INTEROPERABLE HUMAN PERFORMANCE MODELLING OF DISTRIBUTED COGNITIVE AGENTS

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Abstract: This paper presents an approach towards distributed human-machine systems based on an open modeling framework. The approach aims to develop a core of new modeling techniques independent of specific engineering domains that allows to analyze different communication channels and cooperation strategies with regard to their effect on the distribution of knowledge and the overall team performance including human errors. The paper presents the framework architecture on a conceptual level derived from a detailed analysis of the communication and cooperation requirements from the perspective of three application scenarios.

Keywords: Human-centered design, Human-machine interface, Distributed simulation, Cognitive systems

1. INTRODUCTION

Human Performance Models are increasingly used to support Human-Centered Design of operator assistance systems. For long human models served as research tools for implementing psychological theories and investigating the computational implications. Only over the last decade necessary advances have been realized that allow their application to simulate and analyze highly dynamic human-machine interaction. The next logical step is to enhance prevailing single operator models towards multi operator models towards the ends to simulate and analyze distributed human-machine systems (dHMS). For the design and validation of dHMS the analysis of communication, interaction and cooperation among the operators and prevailing technical systems is of utmost importance. In order to support the design of dHMS improvements of current computational human performance models are necessary. The proposed paper presents an approach towards this objective that is currently under development by three German research partners: Fraunhofer IITB, OFFIS and TU Dresden. This project aims to develop a core of new modeling techniques that are independent of specific engineering domains. This core will be extendable to add specific modeling concepts. The techniques will be embedded in an open modeling framework of dHMS. This framework will allow to analyze different communication channels and cooperation strategies with regard to their effect on the distribution of knowledge and the overall team performance including human errors. The framework will be implemented in form of a distributed software architecture as specified by the design pattern of multi agents systems and is currently developed taking into account the requirements of three application scenarios: Flight Guidance, Information Management in Defence and Security, and Communication and Coordination in Distributed Plant Operation.

The development of frameworks for dHMS is a means to implement the ideas of distributed cognition. Thus, the remainder of the paper first briefly introduces the field of distributed cognition and distributed simulation. Then, the three application scenarios are described with their framework requirements to subsequently derive an architectural design that realizes these requirements.

2. INTEROPERABLE HUMAN PERFORMANCE MODELLING

2.1 Distributed Cognition

Distributed Cognition extends the concept of traditional cognition beyond the processes taking place in individual minds. This research field aims at understanding and modelling the interaction between a group of human and machine agents (Hollan, et al., 2000). It investigates the coordination and mutual influence between members of a group including the use resources and material. Cognitive processes can be distributed across the members of a group and are constrained by the relationships between these entities, like roles and access to resources. The task performance and communication is mediated and supported by a set of assistance systems and communication channels. The access to systems and channels differs among the agents and thus constrains individual action. In many applications the assignment of agents to tasks, resources, systems and channels may change dynamically according to the situational demands. For example one agent may take over additional tasks to reduce the workload of another agent. The level of detail can go down to processes in the minds of individual participants but does not have to do so.

In this paper we view distributed cognition as an useful approach to model, simulate and analyze dHMS with regard to communication, interaction and cooperation among the operators and technical systems with the purpose to identify weak points in current distributed systems and to derive potential improvements. The state of the art with regard to modelling distributed cognitive is to combine separate cognitive models for individuals and to equip them with some knowledge about social interaction (e.g. as part of Standard Operating Procedures (SOPs)). Group interaction emerges from the interaction between such interaction rules in specific situations (e.g. Gore, 2002). But a system that can dynamically configure itself within the limits of functional relationships and cognitive principles of participating elements has not yet been achieved.

2.2 Distributed Simulation

Re-using existing simulations of technical processes and cognitive models is a key requirement for dHMS platforms. Thus the system architecture has to support *distributed simulation*. That means that all simulators in a scenario are interconnected. They can reside on one single computer or can be distributed over a computer network. (1) Infrastructures to support distributed simulations have to facilitate loosely coupling of simulation components as nodes of a network (i.e. finding components, addressing components, handling communications). (2) The infrastructure has to provide time synchronization mechanisms and handling communications with time stamps in order to achieve a consistent system wide clock. (3) The information exchange between simulators has to be according to a data model that is common to all simulation nodes or at least to node that communicate with one another.

IEEE has adopted standards for distributed simulation. DIS (distributed interactive simulation, IEEE 1278.1) is a communication protocol based on UDP/IP. It also has standardized message content format ("protocol data units", defined for entity state and events). It lacks support for synchronization between simulators. DIS was deployed in SIMNET, a large scale distributed simulation for military training applications by US Department of Defense. ALSP (Aggregate Level Simulation Protocol) is an extension of DIS suited for trainings simulations. DIS has been superseded by HLA (high level architecture, IEEE 1516). HLA is not a communication protocol but a software architecture with defined interfaces in the form of APIs to foster object or component interaction between distributed simulation nodes (called "federates"). It includes time synchronization. The system architecture is realized through a RTI (run time infrastructure) that acts as a communication bus between the nodes. RPR-FOM (Real-Time Platform-Level Reference Federation Object Model) specified by SISO is an object model used by many HLA aware real-time simulations. Although there are other infrastructures to build a distributed simulations (e.g. MSI: Multi-Simulation Interface), only HLA and DIS are supported by a wide range of simulators. It is also possible to connect DIS simulations with (RPR-FOM based) HLA simulations through gateways.

3. REQUIREMENTS FOR THE MODELLING FRAMEWORK

The framework will be developed to support three application scenarios with similar as well as very specific requirements. This section gives a high-level overview of the requirement analysis.

3.1 Flight Guidance - Scenario I

In the domain of flight guidance we pursue the goal to analyse the effectiveness and efficiency of the interaction between Pilot-Flying (PF) and Pilot-Non-Flying (PNF) within the context of a modern aircraft Glass-cockpit. The flight tasks are shared between the two agents in order to guaranty redundancy and mutual surveillance as an important safety feature of the pilot-cockpit interaction. In modern highly automated cockpits the role of the flight crew has shifted to what has been termed supervisory control where the pilots supervise several computers, which perform direct control and provide information about the current flight and systems state. This role imposes increased demands on the mental and cognitive capabilities because the crew has to stay aware of the system's behaviour all the time (situational awareness). Thus efficiency of human-machine interaction is a crucial factor in crew coordination. Another factor is the required degree of multi-tasking. Pilots must handle several tasks at the same time and have to dynamically adapt task priorities especially in case of sudden events. Several studies have shown that this role may exceed the cognitive capabilities of flight crews in highly dynamic situations leading to breakdowns in the pilot-cockpit and pilot-pilot interaction.

The distribution of flight tasks between PF and PNF is stipulated in documented flight procedures, e.g. for takeoff and approach. These procedures involve so called "crosschecks" of instruments where information is checked by each pilot from either the same source or from different sources. Empirical studies of pilot behavior demonstrated that pilots tend to use indirect cues instead of retrieving readings directly from the flight instruments (Hüttig, et al., 1999). Furthermore, prescribed callouts are omitted under high workload conditions, which has a crucial impact on shared knowledge about the aircraft and environment state. Call-outs are relevant to synchronize the progress of flight tasks and thus to synchronize the "common ground" necessary for effective communication and coordination. Pilots use communication schemata in order to interpret communicated information. Call-outs are a means to synchronize the usage of such schemata.

One goal of distributed simulation of PF-PNF interaction within the work reported in this paper is to analyse if crucial coordination actions are likely to be omitted or to be performed in a non-optimal way due to high workload. The approach is to predict pilot specific workload profiles to be able to assess the workload distribution for different SOPs as well as system designs and to predict the resulting coordination errors. The intended analysis requires fine grained cognitive models of individual behaviour with a time horizon of seconds or even milliseconds. The cognitive state with regard to resource consumption and resulting workload has to be modelled. SOPs and schema describing common ground in flight procedures have to be elicitated (by observational studies and pilot interviews) and modelled. In the past OFFIS developed a PROLOG based cognitive pilot model capable to predict potential pilot errors due to routine learning effects. The intention is to extend this model with cognitive processes for situated team performance.

3.2 Information Management in Defence and Security - Scenario II

The aim is to support the development of SOPs, organization, and technical support systems that are used to manage safety (e.g. handling of results of natural disasters) and security (military intelligence, surveillance, and reconnaissance) related situations. These situations have in common that information from multiple sources with different levels of reliability, trustworthiness, and quality has to be used to interpret the situation which is necessary for making decisions. This application domain is concerned with computer mediated message exchange between dislocated communicants. The goal of simulations is here to optimize procedures and systems for managing information used for military and civil security.

This domain is knowledge intense and often time critical. Erroneous decisions based on insufficient or wrong information may result in death or serious injury of humans. Thus information management has to be supported as good as possible. The tasks that have to be supported are collection, fusion, correlation, archiving, and provision of relevant information according to task and role of the user. Big distributed teams with hierarchical as well as many to many communication organization are typical scenarios for this application domain. Thus information distribution is often realized with information and communication technology. But often there is the possibility for oral communication in addition. Organization is an important factor that influences effectiveness and efficiency of communication (e.g. civil military cooperation). The following aspects and elements have to be taken into account for simulating such scenarios: State of sender and of receiver, form, structure, content and transmission of messages, organization and technical infrastructure for communication (message exchange matrix).

In this application domain the characteristics of the communication line has a big influence on the overall system performance. In the military domain a very important characteristic is the security of communication. The security level of a communication affects which information one is allowed o transmit. Other relevant attributes of communication are bandwidth, latency, and type of media. They affect content and style of communication. Communication relationships are analysed and formalized with methods and tools from business process modelling. The appropriate knowledge structures and communication procedures for the cognitive agents are generated with a compiler approach from a formal specification.

Generally this domain is characterized by knowledge and communication intense tasks. Users have to use background knowledge for interpreting messages. The level of analysis that is of interest here is relatively high (rather the scale of hours than of minutes). For this reason cognitive nodes are to be implemented with SOAR (Lewis, 2001) models. But SOAR has to be extended with some agent oriented software engineering methods (e.g. BDI logic) because manifold communication relations have to be managed by the cognitive nodes and default communication procedures must be followed. Human factors analysis methods derived from human performance modelling (HPM) are not applicable on this inspection level because it is not possible to collect and model every of the multitude of influencing factors. Additionally motivational and emotional aspects take affect that cannot be yet satisfactory included into HPM. The solution is to model selected human factors only as parameters in SOAR based cognitive models.

The content of the speech acts between the agents in this scenario is oriented at the information requirement that is specific to the concrete application. Nevertheless an ontology has to be defined that must be used by all components in order to communicate interoperable.

Two different kinds of analyzes are intended with this approach. First the organizational structures of the cooperation are varied to optimize organization and communication network characteristics. Second the procedures implemented with rule sets in the cognitive agents are varied to represent different training levels, amount and type of background knowledge, and standard operating procedures to optimize the procedural part of the system.

3.3 Communication and Coordination in Distributed Plant Operation - Scenario III

Most plants of the process industries are highly automated and require mostly supervisory control skills from their human operators, that is, during normal operation they need to monitor the state of the different systems and processes, detect deviations and derive and implement counter measures. Typical tasks that have to be executed under normal operation conditions are (see e.g. Ormerod and Sheherd, 2004):

- monitor system state by scanning relevant information
- activate or deactivate subunits like controllers, actors, parts of the plant or even the whole plant to change the structure for different products or maintenance.
- adapt parameters of the automation system to unexpected drifts in system parameters due to fouling, changes in educts, different products or deviances between product and specification.

In case of unexpected disturbances and errors, which may not be managed correctly by the automation systems, operators have to

- manually stabilize the disturbed processes and shutdown whenever stabilization is not possible.
- Locate and explain the source of the unexpected plant behaviour by deduction, exploration and hypothesis testing
- Find, plan and execute counter measures to remove the source of error

Most of the procedures that are part of the normal operation regime contain only a small number of non deterministic system state dependent task structures, that is, they can be planned and described in terms of SOPs: startup and shutdown, modification of throughput or product grades and product quality management. However, procedures for the management of every day errors are comprised of many activities that cannot be planned in advance. These activities are creative, ad-hoc, custom-made, not shared by everyone. Kanse (2004) finds a large amount of those activities during error detection (42-66%) and error explanation (48-76%). As soon as it comes to the planning and execution of counter measures the amount of preplanned actions rises, the amount of unplanned activities is as low as 20-30%.

Communication and coordination processes in the normal operation regime are as regular as the process operation. There is a quite constant amount of vertical (plant-to-management) communication to quality management, sales & distributions, logistics and maintenance departments. In particular in plants that are integrated in tightly coupled supply chains, one can observe a horizontal (plant-to-plant) exchange of forecasts about expected quality and quantity on the one hand and needs or capacity on the other hand to balance the whole production. This picture changes drastically in case of errors. In respect to communication Kanse (2004) observes with only few exceptions that after error detection more than one person is involved or at least further action is shifted to another person. This is due to organisational differences in competencies, roles and responsibilities of team members as well as insufficient resources (knowledge, expertise, tools, time) of individual workers.

Thus, besides performance of the individual, task related communication of the group members is a key component to safe and efficient operation of chemical plants. To model, simulate, analyse and finally prospectively design communications channels, protocols, organisational structures, an integrative high level description of those aspects has to be derived. Models of normal operation described by SOPs will be formulated at a somewhat less detailed level than in the flight guidance scenario. Due to the regular structure of the tasks, the formal task analysis language

HTAmap (Heinath and Urbas, 2006) and the human-machine communication sublayer (Urbas and Leuchter, 2004) seem to be suitable candidates. Firstly, HTAmap will be extended to include modelling primitives for team communication over the channels provided by the dHMS framework. Secondly, the HTAmap approach will be extended to include aspects of business process modelling like role, responsibilities, as can be found in the information management domain. This allows to formulate templates that describe not only task execution but also task allocation and task take over and to analyse the interplay of individual performance and knowledge and organisational measures.

4. FRAMEWORK DESIGN

We conducted an analysis of the intended use cases as well as the common and specific requirements for the three application scenarios and derived an architectural framework design.

Use Cases:
- UC1: to support the development of SOPs
- UC2: to support the development of robust but efficient organizational structures
- UC3: to support design of assistance systems

The three application scenarios share a number of features like sharing of tasks, distributed knowledge, communication between agents and different roles. Furthermore, the tasks are knowledge intense and often time critical, erroneous decisions based on insufficient or wrong information may result in death or serious injury of humans. Other requirements are application specific. Table 1 gives an overview of the application specific features on six dimensions.

Table 1 Summary of application specific framework requirements

No.	No. of Agents	Nature of Task	Human Performance Processes	Communication	Coordination Tasks	Agent Roles
I	PF and PNF	scale of seconds; supervisory control	workload, attention & multi-tasking on the level of cognitive resources	same location; oral; horizontal	same goal, distributed tasks, coordination via call outs, cross checks	based on task allo-cation
II	small team	scale of minutes; supervisory control & manual control; diagnosis, deduction, exploration & hypothesis testing	situation awareness, multitasking, timing, decision making, case based reasoning, abductive reasoning, communication, coordination	dislocated; horizontal & vertical; multiple info sources	different goals; distributed tasks; coordination by delegation	based on access to infor-mation, tools
III	big team	scale of hours, information management	information demand, situation awareness, workload and attention on the level of tasks	dislocated; oral & via typed media channels; horizontal and vertical; multiple info sources	different goals; distributed tasks; coordination by information management	based on access to infor-mation, tools

The common and specific features served as a basis as a basis to derive the following design requirements for the framework:
- R1: Arbitrary number of agents must be supported
- R2: Agents interact with other agents as well as with assistance systems
- R3: Agents must be able to adapt their behaviour dynamically based on communicated information and events in the environment.
- R4: Temporal behaviour ranging from the scale of seconds to hours must be supported.
- R5: Cognitive processes varying from low level mental processes to high-level task coordination processes must be supported
- R6: Horizontal and vertical communication must be supported
- R7: Communication must be possible via typed channels.
- R8: Distributed information sources have to be incorporated
- R9: The link between agents and information sources must be configurable.
- R10: Dynamic allocation of tasks to agents must be supported.

The framework design (Fig. 1) will facilitate these requirements creating a system of interoperable cognitive agents. The design builds upon the well established standard HLA. For the simulation of dHMS current multi agent models have to be extended by the provision of communication channels taking into account priorities for channels and transmitted information, communication procedures and regulations, communication modes (e.g. broadcast) and the communication behavior of the agents. The requirements have been realized in the following ways:

- R1, R2: Operators and technical systems will be modelled as individual agent.
- R3: We intend to connect different human performance models (like SOAR, PROLOG, HTAmap) in order to implement cognitive agents enabling simulation of cognitive information processing.
- R4, R5: Depending on the deployed human performance model different ranges can be represented.
- R6: Since all communicating entities are represented as agents using application specific strategies for coordinating their behaviour horizontal as well as vertical communication can be easily represented easily.
- R7: A configurable component to simulate the attributes of the communication network (delays, restricted band width, content based selection) can be used to link agents.
- R8: HLA as a communication infrastructure allows connecting different distributed simulators and other active components.
- R9: HLA makes it possible to flexibly link components on demand at runtime.
- R10: Task allocation strategies can be represented as agent coordination. Thus variable task allocations can be simulated by different configuration of agents' features.

5. CONCLUSION

Based on a detailed requirements analysis of three application scenarios a framework design for distributed human-machine systems has been derived. The next logical step will be to implement the framework and to perform tests for all three scenarios.

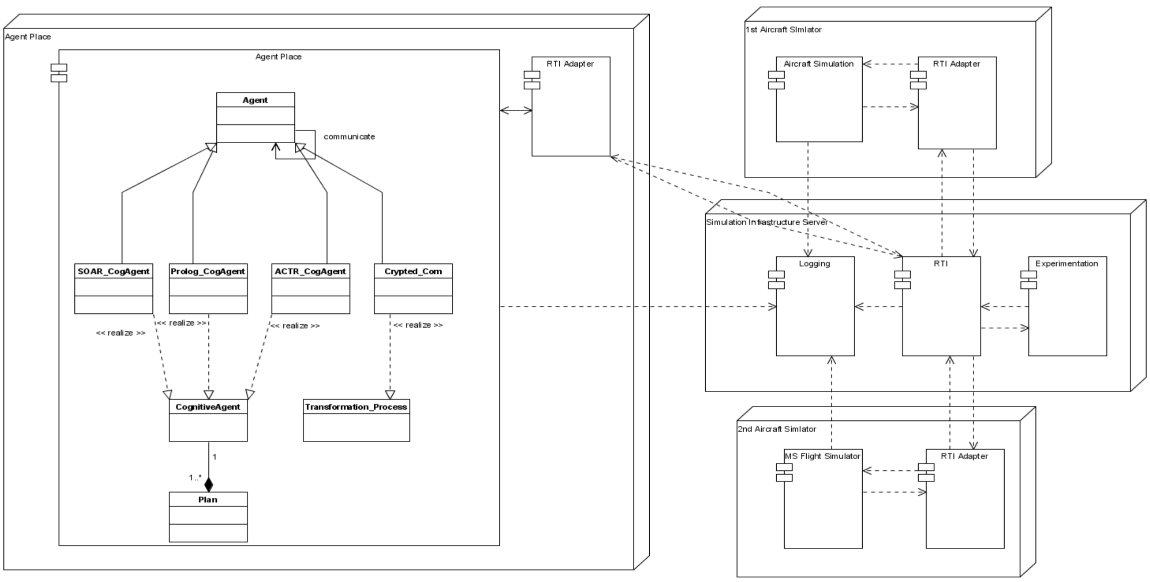

Fig. 1. Framework architecture for interoperable distributed cognitive agents

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