of the entire unmanned team are figured out.

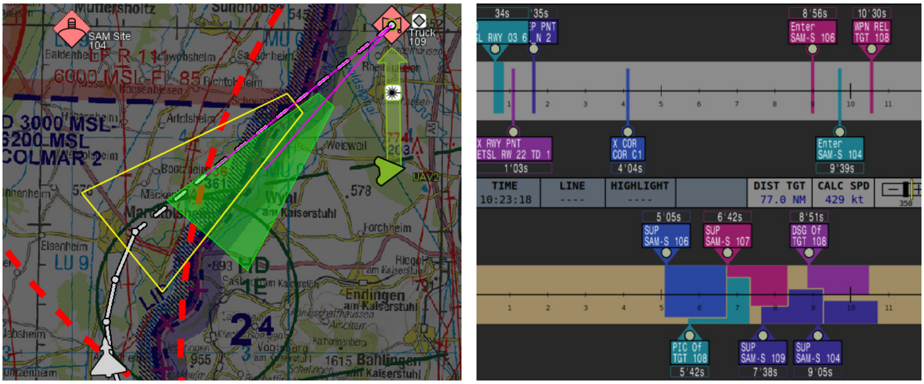

Fig. 5. Spatial and temporal visualization of coordination information

4 Evaluation

The system designed along the lines of this concept has been integrated in a fighter cockpit and mission simulator at UBM. This simulation environment facilitates human-in-the-loop experiments with a modern generic single-seat fighter cockpit representing the manned component of the strike package with up to three unmanned aircraft in different scenarios.

In first pre-experimental runs our concept was evaluated by German Air Force Pilots. In these runs pilots approved the usability of the simulation environment for realistic human-in-the-loop experiments. In addition military relevance of selected evaluation scenarios was confirmed. All conducted missions were accomplished successfully, indicated by the successful abatement of the target object, adherence of time constraints and no observed losses of UAVs. According to participating pilots' workload situation during mission execution was always on a manageable level, provided by subjective ratings.

To evaluate the implemented concept systematically, a human-in-the-loop experimental campaign with six experienced German Air Force pilots is scheduled for end of April 2013.

In this campaign pilots have to accomplish CAS missions on basis of a work objective assigned to the manned-unmanned team from a super-ordinated unit. Starting with an initial situation as shown in Fig. 6, subsequently unmanned platforms enter enemy territory and start to suppress relevant SAM-sites. Meanwhile the manned aircraft crosses the corridor and pictures of the intended target are taken by one UAV and provided to the fighter pilot. The pilot verifies the target and one UCAV prepares for target designation. As soon as the fighter aircraft is in position for weapon deployment the laser designation is started and the LGB is released. After weapon impact, new reconnaissance pictures are provided to the pilot for battle damage assessment. In case of mission success, the team returns to friendly area.

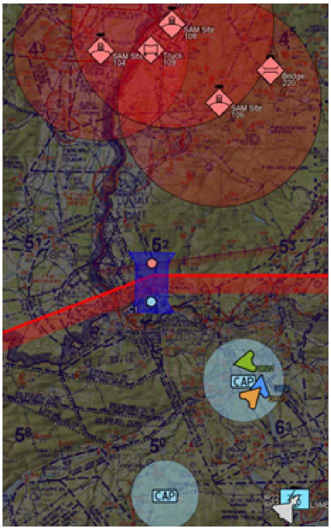

Fig. 6. Overview reference mission

Due to the limited number of available test subjects, a within-subject design was selected as experimental design. As independent variables variants of the assistant system's components, namely the Team-Coordination-Module (spatial and temporal information representation) and Self-Explanation-Module, will be investigated. Every participating test subject has to pass four experimental runs, with different sets of independent variables as shown in Table 1. The dependency between the quality of cooperation towards unmanned team mates and the selected set of cooperation supporting components will be the subject of investigation. The quality of cooperation is therefore the depended variable of this experiment. To evaluate this variable we characterize the quality of the cooperation by the parameters mission performance, workload of the pilot from team management tasks, trust toward team members and team situation awareness.

Table 1. Variation of the independent variable

Setup	SEM	TCM	
		spatial	*temporal*
1	X	X	X
2		X	X
3	X	X	
4			X

These parameters will be quantified in all experimental runs by different measurements. Team Situation Awareness will be measured by the well-established situation awareness tests SART [12] and SAGAT [6]. Mission performance is indicated by a selection of parameters like mission success or overall mission execution time. The task load of the pilot by team management tasks is determined by summing up the times during which he is busy with tasks like monitoring the team. This will be accomplished by analyzing attention distribution by use of gaze measurements. To analyze trust between the pilot and the unmanned assets the trust level during all runs will be measured by the subjective trust rating scale developed by Jian et al. [7].

In addition to this, trust of the pilot is rated by analyzing video streams of the experiments towards “double-check” behavior of the pilot, by this we understand that the pilot tends to verify information received from the unmanned team members.

Results of this experimental campaign will be provided in upcoming publications.

References

1. Baxter, J., et al.: Fly-by-agent: Controlling a pool of UAVs via a multi-agent system. Knowledge-Based Systems 21(3), 232–237 (2008)
2. Baxter, J., Horn, G.: Controlling teams of uninhabited air vehicles. In: Proceedings of the Fourth International Joint Conference on Autonomous Agents and Multiagent Systems, pp. 27–33. ACM (2005)
3. Billings, C.: Aviation Automation: The Search for a Human-Centered Approach. Lawrence Erlbaum Associates Publishers, Mahwah (1997)
4. Cummings, M., et al.: STANAG 4586 Human Supervisory Control Implications (2006)
5. Deutsch, M.: Cooperation and trust: Some theoretical notes. In: Nebraska Symposium on Motivation, pp. 230–275 (1962)
6. Endsley, M.R.: Situation awareness global assessment technique (SAGAT). In: Proceedings of the IEEE 1988 National Aerospace and Electronics Conference, pp. 789–795. IEEE (1988)
7. Jian, J., et al.: Foundations for an empirically determined scale of trust in automated systems. International Journal of Cognitive Ergonomics 4(1), 53–71 (2000)
8. Meitinger, C., Schulte, A.: Cognitive machine co-operation as basis for guidance of multiple UAVs. RTO-Meeting Proceedings HFM-135, Biarritz (2006)
9. Meitinger, C., Schulte, A.: Human-UAV Co-operation Based on Artificial Cognition. In: Harris, D. (ed.) EPCE 2009. LNCS, vol. 5639, pp. 91–100. Springer, Heidelberg (2009)
10. Onken, R., Schulte, A.: System-Ergonomic Design of Cognitive Automation. SCI, vol. 235. Springer, Heidelberg (2010)
11. Putzer, H., Onken, R.: COSA–A generic cognitive system architecture based on a cognitive model of human behavior. Cognition, Technology & Work 5, 140–151 (2003)
12. Taylor, R.M.: Situational Awareness Rating Technique(SART): The development of a tool for aircrew systems design. Situational Awareness in Aerospace Operations, 23–53 (1990)