The Architecture HuFaNCO - Modeling Imperfect Human Information Processing with Special Reference to Network Centric Operations

Bernhard Schneider and Gunther Schwarz
EADS Deutschland GmbH, System Design Centre Germany, SDGE1
Landshuter Straße 26, D-85716 Unterschleissheim
bernhard.schneider at eads dot com / gunther.schwarz at eads dot com

Dietmar Kunde, PhD
LTC, German Army
Federal Office for Information Management and Information Technology of the Bundeswehr
Ferdinand-Sauerbruch-Straße 1, D-56073 Koblenz
DietmarKunde at Bundeswehr dot org

Keywords:
Agent-based simulation, human factors modeling, attention dynamics, information filtering, situational awareness, anticipation, decision making, Naturalistic Decision Making, NCO, CROP

ABSTRACT: This paper presents new general agent architecture (HuFaNCO) for simulating a human decision maker as a single node embedded in Network Centric Operations (NCO) scenarios. The architecture is structured modularly and integrates psychologically funded modeling concepts for selected aspects of the human information processing system such as information intake and filtering based upon attention dynamics, situational awareness and problem solving strategies such as evaluation of decision trees. The modeling approach takes into account the influence of stress in terms of arousal, exhaustion and time pressure on the quality of results generated by the modeled cognitive functions. First experiments with a simulation model based on the architecture HuFaNCO demonstrated the capabilities to reproduce human errors concerning situational awareness and decision making in a realistic fashion.

1. Introduction

The relevance of NCO and especially Common Relevant Operational Picture (CROP) is obvious for increased effectiveness of nowadays military operations in terms of enhanced speed of decision making, increased tactical agility and in consequence higher effectiveness and reduced risks for our forces. The development of strategies and processes to establish a shared situational awareness as an expression of CROP based on increased quality of information hence seems to be one of the key challenges that armed forces have to face.

Simulation is a tool that enables military experts to analyze and, in the long term, improve NCO processes. Due to the fact that quality of information in NCO by means of CROP depends not only on the capabilities and performance of deployed technical systems, the human expert working with CROP systems and generating CROP data has clearly to be taken into account in related simulation models. Factors like stress, emotional arousal, and physical constitution etc. that can possibly result in suboptimal or erroneous reactions of human beings to specific situational demands have to be considered.

One approach in the direction of modeling the influence of the human factor on CROP quality was taken by an R&D study activity concerning the modeling of human factors in NCO conducted by EADS Deutschland GmbH, System Design Centre Germany on behalf of the Federal Office for Information Management and Information Technology of the Bundeswehr in the years 2005-2008. That work focused on introducing human factors in NCO simulation by incorporating modeling approaches for selected aspects of the human information processing system such as attention dynamics, information filtering, situational awareness and the human decision making process.

This paper concentrates on describing the overall modeling approach and the agent architecture. Additionally, we present first simulation results gained by experiments with the respective agent-based simulation model performed in the course of plausibility considerations.

Related Work

To date, there is a variety of attempts to model human information processing. Of special interest for the research work to be presented are approaches to model reduced human performance as presented by Wellbrink (2003). Some approaches regard especially the interplay between emotion and the quality of human decision making. Belavkin (2001) investigated effects of
emotion during problem solving based upon ACT-R cognitive architecture. Marinier (2008) combined a cognitive theory of behavior control and a theory of emotion in a unified computational model. Besides, there are approaches to model arousal’s impact on memory. Cochran (2006) proposed a framework for emotion to be included in an integrated cognitive architecture that does originally not account for emotions. The idea to employ decision trees in the decision making process as suggested by Kunde and Darken (2006) was adapted for the research work to be presented.

2. HuFaNCO Agent Architecture

The HuFaNCO agent architecture is composed of six main modules: Perception, Anticipation, Conflict Resolution, Acting, Memory and Stress. Each module comprises a set of cognitive processes. Additionally, instances of a Rule System are embedded in the architecture. Figure 1 shows the flow of information in a single simulation step starting from a simulated C2 information system and flowing through the single modules. The modules will be described in detail in the following paragraph.

![Figure 1: Modules and flow of information](image)

2.1 The Module “Stress”

By investigations during the field test of a new C2I system 2006 in Germany, a set of four variables could be established, which seemed to influence a human operator's capability to process information the most: the operator's emotional arousal, the degree of motivation, the amount of cognitive resources and time pressure.

The agent's emotional state is expressed by a single state variable called Arousal. The modeling of the dynamics of an agent's arousal is leaned on a concept suggested by Schmidt & Schneider (2004) that is funded on the Theory of Cognitive Appraisal for Emotions, as described in detail by Cañamero (1997), Moffat et al. (1995) and Ortony et al. (1988).

The value of the state variable Arousal decreases continuously over time if the agent does not recognize any fear-inducing stimulus. If the agent e.g. receives a report concerning a possible bomb attack in the mission area, the value for the state variable increases discretely. The strength of the increase depends on the distance between headquarter and the center of the bombing area weighted by a personality constant that represents the agent’s innate fearfulness. This can be seen as cognitive evaluation of a perceived danger.

The degree of the motivation of an agent is defined by an internal state and is derived from the agent's mental workload (see Figure 2). Motivation dynamics is modeled with reference to the Yerkes-Dodson graph: a mean degree of mental workload results in a maximum degree of motivation.

![Figure 2: Motivation dynamics](image)

The degree of exhaustion of an agent is suggested to be proportional to the span of time that the agent is on duty. The amount of cognitive resources is connected to the degree of exhaustion: as the degree of exhaustion rises, the amount of cognitive resources decreases continuously. The cognitive resources parameter expresses the maximum cognitive performance of an agent at a certain point of time. Calculation of the agent's cognitive resources takes into account the complexity of applied problem solving strategies, defined by the number of hostile units and available taskforces the agent has to consider in his planning processes. Time pressure is evaluated taking into account the number of cognitive jobs to be handled, and the ratio between needed time to completion and the maximum available time to completion per job waiting for execution.

The variable CognitionIntensity determines the cognitive efficiency of the operator. It is calculated based on the minimum of cognitive resources and the degree of motivation of the operator to use them. The agent's motivational status, strictly speaking the computation of his mental workload, depends on the value for the parameter CognitionIntensity. Mental underload is defined as ability to solve problems successfully even with low intensity of the cognition. By contrast, mental overload is defined by inability to solve a problem despite high cognition intensity.
2.2 Rule Systems

As shown in Figure 1, the architecture HuFaNCO consists of different cognitive processes, each responsible for performing a different task. Each of these tasks can be performed by real human operators in different ways, for example quick, easy and vague or time-consuming but precise. The agent’s performance depends on the requirements of the current situation and the operator's internal state. In order to fulfill this modeling requirement, rule systems were introduced which base on the concept of classifier-systems (see Booker et al. (1989)). According to that concept, a set of rules is specified, which relate the way of information processing in mental processes to the influencing factors cognition intensity, time pressure and emotional arousal (see Figure 3).

The rule system $RS$ which is connected to cognitive process in Figure 3 is formally defined as set of quadruples:

$$RS: = \{(T, S, I, R)\}$$

For a given cognitive task $T$, a logical rule $R$ assigns a solution-module $S$. The parameter $I$ defines a set of concrete values for the influencing factors (the description of $R$ contains correspondent variables). In the choice of a solution-module the rule including the most restricting conditions according to given requirements is preferred. A solution-module, which is chosen to perform a task, is said to be active.

The concept of rule systems in principle gives the opportunity of refine the initial rule set during a simulation run by modifying existing rules or developing additional rules based on previous experiences of the agent. In that way, a learning process can be assimilated. In the case of time pressure, quick solution strategies should be preferred for cognitive tasks connected to a rule system. Hence, only simple problem solving strategies are taken into account by the agent, if the motivation or cognition-intensity is low. In contrast, if the motivation or cognition-intensity is high, complex and precise strategies are preferred.

A rule system can in principle be used in each of the cognitive processes of the presented architecture.

2.3 The Module “Memory”

The Memory Module consists of four processes:

FocusCalculation, Memory, RelevantUnitsChooser and Mental Simulation.

The FocusCalculation process determines the perception mode of the agent and his current focus area. Two different modes of perception are modeled: screening and observing. In regular time intervals, perception is done in screening mode. All objects visible on the screen of the C2 information system are perceived by the agent, but just at a low level of detail. This models expert behavior to gaze at different parts of the monitor in a certain order to get a rough overview about the scene. Between two screenings, the agent performs several observations to get a certain degree of accuracy. The radius of the observation area depends on the agent’s cognition intensity: the lower the cognition intensity, the smaller is the resulting radius and thereby the observation area. Only objects located inside the observation area are perceived by the agent in the observing mode but in contrast to screening mode with a high level of detail.

The Memory process is responsible for storing and providing the set of cognitions in the agent’s mental world view. Cognitions of an agent are mental representations of real world objects as well as existing relations between them ($A \ relations B$ with $A,B$ units and $rel \in \{approaching, conflict_ongoing\}$). Besides, the mental world view contains background information relevant for the current mission (e.g. mental representations of all known buildings, streets and units in the mission area). The agent uses two different kinds of mental representations: observations and expectations. Observations are actually perceived objects that are transformed to representations by the process of perception. Expectations are generated by the process of Mental Simulation and represent possible future states of real world objects.

By introducing the process RelevantUnitsChooser, the architecture expresses cognitive limitations of a human being: at some stages during the agent’s information processing this process selects a subset among all available representations in memory to fulfill the corresponding cognitive task. Two selection criteria are defined for the connected rule system: subjective relevance of representations to solve the current task and compliance of the current capacity limit for the simultaneous utilization of cognitions. The capacity limit depends on the current cognition intensity of the agent. The process Mental Simulation enables the agent to anticipate previous and future states of once perceived objects. The process of mental simulation is invoked by the processes Anticipation and ConflictResolution as described later. Two different instances of mental simulation are modeled. One instance predicts the state of the environment without taking into account possible actions of the agent, the other instance does. The last instance is used to test the success of a developed action plan by executing the subsequent planned actions on the mental world view. In common for both
instances is that a predefined time slice is iterated in a given step-size. At each of these steps, the agent computes the position of the simulated objects and tries to identify their most probable intention.

2.4 The Module “Perception”

The Perception module consists of the cognitive processes Sensor, Identification, RelevanceDecrease, Filter, Activation and SituationClassification. The Sensor process creates mental representations of perceived and reported objects in the environment, including information about position, type, strength and ID of the corresponding real world object. Information about objects, which are located beyond the current area of focus, is already lost at this level of perception. In the next step of the perception process – Identification – the agent compares single perceived objects to accessible observations and expectations already stored in memory in order to identify the perceived objects. Perceived objects for which no mental representations exist in memory – that means, they are seen for the first time – are marked as 'new objects'. The process of Identification allows emulation of a possible error: confusion of perceived objects in the agent’s mental world view. The process RelevanceDecrease models the general continuous decrease of the perceived objects’ relevance over the time. Relevance describes the individually interpreted significance of objects in the environment that has always to be seen in relation to the current situation.

The Filter process deletes mental representations with low significance in terms of low salience and low relevance depending on the cognition intensity of the agent. Salience means the accentuation of a stimulus out of its context, which makes this stimulus more easily accessible for the human consciousness. A salient stimulus automatically attracts attention. Perceptions with low salience and relevance are not deleted, if the cognition-intensity is high enough, that means a filter threshold decreases with increasing cognition intensity. According to that, different perceptions can be important for the agent depending on the situation.

Additional to the determination of the relevance of just perceived objects, the relevance value of all objects represented in memory decreases over the time. The process Activation finally stores perceptions in the agent's memory. Perceptions of already known units are assigned to the corresponding mental representations in memory. In case of perceiving a unit for the first time the process of Anticipation is invoked to investigate the impact of the new unit on the entire situation. The Activation process additionally increases a mental representation’s accessibility because of its relevance.

The process SituationClassification determines the current threat potential CTP according to equation (eq.a).

\[
CTP = \sum_{e} \left[ \frac{1}{\sum_{k(e')} d(e,e')} + a \right] \left[ \sum_{k(e')} d(e,e') \right]
\]

The parameters in (eq.a) are defined as follows: \( e \in E \), \( e' \in E' \) and \( e'' \in E'' \) represent units where \( E \) is the set of units belonging to blue forces, \( E' \) is the set of hostile units and \( E'' \) is the set of civilian units (e.g. groups of demonstrating people). The expression \( d(e,e') \) describes the distance between units \( e \) and \( e' \), \( k(e) \) stands for the fighting strength of unit \( e \). The parameter \( a \) is a weighting constant to take into account an even lower fighting strength of civilian units. In case of a high threat potential, the process of Anticipation is invoked for further investigation of the situation.

2.5 The Module “Anticipation”

The Anticipation process is triggered if the agent discovers a new unit (not identifiable) or if the process of SituationClassification has determined a value for the CTP that exceeds a predefined threshold. Once invoked, Anticipation calculates the expected future threat potential under the precondition that the agent does not intervene (by giving orders to blue forces). This is done by using mental simulation functionality. Expectations on the future state of corresponding real world objects and on possible interplay between these objects are created. Expectations are provided with a reliability value. If the reliability of an expectation is not sufficient, the Perception module is activated (observing mode) to get new information about the objects (e.g. the exact position of an object in the real world at the current point of time). Based upon new data, a new Anticipation process is started. If the reliability of expectations was sufficient, the corresponding data in memory is used to start a new mental simulation.

Based upon the generated expectations, the CTP is calculated. If the corresponding value lies under a given threshold, the information processing is stopped for the current simulation step. Otherwise, the process of ConflictSolving is started. In this case, Anticipation prepares a decision tree and handles it over to ConflictSolving for the next step.

The general concept of decision tress as part of the decision making process was introduced to model reactions of a decision maker dependent on situational factors straightforward. The evaluation of decision trees (if defined/implemented by the user) is triggered if the agent recognizes need for action that depends on the concrete scenario and task of the agent.

In the course of an exemplary implementation of the HuFaNCO architecture, the reception of a report that indicates immediate intervention and evaluation of the current situation was defined as trigger-event. The structure of a decision tree is shown in Figure 4.
The inner nodes of the tree (K{1,2,3}) are conditions that must be evaluated by the agent’s *Anticipation* process according to the present information about the state of the environment. The leaves of the tree (B{1..6}) are prefabricated patterns for orders. Nodes can be connected to leaves that are reached compulsory (B{1,2}). The selected patterns are passed on to the process of *Conflict Solving* in order to be put into concrete terms. The advantage of decision trees over a simple rule set is that the priority of rules is defined implicitly by the tree’s structure. Figure 5 shows an exemplary implemented instance of decision trees.

2.6 The Module Conflict Resolution

The Module Conflict Resolution encapsulates scenario specific problem solving functionality. In general, Hu-FaNCO suggest a chain of three interconnected processes: *GenerateSolution* (GS) to create a set of simple solutions, *Evaluation* (EV) to select a ‘best’ solution, and *ImproveSolution* (IS) to handle the case, that the determined best simple solution does not still fulfill specific mission requirements and more complex planning processes are needed. By means of the exemplary implementation of the HuFaNCO architecture, the general components were concretized to enable the agent to guide a convoy of civilian vehicles through a given mission area and to coordinate activities of blue units. The process *CalculateRoutes* (representing GS) determines the set of possible routes for the convoy through the city at the time of process activation starting at the current position of the convoy, ending at the predefined destination. The position of hostile units is thereby taken into account. The route determination is delegated to the process *MentalSimulation*. The process *CalculateThreat* (representing EV) determines the best route out of the set of computed routes for the convoy, considering following criteria in the given order: potential threat for the convoy, length of route and preference of the decision maker. If the potential threat provided by the "best" route lies under a predefined threshold, the agent specifies a corresponding order pattern with the concrete navigation data and passes the order on to the module *Acting*. If not (mission requirement not fulfilled), the process *PlanTaskforce* (representing IS) is triggered. In this case, the agent develops a mission plan for patrols and taskforces to make the "best" route safe for the convoy (e.g. by elimination red forces near the determined route).

2.7 The Module “Acting”

The module *Acting* consists of a single process: *Action Execution*. This process interfaces the agent and the C2 information system. Orders for blue units worked out by the processes *CalculateRoutes*, *CalculateThreat* and *PlanTaskforce* are getting passed on to the modeled information system and, in the next time step, send the corresponding units. The overall structure of the HuFaNCO agent architecture, adjusted to the requirements of the given scenario is depicted in detail in Figure 6. Interfaces to the C2 information systems are represented as light green boxes.

2.8 Reproduction of human errors

Processing the sequential steps of perception hides a number of potential sources of error. These are for example delay of information intake, mental confusion of real world units, disregarding important information...
and as a consequence, emergence of inaccuracies in the mental world view. A technical delay in the information channel or delayed information processing by the agent, for example due to information overload or exhaustion, may lead to a critical delay of information provision for the users of the C2 information system. As in the other cognitive processes, errors can occur even in the process of decision making. Sources of error in this process are the selection of inappropriate problem solving strategies and thus the selection of inappropriate actions to execute.

3. Agent-based simulation model

The HuFaNCO architecture as a basis for the decision maker agent and additional modeling concepts concerning the environment, unit behavior and an abstract C2I system were realized following the paradigm of agent-based modeling. The deriving discrete-event simulation model was implemented using the programming language JAVA. In the following chapters the scenario setting and experiments done with the simulation are described to give an impression of the applicability and power of the HuFaNCO architecture.

4. Scenario definition

The chosen scenario models the transport of VIP guests in a convoy of civilian vehicles (CCV) along a predefined path through an Afghan city. The VIP visit is announced, so the threat level is supposed to be high. Demonstration groups (DEM) and paramilitary groups (PGR) are allocated in the mission area.

Blue forces (patrols (PAT) and task forces (TFO), blue force tracking) are connected to C2 information systems and are deployed in the city center to protect the convoy. Human Intelligence and observers in the city are responsible for information retrieval about hostile activities.

The military decision maker – the "heart" of the simulation implemented here – is located at the headquarter of the blue forces in the city. His task is defined by controlling the mission in terms of mission planning for taskforces and target definition and decisions about possible re-routing of the convoy. Figure 7 is a screenshot taken from the developed scenario editor and gives an overview over the defined scenario.

The scenario frame serves as a basis to investigate the dependency between external influences like the complexity of constellations of units in the environment or the quantum of information available and the internal state of a decision maker becoming manifest in his performance, the quality of CROP and mission success.

Based on the presented scenario definition, a set of experiments was conducted to test the plausibility of the model with special reference to the dynamics of arousal and cognition intensity.

Three scenario variations were defined: a less challenging "low threat" experiment (LTE), a more challenging "high threat" experiment with early reconnaissance (HTE-ER) and a variation of it with late reconnaissance (HTE-LR).

5. Experiments and Results

In the period of time T=[26..49.2][min], there are no more tasks for the agent, so that motivation and as a consequence cognition intensity stays at a low level (figure 8). The arousal stays on a low level and even declines during the simulation (blue graph in figure 8). This was expected as no fear-inducing events (bomb alert) took place in the LTE scenario.
5.2 The experiment HTE-ER

The HTE-ER scenario contains the following elements: CCV(1), TFO/PAT(3), PGR(4), DEM(1). At simulation time \( T = 10 \text{[min]} \) a bomb alert is given by Human Intelligence. The potentially influenced area is expected to cover a part of the predefined route of the convoy. In the city center, paramilitary groups are gathering to wait for the convoy and to attack it.

The decision maker is confronted early with the information of a possible bomb attack on the convoy route. So, he decides for rerouting the convoy. That step of the decision making process is depicted in figure 9.

![Figure 9: Decision about rerouting of convoy due to a bombing threat in experiment HTE-ER](image)

In the course of the simulation, more challenging events occur, partially causing a high level of motivation. Due to time pressure and the order in which reconnaissance reports reach headquarter, he even makes suboptimal decisions, e.g. giving the "right" order to the "wrong" (at least not to the optimal) military unit. The dynamics of the arousal is shown in figure 10.

![Figure 10: Cognition intensity and arousal of decision maker in experiment HTE-ER](image)

The reception of a bomb alert does not affect the arousal due to the great distance between headquarter and bombing area. The slight increase in the period of time \( T = [17.2..26.1] \text{[min]} \) results from incoming reports about reconnoitered paramilitary groups. Solely the amplitude of the underlying function seems to be too small and hence should be subject of intensive calibration activities. Arousal starts to sink with initiation of disarming actions by the task forces in the period of time \( T = [26.1..33.4] \text{[min]} \).

5.3 The experiment HTE-LR

The experiment HTE-ER was repeated with one slight change: two patrols were removed from the scenario. That results in late reconnaissance of hostile activities in the city center. As a consequence, convoy and hostile units are located close to each other at the reconnaissance time so that the agent has very little time to decide upon the situation depicted in figure 11.

![Figure 11: Late reconnaissance of paramilitary groups](image)

In this case, it was observable that the agent deployed task forces only to neutralize paramilitary groups following the convoy (even if not attacking), but not to protect the convoy against expected threats located on the future path of the convoy. Additionally, the agent did not consider the possibility to redirect the convoy to the safety area (light green rectangle in figure 11). In both cases clear instances of suboptimal strategies could be ascertained. The mission ends with the convoy reaching headquarter after being attacked permanently by paramilitary groups.

Table 1 summarizes characteristic parameter values deriving from the three experiments. The small degree of deviation among the results in some rows can be explained by difficult calibration of the model.

<table>
<thead>
<tr>
<th>Measured quantity</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LTE</td>
</tr>
<tr>
<td>Arousal (MIN)</td>
<td>0.42</td>
</tr>
<tr>
<td>Arousal (MAX)</td>
<td>0.5</td>
</tr>
<tr>
<td>CognitionIntensity (MIN)</td>
<td>0.0</td>
</tr>
<tr>
<td>CognitionIntensity (MAX)</td>
<td>0.9</td>
</tr>
<tr>
<td>Duration of mission ([min])</td>
<td>49.2</td>
</tr>
</tbody>
</table>

Table 1: Results (LTE, HTE-ER, HTE-LR)

6. Comments on plausibility testing

By executing experiments with the simulation model, small scale plausibility considerations were done to test
the consistency of the model behavior by exclusion of obvious wrong simulation results. In a first step, a "standard" scenario was defined to enable observation of the entire behavior potential of the decision maker. Based upon that scenario, expected situations were ascertained that can occur during a simulation run (e.g. constellations for units in the environment, indicating need for action). For each situation expectations for the behavior of the decision maker were expressed and collected as a set of comparison data against which the model behavior was tested. Regarding the tested aspects of behavior, the plausibility considerations offered on the whole a plausible model behavior. Due to the high complexity of the architecture and the deriving model and due to a lack of available comparison data, calibration of the simulation model turned out to be difficult.

7. Prospects & Conclusions

The architecture HuFaNCO can be an appropriate basis to enable the modeling and examination of human factors related question sets in NCO scenarios. The plausibility and practicability of the modeling approach of HuFaNCO were demonstrated by the set-up of an agent-based simulation model and experiments conducted with it. On the basis of such a model, analysts could gain better insights and possibly even conclusions about the strengths and weaknesses of human decision makers in connection to certain conditions or situations. These results could be used to give recommendations for the optimization of technical or procedural issues relevant for NCO.

The integration of the concept of decision trees in the decision making process of our approach could allow in the future to construct more sophisticated C2 automata including realistic human aspects of the decision maker. These automata could be used in experiments or even exercises to replace real human beings (to a certain extent), e.g. to save costs. The agent-based simulator discussed here could be a basis for a variety of new activities. Further plausibility tests involving more measurements of real decision makers and the validation of the model are reasonable next steps.

8. References


Author Biographies

Bernhard Schneider
Project Manager for Human Factors Modeling in the System Design Centre Germany at EADS in Unterschleißheim.

Gunther Schwarz
Head of Modeling Methodologies and simulation expert in the System Design Centre Germany at the EADS in Unterschleissheim.

Dietmar Kunde, PhD
LTC, German Army, Federal Office for Information Management and Information Technology of the Bundeswehr.