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Situated and event discrete decision making support system applied to remotely operated vehicles

Abderahman Bejaoui, Dirk Söffker
Chair of Dynamics and Control, University of Duisburg-Essen, Germany.
E-mail: abderahman.bejaoui,soeffker@uni-due.de

The monitoring of the human-machine interaction, the planning and prediction of possible behaviors, and the detection of missing actions or other errors in advance contributes to the safety of human-machine systems. The development of supervision support algorithms may focus to decision making and also to the related detection of critical decision making situations. With the knowledge of consequences the effects of possible human errors can be evaluated in advance. Based on this online generated knowledge about possibly upcoming consequences the human-machine interaction can be effected for example by additional warnings. This is of special relevance for vehicles which are remotely operated. In the public-supported project FernBin beside others the supervision of the captain's actions in inland shipping is addressed. The focus is to model possible human-guided driving maneuvers several action steps ahead, the detection of human errors, and also of non- optimal behaviors by defining optimal ones. The final system supervises the captain's behavior supports her or him in critical situations based on the automated decision making support system.
Technical core of this contribution is a Situation-Operator-Modeling (SOM) as event-discrete approach used to model the captain-vessel-interaction of a remotely guided vessel as a graph-based-model. Using this approach sequences of possibly connected actions can be generated describing the human interaction options and therefore possibly upcoming future behaviors which allows beside the detection of not allowed actions, omitted but required actions, the detection of intended as well as unintended upcoming future situations. The approach is applied to experimentally-generated real situations within the context of the FernBin project in combination with the research vessel 'Ernst Kramer'.

Keywords: Situated monitoring, Decision making support system, Human-Machine-interaction, Situation-Operator-Modeling, cognitive technical systems

1. Introduction

The realization of a safe and connected traffic requires the development of supervision strategies to monitor the driving behavior and so that the Human-machine interaction. The planning and prediction of possible behaviors allows the detection of missing actions, human errors, and the distinction of possible and safe behaviors leading to desired goals. A decision making support system can be developed which supports the human operator by suggesting options from a set of predicted possible behaviors. If necessary the system can take over the functionality and execute an action-plan based on predicted behaviors to avoid critical situations and to lead to the desired final situation. 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. A fuzzy logic-based collision risk assessment is proposed in (Hu and Park (2020)). In (Tang et al. (2022)) the authors analyze the interaction between the human and intelligent ship systems in context within ship autonomy levels and based on "perception-decision-execution" modules.

A Situation-Operator modeling developed by (Söffker, 2001) allows the mapping of changes from the real world as a graph-model and to illustrate the Human-machine interaction. HÄGLE and SÖFFKER used the SOM-approach to develop a fall-back layer for aerial systems for a Safe System surveillance allowing the detection of risk areas (Hägele and Söffker (2020)). The Situation-Operator-Modeling is applied using Higher Petri-Nets to develop an automated supervision method of the Driver-Vehicle-Interaction

(Söffker and Ahle (2006)). An action-space- based supervision concept is proposed by (Bejaoui and Söffker (2022)) and applied to the captain-vessel-interaction.

The contribution of this work includes the development of an automated assistance system for support. Possible driving behaviors are planned and predicted as action sequences.

The approach is based on the situation operator model building methodology, here especially changes of the environment of a dynamic environment are considered. Actions that do not make sense or do not lead to the goal can be detected in advance and the human operator can be warned to avoid critical situations. In addition, the monitoring system suggests possible alternative action to achieve the given goal, can intervene, and take over the driving functionality if necessary. In previous works the application of the SOM-approach to the inland shipping area and the concept to calculate of an action space are discussed. In this paper, the development of a situated and continuously decision support assistance system is proposed and validated to a 'crossing-maneuver' described in (Bejaoui and Söffker (2022)).

This paper is organized as follows: The definition of the used SOM-approach and its application to inland shipping area are explained in the section 2. In section 3, the decision making with respect to possible actions depending on changes in the environment and the computation of discrete-event situations resulting from actions are explained. The method of the situated behavior planning and prediction, its application to a 'crossing-maneuver', and the results are shown in section 4.

2. Situation-Operator Modeling applied to inland shipping

The Situation Operator Modeling allows the modeling of scenes and changes from the real world as situations and operators and the illustration of the Human-Machine interaction as a graph-based model Söffker (2001). Situations refer to scenes and operators describe actions from the outside world. An initial situation S_i describes the current scenes and following situations are resulted because the execution of an operator-sequences (cf. Fig. 1). An operator effects the inner structure of the resulted following situation.

In the Fig. 1 a situation is presented as a gray ellipse. The inner structure of a situation vector consists of characteristics which can be to informational, physical, or logical terms (Söffker (2001)). An operator is presented as a white circle and connects two successive situations. The execution of an operator depends on fulfillment of explicit and implicit assumptions described by suitable mathematical, logical, or textual expressions (Söffker (2001)).

The modeling of the Human-machine interaction enables the realization and design of the cognitive functions planning, acting, and supervision. Planning and acting are understood as the the establishment of a sequence from the initial situation S_i to a desired final situation S_d (cf. Fig. 1). Relevant operators and characteristics are obtained considering real driving scenarios. The characteristics building the inner structure of a situation are listed in Table. 1. Data from the environment and sensors can be fused and compressed by prefilter to calculate the characteristics C_8, C_9, and C_{10} (cf. section 3.1).

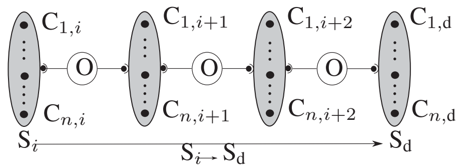

Fig. 1. Action sequence from the initial situation S_i to a final desired situation S_{i+1} (Söffker (2001))

The operators in context within the Captain-vessel interaction are illustrated in Table. 2. The mathematical description of the operators O_1 and O_2 is to increase/reduce the longitudinal speed over ground using the throttle. The operators O_4 and O_5 describe the route trip to the left and to the right using the rudder. The blue board can be activated by the operator O_6 for passing traffic-vessels starboard on starboard.

3. Event-discret calculation of situations for the decision support

In this section, the artificial generation of situations necessary for planning is explained as a con-

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(s) to river bank	[m]
C_{10}: Distance(s) to traffic vessel(s)	[m]

Table 2. List of operators

Name of operator	Description
O_1: Acceleration	Pressing the throttle
O_2: Deceleration	Pulling the throttle
O_3: Waiting	Doing nothing
O_4: Route trip to the right	Operating rudder
O_5: Route trip to the left	Operating rudder
O_6: Blue board	Activate blue board

sequence by conceivable actions mapped by describing operators. Depending on the environment conditions, different sequences of actions can be proposed to the human operator (captain) as decision options, which are tested for feasibility. The decision options also refer to the individual experiences of the operator. Central here, however, is the behavior of the other traffic vehicles which has to be integrated based on the results of a specific trajectory prediction. The generation of possible situations has to be adapted to the environmental conditions and the predicted behaviors of other traffic vessels.

3.1. *Conditions and assumptions*

The evaluation of driving behavior requires the consideration of assumptions and logical relationships, as well as the dependence of the environment. The relationships used are explained as follows:

Expected driving area: The area consists of channels and fairways leading to the end desired situation (position and orientation, if applicable, speed).

Distance(s) to the river bank: The distance can be determined using infrastructure data. The distance to the right river bank must not exceed the minimum distance $u_{\mathrm{r,min}}$, the distance to the left river bank must be not fall below the maximum distance $u_{\mathrm{l,max}}$. The calculation is based on the method from (Abromeit and et. al. (2010)) and depends on the length, width, and the class of the vessel.

Speed over ground (SOG): The speed over ground must be not exceed a critical speed v_{cr} considering the water depth. According to (Li et al. (2017)) and based on the 'Römisch model' the critical vessel's speed v_{cr} can be calculated depending on the water depth, the draft, the length, and the width 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 between each other. The TCPA is used for the evaluation of risk collision. The TCPA depends on the speeds, positions, and the course over ground of the ego-vessel and traffic vessels (cf. formula by (Nguyen et al. (2018))).

Distance to the traffic vessels: Euclidean distance, if traffics vessels exist in the driving area.

3.2. *Trajectory prediction*

This module allows the prediction of trajectories of other traffic vessels. The predicted positions of traffic vessels is continually calculated in parallel to the generation of possible actions and situations. For example the minimum distance between the predicted position of the traffic vessels and the position of the ego-vessel results by the planned action as performance condition. The TCPA can be calculated from the position, velocity, and COG resulting from planned actions for the ego-vessel and the position ,velocity, and COG obtained from the trajectory prediction. The used approach for the trajectory prediction is model-based method including an online system identification (cf. Thind et al. (2022)). A sliding window approach is used allowing the estimation and adaption of local parameters of the state space considering the time history of the motion of the traffic vessels. The predicted COG and SOG can be calculated from the predicted position.

3.3. *Event-discret calculation depending to environment conditions*

An operator effects the inner structure of a situation so that the values of the characteristics change or also the structure of the situation itself. The developed 'decision support control loop' method allows to calculate the following situation, to check assumptions and performance conditions, and to check reachability of goals leading to the final desired situation (cf. Fig. 2). The main components of the loop are the model-based operation, checking of assumptions, and the warning module, and the checking of goal reachability. For the specific application the model-based operation module consists of a considered operator from Table 2 and in combination with the Abkowitz model as kinematic motion model. The functionality of the operator is described by the variation of a state variable as input. The characteristics of the initial situation S_i are given as inputs in the model and its values are effected by the considered operator. The outputs of the model are the new calculated values of the characteristics because the execution of the operator. The operation O_1 is defined by the increase of the value of characteristic C_1, O_2 by the decrease of C_1. The variation of the value of the rudder angle C_6 describes the steering operations O_5 and O_4. The activation or deactivation of the blue board is related to C_7.

In the module 'checking assumption', the new state resulting by the applied operator is compared with conditions depending on the environment (infrastructure, traffic vessels in the driving area). If the assumptions are not fulfilled, the operator is not admissible and the calculated situation will be not considered.

In contrast to the checking assumption module, issuing warnings does not mean that rules are directly not fulfilled and that operators are directly leading to conflicts. In the 'warning module', conditions are analyzed with regard to the actual state, which may lead to a conflict in the future, for example, a warning value is determined with regard to the underlying conditions. The warning value can thus be interpreted as the upper limit value of a tolerance interval. When a corresponding situation (warning) is detected for the first time, the associated maximum time until the limit value is reached, i.e. the next situation S_{i+1} can be calculated without exceeding the permissible time. Only or then the next decision options can be generated. If the warning exists from the previous situation, the conditions and assumptions are evaluated, not admissible situations resulting by falling the lower limit of tolerance interval are excluded, and admissible states are checked for the goals reachability.

Goals leading to the final desired situation are predefined. A goal can be an area, a position, an orientation. If no warnings are detected, the calculated situation is checked for reachability of the next predefined goal. If the next goal is reached, the next situation S_{i+1} and new decision options are generated. If the goal is not reached, the characteristics must be calculated for the next time t_{k+1}.

4. Situated behavior planning & prediction and supervisory control

The graph-based behavior planning and prediction based on the SOM-method allowing the suggestion of possible decision options is introduced in this section. The generation of situations as results of possible operations according to the method introduced in section 3.3 and the Fig. 2 is the core of the proposed supervisory control method.

4.1. *Planning and Prediction of decision options*

The planning and prediction of decision options consists of three main steps shown in Fig. 3 and are explained as follows:

In step 1 all predefined operators are considered. The effect of every action to the following situation are analyzed in following steps.

Step 2 refers to the event-discret calculation, the decision making considering the assumptions depending to the environment changes and the reachability of predefined goals leading to the final desired situation (cf. section 3.3 and Fig. 2). Every predefined operator must be checked

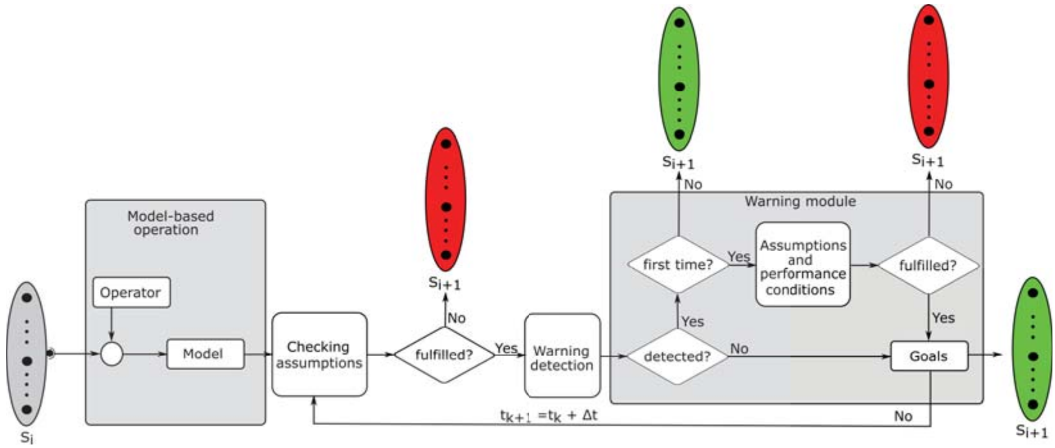

Fig. 2. Event-discret calculation of situations depending to the environment

with respect of the requirements related to the assumptions and performance conditions and on the reachability of with respect to the next predefined goals. In Fig. 3 possible decision options are marked (green) as examples, (red) ellipses refer to generated next situations resulting by erroneous actions which are neglected in the next steps.

In Step 3 the selection of a decision option from the list of possible action is realized: In this step only the set of possible actions obtained from the analysis in step 2 is considered. Only one decision option from the set can be selected. Here, the following prioritization applies: In this work, situations that can be reached when a following and given goal becomes attainable, are preferred to those that are only reached by triggering warning (cf. section 3.3). Situations that can be reached without warnings are preferred to others that can be reached with warnings. If there is no warning and no conflicts, processes with shorter operation time are preferred.

The situation resulting from the decision option in the step 3 is now the current situation. Starting from the new situation the steps 1 to 3 will be repeated for every new obtained or triggered situation. This repetitive process is executed until the final desired situation is reached. The main idea of the developed method is to situatively and continuously support the human operator to reach the final desired situation (cf. Fig. 3).

4.2. *Application to a 'crossing maneuver'*

The development method of the situated behavior planning and prediction is applied to the 'crossing-maneuver' shown in Fig. 4.

4.2.1. *Assumptions & performance conditions:*

The expected driving area consists of the channel of the port and the fairway of the river (cf. Fig. 4). The maximum distance to the left river bank $u_{\mathrm{r,min}}$ when the Ego-vessel is in the river in this example is 201,83 m. If an operator leads to leave the expected driving area or if conditions related to the distance to the river bank are not fulfilled, the operator is not admissible and therefore is not considered as a possible decision option (cf. section 3.1). The critical speed v_{cr} depending on the water depth is 5.07 m/s. If v_{cr} is reached after accelerating, the maximal time of this operation is reached, new decision options must be generated, and a new admissible action must be executed (cf. Fig. 3). According to Fig. 3 and the strategy given in section 3.3, the TCPA and the distance to traffic vessels are based on warning and conflict values. In the case of TCPA the warning value is 30 s. If 10 s $\leq$ TCPA $\leq$ 30 s, a warning is detected, new decision options must be generated so that a new possible operation can be carried out. If a warning exists from the last operation and TCPA falls below the threshold value 10 s because the current operation instead of exceeding

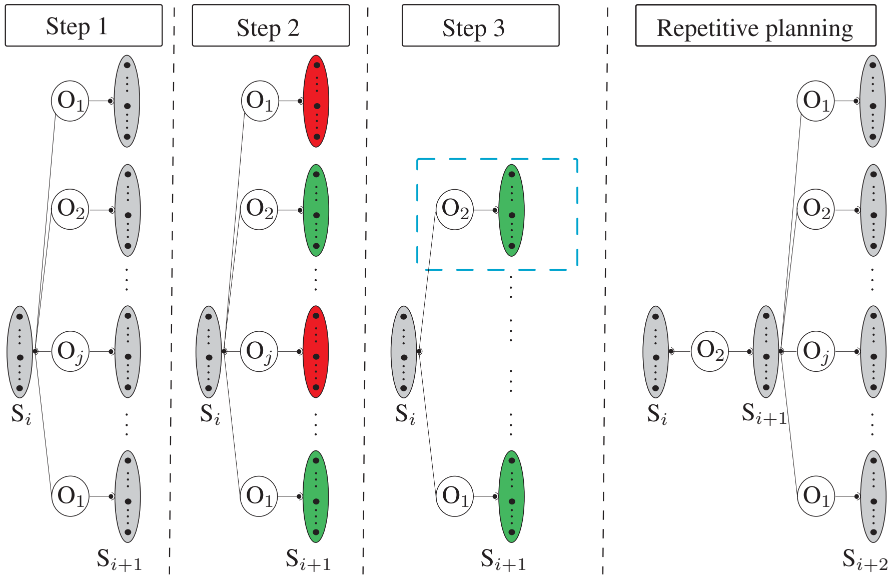

Fig. 3. Process of the planning and prediction of decision options

the warning value 30 s or other assumptions are not fulfilled, the operator is not admissible and not considered as a decision option. In the case of the distance to traffic vessels r a warning is generated and new decision options must be calculated, if 150 m $\leq r \leq$ 300 m. If a warning exists from the last operation and the current operator leads to r $<$ 150 m or other assumptions are not fulfilled, the operator is not admissible.

4.2.2. *Predefined goals:*

According to the strategy as discussed in section 3.3 goals leading to the final desired situation must be predefined. The first goal is to reach the port confluence, so the crossing area between the channel of the port and the river. The second goal is driving to the river in straight direction with a course over ground (COG) of 20° after leaving the port. The third goal is to reach the area closest to the bridge. This goal is equivalent to the final desired situation.

4.2.3. *Results of planning & prediction:*

The application of the method from section 4.1 to the crossing driving maneuver (cf. Fig. 4) is shown in Fig. 5. Only situations caused by possible operators are illustrated (green). The situation

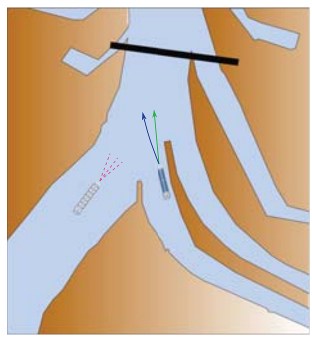

Fig. 4. Driving scenario ”Crossing-maneuver”: Ego-vessel (blue), traffic-vessel (white)

related to the selected operator is framed. The most important characteristics are shown in the following order: C_1, C_2, C_8, and C_{10} (cf. Table 1). The results are generated using the proposed algorithm programmed in C++ and Python.
The situation S_0 refers to the initial state and position of the Ego-vessel. Possible decision options are ’Acceleration’, ’Deceleration’, and ’Route trip to the right’. The operator ’Acceleration’ is possible until warning is detected because the distance to the traffic vessel falls bellow 300 m and the maximal time of operation is 59 s. ’Deceleration’ is possible and no warnings are detected. The

maximal time of the operation ’Route trip to the right’ is 55 s. The operator O_2 is the safest operator without warning detection and is selected as decision option. The current situation is now S_1 (cf. Fig. 5) and the ship is at a standstill in the channel of the port.

Possible next operators are O_1 and O_3. The operator O_3 (Waiting) denotes the case that the vessel waits 75 s at the standstill as long as warnings or conflicts related to TCPA or the distance to traffic vessel are detected. Than the driving area is free. The maximal time of the operation ’Acceleration’ from the situation S_1 (and so from the standstill) is 24 s because TCPA falls below the warning threshold 30 s. The optimal operator in this case is O_3. The current situation is now S_2.

In the situation S_2 the vessel is at standstill and the driving area is free. The only meaningful and possible operation is to accelerate O_1. The operator allows to reach the first goal area ’port confluence’ after operating 114 s. The new current situation is S_3 and new decision options must be generated.

After reaching the first goal area ’port confluence’ in the situation S_3 the operators O_2 and O_4 are evaluated as possible decision options. The operator O_4 (route strip to the right) leads to the second goal ’driving in straight direction in the river’ defined with the mathematical expression $\mathrm{COG} = 20^\circ$ and with time of operation of 39 s. The operator O_2 delays to reach goals leading to final desired situation. The operator O_4 is selected and the new current situation is S_4.

The only possible operator to reach the desired final situation is O_5 by operating the rudder and steering to the left. The algorithm shows that the operators O_1 and O_3 leads to leave the fairway of the river and so that the expected driving area. The action-sequence leading to the desired final situation is to decelerate, wait, accelerate to reach the first goal area, to steering to the right to drive in straight direction in the river, and than to operate the rudder to the left to control the orientation.

5. Conclusion and future work

In this work a decision support method based on the planning and prediction of possible actions leading to predefined goals and the final desired situation is developed and explained in detailed. The developed strategy is applied and validated to a ’crossing maneuver’ for an inland vessel sailing task. The method allows for the first time the prediction of possible actions as a event-discrete supervisory control considering dynamical changes in the environment. In future work the event-discrete calculation will be integrated in action spaces to enable the prediction of action-sequences. This allows the support of the human operator by suggesting a sequence of actions.

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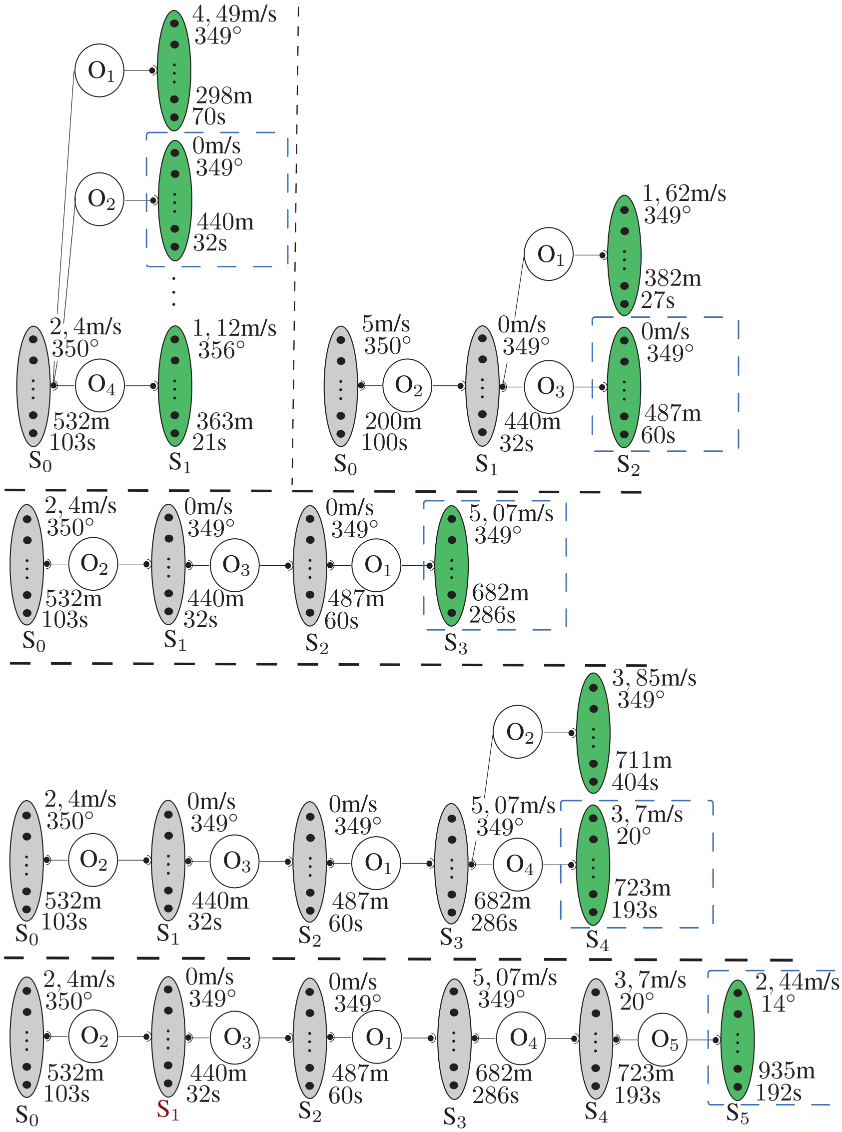

Fig. 5. SOM-based representation of the application of planning and prediction method to the 'crossing maneuver'

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