# Towards an anticipatory agent to help pilots

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**Abstract**

Flying commercial aircraft requires the crew's prediction capability to anticipate the future states of the world (failures, weather situation...), especially those that may harm the safety of the aircraft and passengers. Incident and accident analyses and experimental studies have shown that the occurrence of a conflict during flights (crew/system conflict, pilot/copilot conflict) disrupts the crew's cognitive capabilities. Therefore the idea is to design a prediction assistant, based on a joint estimation of the state of the aircraft and of the crew's actions, especially on the autopilot. The prediction of possible conflicting states will allow to enhance the crew's capability to anticipate the aircraft behavior.

## Introduction

Flying aircraft presupposes cognitive and emotional capabilities for controlling the flight and anticipating the evolutions of the environment correctly (e.g. the weather situation, incoming aircraft, Air Traffic Controller (ATC) clearances...) The cognitive capabilities support the rational process from the sensorial cues regarding the task. This process is based on the activation of the prefrontal cortex that provides executive functions like planning, working memory, focusing, shifting, inhibition (Miyake *et al.* 2000). The cognitive system interacts with the emotional system – also known as the limbic system – that plays a major role in decision making, motivation, focusing, and in "flee or fight" ancestral reactions. Both systems maintain complex inhibition/activation relations and optimize the human performance, provide accurate social reactions, and ensure survival (Simpson *et al.* 2001a; 2001b).

Under some circumstances (brain damage, stress, hypovigilance, fatigue, great age...) the homeostasis of the interactions is disrupted and may impair cognitive and emotional fonctions. It is worth noticing that the same kind of deterioration is observed both in stressed operators (e.g.: a pilot facing a major breakdown) and in brain-injured patients (i.e. frontal syndrom) performing a complex cognitive task (Pastor 2000): anticipation and planning incapacity, loss of emotional control (e.g.: aggressiveness), loss of working memory...



Recent experimental research in aeronautics (Dehais, Tessier, & Chaudron 2003) have shown that the occurrence of a conflict during flight management (e.g.: pilot/system conflict, pilot/copilot conflict...) provokes such cognitive and emotional disorders with a trend towards perseveration. This particular behavior, which is studied in neuropsychology (van der Kolk 1994) and social psychology (Beauvois & Joule 1999), is known to summon up all the pilot's mental efforts toward a unique objective (excessive focus on a single display or focus of the pilot's reasoning on a single task). Once entangled in perseveration, the pilot does anything to succeed in their objective even if it is dangerous in terms of security. Their anticipating and predicting capabilities are lost, and worse, any kind of information that could question their reasoning (like alarms or data on displays) is ignored. These findings are akin to a recently published report of the BEA[1] (the French national institute for air accident analysis) that reveals that pilots' erroneous attitudes of perseveration have been responsible for more than 40 percent of casualties in air crashes (in civilian aeronautics).

The review of neuropsychological literature has led us to design cognitive countermeasures to cure pilots from perseveration. Since adding information (e.g.: audio alarm) may have no effect to shift the pilot's attention (i.e. inhibition impairment theory (Berthoz 2003)), these countermeasures are based on information removal: the interface on which the pilot is excessively focused is removed for a while and replaced with an accurate message that is sent directly in his visual field (Dehais 2004). Such an approach based upon artificial intelligence and neurosciences paves the way to enhance teams of operators' cognitive and social interactions (e.g.: crew, ATC) to cooperate with intelligent and semi-autonomous agents (onboard systems, autopilot). The idea (figure 1) is therefore to:

- formally anticipate aircrew/onboard system conflicts, which are known as remarkable precursors of loss of situation awareness,
- design cognitive countermeasures suited to neural data processing to assist aircrew facing a cognitive conflict.

[1] http://www.bea-fr.org

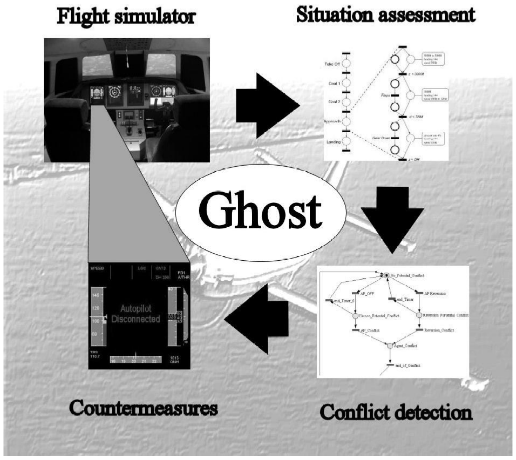


Figure 1: Ghost: estimate, detect, help.

## Pilots, autopilot and shared authority

Modern commercial planes can be considered controlled by two agents: the human agent (the crew) and the artificial agent (the autopilot and the Flight Management System (FMS)). The flight is realized under the interaction of another human agent: the ATC, who can order any modifications for the flight: altitude clearance, heading, holding pattern, airport approach.

Modern autopilots and FMSs are designed to increase the flight safety by reducing the aircrew workload. They are complex state-machines, able to manage a preprogrammed flight from takeoff to landing with very few crew actions during the flight. They manage the flight in the "lateral mode" (i.e. Navigation) and in the "vertical mode" (i.e. optimizing the performance during the Climb, Cruise and Descent phases of the flight), but the crew can select some flight parameters (for example the Heading in the "lateral mode" or the Vertical Speed in the "vertical mode"...), in order to follow the ATC's instructions.

The human agent can always have the priority on the artificial agent. The crew can always disengage the autopilot, reconfigure the FMS or go "back to the basics". However, in particular conditions (protection of the flight domain), the autopilot makes a "mode reversion", i.e. an automatic state modification to anticipate an overspeed or underspeed and, if the speed limitation is reached, the autopilot automatically disengages.

It is easy to understand that such complex interactions may induce conflicts, especially during "abnormal operations".

Let us review three real incidents for which we have identified three kinds of conflicts between the human and the artificial agents:

1. Automatic disconnection not perceived by the crew: the autopilot sent the control of the flight back to the crew, while the aircrew still thought that the autopilot is in control. Every disconnection of the autopilot is signaled by an audio warning and a visual warning on the cockpit alarm display. But when the autopilot is disconnected after an overspeed for example, the overspeed audio warning has priority on the autopilot disengagement audio warning. The crew applied the overspeed procedure, but did not notice the autopilot disconnection (BEA 2002 2003a).
2. Inconsistent orders to the autopilot: an order can be consistent in some phases of the flight, but not consistent in other phases. In this particular case, the autopilot was in the approach mode (APPR), at 1200 ft Above Ground Level (AGL), the pilot not flying (PNF) selected a new waypoint on his MCDU (Multifunction Control Display Unit). At this time, the autopilot mode changed from APPR to NAV (managed navigation) and V/S (vertical speed, automatically set at the current vertical speed, here -1000 ft/min). The crew did not immediately perceive the changes and the plane leveled off around 400 ft AGL (BEA 2002 2003b).
3. The autopilot and the crew have different goals: the selection of a specific mode by the crew has unexpected consequences on the autopilot behavior. A typical example of this kind of conflict is the inadequate selection of the Go Around altitude on the autopilot interface (FCU) when the autopilot is in the Glide/Slope (G/S) mode, i.e. descending on the ILS path. At this time, if the plane reaches a too high speed due to its configuration (for example during flaps extension) the autopilot automatically discards the G/S mode and tries to reach the target altitude. The plane climbs whereas the crew wish to land (Crow, Javaux, & Rushby 2000).

As a matter of fact, conflicts stem from a bad design of the shared authority between the crew and the autopilot.

Generally speaking shared authority is the way the decision functions are shared out among the various agents involved in a mission. Most of the time, shared authority implies that artificial (i.e. non-human) agents are equipped with a certain level of "autonomy" with regard to the particular decisional agents the human agents are – this is the case for example in collaborative control (Fong, Thorpe, & Baur 2003) or in mixed-initiative control (Murphy 2000) – as *people can provide valuable input that improves the performance of the system* (Scerri *et al.* 2003). It is worth noticing however that autonomy is neither an end in itself nor an absolute notion (Steels 1995), but aims at meeting specific operational requirements within a well-defined context. Consequently, autonomy necessarily implies a shared authority between agents at a certain time scale and at a certain decisional level. As a matter of fact, autonomy and shared authority are dual concepts for the same notion.

The key issue of shared authority is *situation assessment* i.e:

1. Maintaining the human agents' situation awareness (Endsley 2000; Nofi 2000) i.e. their understanding of the current state of the automatisms, of the environment, of the (flight)plan execution, and of how the various states are likely to evolve in the near future. The situation awareness has to be:

- suited to the operators' roles within the mission,
- consistent with the current automatism / autonomy levels of the artificial agents (i.e. consistent with the operators' current control level on the artificial agents),
- consistent with the current mission phase (Murphy 2004),

so as to enable the operators to send relevant orders.

2. Maintaining situation assessment for the artificial agents, i.e. the current models and predictions the agents have for themselves, for the environment, for the execution state of the (flight)plan, for the operators' actions. The situation assessment has to be:

- suited to the current automatism / autonomy levels of the artificial agents,
- consistent with the current mission phase,

so as to allow the automatic triggering of relevant actions.

Therefore intelligibility must be mutual. For instance, the task context must not be lost when an automatism (the autopilot) cedes control to the human agent (the crew), so as to prepare for a return to the automatism control (Brookshire, Singh, & Simmons 2004).

What is suggested to guarantee an intrinsic consistency of situation assessment, is a way to estimate and predict the states of both human operators and automatisms through a unified hybrid model, so that any agent might keep a relevant and consistent awareness / knowledge of the situation through a common reference and switch authority levels with full knowledge of the facts. This approach is significant for the autopilot / crew system as the autopilot is designed in such a way that (1) its communication with the crew is quite poor and (2) the details of shared authority are not always clear to the crew.

## A prediction assistant

The aim of the system presented in this paper is to help both automatic and human agents estimating and predicting the aircraft behavior. The estimation is performed using (1) the *particle Petri net* model (Lesire & Tessier 2005) to represent the aircraft–pilot interactions and evolutions and (2) classical Petri nets to represent the autopilot functioning. The estimation principle allows *inconsistencies* to be detected and studied, thus helping the crew understanding the autopilot behavior and anticipating possibly dangerous situations.

### Petri nets (refresher)

A *Petri net* $< P, T, F, B >$ is a bipartite graph with two types of nodes: $P = \{p_1, \ldots, p_i, \ldots, p_m\}$ is a finite set of places; $T = \{t_1, \ldots, t_j, \ldots, t_n\}$ is a finite set of transitions (Petri 1962; David & Alla 2005). Arcs are directed and represent the forward incidence function $F : P \times T \rightarrow \mathbb{N}$ and the backward incidence function $B : P \times T \rightarrow \mathbb{N}$ respectively. An *interpreted Petri net* is such that conditions and events are associated with places and transitions. When the conditions corresponding to some places are satisfied, tokens are assigned to those places and the net is said to be marked. The evolution of tokens within the net follows transition firing rules. Petri nets allow sequencing, parallelism and synchronization to be easily represented.

### Predicting the aircraft state...

Estimating and predicting the aircraft state and the crew's actions are performed using a hybrid model whose numerical part represents the continuous evolution of the aircraft parameters and the symbolic part represents the crew's actions on the aircraft and on the autopilot.

Let us consider the Climb phase. The particle Petri net of this phase is shown in figure 2. The first step consists of a climb (FL $\nearrow$) and acceleration (S $\nearrow$) of the aircraft while the pilot has to set the gear up, set the FCU altitude to flight level 210 (FL 210), engage autopilot 1 (AP1) and mode thrust/climb (THR/CLB). When the 300kt-speed is reached (S$\geq$300), the aircraft goes on climbing (FL $\nearrow$) at a 300kt-speed (S 300). When FL 210 is reached, the Climb phase is completed, and the aircraft enters the next phase (Cruise). If an overspeed warning appears (coming from the autopilot Petri net), the procedure is to set speed brakes (SPD BRK). Then the speed decreases (S $\searrow$), and when a "normal" situation is recovered (S $\leq$ 300), the pilot has to engage the autopilot again (AP 1).

Tokens $\pi^{(1)}$, $\pi^{(2)}$, $\delta^{(1)}$ represent the current estimated situation:

- *particles* $\pi^{(1)} = \{Speed260, FL180, Heading53\ldots\}$ and $\pi^{(2)} = \{Speed270, FL185, Heading53\ldots\}$ are two probable numerical vectors corresponding to the estimated aircraft parameters;[2]
- $\delta^{(1)} = \{GearUp, FL210\}$ is a possible symbolic vector representing the aircraft (and autopilot) *configuration*.

Prediction is achieved through the computation of the *reachable markings* of the Petri net, i.e. the set of expected states. Let us consider the initial marking (the current situation) the Petri net on figure 2. The possibly future situations are those where the crew has engaged AP1 and mode THR/CLB, and where the aircraft parameters are predicted according to differential equations associated to places "climb and accelerate" and "climb" respectively (figure 3).

Correction is achieved through the comparison and selection of the "best" matchings between the predicted tokens and a new observation. The numerical correction consists in weighting the particles according to the noisy numerical measure. The symbolic correction consists in ranking the configurations according to a partial preorder. Finally, corrected particles and configurations are matched. This *hybrid matching* allows to:

- *resample* a marking, when it corresponds to both numerical and symbolic measures and is consistent: the particles are resampled and the configuration is kept for the next prediction step;

[2] For the sake of clarity only two particles are considered in this paper. In fact the higher the number of particles, the better the representation of the uncertainty on the aircraft state.

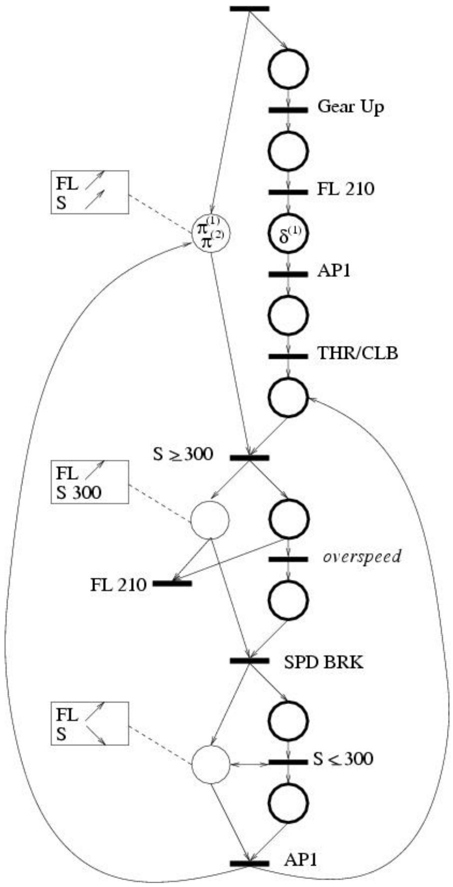


Figure 2: Particle Petri net for the Climb phase: numerical places (in lite) represent the continuous evolution of the aircraft state according to differential equations; symbolic places (in bold) represent the discrete evolution of the aircraft configuration according to the crew's actions.

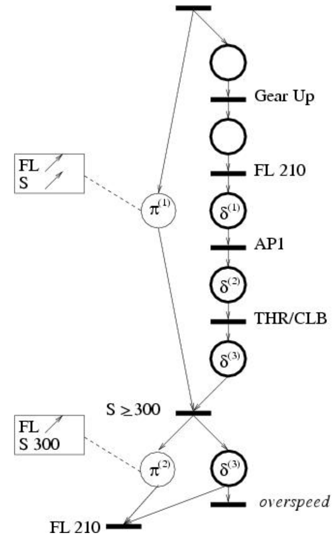


Figure 3: Marking of predicted situations.

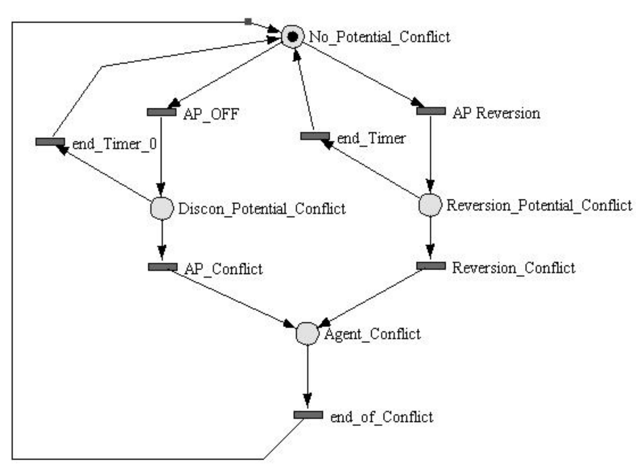


Figure 4: Autopilot Petri net (implemented with ProCoSA (Barrouil & Lemaire 1999)).

- *discard* a marking, when it does not correspond to the measures;
- analyse a marking when it corresponds to the measures but is *inconsistent* (it does not correspond to a reachable marking of the Petri net).

The next section introduces the *overspeed* detection and its relation to prediction and conflict detection. Then the case of *inconsistent matchings* is detailed, as it may reveal possible conflictual situations.

## . . . and detecting conflicts

The Petri net of figure 4 corresponds to the Pilot/Autopilot conflict detection process. The initial place (No_Potential_Conflict) represents the "normal" state, i.e. when the autopilot controls the aircraft. The next two places represent two possible states of potential conflict: (1) autopilot automatic disconnection (AP_OFF transition has fired) and (2) autopilot mode reversion (AP_Reversion transition has fired). When one of these transitions fires, two processes are run: a timer and a conflict detection process.

Detecting inconsistencies (and consequently conflicts) in the crew's actions or in the aircraft state is based on the estimation principle presented in the previous section. Let us consider the following scenario: during the climb to flight level 210, a jet stream makes the aircraft accelerate. The result is an overspeed that disengages the autopilot. A conflictual situation may come from: (1) the crew do not notice the autopilot is not engaged any longer, or (2) the crew engage the autopilot, but if the target altitude (level 210) has been overshot, the autopilot mode switches to V/S and the aircraft keeps on climbing indefinitely (whereas it should descend to reach level 210). The current estimated situation is marking $(\pi^{(2)}, \delta^{(3)})$ within figure 3 Petri net. The overspeed event is caught by the autopilot Petri net (AP_OFF transition fires, figure 4), that enables the *overspeed* transition of the particle Petri net of the Climb phase. Then the estimation process goes on considering the overspeed procedure. Let the predicted situation be the marking shown in figure 5, where the tokens values are such that

- within particle $\pi^{(1)}$, the speed is 280kt, and FL 215;
- within particle $\pi^{(2)}$, the speed is 300kt, and FL 220;
- within configuration $\delta^{(1)}$, speed breaks are set, and AP 1 disengaged;
- within configurations $\delta^{(2)}$ and $\delta^{(3)}$, the AP is engaged in mode climb (CLB).

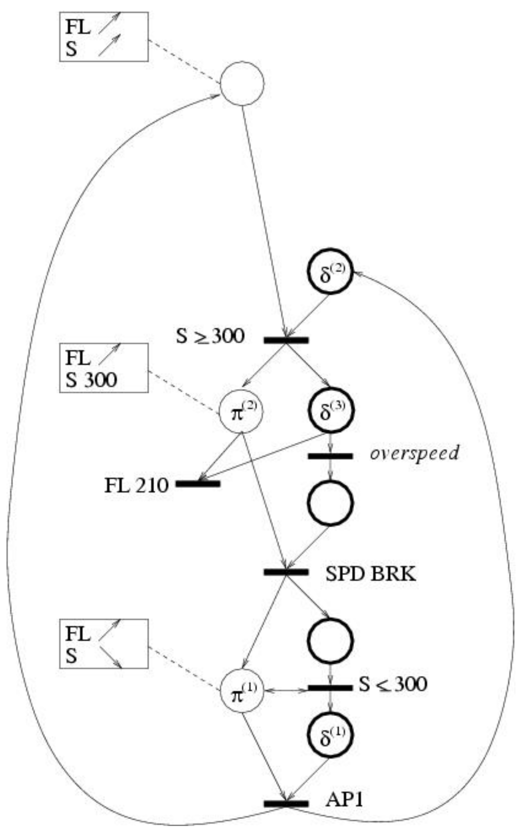


Figure 5: Predicted states after the overspeed event.

The predicted markings are then updated according to the correction step. Three cases can be pointed out:

- The timer goes out while no inconsistent marking has been detected, and
  1. the corrected states (according to the measures) do not mark the "overspeed procedure" part of the Petri net: the end_Timer transition (figure 4) fires and the Petri net goes back to a "normal" situation;
  2. an estimated state is marking the "overspeed procedure" part of the Petri net: $\delta^{(1)}$ situation reveals that the crew may have forgotten to engage the AP, which is considered as a *Conflict*;
- Correction results in an *inconsistent marking*: the symbolic observation is such that the AP is engaged and mode Vertical Speed is selected. Particle $\pi^{(2)}$ corresponds to the numerical observation (numerical correction), but no predicted configuration corresponds to the symbolic observation. Therefore marking $(\pi^{(2)}, \emptyset)$ is inconsistent, and a *Conflict* is sent to the autopilot Petri net.

Finally, when a conflict is detected by the estimation process, the Conflict transition within the autopilot Petri net fires and the Agent_Conflict state is reached. At this time, the purpose is to send cognitive countermeasures to enhance the crew's capability to anticipate the behavior of the aircraft.

## Further research

The next step will consist in an empirical validation of the predicting tool with pilots in the 3-axis Airbus flight simulator at Supaero. The idea is to conduct experiments where aircrews will be placed in conflictual situations with the automatic systems.

A first challenge of these experiments is to test the tool capability to anticipate real pilot/autopilot conflicts: both objective (flight parameters analysis) and subjective (debriefing with pilots) methods will be used to assess its effectiveness . The second challenge is to determine on which display the countermeasures should be sent to assist the crew facing the conflict. The idea is to use an eye-tracker to analyse gaze motion and fixation points in the cockpit according to each flight phase.

Eventually, another interesting challenge for air safety is the online detection of cognitive deterioration like perseveration: a solution could consist in an empirical integrative approach including stress physiological indicators (occulomotricity parameters, electro dermal response, voice tone), and the use of electro encephalogram. These physiological parameters are planned to be integrated in the prediction tool so as to anticipate conflicts as early as possible.

## References

Barrouil, C., and Lemaire, J. 1999. Advanced real-time mission management for an AUV. In *Symposium on Advanced Mission Management and System Integration Technologies for Improved Tactical Operations*.

BEA. 2002-2003a. Débrayage du pilote automatique (in French). www.bea-fr.org/itp/events/debrayagpa/debrayagpa.html.

BEA. 2002-2003b. Ecart de trajectoire (in French). www.bea-fr.org/itp/events/ecartdetrajectoire/ecartdetrajectoire.html.

Beauvois, J., and Joule, R. 1999. A radical point of view on dissonance theory. In Harmon-Jones, E., and Mills, J., eds., *Cognitive Dissonance: Progress on a Pivotal Theory in Social Psychology*.

Berthoz, A. 2003. *La décision (in French)*. Odile Jacob.

Brookshire, J.; Singh, S.; and Simmons, R. 2004. Preliminary results in sliding autonomy for coordinated teams. In *Interaction between humans and autonomous systems over extended operations*, AAAI Spring Symposium, 127–132.

Crow, J.; Javaux, D.; and Rushby, J. 2000. Models and mechanized methods that integrate human factors into automation design. In *HCI-AERO'00*, 163–168.

David, R., and Alla, H. 2005. *Discrete, Continuous, and Hybrid Petri Nets*. Springer.

Dehais, F.; Tessier, C.; and Chaudron, L. 2003. Ghost: experimenting conflicts countermeasures in the pilot's activity. In *IJCAI'03*.

Dehais, F. 2004. *Modélisation des conflits dans l'activité de pilotage (in French)*. Ph.D. Dissertation, ENSAE - Supaero, Toulouse, France.

Endsley, M. 2000. Theoretical underpinnings of situation awareness: a critical review. In Endsley, M., and Garland, D., eds., *Situation awareness analysis and measurement*. Lawrence Erlbaum Associates.

Fong, T.; Thorpe, C.; and Baur, C. 2003. Multi-robot remote driving with collaborative control. *IEEE Transactions on Industrial Electronics* 50(4).

Lesire, C., and Tessier, C. 2005. Particle Petri nets for aircraft procedure monitoring under uncertainty. In *ATPN'05*.

Miyake, A.; Friedman, N.; Emerson, M.; Witzki, A.; and Howerter, A. 2000. The unity and diversity of executive functions and their contribution to complex "frontal lobe" tasks: a latent variable analysis. *Cognitive Psychology* 41.

Murphy, R. 2000. *Introduction to AI Robotics*. The MIT Press.

Murphy, R. 2004. Human-robot interaction in rescue robotics. *IEEE Systems, Man and Cybernetics Part C: Applications and Reviews, special issue on Human-Robot Interaction* 34(2).

Nofi, A. A. 2000. Defining and measuring shared situation awareness. Technical Report CRMD0002895.A1/Final, Center for Naval Analysis.

Pastor, J. 2000. Cognitive performance modeling - assessing reasoning with the EARTH methodology. In *COOP'00*.

Petri, C. 1962. *Kommunikation mit Automaten*. Ph.D. Dissertation, Institut für Instrumentelle Mathematik, Bonn, Germany.

Scerri, P.; Pynadath, D.; Johnson, L.; Rosenbloom, P.; Si, M.; Schurr, N.; and Tambe, M. 2003. A prototype infrastructure for distributed robot-agent-person teams. In *AAMAS'03*, 433–440.

Simpson, J.; Drevets, W.; Snyder, Z.; Gusnard, D.; and Raichle, M. 2001a. Emotion-induced changes in human medial prefrontal cortex: I. During cognitive task performance. *PNAS* 98(2).

Simpson, J.; Drevets, W.; Snyder, Z.; Gusnard, D.; and Raichle, M. 2001b. Emotion-induced changes in human medial prefrontal cortex: II. During anticipatory anxiety. *PNAS* 98(2).

Steels, L. 1995. When are robots intelligent autonomous agents? *Robotics and Autonomous Systems* 15(1-2):3–9.

van der Kolk, B. 1994. The body keeps the score: memory and the evolving psychobiology of post traumatic stress disorder. *Harvard Review of Psychiatry* 1.