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Simulation Based Situation Awareness Training for Control of Human-Machine-Systems

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Abstract

We present a novel method to facilitate simulation based training for controlling complex and dynamic human-machine-systems (HMS) using experts' cognitive models. Example applications in en-route air traffic control (ATC) and chemical process industry exist resp. are being developed.

First we introduce the notion of human-machine-systems and argue for the application of and need for simulation based training in HMS. Then we discuss the important engineering psychology concept situation awareness. *Previous attempts in situation awareness training for aircraft pilots [2] have introduced context based state monitoring (CBSM) deploying finite state machines and attention guidance with moving color codes in simulation displays. Gopher positively evaluated [5] that attention guidance in simulation training has an effect on real-world performance in situations where distribution of attention is important. We present domains where CBSM is not applicable. For such domains our approach is to get information on importance of simulation elements from parallel simulations of experts' cognitive models and use it to direct the trainee's attention. We further present the conception of an evaluation of the ATC training system that is being conducted using eye tracking, memory tests and performance data.*

1. Introduction

Operators in complex and dynamic human-machine-systems (HMS) are required to monitor the state of a technical system and to intervene e.g. by setting command variables according to external demands. The state is normally computer mediated and presented via a graphical user interface. The overall dynamics of human-machine-systems results from the internal dynamics of the technical system and further from actions the operator can initiate. From a certain degree of complexity on future states of the technical system cannot be all sufficiently enumerated in advance. Thus during development time of a training system it is not possible to plan all possible system conditions and training treatments without limiting the life-likeliness of it. Using simulations of the involved processes and feeding trainee's actions back into it yields in a more realistic training scenario that takes complexity into account.

1.1. Situation awareness

Operators have to make decisions for actions to be initiated upon perceived or deduced information about the system's state. If cost (in terms of time or physical effort needed) of getting this information is too high in time critical situations the operator has to fall back on a mental copy of the situation from where the information needed can be taken.

The concept *situation awareness* (SA) is defined as the knowledge an operator has about the objects and their features that constitute the situation under control. Endsley and Smolensky [4] divide it into three levels:

1. Knowledge about the current state of objects.
2. Knowledge about the relevance of objects for the current situation.
3. Knowledge about future states of objects.

The first two levels are important to cope with the control task's complex system demands. Graphical user interfaces mediate information on the state of objects. In dynamic systems level three SA is often useful or even necessary to meet the task requirements.

A representation of the situation has to build up initially. After that two different processes affect the degree of SA: The representation has to be kept current by continuous "updates" of object features. A selection of relevant objects has to be made if cost for update is too high because access to up-to-date information cannot easily be achieved or too many objects had to be monitored. Knowledge about the meaning of objects in the current situation is essential to get to a reasonable selection set.

This knowledge is a result of active processing during operation as well as of learned rules about recurring constellations and standard operation procedures.

2. Situation awareness training (SAT)

Different factors influence the process of building up and maintaining SA. They result from individual prerequisites, task requirements and their presentation. Some individual requisites can be enhanced by training.

Especially the skill to distribute one's attention across different task elements is one of them. And just that is essential for control of complex dynamic situations and to maintain SA. Gopher [5] reports respective results from training jet fighter pilots. A computer game was used in which a complex and dynamic problem was presented to guide attention by visual cues. Subjects showed different performance in real jet fighter missions depending on the degree of attention guiding. This applied especially in situations with high cognitive workload.

Computer based SAT can be sufficiently deployed in complex and dynamic HMS (e.g. [2], [3]). Depending on the organizational conditions computer based job training can be cost efficient and – as self-paced learning – motivating. Computer based training for controlling HMS can only be done using simulations because of the dynamics such systems have [7]. It is a reasonable approach to guide the trainee's attention – enhancing SA level two – to relevant elements of the simulated task environment e.g. through using changing color codes of interface objects in a simulator. We assume that this approach supports trainees learning strategies for selective and goal-oriented perception. It has already been applied in jet pilot training [2]. A diagnostic component is needed to select for relevant information in the task environment necessary for maintaining SA. It has to estimate pertinence of elements and their features for control of the current situation.

2.1. Context based state monitoring

In some human-machine-systems (HMS) an adequate method is *context based state monitoring* [2]. Meaningful states of the system under control are represented by states of a finite automaton. Certain states are linked with training interventions that are executed when the state is reached. Trainees' actions, the system's behavior and outer noise are used as triggers for transitions of the finite automaton.

Bass [2] describes different training interventions that build on the diagnosed state: There is a *coaching display*, which shows a list of support messages of three categories different in sorting and presentation ("warning", "caution", "advisory"). A *textual debriefing* is automatically generated after every training session from the automaton's log-file of the visited states, which suggests special demands for the future. *Attention guidance* through moving color coding of elements in the training simulator.

Jones [6] adds further information that presents aspects of SA of simulated pilots to a simulated military ATC system: An additional window presents *active goals*, *important actions* of the software agents and *state of aircraft*. Although the current system is designed to support developers of military simulations an application in training would be thinkable.

2.2. Model based state monitoring

Context based state monitoring cannot be deployed in all HMS because the complexity induced state space might be too big for development time linking to training interventions. Especially if the actions of operators/trainees are not only possible at some few fixed points in time or if different times of action or sequences result in different situations finite state machines are not sufficient to diagnose the relevance of objects context based.

Instead a model-based concept has been developed for such HMS [7]. With this approach a simulation of a model of the cognitive activities of expert operators is used to deduce relevance of objects and features in a situation. The cognitive model "watches" the technical system just as an expert would do and builds up a representation of the current situation. Objects are combined to relations and prioritized through task specific (simulated) mental processes. This representation is read out of the running simulation of the cognitive model and is used for controlling of SAT e.g. by attention guiding with moving color cues.

Modeling cognitive processes is often done using *production systems* where semantic networks are taken to represent perceived or deduced information. Chunks are nodes in the net describing objects or state variables. Links between them constitute dependencies, constellations or known causal relationships. Every chunk then gets a numerical value that stores importance or attention demands and that controls and is altered by mental processing and perception. This relevance value is propagated through the semantic net. Thus attention is spread between related entities of the situation.

Model based state monitoring has already been applied for air traffic control training [7]. The cognitive simulation for this system is built on top of a cognitive model that reproduces the mental representation of the current traffic on the basis of information selection and anticipation processes [9]. The model is formulated within the cognitive architecture theory ACT-R [1].

3. Applications

The proposed approach to model based SAT can be applied independently of the domain where complexity and dynamics of the HMS do not permit prediction of future states when a training system is being developed.

Training SA requires especially information selection strategies that permit reducing information overload to situation specific needs and updating internal representation where necessary. This section deals with systems that support the acquisition of such strategies in domain specific training environments.

3.1. En-route air traffic control

Demands in en-route air traffic control (ATC) are high: Controllers have to monitor many aircraft and their features on a radar screen at the same time. Dangerous approximations have to be anticipated in advance and pilots have to be instructed via radio link accordingly. Actions have to be planned in a way that comfort of passengers, safety and economic efficiency are met. Conflict resolution may not lead to consecutive clashes, which requires further mental simulation. En-route ATC is a team-afford: During normal operation two persons are in charge for one sector that is a spatially defined part of the whole area under ATC. One person in this team is the planning controller who's focus is mid-term: He or she uses flight strips to be informed of coming aircraft and coordinates with planning controllers of neighbor sectors. The other controller is the executive controller who operates directly with the radar screen and coordinates on short a term basis with the pilots in the controlled sector.

The behavior of this system is dynamic: Aircraft are constantly entering and leaving the sector, they possibly don not behave as planned in advance (illegally alter direction, speed or altitude without being instructed to do so or if instructed they change to quickly or slowly). This results in the need to continuously establish, evaluate and maintain new relationships between aircraft objects thus constant attention onto the traffic is necessary. The controllers have to use certain strategies for selecting potentially hazardous or monitoring-requiring aircraft because a distance relation exists between every possible pair of them and the combinatorial complexity has thus to be reduced by producing and using knowledge about the changing state of objects and their relevance for the current situation.

Taking this task and its requirements into account we have applied the model based SAT concept for the ATC domain as a simulation based training system for self paced learning [7].

The system can either be installed as a single workplace or in a training network between several trainees. It consists of a simplified airspace simulation that is controlled via one or more "ghost-pilot" consoles and connected radar screens (s. Figure 1), which display aircraft (positions and features such as altitude, speed etc.), sectors, and airways. SAT-support is done with moving color cues between aircraft that's purpose is to facilitate attention sharing, distribution and direction. The diagnosis of the current state is accomplished by model based state monitoring.

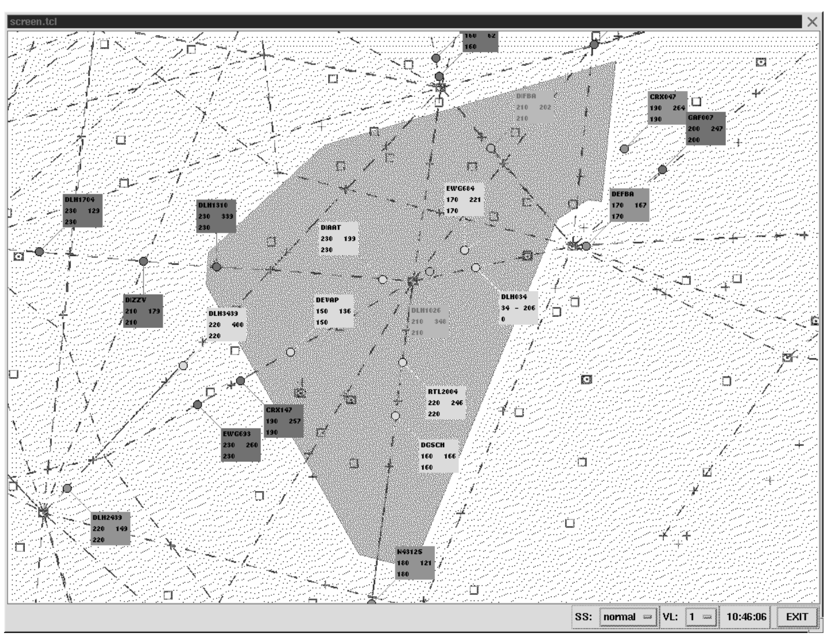

Figure 1. ATC-radar screen with color cues.

A cognitive model of experienced air traffic controllers' mental activities [9] is run (simulated) in parallel to the airspace. The model "looks" on the radar screen and builds up an internal traffic representation using information selection and processing rules. The current and future relevance of aircraft objects is then read out of the mental representation and reflected through color cues in this display (see Figure 1).

The mental representation is the result of a knowledge-based anticipation of the future movements. Objects that are reproduced are airways, aircraft, and relations between all of them. Some aircraft are for example connected with their current airway, airways are in relation with other that they cross or aircraft have "conflicts" relations between them. Especially every aircraft is marked as belonging to one of the following attention relevant categories that are reflected in the training display: "not under control", conflict(s) exist", "must be monitored", "has signal features", "safe". The attribution of one aircraft will change during a training simulation session because of further information that is to be integrated into the mental representation.

The cognitive model has been expanded with functions that permit the simulation to transfer the current state of the simulated mental model of the traffic situation to the radar display as color cues (see Figure 1).

The trainee is presented attention distribution strategies through the scheduling characteristics of the cognitive model and their presentation in the display. They permit the trainee to develop own perception and attention sharing processes through induction and help to construct own structures for a mental model of traffic and airspace.

3.2. Chemical process industry

In the wide area of process control in chemical plants we focus on continuous processes that are run with distributed control systems. These systems are used as platform for automatic control of the processes and provide a control room operator with access to all measured process variables through graphical interfaces. The operators task typically is to choose relevant process variables from a multitude of accessible ones, monitor them, and condense them to a model of the state of the process. Derivations from normal operations have to be anticipated and where necessary interventions have to be planned in a way that the quality and quantity of overall production is least possibly disturbed. The possibility of conflicts with plants in the neighborhood has to be considered. Typical interventions are setting process variables, establishing changes in the use of resources, and the automatic and manual control of utility units. Further actions include management of alarm messages, execution of start-up and shutdown procedures, and planning and execution of product changeover. The operators use different types of process display windows to achieve these tasks: graphical process display, groups of faceplates, trend displays and event and alarm lists.

Continuously operated systems are at least stepwise structural invariant i.e. process elements and their relations do not change like they do in the ATC domain. Nevertheless, due to switching of utility units or changing of energy or mass-integrating streams the dynamic behavior of the system and the situation specific meaning and importance of single process variables can show significant variance [8]. This entails, that the availability of information on the past as well as the proper maintenance of a certain prediction horizon is crucial for proper operation of chemical plants and consequently indicates that SAT would be beneficial for training in this domain.

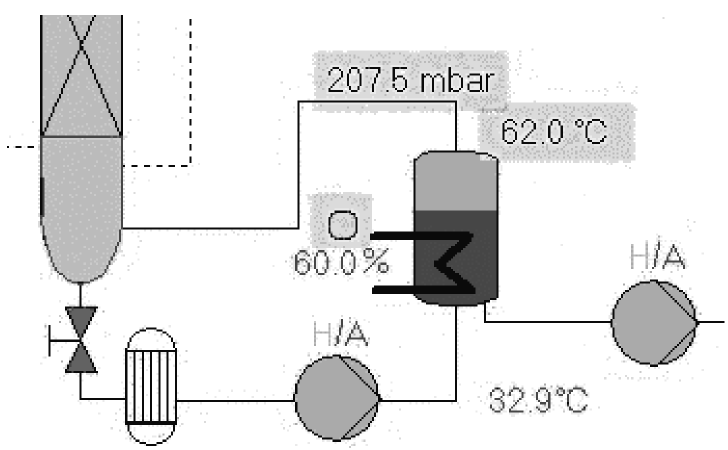

Figure 2. Process with color cues for attention guidance.

The strategy of a priori selection and evaluation of data and activities for context based state monitoring is applicable only to a very limited range of systems and scenarios. Because of the high degree of freedom and the multitude of possible interventions by the operator a model based state monitoring approach has to be chosen to implement SAT for the chemical process industry.

Some tasks of the operators, in particular “selection of relevant process variables”, “evaluation of single process variables”, and “evaluation of constellations”, can be supported with color cues analogous to the strategies used in ATC training. Figure 2 shows an attempt to visualize positive evaluation of the values of pressure, temperature and state of heating by the expert model.

In contrast to the ATC domain the process control and supervision tasks of the operators often require an explicit evaluation of the dynamics of the system. We have conducted a task analysis of the start-up of a desorption plant which shows strong evidence for the importance of trend displays (see Figure 3) for interpretation of temporal plant behavior. Single parts of a trend were labeled “shoots over”, “increases”, “within normal variation”. Furthermore the trend is actively searched for the evidence of expected temporal and dynamic behavior. Figure 3 presents some typical patterns for semantic accentuation: The characteristic response of a damped system is emphasized through its deactivation curve. The similar pattern for repeated disturbance is presented with a box. Parallel lines point out an expected linear increase.

4. Conclusion and perspective

First experiences with the ATC training system show that the proposed model based SAT approach is an encouraging way to support self paced learning in complex and dynamic HMS.

We have started an evaluation of the ATC training system. Since it is extreme costly to investigate the long time effect of training strategies – as they are needed for expert domain SA (esp. level three) – we concentrate on the aspect of attention guidance and subjects’ performance. In a two-day experiment novice subjects control air traffic in a sequence of short scenarios alternating with and without SAT support (control group: no support system) after a CBT introduction. We use eye tracking, performance measures (quality of interventions) and memory tests on aircraft positions and features (conventional SA test) to study learning effects.

We plan to introduce a fading mechanism later: The SAT support should slowly disappear as the trainee gets better in the control task thus facilitating transition to the operational system.

A result of a task analysis and general system’s features in the process control domain support plans to apply the SAT concept there. To prove its capacity a process control training simulator [10] is currently expanded with the transferable elements from the ATC system.

5. Acknowledgement

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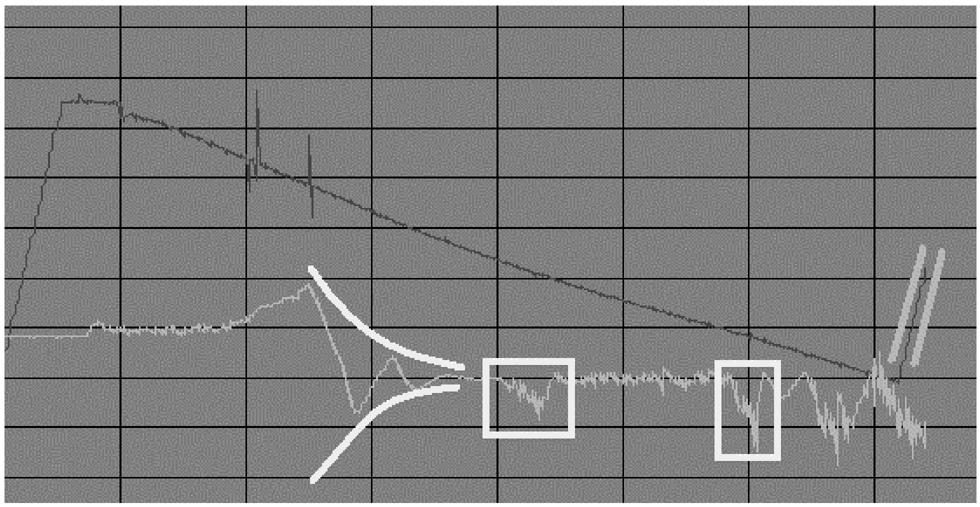

Figure 3. Trend picture with color- and shape codes.