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Integration of human factors-related knowledge into decision support systems applied to assisted and automated operating vehicles using examples for inland vessels

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In human-machine systems, human behaviors are the main contributor to the safety of the overall system. Recognizing upcoming critical situations or knowing about critical actions in advance would enable the design of a new generation of human-machine systems that allow a smooth/fluid transition from assistance and intervention to direct guidance of the system. For most professionally operated complex systems such as power plants, aircrafts, or even ships, the workflow of human operation is highly regulated and can be considered in a formalized manner, which is helpful to serve as underlying system model. Future automation systems that allow to incorporate human assistance and monitoring are based on detailed sensor- and model-based situation awareness in the sense of knowing the consequences of possible alternative actions. With existing individualized knowledge about preferences and experiences from previous interactions as well as human error rates (e.g., from literature), a new quality of human-machine systems can be generated that focuses on reliability and safety as goals.

As example for such a new system in this contribution a Situation-Operator-Modeling (SOM) approach is used to describe the captain-vessel-interaction and to illustrate the rule-based behavior as a graph-based-model. SOM-based action spaces consisting of possible captain's behaviors leading to a meaningful desired final situation are online analyzed and evaluated with respect to unsafe and unreliable actions components and or sequences, so from the manifold of possible sequences the best options can be defined and suggested in advance, critical and harmful ones can be denoted as critical by warnings etc. The reliability of the action sequences included in the action space are evaluated using a probabilistic risk assessment method called human error probabilities (HEP). The reliability analysis of the captain's actions in real time, newly introduced in the paper, enables safer driving behavior, reduction of accidents and dangerous situations. The manner novelty consists in the identification of dangerous situations and the intervention by appropriate warning and interaction strategies of the assistance system. Based on experimental examples, the paper evaluates the action components considering literature knowledge in addition to the underlying modeling.

Keywords: Automated and Assisted Operating vehicles, Decision Support System, Human-Machine-Interaction, Situation-Operator-Modeling, Human Error Probability, Action Space

1. Introduction

Traffic safety is a social necessity, this aspect of traffic is becoming of increasing importance in case of autonomous, automated or connected traffic. The focus of this work is related to the automation of inland vessels, which is one of the actual traffic automation topics required to increase freight throughput and in the same moment meeting the personnel shortage in this economic sector. New methods to evaluate and to assist driving behaviors intends to solve the mentioned goals and to avoid dangerous situations and therefore to increase safety. An assistance systems which evaluates possible actions and action plans and related integrated behaviors in advance was developed in previous publications (Ahle and Söffker (2008); Fu and Söffker (2011); Ameyaw et al. (2022)). In Bejaoui et al. (2022)) a new human error probability (HEP)-related approach (He et al. (2021)) was applied to an inland vessel example for the first time. It can be assumed that considering relevant human factors-related knowledge can support humans especially when the system will be able to warn the captain about dangerous situations in advance.

Previous works (Man et al. (2015)) (Wróbel et al. (2021)) are focused on the investigation of the effects of human factors to the captain's behavior in case of remote-controlled vessels. Human factor issues related to remote ship operations are classified and some affecting to Human-Machine-Interaction are discussed in (Kari and Steinert (2021)). The authors of (Shappell and Wiegmann (2000)) develop a Factors Analysis and Classification System-Maritime Accidents framework for an expert study allowing to analyze the influence of Human Factors on the safety of remotely-controlled merchant vessels. Unfortunately this and similar approaches are considering principal effects and therefore are well suited for work or interaction/guidance design, but can not be directly applied to concrete situations which means for realtime applicable assistance.

The SOM approach developed by (Söffker, 2001) is used to illustrate the Human-Machine-Interaction so the interaction with the captain, the vessel, and the environment is modeled as a graph-based model. In Ahle and Söffker (2008) the approach is used for the development of an automated supervision strategy of the Driver-Vehicle-Interaction. In Bejaoui et al. (2022) the SOM-approach is combined with the newly developed cognitive reliability and error analysis (CREAM)-based method denoted as HPRS (Human Performance Reliability Score) to realize a new assistance approach based on the calculation of the human performance reliability, applied to the Driver-Vehicle-Interaction by (He et al. (2022)) and to the Captain-Vessel-Interaction by (Bejaoui et al. (2022)).

The contribution of this work is different. Using the same example as well as the interaction structuring approach (SOM) the reliability measure to be used for realtime evaluation is replaced. The previous approach (CREAM-based HPRS) must be generated and individualized in advance (trained) to be applied (Bejaoui et al. (2022)). The kind of knowledge can not be assumed, possibly not during the training and learning phase of new staff or when no knowledge is available for new interactions in general. Therefore in this contribution this kind of required background knowledge is taken from human factors-related databases. The use of the method allowing the analysis of the safety and reliability of action-sequences related to the Captain-Vessel-Interaction can remain in comparison to previous contributions. Using the SOM-approach action spaces consisting of captain's behaviors is calculated for using the HEP parameters describing the reliability of action sequences so generalized human factors knowledge is used. As in previous contributions also in this work the captain-vessel-interaction is modeled using SOM. A SOM-based action space consisting of possible captain's behaviors to reach the desired final situations builds the base for the analysis step. The performance reliability of the captain's action can be evaluated by allocating HEPs.

The work is structured as follows: In section 2 the theoretical background of the used approaches (SOM-approach, SOM for interaction modeling, HEP-based evaluation) is explained. The application in relation to inland shipping is introduced in section 3 and the SOM-based reliability evaluation is applied to a 'crossing maneuver'. An action space including the possible captain's behavior to reach the desired final situation is developed and the safety-related reliability score of each possible behavior is computed using the action-assigned HEPs.

2. SOM-HEP-based human reliability evaluation

In this section the used approaches are introduced. The Situation Operator Modeling which enables the mapping of dynamical changes within the real world including the technical system and the guiding human operator (here: the captain) as Human Machine Environment interaction to a graphical/formal representation is presented in section 2.1. In section 2.2, the probabilistic risk assessment method/the quantification of the approach by using parameters from the literature is described using human error probabilities (HEP).

2.1. *Situation Operator Modeling*

The Situation Operator Modeling developed by (Söffker, 2001) allows the modeling of the HMI and also to visualize the HMI as a graph-based model. Actions are modeled as operators and scenes as situations. In Figure 1 two sequential situations (modeling scenes) are connected with an operator (modeling the action which changes the problem constellation in the previous scene to those of the following scene) are illustrated using the SOM-approach. A situation vector including a set of characteristics C_i (informational, logical, physical terms) (cf. Figure 1) as a gray ellipse, the white circle refers to the operator connecting the situations. The operator effects the characteristics value of the inner structure of the following situation S_{i+1}. This relations as well as the characteristics are used to describe the problem of the scene. The modeling of technical systems using the SOM allows the design of cognitive functions and procedures. In this work the cognitive functions and procedures acting, planning, and supervision are of relevance. The generation of a plan using the SOM-approach is defined by the generation of a sequence of actions designed to that a problem configuration (initial scene > initial situation) is changed to another one (final scene > final situation). The logic behind is connecting the physical and/or technical restrictions and the tasks to be solved. The degree of freedom of the operator (here: captain) is to choose suitable actions and therefore to plan action sequences so that problems or tasks can be solved in according to physical and/or technical restrictions. The cognitive aspect here is related to the human perception, planning, and control abilities.

In Figure 1 a action-sequence from an initial situation S_i to a desired final situation S_d referring to the example of a planned sequence using the SOM-approach.

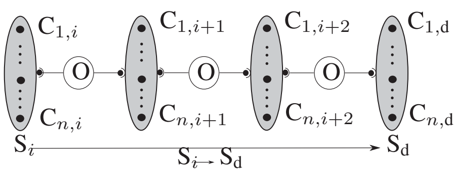

Fig. 1. Action sequence from the initial situation S_i to a final desired situation S_d (Söffker (2001))

2.2. *HRA approach*

Methods of probabilistic safety analysis (PSA) are important tools in safety engineering for the structural analysis of structural dependencies in complex systems in combination with the methodically or experimentally obtained characteristic values of individual components. Human reliability can also be assessed in a methodically comparable way and used for specific contexts with clearly defined tasks. Human reliability analysis (HRA) methods offer structured procedures for the qualitative and quantitative definition of human reliability for specified scenarios. Numerous HRA methods have been developed over the last decades, which can be divided into different generations based on their characteristics. The probabilistic HRA approach applied in this contribution belongs to the so-called "first generation". The core assumption of the "first generation" HRA methods is that humans logically fail to perform tasks, similar to mechanical and electrical components. Depending on the task performed, a nominal HEP can be assigned. With respect to Performance Shaping Factors (PSFs) related to the human education, actual status, working conditions, and activities etc. a final HEP can be calculated. Using this probability values, the reliability of the human performance for specific tasks can described.

2.2.1. *Human Error Probability*

To quantitatively determine human reliability in an operation, data for human error behaviors are required, referred to as (HEPs). For inland vessels, human error probabilities are not known, so in this work, values generated in maritime shipping are used. Some HEPs determined in Martins and Maturana (2010), which were generated by analyzing a Suezmax tanker on the Brazilian coast, are suitable for this purpose. The generation of these values is based on the Guidelines for Formal Safety Assessment published by the International Maritime Organization IMO (2004); Martins and Maturana (2010). Using event and fault trees, the events associated with the accidents of interest were modeled, and the HEPs were associated with the activities in the event trees, taking into account the factors that influence human actions - represented by the Performance Shaping Factors (PSFs)Martins and Maturana (2010). Consequently it is possible to determine the probability of this events in fault trees Martins and Maturana (2010) or to use these values in other context.

3. HMI-related modeling of the guidance of inland vessels

Based on real driving scenarios the characteristics including in the situation vector and the operators can be obtained. The definition of required characteristics is realized by the designer. The problem configuration describing situation vector must be suitable to express physical and technical constraints and requirements as well as the problem/task itself. In Table 1 the characteristics allowing to express the inner structure of a situation are given. The blue board is actively used by the captain to require passing maneuvers by passing on the starboard side of other ships.

Table 1. Set of characteristics of the situation vector

Name of characteristic	Unit
C_1: Speed Over Ground	[Km/h]
C_2: Course Over Ground	[°]
C_3: Latitude	[°]
C_4: Longitude	[°]
C_5: Acceleration	[Km^2/h]
C_6: Rudder for steering	[°]
C_7: Blue board	[-]
C_8: Time to closest point of approach	[s]
C_9: Distance to right river bank	[m]
C_{10}: Reliability score	[m]

To describe the captain's behavior, actions have to be modeled as operators. Relevant operators are listed in Table 2. The operators O_1 and O_2 refer

Table 2. List of operators

Name of operator	Description
O_1: Acceleration	Pressing the throttle
O_2: Deceleration	Pulling the throttle
O_3: Route trip to the left	Operating rudder
O_4: Route trip to the right	Operating rudder

to the acceleration and deceleration by pressing and pulling the throttle which effects the value of the longitudinal part of the speed over ground. For steering to the right and to the left the rudder has to be operated (operators O_3 and O_4).

3.1. *Performance measures*

The human reliability during interaction is affected by several influences from the person itself, die interaction options, as well as the outside world (machine, environment). The most important performance conditions in context within the captain-vessel-interaction and used for evaluation of the human reliability in this work are introduced in Table 3. Situations are connected with operators so the reliability of each operator describing the human's action should be considered. For the crossing-maneuver discussed in the paper, the human error probabilities were taken from Martins and Maturana (2010). The operators O_i are the same operators as defined in the Table 2.

Table 3. Used HEPs from Martins and Maturana (2010) for the crossing-maneuver

Operator	Operational error	HEP
O_1: (Acceleration)	propulsion	$5.00E{-2}$
O_2: (Deceleration)	propulsion	$5.00E{-2}$
O_3: (left)	rudder	$1.25E{-8}$
O_4: (right)	rudder	$1.25E{-8}$

3.2. *Crossing maneuver*

A crossing maneuver between the ego-vessel (blue) and a traffic vessel (white) in a estuary is modeled using the SOM-approach (cf. Figure 2). The 'crossing-maneuver' describes the exit of ego-vessel from the river 'Ruhr' (right side) and its entering in the river 'Rhine' (left side) (Bejaoui et al. (2022)).

3.3. *Graph-based representation of the action space*

In Figure 3 the action space describing the possible behaviors leading to the desired final situation of the example driving scenario 'crossing-maneuver' is shown. Only paths involving permissible operators are considered. Operators which

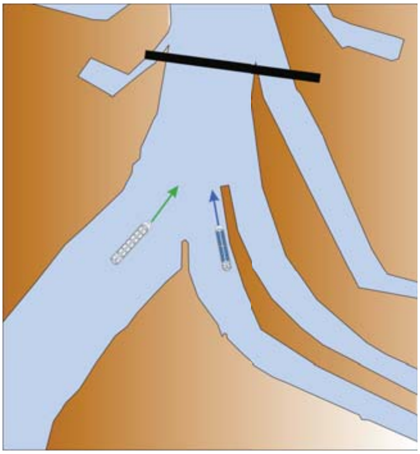

Fig. 2. Driving scenario 'Crossing-maneuver': Ego-vessel (blue), traffic-vessel (white) (Bejaoui et al. (2022))

lead to dangerous situations and to collision are not considered. The paths presented in the action space (cf. Figure 3) are explained as follows (Bejaoui et al. (2022)):

Path I: The captain waits in the situation S_1 and S_2 for passing of the traffic vessel. In the situation S_3 the captain accelerates after the traffic vessel is far from the estuary. The direction of the vessel is changing by operating the rudder. The vessel drives in the Rhine in the situation S_5.

Path II: The captain decelerates so that the vessel's speed is reduced continuously the situations in S_2 and S_3. After waiting of passing of the traffic vessel, the captain of the ego-vessel accelerates and drive in the Rhine. The ego-vessel turns to the right and is in the situations S_5 and S_6 in the Rhine (cf. Figure 3).

Path III: The captain of the ego-vessel decelerates. The course over ground is changed and is higher in the situation S_3 to increase the relative direction between the ego-vessel and the traffic vessel. In the next situation the ego-vessel accelerates to drive in the middle of the river 'Ruhr' so that the relative direction and distance increase and the captain have a better visibility condition of the river 'Rhine'. The ego-vessel drives turns to the right by operating the rudder and is in the situation S_5 in the river 'Rhine'.

3.3.1. *Decision support evaluating option of action sequences using HEP-related performance scores*

The SOM-based action space denoting all possible actions in the moment of consideration and consisting of all possibly intended and yet not decided action/operator sequences should be evaluated before the captain is deciding which action (and therefore action sequence) he or she is applying next. The evaluation can be related to allowed or not allowed next actions itself, an individualized reliability-related performance score denoted as HPRS in Bejaoui et al. (2022), to the reachability of given or useful goals, or to a pure reliability-based measure of allowed action sequences leading to a given and theorefore comparible goal situation. The main idea can be explained using the 'crossing maneuver' example as follows: Three possible action sequeneces (options) are leading to the desired final situation (cf. Figure 3). For each action/operator a suitable HEP is choosen from an available data base (cf. Table 3, denoting a generalized risk to fail to reach the considered goal situation. The reliability value $HEP\text{-}RS$ is obtained from

$$HEP\text{-}RS = 1 - HEP, \qquad (1)$$

with the error probability value HEP. Following the logical approach to the reliability calculation of electrical or mechanical components, the situation can be considered as a model of the series circuit. All the elements (in this case sequences) have to to executed correctly (to function as elements of a series system) for the success of the system (maneuver). The reliability $HEP\text{-}RS$ is the probability of success of all the elements and therefore can be assumed as the product of the individual probabilities Verma et al. (2016)

$$HEP\text{-}RS_i = \prod_{j=1}^{n} HEP\text{-}RS_j. \qquad (2)$$

The overall reliability score $HEP\text{-}RS$ for all different options i $HEP\text{-}RS_i$ for each path is calculated with using the applied equation (2). As result the now quantitatively defined options can be compared numerically, so that i) those options for which the resulting $HEP\text{-}RS_i$ score

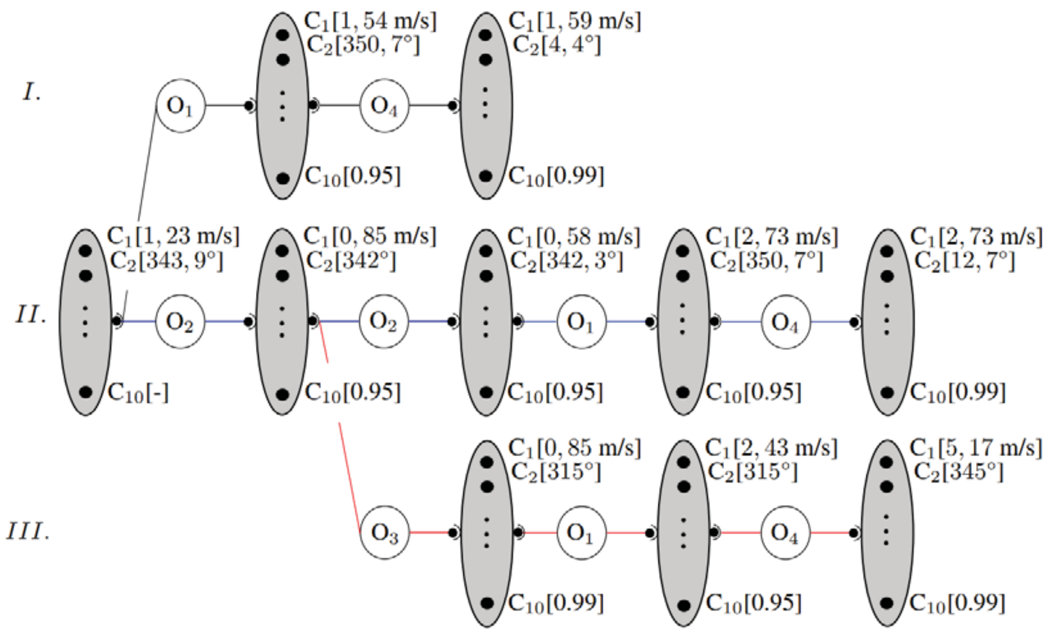

Fig. 3. SOM-based Action space of the 'Crossing-maneuver' (cf. Figure 2) (Bejaoui et al. (2022))

is lower than a given threshold can be defined as risky or ii) those option for which the resulting $HEP\text{-}RS_i$ score is maximum can be assumed as best and therefore recommendable. From Table 4, it is found that the human performance reliability of operations with each option in the task are evaluated and summarized as values, making it possible to directly compare the reliability of operations, and determine the optimal option. It could be obtained that option/path I has relatively higher $HEP\text{-}RS$ score than the other two paths indicating this as the best option for the task. Following option i) it can also be concluded that option/path II should be excluded from the set of allowed and reasonable decision options.

Table 4. The reliability of operations in action space

Paths	Operators	HEP-RS
	O_1	0.95
	O_4	0.99
Path I	$HEP\text{-}RS_1$	0.94
	O_2	0.95
	O_2	0.95
Path II	O_1	0.95
	O_4	0.99
	$HEP\text{-}RS_2$	0.85
	O_2	0.95
	O_3	0.99
Path III	O_1	0.95
	O_4	0.99
	$HEP\text{-}RS_3$	0.88

4. Summary and Conclusion

This contribution focuses on the development of a situated assistance or monitoring approach for the task of guiding an inland waterway vessel. A new approach related to individualized performance scores as well as known task-specific failure rates is established. In the concrete example, it is assumed that the vessel captain remotely controls the inland vessel. The approach uses the Situation-Operator Modeling approach to structure the human action options. The action options identified in real time are evaluated from a reliability engineering perspective so that alternative action options become comparable in terms of reliability engineering. In this work, parameters from the maritime domain on the human reliability of individual activities are used for evaluation. In contrast to previous approaches on the same topic, the presented approach is still situational, but neither needs to be trained to be nor individualized. By combining the two approaches (SOM, HEP), it will be possible to support the captain's decision making during operations, to warn of hazards and to make recommendations. A concrete example of a crossing maneuver is used to demonstrate the concrete applicability of the approach.

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References

Ahle, E. and D. Söffker (2008). Interaction of intelligent and autonomous systems - part ii: Realisation of cognitive technical systems. *MCMDS-Mathematical and Computer Modelling of Dynamical Systems Vol. 14. No. 4*, pp. 319–339.

Ameyaw, D. A., Q. Deng, and D. Söffker (2022, 6). Evaluating Machine Learning-Based Classification Approaches: A New Method for Comparing Classifiers Applied to Human Driver Prediction Intentions. *IEEE Access Vol. 10*, pp. 62429–62439.

Bejaoui, A., C. He, and D. Söffker (2022, 11). Novel model-based decision support system for reliable human machine systems in complex situations. *Proceedings of the Annual Conference of the PHM Society Vol. 14*(1).

Fu, X. and D. Söffker (2011, 6). Concept for SOM-based computer supported cooperative work. *IEEE Conf. Computer Supported Cooperative Work in Design (CSCWD), Lausanne, Switzerland*, pp. 261–267.

He, C., A. Bejaoui, and D. Söffker (2022, 09). Situated and personalized monitoring of human operators during complex situations. *Proceedings of the 32nd European Safety and Reliability Conference (ESREL 2022)*.

He, C., Y. Lum, K. Lee, and D. Söffker (2021, 5). Human reliability estimation based on fuzzy logic-modified CREAM approach. *IEEE Conference on Cognitive and Computational Aspects of Situation Management (CogSIMA), Tallinn, Estonia*, pp. 45–50.

IMO (2004). *Guidelines for Formal Safety Assessment (FSA)*. London: International Maritime Organization.

Kari, R. and M. Steinert (2021, 4). Human factor issues in remote ship operations: Lesson learned by studying different domains. *Journal of Marine Science and Engineering 9(4), 385*.

Man, Y., M. Lundh, T. Porathe, and S. Mackinnon (2015, 07). From desk to field - human factor issues in remote monitoring and controlling of autonomous unmanned vessels. *Procedia Manufacturing Vol. 3*, pp. 2674 – 2681.

Martins, M. R. and M. C. Maturana (2010, 4). Human error contribution in collision and grounding of oil tankers. *Risk Analysis Vol 30. No. 4*, pp. 674–698.

Söffker, D. (2001). From human-machine-interaction modeling to new concepts constructing autonomous systems: A phenomenological engineering-oriented approach. *Journal of Intelligent and Robotic Systems 32*, 191–205.

Shappell, S. A. and D. Wiegmann (2000). The human factors analysis and classification system–hfacs. *Part of the Aviation Safety and Security Commons, and the Human Factors Psychology Commons*.

Verma, A. K., S. Ajit, and D. R. Karanki (2016). *Reliability and Safety Engineering*. Springer Series in Reliability Engineering, Springer-Verlag London.

Wróbel, K., M. Gil, and C. J. Chae (2021). On the influence of human factors on safety of remotely-controlled merchant vessels. *Applied Sci. 11(3), 1145*.