INTEGRATING AIRCRAFT WARNING SYSTEMS

Mark MULDER
Pedro PEDROSO
Max MULDER
M.M.(René) VAN PAASSEN

Delft University of Technology, Faculty of Aerospace Engineering
Kluyverweg 1, 2629 HS Delft, the Netherlands
m.mulder@lr.tudelft.nl, m.m.vanpaassen@lr.tudelft.nl

ABSTRACT

With the increase of warning systems the cockpit will become more crowded with different warnings. Cockpit crews spend a lot of time recognizing the cockpit warning indicators, identifying the nature of the problem, and choosing the correct procedure. To avoid increasing workloads in the cockpit, warning systems need to be integrated. This paper discusses the possibilities for integration, based on a multi-agent system. Two layers of integration can be identified that prevent unnecessary warnings and prioritize simultaneous warnings: direct agent-to-agent communication, and a 'selector'. From a human perspective, the integration should lead to a decision support system rather than a new automation which needs to be monitored only.

KEYWORDS

Agents, Multi-Agent Systems, GPWS, TCAS, Integration

INTRODUCTION

Most of today's avionics systems, such as the Ground Proximity Warning System (GPWS) and the Traffic alert and Collision Avoidance System (TCAS), are designed and implemented as stand-alone, hard-wired monolithic applications of software. These stand-alone systems have proved to increase the safety of the aircraft. However, with the late increase of warning systems in the cockpit, such as the enhanced GPWS (EGPWS) and the Predictive Windshear Warning System (PWS), and the anticipated future Airborne Separation Assurance System (ASAS), the need to prioritize warning messages to avoid increasing nuisance warnings, and to provide a more intuitive human-interface (Abeloos *et al.*, 2000), becomes more and more apparent. With the current stand-alone approach of the avionics systems this is difficult to achieve.

To come to a more integrated, intelligent avionics system a new avionics architecture is needed that is adaptive, intelligent, easy to expand, and supportive of new interface technology. It is believed that this can be achieved by an avionics system in the form of a multi-agent system.

This paper discusses the integration of aircraft warning systems (limited to those warning systems that warn pilots for external threats like terrain, traffic, and weather) based on a multi-agent system.

AIRCRAFT WARNING SYSTEMS

Aircraft warning systems are typically introduced to monitor specific environmental properties that are difficult to observe or not observable at all by the human operators. The system keeps track of a number of parameters and when these parameters exceed a certain threshold a visual and/or aural warning will be generated to warn the pilots for the threatening situation.

Warning systems generally perform four functions: hazard detection; attention-getting; display of resolution status and commands; and resolution guidance (Kuchar, 1998). With the increasing number of warning systems, the attention getting function (and the following status display and resolution guidance), will cause an increase in activity in the cockpit, since all warnings accumulate in the cockpit.

Three scenarios with multiple, independent warning systems can be distinguished:

1. Different warnings occur during flight, with ample time between warnings for the pilots to solve the problems according to standard procedures. The pilots can rely on their rule based skills (Rasmussen, 1983).

2. Different warnings occur shortly after each other, or simultaneously, that support each other. Solving the main problem solves all other problems too. For example, an EGPWS warning is likely to be followed by a GPWS warning. The systems are designed that way. The pilots must use their knowledge-based skills to determine what relationship exists between the warnings to choose the right procedure to solve the problems using their rule-based skills.

3. Different warnings occur shortly after each other, or simultaneously, that have no direct (apparent) relation, e.g. a traffic alert and a weather alert. Each warning asks for a different procedure/solution. The pilot must evaluate which problem is most critical, what relation there is between warnings, to decide which problem needs to be solved first. Attention must be economically spread between the warnings. Situations like this put high demands on the pilots.

Especially scenario three increases the workload in the cockpit. Unfortunately, with more systems monitoring more parts of the environment, it is exactly this scenario that will occur more often. How confusing such a situation can be is illustrated by the following incident report (Mellone, 1993):

> *"Climbing through 1,200 feet [on departure] we had a TCAS II Resolution Advisory (RA) and a command to descend at maximum rate (1,500 to 2,000 feet per minute). [The flight crew followed the RA and began a descent.] At 500 feet AGL we leveled off, the TCAS II still saying to descend at maximum rate. With high terrain approaching, we started a maximum rate climb. TCAS II showed a Traffic Advisory (TA) without an altitude ahead of us, and an RA [at] plus 200 feet behind us...Had we followed the TCAS directions we would definitely have crashed. If the weather had been low IFR, I feel we would have crashed following the TCAS II directions. At one point we had TCAS II saying 'Descend Maximum Rate,' and the GPWS (Ground Proximity Warning System) saying 'Pull Up, Pull Up.' [The] ATC [Controller] said he showed no traffic conflict at any time." (ACN 201637)*

Cockpit crews are very sensitive to abnormal situations. Recognizing the cockpit warning indicators, identifying the nature of the problem, and choosing the correct procedure require considerable attention (Dismukes *et al.*, 1998).

Thus, with the anticipated future increase in warning systems, like ASAS, it is important that the number of warnings be kept to an absolute minimum, so as not to increase the workload in the cockpit. We believe that integration of warning systems in the form of a multi-agent system cannot only prevent the cockpit from further crowding with warnings, but it can possibly even decrease the number of warnings that eventually find their way into the cockpit.

MULTI-AGENT SYSTEMS

Multi-Agent Systems (MAS) find their origin in the field of Distributed Artificial Intelligence (DAI). The system consists of a set of autonomous software agents that are capable of co-operation. Each agent is a relatively simple, but highly specialised entity. System intelligence is the result of the emergent behaviour of the collection of co-operating agents (Khalil, 1999).

The agents in the MAS are modelled by their desired behaviour. This goal-oriented behaviour is determined by 'mental attitudes' like beliefs, desires, and intentions (Wooldridge & Jennings, 1995). These 'mental attitudes' are used by the agents to reason about themselves, their goals, their (perceived) environment, other agents, etc.

A multi-agent system is a flexible system, because of the autonomy of its agents; each agent can perform its tasks independent of the other agents. This minimum functionality is where today's stand-alone systems are; inter-agent communication improves the system performance beyond the stand-alone approach that greatly increases the over-all system functionality.

A multi-agent system is an adaptive system; the high level, goal-oriented behaviour of the agents avoids the low-level rigidity of stand-alone systems. A multi-agent system forms the core of a support system architecture for aircraft support and warning systems (van Paassen *et al.*, 2000) that is being researched at the department of Aerospace Engineering of Delft University of Technology.

INTEGRATING WARNING SYSTEMS

Each warning system can be represented as an agent. This agent will monitor a particular part of the environment based on air data and information databases like for terrain and airports. Functionality of each system is therefore still separated, like with the stand-alone systems of today. The integration of warning systems will take place on a higher, more abstract level: the agent-to-agent communication level. This approach offers two advantages with respect to man-machine interactions. First, the system designers are still working with separate systems, with a distinctive functionality. Second, the integration itself keeps the warning message-flow into the cockpit at an absolute minimum.

In the context of the support system architecture as described by van Paassen *et al.* (2000), two layers of integration on the communications level are possible:

1. The agents communicate directly with each other and negotiate for the best possible solution for existing problems. A TCAS agent could for example request terrain information of the GPWS agent before it decides what kind of resolution advisory is appropriate.
2. Agents communicate specific warning information to a 'selector' (fig. 1), which selects format and priority of all information that needs to be presented to the pilots.

These two layers together should be able to minimize the warning message flow into the cockpit in a dynamic way.

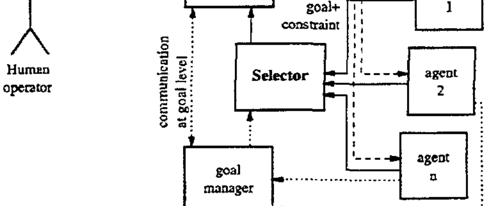

Figure 1: Intelligent support system (van Paassen et al., 2000).

Direct agent-to-agent communication

Direct agent-to-agent communication is the first layer of integration and is active even before a warning is actually generated. When one agent detects a threatening situation it can determine the constraints for resolution advisory by questioning relevant agents before generating a warning. For example, standard resolution advisory for GPWS warnings is a "Pull up, Pull up" aural warning. However, in heavy traffic a sudden change of trajectory of one plane can have serious consequences for other planes. Communicating GPWS and TCAS agents, however, may conclude that a left turn, for example, would solve the terrain proximity problem without creating a new hazardous situation.

For this kind of integration, it is necessary that each agent knows all relevant agents that it needs to communicate with. This knowledge must be present for each agent, before it becomes part of the MAS. A disadvantage is that the MAS will lose some of its flexibility: older agents will not be able to make use of newer agents, since they were not known yet.

The selector

For the selector to be able to select which warning messages have which priority it must be able to compare warnings. Messages must first of all contain all information necessary for identification of the warning. Second, messages from different systems must have the same form and same kind of parameters that makes these messages comparable. The selector or another agent must be able to reason about warnings from different systems. Therefore, when agents communicate a warning to the selector the message only consist of certain warning system parameters, and not the actual content of the warning. The actual content of the warning is only relevant for the pilots, containing the information that needs to be displayed and/or made audible, fulfilling the display of resolution status and commands, and resolution guidance functions mentioned earlier. These warning system parameters identify the warnings in terms that apply to all warnings so that a comparison can be made.

Typical parameters that can be thought of are:

- time to act;
- resolution advisory;
- number of actions to be taken by the crew;

- warning system;

The 'time to act' and the 'number of actions to be taken by the crew' parameters can be used to determine the priority of a warning, in relation to other warnings. A warning message with a 'time to act' of a few seconds clearly has priority over a warning message with longer 'time to act'.

The 'number of actions to be taken by the crew' (according to a standard procedure that is to be followed by the respective warning) influence the importance that should be attached to the 'time to act.' More actions need more time; thus, more 'time to act' is needed. The resolution advisory parameter can be used to determine whether there are any conflicting resolution advisories or whether different warnings require the same kind of action. In the latter case, only the most time critical warnings need to be dealt with.

Of course, the selector needs to know which warning system generated the warning. The 'warning system' parameter identifies the sender of the message and can be used by the selector to determine the consequences of failure to act to the warning. Failure to act on TCAS or GPWS warnings is more likely to have severe consequences than failing to respond to weather radar warnings, for example.

Still, with this information, conflicting advisories cannot be prevented by the selector (in fact, this should already have been avoided by the inter-agent communication). Nevertheless, when one warning is the result of another warning, the selector can refrain from having those warnings sent to the cockpit, since solving the main problem also solves the resulting additional warnings. For example, in windshear, during take-off or approach, a PWS warning could soon be followed by a GPWS warning if the crew doesn't take proper action in time. Solving the windshear problem will likely solve, or avoid the ground proximity problem too. If the ground proximity warning persists after the windshear problem has been solved, it can still be sent to the cockpit. The pilots are presented with only one problem at a time, keeping the workload as low as possible, without decreasing the safety of the airplane.

Disadvantage of the selector is that it creates an extra step in the communication channel, introducing extra time-delays before (time-critical) warnings eventually reach the cockpit. To avoid that the selector becomes a bottleneck each warning agent should be able to send warnings to the cockpit directly, bypassing the selector when it is too busy or not functioning properly. To make sure warnings reach the pilots with minimum time delays, the selector should acknowledge receiving and processing the warning information within a maximum amount of time, to the agent that generated the warning. If the acknowledgement is not received within this maximum time-delay, the warning agent sends the warning to the cockpit directly (via the interface mapper), without any more interference of the selector.

HUMAN PERSPECTIVE

Too many warning systems are overcrowding the cockpit in case of abnormal situations. Overlap in system responsibilities and contradicting or different resolution advisories create confusing situations for cockpit crews, leaving them with the difficult choice which system is generating the most urgent warnings. However, since human operators are poor performers in monitoring low probability events that must be noticed quickly, these warning systems must be available to assist them when necessary (Bainbridge, 1987). Thus integration, to reduce the number of unnecessary warnings, seems to be a logical next step in the automation of monitoring environmental factors.

Most warning systems have been introduced not only to monitor environmental abnormalities, but also to improve the pilot's situational awareness before a threatening situation arises. When a threatening situation does arise and more than one warning is generated in the same period of time, this may cause confusion in the cockpit as to which warning needs what kind of attention, but at least the pilots are made aware of the kind of situation they are in.

If, by integrating warning systems as described above, warnings are prioritized and withheld from the pilots until more important problems have been solved first, the pilots may get a wrong impression of their situation. In addition, pilots may feel uncomfortable about a system that makes decisions for them concerning critical situations regarding the safety of the airplane. The early GPWS, for example, have suffered a lot from giving too many false warnings or none when needed (Bateman, 1994), degrading the trust pilots had in the system.

The emphasis in integrating warning systems should therefore be on supporting the decision making for the pilots, rather than taking over.

Abeloos *et al.* (2000) discuss an adaptive Human-Machine Interface that supports the pilots in decision making and maintaining and acquiring situational awareness.

CONCLUSIONS.

Warning systems generate warnings that indicate abnormal situations. Cockpit crews need to spend considerable attention to recognize warning indicators, identifying the nature of the problem and choosing the correct procedure to solve the problem.

Making use of a Multi-Agent System, aircraft warning systems can be integrated on a warning message level. Two layers of integration can be distinguished: direct agent-to-agent communication, and prioritization of warning messages by a 'selector'. The direct inter-agent communication approach prevents unnecessary warnings to be generated, but reduces the flexibility of the system. Evaluation of all outgoing warnings by a selector allows the warnings to be related to many other systems and information databases, but creates an extra link in the communication chain and could become the bottleneck of the system. Warning agents should be able to by-pass the selector to avoid this problem.

The integration of warning systems should be used to support pilots in making decisions on what problem needs what kind of attention in time-critical warning situations.

REFERENCES

Abeloos, A.L.M., Mulder, M., van Paassen, M.M. (2000). The Applicability of an Adaptive Human-Machine interface in the cockpit, *19th European Annual Conference on Human Decision Making and Manual Control*, Ispra, Italy.

Bainbridge, L. (1987). Ironies of Automation, *New Technology and Human Error*, John Wiley & Sons Ltd.: 271-283.

Bateman, D. (1994). Development of Ground Proximity Warning System (GPWS), *Royal Aeronautical Society Controlled Flight Into Terrain – One Day Conference*, London.

Dismukes, K., Young, G., Sumwalt, R. (1998). Cockpit Interruptions and Distractions, *ASRS Directline*, Issue Number 10: 4-9.

Khalil, C.J. (1999). The Architecture of the AMEBICA Agent Based Adaptive Process Control Interface, *18th European Annual Conference on Human Decision Making and Manual Control,* Loughborough University, UK.

Kuchar, James K. (1998). White Paper on Multiple Independent Alerting Systems, *Written at the request of the NASA Ames Research Center and the Cargo Airline Association*, July 13, 1998.

Mellone, Vincent J. (1993). TCAS II, Genie Out Of The Bottle? *ASRS Directline*, Issue Number 4: 4-11.

van Paassen, M.M., Mulder, M, Abeloos, A.L.M. (2000). A Model for Cooperation between Humans and Intelligent Systems, *19th European Annual Conference on Human Decision Making and Manual Control*, Ispra, Italy.

Rasmussen, Jens (1983). Skills, Rules, and Knowledge; Signals, Signs, and Symbols, and other Distinctions in Human Performance Models, *IEEE-SMC* 13 No. 3: 257-266.

Wooldridge, M. J., Jennings N.R. (1995). Intelligent Agents: Theory and Practice, *The Knowledge Engineering Review* 10 (2): 115-152.