Multilevel Analysis of Human Performance Models in Safety-Critical Systems

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Abstract. Safety-critical systems are technical systems whose failure may cause injury or death to human beings. Tools used in the design and evaluation of safety-critical systems are redundancy and formal methods to ensure a proper operating behavior. To integrate human factors into the engineering-process of safety-critical systems it is necessary to take into account cognitive aspects of human beings while interacting with these systems. Formal human performance models can be applied to support the design and evaluation. These cognitive models interact with the technical system and provide a wide range of objective data (e.g., execution times). But using human performance models requires validating their behavior and internal structure in advance. Especially in the context of safety-critical systems this is an important issue. In this contribution the possibilities of multilevel analysis of human performance models are shown and discussed. Selected tools are introduced and related to a derived taxonomy of multilevel analysis.

Keywords: cognitive architectures, multilevel analysis, human performance models, tools, human factor, evaluation and design, safety-critical systems.

1 Introduction

Safety-critical systems are technical systems that integrate a complex system of input and output devices and whose failure may cause injury or death to human beings and (e.g., nuclear power station or aircraft control systems). These systems have to be operable by the user in all kinds of situations and circumstances. For the design and evaluation of safety-critical systems a wide range of specific methods is available to ensure a proper operating behavior from a technical and systemic view (e.g. redundancy and formal methods). But next to the technical system the human operator is an important part of the safety-critical systems. Especially in the case of a failure or an accident the human operator has to act adequately to secure the function of the safety-critical system. To support the workflow and to ensure access to all important information in safety-critical systems more devices, displays and automated routines are integrated into human-machine interfaces. This leads to a growing information density and more cognitive load of the operator to handle all tasks. Thus designing and developing human-machine interfaces or safety-critical systems demand not only an

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understanding of technical aspects but also an appreciation of human factors, i.e. an appreciation of the capabilities and cognitive demands of the human operator. Hence, it is essential for engineers and designers to be aware of the requirements and constraints of the future users to adjust the functionality and the design of human-machine interfaces in particular for safety-critical systems. For example, important issues are what kind of interface best supports cognitive processes and how an interface can be designed to best match the future user requirements.

To integrate human factors into the engineering-process of safety-critical systems it is necessary to take into account cognitive aspects of humans while interacting with a technical system. Human performance models can be applied to support the design and evaluation of human-machine interfaces of safety-critical systems. These models incorporate formal theories of human information reception and processing and allow simulating the interaction of humans with technical systems. Based on the simulated data (e.g., eye-movements, execution times) it is possible to derive statements from the simulated interaction in regard to state-of-the-art psychological findings (e.g., visual search). Subsequently it is possible to transfer these finding on the interaction of humans among themselves and with technical system. But using human performance models requires validating and verifying their internal and external aspects in advance to ensure the correct implementation of a human performance model and its underlying cognitive architecture. Thus, in the design and development of human performance models the analysis of the model data and its fit to psychological and empirical findings is an important sub-step to ensure the proper use of human performance models. Especially for human performance models implemented for the design process and the evaluation of safety-critical systems this is a very important issue.

2 Human Performance Models

Human performance models or cognitive user models attempt to provide formal symbol structures for selected cognitive processes and attempt to show that these symbol structures can generate the corresponding cognitive behavior [1,2]. These models are developed within cognitive architectures, i.e. software frameworks integrating cognitive and psychological theories, such as theories of visual information processing, decision making, and motor commands. For an overview, see [3]. Most cognitive architectures consist of discrete modules that encapsulate specific cognitive aspects (e.g. visual module, motor module, speech module) that are regulated and ordered by a central processor (i.e. production systems) to simulate human information processing and higher cognitive processes. These architectures are independent of the simulated task and its domain and require a constant task-development in time [4].

These formal human performance models can be applied to predict the users' behavior and future needs and allow an explicit insight into mental processes and structures that are not accessible by direct observation [5,6,7]. Applied in the engineering-process of human-machine systems this method provides statements comparable with empirical data and supports the design and evaluation of human-machine interfaces [8]. This helps to detect errors in the interaction design and gives indications about the cognitive demands of future users. Summing up, human performance models extend classical usability methods and expand their repertoire by cognitive aspects, are reusable and can be deployed as formal method to evaluate the usability of human-machine systems

3 Adequacy of Human Performance Models

For the construction of human performance models no general procedural method exists. But it is possible to describe the model construction as a process of four non-linear phases [7,9]: (1) the task analysis to explore the contextual aspects and the intended use of the human performance model, (2) the conduction of experiments with human subjects to benchmark the task analysis and to provide data for the modeling, (3) the implementation of the human performance model and (4) the validation of the human performance model to detect errors in the technical implementation or the used theories the model is based on (see Fig. 1). The non-linear change between these four phases is part of the model construction and allows fitting the behavior of the model to empirical data and theoretical findings. For example it is possible to repeat the task analysis if the model validation shows that the task analysis was not adequate to model the given task.

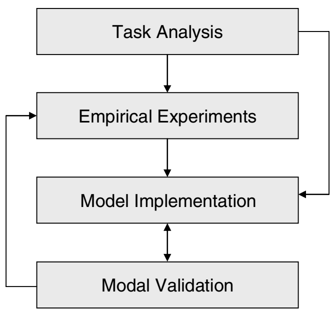

Fig. 1. The four non-linear phases of the construction of human performance models as stated by [7]

Regarding the application of human performance models in the engineering-process of safety-critical systems, it is an important issue to validate the cognitive model to show its adequacy. The prove of adequacy includes the validation of the human performance model in comparison to an empirical database and structural comparisons between model, theory and human with the aim to demonstrate the empirical and theoretical validity of a specific human performance model. The superior aim is to give creditability and confidence in applied human performance models [10]. Regarding mathematical and numerical simulations it is possible to apply statistical methods to show the adequacy of these kinds of models [11]. But these methods are not applicable for human performance models that reproduce hypothetic constructs of human cognition [7]. This problem is stated as the identification problem by [12]: „Given any machine S and any multiple experiment performed on S, there exist other machines experimentally distinguishable from S for which the original experiment would have had the same outcome“ (S. 140). This shows that it is not possible to give final evidence on the correctness of one approach out of concurrent approaches. But a feasible way is to justify the human performance model in comparison with its underlying theory, further human performance models and empirical data from humans [13]. For this purpose a relation between simulation experiments and experiments with humans is established in experimental studies (cognitive empiricism; [9]). The input data and respectively the output data of humans and human performance models is compared with each other and allows to draw conclusions regarding the validity of human performance models and their implemented cognitive processes and structures. For example empirical and simulated data of different human performance models can be set in relation to determine the model with the highest validity.

In the context of cognitive empiricism it is necessary to demonstrate the empirical and the theoretical adequacy of human performance models [7]. The empirical adequacy means to prove a sufficient correspondence between human performance model and observable human behavior. The theoretical adequacy implies the correctness of the human performance model by means of the applied cognitive architecture and the actual implementation of the model.

4 Multilevel Analysis of Human Performance Models

Human performance models integrate a complex internal structure to simulate human behavior. Three control levels can be identified that regulate their behavior and the internal interaction of the modules and cognitive processes [14]. These levels describe (1) the communication between functional modules of a cognitive system, (2) the internal structures of a functional module and (3) the interaction of a human performance model with its environment.

Regarding the analysis it is possible to derive three similar levels of analysis to cover the complexity of human performance models. Therefore we developed a taxonomy of multilevel analysis of human performance models that itself characterizes the same control levels but reorders them regarding the internal complexity of involved kinds of interactions (see Fig. 2). Hence the first level analysis is the analysis

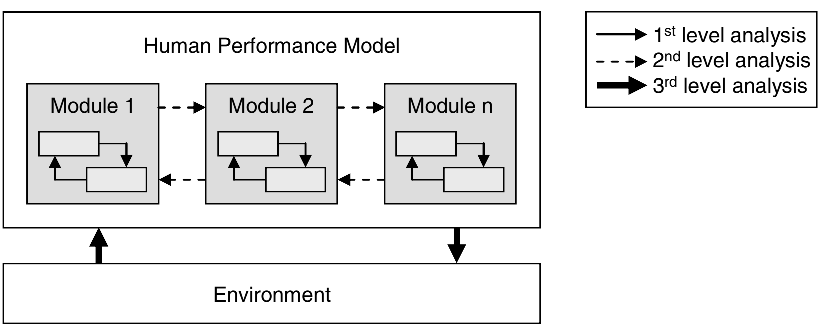

Fig. 2. Multilevel analysis of human performance models. Displayed are the three different level of analysis to cover the complexity of human performance models (1st level: interaction within a module, 2nd level: interaction between different modules, 3rd level: interaction between model and environment).

of each module structure separately. This allows validating the internal structure of the individual modules in detail and indicates if the implemented module is sufficient to model the encapsulated cognitive processes and theories (e.g. validating the vision module). The second level analysis is the analysis of the internal processes between different modules of a human performance model. With this level analysis it is possible to validate the internal structure of the human performance model with its flow of information and action control between all modules concerned (e.g. the exchange of chunks between different modules). The third level analysis is the analysis of the interaction of the human performance model with its environment. This enables the modeler to evaluate the model in the same way as in empirical studies (e.g. eye-movements, mouse and keyboard input).

5 Methods to Validate Human Performance Models

For the validation of human performance models and their behavior different levels of adequacy can be evaluated. For this purpose five grades of adequacy can be differentiated [7]. (1) The correspondence of product identifies the reconstruction of the main task (i.e. achievement of objectives). (2) The correspondence of intermediate steps allows a detailed insight into the modeling of cognitive processes (e.g. sequence of actions). (3) The correspondence of time provides a measurement to judge the temporal behavior of a human performance model (e.g. latency periods). (4) The correspondence of learning shows the correlation of mechanisms for knowledge acquisition (e.g. learning curve). (5) The correspondence of errors enables the modeler to examine errors and their allocation over time.

It is obvious that the granularity from (1) to (5) increases and in this way allows a deeper and more complex analysis of cognitive processes and structures. Regarding the grade of analysis these five parameters of correspondence can be varied and combined. But in most validation studies of human performance models only a few correspondences are used to validate the model. This is because of the high effort to analyze the huge amount of human performance model data for each run and the internal structures of human performance models. The latter is determined by a complex underlying cognitive architecture. To show its validity is very important for both, the definition and the modification of a cognitive architecture. This ensures the correct application of human performance models implemented by a modeler who uses a cognitive architecture as a black box. Due to these facts new methods and algorithms for an automatic and computerized data analysis are developed to overcome the shortfalls. In the following a short example for each level of the introduced taxonomy of multilevel analysis is presented.

5.1 First Level Analysis

To analyze a single module of a human performance model several approaches are presented in literature. Most of them use theoretical findings of a specific phenomenon and align data derived from these theories with data simulated by the corresponding module of a human performance model or its underlying cognitive architecture.

One interesting approach is the competitive argumentation that allows evaluating isolated aspects of the model and to compare them with each other [15]. This approach involves the explication of the principles of a theory and its consequences, and the comparison of theories with other theories and alternative versions of the theory itself. For example it is possible to compare central assumptions, control structures and interaction mechanism of a single module integrated into a specific human performance model with concurrent theories and assumptions to validate the structural and theoretical backing of the implementation (e.g. compare the processing of subsequent actions in the motor module of a human performance model with a predefined list of actions derived from a psychological theory).

5.2 Second Level Analysis

Regarding the second level analysis, i.e. the analysis of the interaction between different modules of a human performance model, promising approaches use numerical aspects to compare and validate internal cognitive processes and structures of human performance models. The application of statistical analysis of the model behavior and the comparison with theoretical findings of the results enables the modeler to appraise the correctness of the implemented data structures and cognitive processes of a human performance model.

The approach by [16] uses extracted simulation data and compares the data with formal data derived from the theoretical framework. The aim of this approach is to show the quality and accuracy of the implementation of internal processes and structures of the human performance model without environmental aspects (e.g. compare a concrete interaction between a memory module and a vision module of a human performance model interpreting visual stimuli with a formal model of the general theory).

5.3 Third Level Analysis

The largest cluster of methods exists for the third level analysis of human performance models, i.e. the interaction of a human performance model with its environment. For this purpose several tools exist to support the analysis and validation of the quantitative simulation data in a similar way empirical data is handled in real experimental studies. The aim of these methods is to minimize the effort of analysis of single datasets and group datasets and their comparison with each other (for both empirical and simulated data). Most of the existing methods provide user interfaces to organize the data and the analyses (see Fig. 3).

The tool ProtoMatch was developed to support the exploratory analysis of single datasets in consideration of the equality of data sequences (e.g. eye-movements, action sequences, mouse and keyboard input; [17]). It provides a collection of protocol analysis tools to align datasets to each other and to compute the similarity between sequences of temporally ordered data. Additionally the tool generates a unified stream of high-density and sequential data to allow the processing with standard analysis tools. ProtoMatch is modularized software and can be extended easily by new filters and analyses. In this way ProtoMatch supports both confirmatory and exploratory sequential data analyses to validate human performance models.

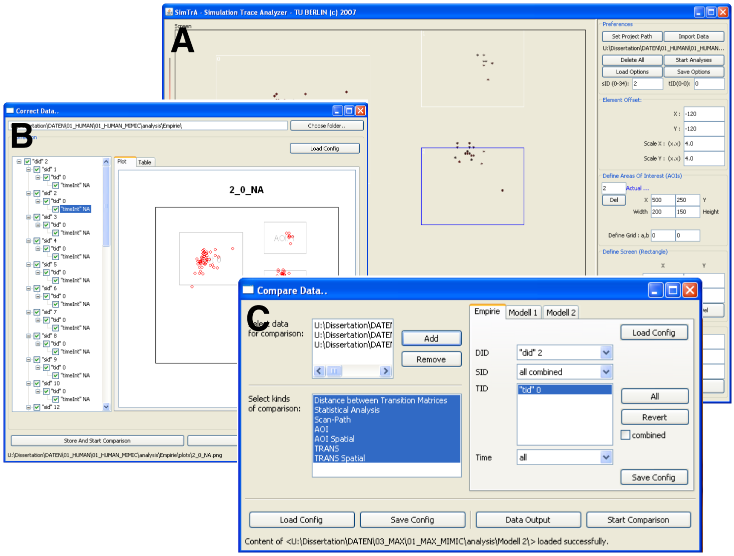

Fig. 3. User interfaces of the Simulation Trace Analyzer for the integration of simulation and empirical data (A), the adjustment of the integrated data (B) and the comparison of single and group datasets from different origins (C)

The Simulation Trace Analyzer (SimTrA; [8]) is a tool and method to simplify the analysis of human performance models. The tool automatically processes and analyzes data from human performance models and allows the comparison of simulated data with empirical data wit the support of a graphical user interface (see Fig. 3). The tool enables the modeler to carry out evaluations of the interaction of human performance models respectively the humans with an environment considering the inherent complexity of the data (e.g. eye-movement pattern and statistical dependencies). Therefore the tool provides a preset and modularized repertoire of methods that is adaptable and expandable by the analyst. To support descriptive and exploratory data analyses SimTrA provides tables and plots of the processed data. Additionally the data is stored in a general-purpose format and can be processed by external tools (e.g. MatLab, R, SPSS).

6 Conclusion

In this article we showed that the analysis and validation of human performance models is an important aspect for the application of human performance models for the design and evaluation of safety-critical systems. In this article we introduced a taxonomy of multilevel analysis of human performance models and assigned selective methods and tools to each level. These different methods and tools assist the modeler and expand the repertoire of today's methods of cognitive modeling. They allow an automatic and computerized analysis and validation of human performance models. Regarding the aspect of team-interaction, i.e. the interaction of multiple human performance models, new methods have to be developed and tested. This is an important issue especially in respect to safety-critical systems and needs to be explored in the future.

We showed that the improvement of human performance models and cognitive architectures by using multilevel analysis is a feasible way. For this purpose each level of analysis has to be performed during the phase of model validation in the process of model construction (see Fig. 1). The derived statements can be used to change the implementation and the underlying theory (i.e. the cognitive architecture) in respect to empirical data or psychological theories. Because of the high complexity of human performance data analysis a grade of adequacy has to be differentiated for each validation that is sufficient to support the analyst and that is applicable in the field of application of the human performance model.

Regarding the analysis and validation of human performance models several aspects have to be kept in view to use the derived statements from a scientific point of view. Most human performance models base on verbally communicated cognitive and psychological theories. This can lead to a difference between the implemented cognitive processes and structures in human performance model and the original theory (theory implementation gap; [18]). One reason for this is that in some cases the modeler has to reduce the complexity of a theory to model the cognitive processes and structures involved in a task. Secondary it is possible that the modeler has to add additional assumptions into a human performance model that are independent from the underlying theory. In some cases this is necessary to support the internal control flow of the underlying programming language or to allow the integration of a single human performance model in an higher-order coherence (e.g., team-interaction). This can lead to an augmentation of a human performance model by aspects not stated in the original theory that are not distinguishable from the essential theory (irrelevant specification gap; [19]). Both aspects need to be known by the modeler and have to be regarded in the process of validating human performance models.

The presented methods and tools in this article cover only a small number of aspects of the behavior of human performance models. On the one hand this is due to the high effort that is necessary to analyze the huge amount of quantitative simulation data. On the other hand no secured knowledge on the cognitive processes and structures is available to analyze the simulation data. Both leads to a complex interpretation of the data and hinder the development of methods that support the standardized analysis of human performance models on the whole.

In this article a short overview of methods to do multilevel analyses of human performance models was given. They provide an insight into different control levels of human performance models and establish a base for their accurate analysis and validation. But there is still a need to develop additional methods and tools to cover a wider range of the behavior of human performance models. This statement is supported by our belief that in future application scenarios of human performance models the focus shifts more and more towards the analysis and validation, because a adequate and validated human performance model is the basic condition for the application of human performance models for the design and evaluation of human-machine interfaces. In particular in the context of safety-critical systems this is an important issue because their application allows the formal integration of human factors into the design and evaluation process and leads to technical systems that are attuned to humans.

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