Novel model-based decision support system for reliable human machine systems in complex situations

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ABSTRACT

Human and machine contribute to the safety of human-machine systems, the interaction between the two is essential for the overall systems safety and reliability. Assuming (formalized) knowledge about the structure of the interactions, monitoring of the human operator becomes possible so that the overall system of human and supervision system can contribute to the safety and reliability of the overall system. The automated recognition of critical situations or the automated detection of human errors allows to intervene in the interaction: to take over the guidance of systems by automation or to warn the human to influence the interaction of human operator and system. Detecting unlogical or errorneous action sequences will help to develop assistance systems to improve the performance of the human-machine system.

In the FernBin project beside others the supervision of the captain's actions in inland shipping is addressed. The focus is to detect human errors and also non-optimal behaviors. Additionally a reliability-based analysis of the captain's actions will also enable safer driving behaviors and the reduction of accidents and dangerous situations due to suitable warning.

In this contribution a Situation-Operator-Modeling (SOM) approach is used to describe the captain-vessel-interaction and to illustrate the captain's behavior as a graph-based-model. As example a 'Crossing maneuver' is considered. A SOM-based action space consisting of possible captain's behaviors leading to a meaningful desired final situation is developed and applied to a 'Crossing maneuver'. Using this approach a manifold of sequences can be generated describing the human interaction options to solve the task.

Subsequently a modified CREAM approach (cognitive reliability and error analysis method) is used allowing the online calculation of the human reliability performance scores (HPRS), resulting to static reliability measures. The HPRS can be also assigned directly to the SOM-action space, as virtual network of upcoming human actions related to goals. In difference to previous developments this allows beside the deterministic supervision (SOM) also the individualized definition of the safest/most reliable action sequence as well as the opposite. Therefore an event-discretized behavior model situated supervision performance of the captain's driving behavior with human reliability score numbers is established for the first time. As example the behavior of remotely operating captains of inland vessels is used as experimental example.

In this contribution for the first time the newly developed dynamic reliability estimation measure HPRS is combined with the known SOM approach for the captain-vessel interaction example. This example serves as a proof-of-concept example for the new type of assistance system allowing to improve the reliability of the overall system.

Key Words: Reliability analysis, modified CREAM approach, Captain-vessel-interaction, Situation-Operator-Modeling, action space, situated supervision

1. INTRODUCTION

A reliable traffic is required for the realization of a safe and networked traffic. The analysis and evaluation of the human driving behavior allows to improve the safety of traffic. In inland shipping a remote-controlled operation on land enables the control of vessels. The mapping and evaluation of the captain's behavior has to be integrated as a monitoring-system in the remote-controlled operation.

Previous works (Man, Lundh, Porathe, & Mackinnon, 2015) (Wróbel, Gil, & Chae, 2021) are focused on the investigation of the effects of human factors to the captain's behavior in case of remote-controlled vessels. Human factors issues for autonomous unmanned vessels supervised by an operator onshore are investigated in (Man et al., 2015). The influence of human factors on the safety of remotely-controlled merchant vessels is analyzed in (Wróbel et al., 2021). The author compares the influence of external factors of external factors, organizational influences, unsafe supervision, preconditions, and unsafe acts with each other. In (Du, Goerlandt, & Kujala, 2020) the authors review different methods to determinate the collision risk in waterways. In (Hu & Park, 2020) a colli-

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sion risk assessment is proposed based on fuzzy logic and considering the time to closest point (TCPA), the distance to closest point (DCPA), and environment conditions (weather, water currents, traffic congestion etc.). The illustration of the captain's behavior and the supervision of the captain-vessel-interaction is hardly discussed.

SÖFFKER develops the Situation-Operator Modeling (SOM) approach which allows the illustration of Human-Machine-Interaction (Söffker, 2001). Using this approach the changes of the real world can be modeled as a graph-based model consisting of situations and operators (cf. section 2.1). In the last two decades the need for assistance systems increased. Human errors are becoming more important due the increase of the related ratio of human error-based accidents (D. et al., 2016). To the knowledge of the authors up to now no combination of underlying task knowledge with personalized assistance exists. In this work the captain-vessel-interaction is modeled using SOM. A SOM-based action space consisting of possible captain's behaviors to desired final situations is developed. The performance reliability of the captain's action can be evaluated using a modified CREAM approach (cognitive reliability and error analysis method) (Hollnagel, 1998).

The work is structured as follows: In section 2 the theoretical background of the used approaches (SOM-approach and CREAM-approach) is explained. The application of a modified CREAM-approach in relation to inland shipping is introduced in section 3. In section 4 the SOM-based reliability evaluation is applied to a 'crossing maneuver' in a estuary between two rivers. An action space including the possible captain's behavior to reach the desired final situation is developed and the safety-related performance score of each possible behavior is calculated using the modified CREAM-approach.

2. SOM-BASED HUMAN-RELIABILITY EVALUATION APPROACH

In this section the used approaches are introduced. The Situation-Operator Modeling which enables the mapping of dynamic changes from the real world and the description of the Human-Machine-Interaction is presented in section 2.1. In section 2.2 the cognitive reliability and error analysis method (CREAM) is explained.

2.1. Situation-Operator-Modeling approach

The Situation-Operator-Modeling (SOM) enables the modeling of the Human-Machine-Interaction and the mapping of actions and scenes from the real world (Söffker, 2001). A scene is modeled as a situation and an action as an operator. A situation describes the internal structure of the system. An operator connects situations with each other and its functionality is related to explicit and implicit assumptions which can be textual, mathematical or logical expressions. In Figure 1 an action sequence modeled as Situation-Operator-Situation sequence is shown.

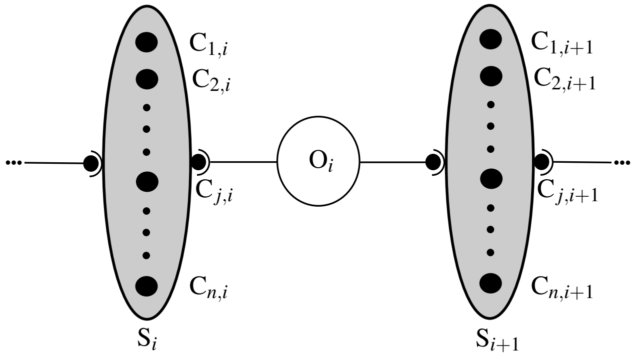

Figure 1. An action sequence modeled as Situation-Operator-Situation sequence

A situation vector is represented as a gray ellipse including characteristics. The characteristics-related variables can be informational, physical, logical, or functional. For the graphically representation of an operator a white circle is used. An actual situation S_i and its following situation S_{i+1} are connected using an operator O_i. Accordingly the values related to the characteristics of the following situation can be effected and changed by the operator. Modeled operators and predefined situations can be stored in a knowledge base.

2.2. Original CREAM approach

Human reliability analysis is a common concept in probabilistic safety assessment (PSA) and is wildly applied in human-related context, such as marine engineering (Ung, 2015). Human reliability analysis (HRA) provides structured methods to qualitative and quantitative define human reliability in specific scenarios. During the last decades many HRA methods are generated which can be categorized into generations based on their features. The CREAM (cognitive reliability and error analysis method) approach applied in this contribution is classified into the so called "second generation" method (Hollnagel, 1998). The core assumption of the "second generation" of HRA methods is that environmental or context related effects has the considered most significant factor affecting human reliability. With the determined evaluation levels of performance shaping factors (PSA), which is commonly accepted as performance conditions in CREAM approach, the expected human performance reliability could be defined.

2.2.1. Contextual control mode

The human cognitive model used in CREAM approach is the contextual control mode (COCOM), which assumes that human operator's degree of control on the situation or context determines human performance reliability. The degree of control can be determined by the context under which human operator performs their tasks. Four control modes are defined in COCOM including scrambled control, opportunistic control, tactical control, and strategic control. Each control mode is related to different human reliability intervals. Strategic control has the highest performance reliability and scrambled control is corresponding to the lowest.

3. MODIFIED CREAM APPROACH APPLYING IN INLAND SHIPPING

In this chapter for the first time human performance conditions for the inland shipping case are formulated. The method to calculate the Human performance reliability score based on the performance conditions is presented in section 3.2.

3.1. Selection of new common performance conditions

The human reliability is affected by its interaction with environment as well as with the machine. 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 can be evaluated. The calculated values are related to the considered vessel and rivers in this work as introduced in Table 2. The relevant geometric parameters of the rivers 'Rhine' and 'Ruhr' in the considered region are presented in Table 1.

Table 1. Parameters of the considered Ego-vessel

Vessel's characteristic	Length	Breath	Draft
Value	110 m	11 m	0.28 m

Table 2. Parameter of rivers in the considered region

Parameter Name	Width	Water depth
Rhine	330 m	3,93 m
Ruhr	110 m	3,93 m

The used performance conditions are explained as follows:

Speed over ground (SOG): The speed over ground must be not exceed a critical speed v_{cr} considering the water depth. According to (Li, Liu, & Liu, 2017) and based on the 'Römisch model' the critical vessel's speed v_{cr} is calculated depending to the water depth, the draft, the length, and the breadth of the ego-vessel.

Time to closest point of approach (TCPA): The closest point of approach is the point, in which two vessels reach the minimum distance (Distance to closest point of approach) between each other. The time to this point is called the time to closest point of approach (TCPA) and is used for the evaluation of risk collision. Time to closest point of approach is a motion parameter and depends to the speed over ground, positions, and the course over ground of the ego-vessel and traffic vessels (Nguyen, Zhang, & Wang, 2018). The calculation of TCPA in this work is based on the formula as given in (Nguyen et al., 2018).

Traffic density: The traffic density is calculated based on the Greenshields linear model using the formula in (Liu & Lodewijks, 2021). The traffic flow q is the number of ships passing through a certain cross section per unit time (Liu & Lodewijks, 2021). The maximum traffic flow q_{m} depends on the average speed of ship traffic flow of the considered cross section and the density of ship traffic flow described by the number of ships in per kilometer of a channel segment (Liu & Lodewijks, 2021). The calculation of the maximum traffic flow q_{m} results to 21 ship/h in the river 'Ruhr' and 56 ship/h in the river 'Rhine'.

Distance to the right river bank (u_{r}): The distance between the vessel and the right river bank u_{r} can be calculated by given distance between the river axis and the vessel and the width of the river. The distance u_{r} must not exceed the minimum distance $u_{\mathrm{r,min}}$. The calculation of $u_{\mathrm{r,min}}$ in this work is based on the method in (Abromeit et al., 2010) and depends to the length, breath, and the class of the vessel.

Visibility: The visibility conditions affects the human perception and is an important factor. The classification of the performance reliability related to the visibility is based on weather conditions (cf. Table 3).

Table 3. New CPCs and performance reliability

CPC Name	Description		Expected effect on performance reliability
SOG	SOG $< 6{,}68$ m/s		Improved
	SOG $\geqslant 6{,}68$ m/s		Reduced
TCPA	TCPA $\geqslant 30$s		Improved
	TCPA < 30s		Reduced
Traffic Density	In Ruhr	$q \leqslant 21$ ship/h	Improved
		$q > 21$ ship/h	Reduced
	In Rhine	$q \leqslant 56$ ship/h	Improved
		$q > 56$ ship/h	Reduced
u_{r}	In Ruhr	$u_{\mathrm{r}} \leqslant 25$ m	Improved
		$u_{\mathrm{r}} > 25$ m	Reduced
	In Rhine	$u_{\mathrm{r}} \leqslant 110$ m	Improved
		$u_{\mathrm{r}} > 110$ m	Reduced
Visibility	Daytime with sunny weather		Improved
	Sunrise or Sunset with sunny weather		Not significant
	Evening, foggy, rainy, or snowy		Reduced

3.2. Human performance reliability score (HPRS) calculation

In the original CREAM approach, the CPC score is calculated as [$\sum$ reduced, $\sum$ improved]. This method is valid for the evaluation of operation as a whole, or major segments of the operation in a period of time. For human operation in situated and dynamic context, the original CREAM approach is not applicable. Therefore, the concept of HPRS applying to dynamic context with time is reasonable for human performance reliability evaluation (He & Söffker, 2020). With the defined levels of CPCs in Table 4, the HPRS of different operators could be calculated. Human captain performance reliability can be calculated as

$$\text{HPRS} = \lambda_1 \cdot \sum \text{reduced} + \lambda_2 \cdot \sum \text{improved}, \qquad (1)$$

where λ denotes the coefficient, the absolute value of λ is 1, when λ denotes to -1, which indicates to reduced effect, while λ denotes 1 indicating improved effects.

4. SOM-BASED HUMAN PERFORMANCE RELIABILITY ANALYSIS

4.1. Operators and situation vector related to the captain-vessel-interaction

The SOM-based modeling of changes in real world as sequences allows to build an inner structure of the system. In this work the needed characteristics and operators describing the captain's relevant actions are obtained by real scenarios. In the Table 4 the characteristics are presented.

Table 4. List of characteristics including in the situation vector

Characteristic	Unit	Typ
C_1 : Speed Over Ground	[km/h]	Real
C_2 : Course Over Ground	[°]	Real
C_3 : Latitude	[°]	Real
C_4 : Longitude	[°]	Real
C_5 : State of the throttle	[%]	Real
C_6 : Acceleration	[km^2/h]	Real
C_7 : Bow thruster for steering	[°]	Real
C_8 : Rudder for steering	[°]	Real
C_9 : Blue board	[-]	Boolean
C_{10} : Water flow	[-]	Boolean
C_{11} : Availability of berth	[-]	Boolean
C_{12} : Suitability of berth for vessels	[-]	Boolean
C_{13} : Distance to berth	[m]	Real
C_{14} : Time to closest point of approach	[s]	Real
C_{15} : Distance to bank on the right side	[m]	Real

The values of characteristics can be physical (C_1, C_6, etc.) or informational (C_9, C_{11}, etc.). Furthermore, some of the characteristics are obtained from prefilters. Prefilters enable the compression and fusion of information data, so that characteristics extracted and situation vectors can be established. The output of the prefilter 'Driving area' is the characteristic C_{14} based on given map information, Speed Over Ground, Course Over Ground, and the position of the Ego-vessel as well as the other vessels in the driving area. The characteristics C_9, C_{10}, and C_{11} are obtained from the prefilter 'Berth'. To describe the captain's behavior actions are modeled as operators based on the SOM-approach. In the Table 5 the used operators are illustrated.

Table 5. List of operators

Name of operator	Requirements and description
O_1 : Acceleration	Pressing the throttle
O_2 : Deceleration	Pulling the throttle
O_3 : Waiting	Doing nothing
O_4 : Maneuver to the right	Bow thruster clockwise
O_5 : Maneuver to the left	Bow thruster counterclockwise
O_6 : Route trip to the right	Operate Rudder clockwise
O_7 : Route trip to the left	Operate Rudder counterclockwise
O_8 : Blue board	Activate the blue board

4.2. SOM-based modeling and the human reliability evaluation of an example driving scenario

In this work 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). The captain of the ego-vessel has to consider traffic vessels driving in the 'Rhine'. In the situations S_1 and situation S_2 the captain has to wait for passing of the traffic vessel (Operator O_3, cf. Figure 3). In the next situation the captain accelerates (Operator O_1) so that the value of the speed over ground described by C_1 changes in the situation S_4 and the vessel is in the river 'Rhine'. The captain operates the bow thruster (Operator O_4) and the ego-vessel turns to the right (cf. S_5 in Figure 3).

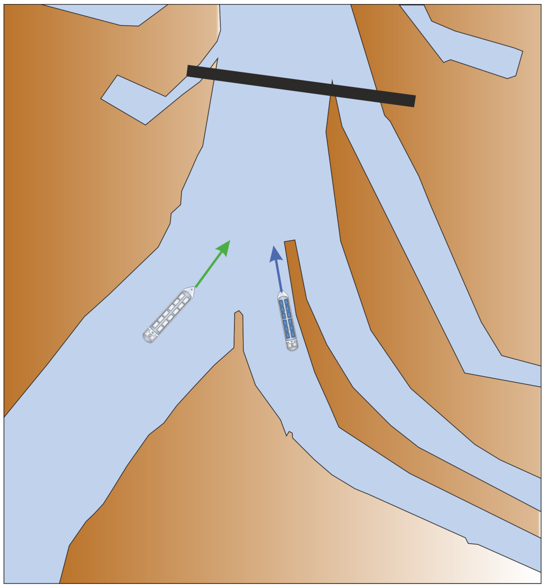

Figure 2. Driving scenario 'Crossing-maneuver': Ego-vessel (blue), traffic-vessel (white)

4.3. Action space of the example driving scenario

A SOM-based action space contains the possible behaviors and actions leading to desired final situations. The devel-

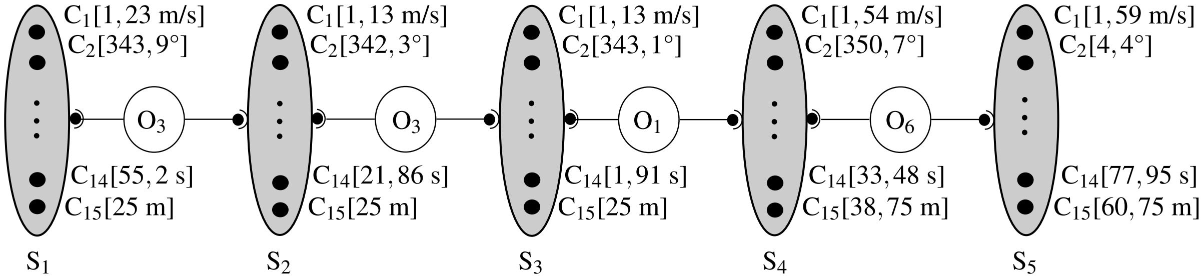

Figure 3. Graph-based-model using the Situation-Operator Modeling of the driving scenario 'Crossing-maneuver' shown (cf. Figure 2)

opment of the actions enables the evaluation of the human actions, the detection of missing actions, and to support the decision making.

4.3.1. Graph-based representation of the action space

In Figure 4 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 lead to dangerous situations and to collision are not considered. The paths presented in the action space (cf. Figure 4) are explained as follows:

Path I: This path is the represented action-sequence in Figure 3. 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 bow thruster. The vessel drives in the Rhine in the situation S_5.

Path II: In contrast to the behavior in path I, the captain decelerates so that the vessel's speed is reduced in continuously the situations S_2 and S_3. The Time to closest point of approach in the situation S_3 is higher than in path I. 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. in Figure 4).

Path III: In this case, 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 bow thrust and is in the situation S_5 in the river 'Rhine'.

In the next part the human reliability of the captain's behavior of the action space is analyzed and the paths are compared with each other in context within the human performance reliability score (HPRS).

4.3.2. Evaluating options by summarizing safety-related performance scores

A SOM-based action space consisting of possible operator sequences, which lead to the desired final situation of the 'crossing maneuver', is developed (cf. Figure 4). Three possible paths lead to the desired final situation. The human performance reliability score (HPRS) of the operations in each path is calculated with the modified CREAM approach. In this case, a SOM-based human performance reliability evaluation approach is established. To quantitatively evaluation of the action sequences in the paths leading to concrete CPC values are defined. The final human reliability performance score $\mathrm{HPRS_f}$ for each path consisting of n operators is calculated according to the equation

$$\mathrm{HPRS_f} = \frac{1}{n}\sum_{j=1}^{n} \mathrm{HPRS}_j, \tag{2}$$

where HPRS_j is the human reliability performance score of one operator.

With the evaluation levels of CPCs in Table 3, the data of each situation can be evaluated as improved effects and reduced effect on human performance reliability, and the HPRS can be calculated with the Eq.1. Different operators result in the changes of CPCs values in the modified CREAM, leading to the change of HPRS, which is shown in Table 6. From Table 6, 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 path II has relatively higher final human reliability performance score $\mathrm{HPRS_f}$ than other two paths indicating it is the better option for the task.

5. SUMMARY AND CONCLUSION

The contribution of this work is the development of a SOM-based human reliability evaluation approach applied to a 'crossing-maneuver' in inland shipping. Therefore a SOM-based action space modeling the possible behaviors of the captain to reach the desired final situation is developed. Based on a model of upcoming action options here for the first

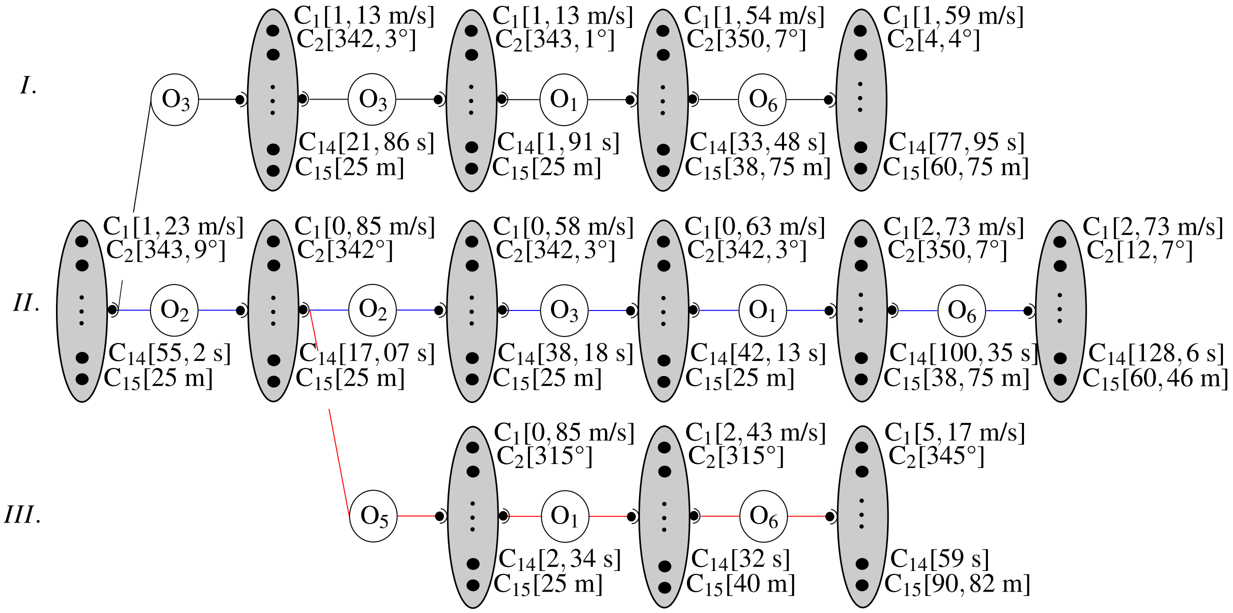

Figure 4. SOM-based Action space of the 'Crossing-maneuver' (cf. Figure 2)

Table 6. The HPRS of operations in action space

Paths	Operators	HPRS
Path I	O_3	3
	O_3	3
	O_1	3
	O_4	3
	$HPRS_f$	3
Path II	O_2	3
	O_2	5
	O_3	5
	O_1	5
	O_4	5
	$HPRS_f$	4.6
Path III	O_2	3
	O_5	3
	O_1	3
	O_4	5
	$HPRS_f$	3.5

time the reliability performance of each possibility is evaluated so that a situated human reliability performance score can be calculated. The combination of the two approaches will allow in the future the support of the decision making of the captain by a remote-controlled operation and the safety on networked traffic in waterways can increase. In the future works the prediction of omitted actions or errorneous actions in advance can be developed and added allowing additionally an automatically generatic sensitivity measure with respect to human errors.

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NOMENCLATURE

SOM	Situation-Operator Modeling
SOG	Speed over ground
CREAM	Cognitive reliability and error analysis method
HPRS	Human reliability performance score
CPC	Common performance conditions
TCPA	Time to closest point of approach
O	Operator
S_i	Situation i
u_r	Distance to the right river bank

REFERENCES

Abromeit, U., Alberts, D., Bartnik, W., Fischer, U., Fleischer, P., Fuehrer, M., … Soyeaux, R. (2010). *Principles for the design of bank and bottom protection for inland waterways*. Bundesanstalt für Wasserbau (BAW).

D., T. A., Guo, F., Lee, S., Antin, J. F., Perez, M. A., Buchanan-King, M., & Hankey, J. M. (2016). Driver crash risk factors and prevalence evaluation using naturalistic driving data. *Proceedings of the National Academy of Sciences*, *113*, 2636 - 2641.

Du, L., Goerlandt, F., & Kujala, P. (2020). Review and analysis of methods for assessing maritime waterway risk based on non-accident critical events detected from ais data. *Reliability Engineering & System Safety*, *200*, 106933. doi:

https://doi.org/10.1016/j.ress.2020.106933

He, C., & Söffker, D. (2020). Establishing a modified cream approach for reliability evaluation. In *2020 ieee international conference on human-machine systems (ichms)* (p. 1-6). doi: 10.1109/ICHMS49158.2020.9209509

Hollnagel, E. (1998). *Cognitive reliability and error analysis method (cream)*. Elsevier.

Hu, Y., & Park, G.-K. (2020). Collision risk assessment based on the vulnerability of marine accidents using fuzzy logic. *International Journal of Naval Architecture and Ocean Engineering*, *12*, 541-551. doi: https://doi.org/10.1016/j.ijnaoe.2020.06.005

Li, H., Liu, J., & Liu, W. (2017, 06). Dynamic speed control model for very large ship in restricted waters. *Proceedings of the Twenty-seventh (2017) International Ocean and Polar Engineering Conference*.

Liu, T., & Lodewijks, G. (2021, 08). Research on the impact of ship traffic flow on the restricted channel segment of the middle yangtze river based on traffic wave theory. *SN Applied Sciences*, *3*. doi: 10.1007/s42452-021-04727-w

Man, Y., Lundh, M., Porathe, T., & Mackinnon, S. (2015, 07). From desk to field - human factor issues in remote monitoring and controlling of autonomous unmanned vessels. *Procedia Manufacturing*, *3*. doi: 10.1016/j.promfg.2015.07.635

Nguyen, M., Zhang, S., & Wang, X. (2018). A novel method for risk assessment and simulation of collision avoidance for vessels based on ais. *Algorithms*, *11*(12). doi: 10.3390/a11120204

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. doi: 10.1023/A:1013905329888

Ung, S. (2015). A weighted CREAM model for maritime human reliability analysis. *Safety science*, *72*, 144–152.

Wróbel, K., Gil, M., & Chae, C. J. (2021). On the influence of human factors on safety of remotely-controlled merchant vessels. *Applied Sciences*, *11*(3). doi: 10.3390/app11031145