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MATHEMATICAL AND INFORMATION PROVISIONS OF BRIDGE TEAM TRAINING CONTROL SYSTEMS

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Abstract*—Despite considerable efforts and resources, expended on soft-, hardware and organizational facilities for navigators' development, it is required to increase the level of navigators' skills, familiarize them with the functions and limitations of ship's equipment. Building a harmonized cooperation between the members of bridge team is one of the most important tasks even for the well-educated and skilled in ship handling officers. A problem of sea transportation safety improvement through increased quality of navigators' simulator training is considered in current article. A critical review of IMO model courses and their use for the tasks of navigators' simulator training was performed. These recommendations pursue the purpose of standardization and unifying the bridge team training in accordance with STCW 1978/ 2010 convention. The main navigational tasks were classified, their formalized form end solutions represented. Because time constant and time of delay do not depend on the decision's responsibility level, it is possible to consider them as the characteristics of a definite Bridge Team member. These descriptions are determined by the simple experiments of reaction on the known signals and it is possible to get the model of Bridge Team behavior depending on the decision-making risks and external indignations. It was suggested to use safe sailing probability function as the criterion of navigator's competence. The essential point in the article is the transition from partial criteria for evaluating the navigators' work to the assessment of the average risk as a single criterion, which makes it possible to assess objectively the prospects of using a definite vessel crew. The implementation of a risk minimization strategy leads to a sequence of steps which allows to achieve an optimally safe trajectory. It was suggested to use Pontryagin's maximum principle on an optimum route plan, thus the task turned to the standard task of optimum operation speed of the linear system. A structure of optimal solution for bridge team simulator training is defined. A training complex structure consisting of visualization complex, where an external situation is designed, Bridge Team members' workplaces, data bases of vessels' dynamics models, navigation database, bases of indignations models and instructor's workplace was suggested.*

Index Terms—Simulator training; bridge team; preliminary route plan; optimal route; full-mission bridge; exercise scenario; decision making; optimal control.

I. INTRODUCTION

In spite of substantial slump in a world economy for the last decade, a marine transport remains a leader on volumes and cheapness of cargo transportation. Safety of navigation remains the issue of the day, and "human factor" – a principal reason of failures and catastrophes on a transport. The most catastrophic consequences have the errors of navigators who are responsible for a safe management of a vessel.

One of the methods to decline the probability of navigators' errors is their training in the conditions of modern centers of seafarers' retraining. However, despite considerable efforts and resources, expended on programmatic, technical and organizational facilities of preparation of navigators, emergency situations are not rare on a fleet.

Such situation requires to increase the level of navigators' skills, their familiarization with the functions and limitations of ship's equipment, building a harmonized cooperation between the members of bridge team who see each other, possibly, first time in life.

II. REVIEW OF PREVIOUS RESEARCHES

There is a great number of different programmatic and technical facilities on a market, providing teaching and achieving knowledge and skills by crews. The basis of these systems are various trainers and simulators [1], differentiating on purpose from the design of wheelhouse to the design of work with separate aggregates.

Only the full size training simulators fulfill the Ukrainian [2] and international legislation on working off the cooperation of bridge team and ship systems, approximately to the real object (a vessel).

A variety of tasks can be decided on such trainer complexes, from a direct navigation in the situations of close quarter [1], maneuvering at a search and rescue, to the tasks of the complete passage along the route.

Nowadays there is a row of the specialized courses on preparation of bridge team members: Maritime Resources Management, Bridge Team Resources Management, Master-Pilot Relations Course, conning the large-capacity vessels etc. The majority of them are based on model courses, developed by the International Maritime Organization (IMO) with the purpose of standardization and unifying the training of bridge team in accordance with STCW 1978/ 2010 convention. For example, model course 1.22 "Ship Simulator and Bridge Teamwork" [3] pulls out requirements to the equipment and personnel, to conduct teaching of bridge team members. Besides technical skills of ships handling, a competence to organize execution of watch and co-operation of all of the persons involved is included in this course [4]. However this and analogical model courses do not describe the detailed procedure on how to assess the competence of the learner, as well as that, on what principles an instructor must carry out the generation of scenarios.

The legs of preliminary route plan Gdynia – Vallvik by multi-purpose dry-cargo ship "HC Bea-Luna", prepared by the navigation mate, are shown on a Fig. 1.

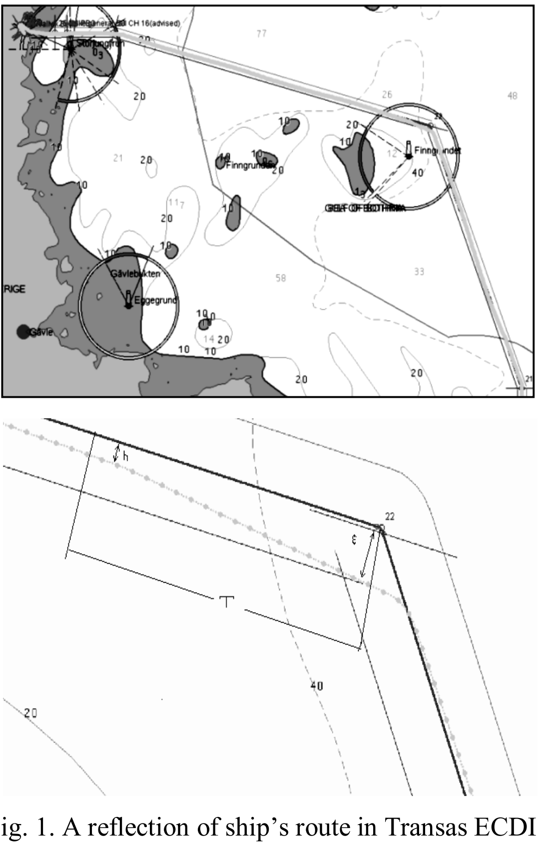


Fig. 1. A reflection of ship's route in Transas ECDIS Demo software environment

As possible to see, the real track of a vessel does not coincide with the lines of general courses of preliminary route. It is possible to draw a conclusion from it, that a preliminary route was not optimum, and/or the officer of the watch (OOW) made a miss in the maneuver calculation. Also probably, that a calculation was made thus because of additional external indignations (state of sea, collision avoiding with other vessels or floating navigational danger etc.).

The functionality of ECDIS (electronic chart display and identification system) TRASAS NAVI-SAILOR 4000™ allows to write down tracks and routes of the real vessels, presence of AIS targets within the limits of action of VHF radio waves. If a connection exists, the system can additionally fix the action of wind, rudder angle, heel of ship and other navigational information. The analysis of this information allows to study the navigator's performance during bridge team training.

Thus, there is a hardware-software complex which enables to estimate the base competence of navigator/instructor by the construction of optimum route and conning the ship on it. The next level of training must be conducted with the use of full-mission simulators and the learners co-operation as a bridge team with the conditions, maximally approximated to the real [5].

III. PROBLEM STATEMENT

A task of research is to ground and develop the methods and means of bridge team simulator training, taking into account the requirements to decline the accidents rate in shipping. It can be done by developing the existing training complex control system and improving its automation level.

IV. BRIDGE TEAM DECISION-MAKING

First of all it is necessary to divide the classes of tasks into the task of base preparation of navigators, which is used for execution of independent watch and task of collective watchkeeping in the enhanced bridge team (master, pilot, OOW, lookout, helmsman, etc.). The first task can be taught individually with the use of small simulators under control of instructor. It has an aim to acquaint the skills of work with ECDIS, decisions of tasks on a maneuver board, mastering the features of specific mathematical ship's model behavior. The second task must be performed by a full bridge team on a simulation complex with complete visualization and has a task of achieving skills of the concerted work and its organization for each member to the extent of his position.

It is possible to consider a simulator training complex as a model of the information-control system of ship from a navigation bridge. It is thus necessary to take into account that regardless of ship's automation level, the bridge team members carry the responsibility for the results of realization of control, and responsibility for organization of work remains after a master [6]. Therefore, further will examine an ambivalent task: base competence of navigator and his capacity for the arranged work as a member of the bridge team of distinctive type of ship (Table I).

Model of decision-making dynamics by a navigator, as an operator, is usually described by the dynamic system [7]:

$$\left.\begin{aligned} \dot{\mathbf{x}} &= A\mathbf{x} + B\mathbf{u} + Q\mathbf{g}, \\ \mathbf{y} &= C\mathbf{x}, \end{aligned}\right\} \tag{1}$$

where the vector of the state $\mathbf{x}$ is described by development of decision-making process. A control and indignation $\mathbf{g}$ are describing the input influences, and a vector $\mathbf{y}$ is describing the level of decision's readiness. Matrices A, B, C, Q describe the linear dynamic system in a state space.

Taking a closer look on a vector model, it is necessary to take into account the difficult decisions, which have few associated components. Possibly such approach differs from generally used [8], but it is more perspective, in our opinion. It is thus necessary to take into account that there are delays in a model (1). First of all it is a delay of perception of information τ_u and delay of decision implementation τ_c. Consequently, for the ith member of bridge team achieve a model:

$$\left.\begin{aligned} \dot{\mathbf{x}}_i(t) &= A_i\mathbf{x}_i(t) + B_i\mathbf{u}_i(t+\tau_{ui}) + Q_i\mathbf{g}_i(t), \\ \mathbf{y}_i(t+\tau_{ci}) &= C_i\mathbf{x}_i(t). \end{aligned}\right\} \tag{2}$$

It is necessary to take into account the level of made decision responsibility $\mathbf{y}^*_i$:

$$\left.\begin{aligned} &\dot{\mathbf{x}}_i(t) = A_i\mathbf{x}_i(t) + B_i\mathbf{u}_i(t+\tau_{ui}) + Q_i\mathbf{g}_i(t), \\ &\mathbf{y}_i(t+\tau_{ci}) = C_i\mathbf{x}_i(t), \\ &\mathbf{y}_{ir} = \left.\begin{matrix} \mathbf{y}_{ri} & \text{if} & a(\mathbf{y}_i, \mathbf{y}^*_i) \ge 0 \\ \mathbf{0} & \text{if} & a(\mathbf{y}_i, \mathbf{y}^*_i) < 0 \end{matrix}\right\}. \end{aligned}\right\} \tag{3}$$

Distance between vectors is determined by $a(y_1, y_2)$ metrics, accepted in this task. The dynamic's model of control step execution by bridge team is a sequence of decisions' acceptance and implementation operations:

$$\begin{aligned} &\mathbf{y}_{1r}, \ldots, \mathbf{y}_{rn}, \\ &\mathbf{u}_1, \mathbf{g}_1, \ldots, \mathbf{g}_n. \end{aligned} \tag{4}$$

TABLE I. NAVIGATORS' TRAINING LEVELS

Competence	"Base"	"Bridge team"		
Equipment	Small simulator	Full-sized training complex		
Aim function	"Individual" watch	Work in a team	Organization of watchkeeping	Co-operating with a pilot and others.

Besides, the plan of management forming in jth situation is determined by the sequence of channel's commutation of transferred information:

$$\begin{gathered} \begin{bmatrix} \mathbf{u}_1 \\ \mathbf{u}_2 \\ \vdots \\ \mathbf{u}_n \end{bmatrix} = \begin{bmatrix} K_{11} & K_{12} & \vdots & K_{1n} \\ K_{21} & K_{22} & \vdots & K_{2n} \\ \cdots & \cdots & \vdots & \cdots \\ K_{n1} & K_{n2} & & K_{nn} \end{bmatrix} \begin{bmatrix} \mathbf{y}_1 \\ \mathbf{y}_2 \\ \vdots \\ \mathbf{y}_n \end{bmatrix}, \\ K_{ij} = \begin{pmatrix} k_{11} & k_{12} & \vdots & k_{1m} \\ k_{21} & k_{22} & \vdots & k_{2m} \\ \cdots & \cdots & \vdots & \cdots \\ k_{m1} & k_{m2} & \vdots & k_{mm} \end{pmatrix}, \qquad k_{ij} \in \{0,1\}. \end{gathered} \tag{5}$$

Thus, setting the sequences of decision-making by bridge team members, it is possible to get the expected time of reaction at the set levels of decision-making responsibility. At the same time, a decision-making level is determined by the expected losses or an average risk of negative decision. Such a way, in a vessels' collision avoidance situation, there can be the following actions: x_1 is the rudder to port with probability P_1; x_2 is the rudder to starboard with probability P_2; x_3 is the increase the speed with probability P_3; x_4 is the reduce the speed with probability P_4. Besides, a decision x_i defines the consumptions C_i with probability P_i. In such a manner, the expected losses it is possible to receive as a mathematical expectation [12]:

$$\bar{C} = M\{C\} = \sum_{i=1}^{4} C_i P_i. \tag{6}$$

Thus, it is possible to estimate the expected risk of maneuver execution negative consequences, which is less than maximum and can serve as an assessment of navigator's decision.

The bridge team decision's optimality on the situation u_1 and indignations $g_1, \ldots, g_n$, is estimated by the expected expenses; and actually a decision must be received as a solvation of an optimization task in finding the minimum expected risk:

$$\mathbf{y}_1^*, \mathbf{y}_1^*, \ldots, \mathbf{y}_1^* \xrightarrow[\mathbf{u}_1, \mathbf{g}_1, \ldots, \mathbf{g}_n]{} \min \bar{C}. \tag{7}$$

After the series of tests, estimating probabilities of making a decision, can define the expected risk, as an assessment of decision made by a navigator. Naturally, different passage conditions are accompanied with different risks, that results in decision's responsibility level assessment y_i^*, for the expected expenses C and at maximal expenses $C_{\max}$:

$$y_i^* = \frac{\bar{C}}{C_{\max}}. \tag{8}$$

Then for one component of decision the estimation of decision-making time t_n can be certain on the maximal module of root λ_m. Taking into account that $T_i = 1/\lambda_{mi}$, achieve:

$$W_i = \frac{1}{T_i p + 1} \to x_i(t) = \left(1 - e^{-\frac{t}{T_i}}\right) \to$$
$$t_{ri} = T_i \ln\left(1 - \frac{\bar{C}}{C_{\max}}\right). \tag{9}$$

Because permanent time and time of delay does not depend on the decision's responsibility level, it is possible to consider them as the characteristics of a definite member of Bridge Team. These descriptions are determined in the simple experiments of reaction on the known signals time determination. Thus, it is possible to get the model of Bridge Team behavior depending on the decision-making risks and external indignations, which it is necessary to attribute to the input controls.

The Figure 2 shows the function of expenses correlated to the planned route, which shall be built beforehand at preparation of task stage.

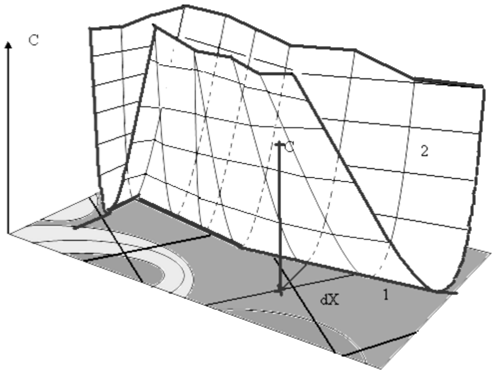


Fig. 2. Function of expenses on the preliminary route plan

It is necessary to take into account that at drawing the expenses function, it is necessary to correlate deviations from a preliminary route plan and condition of sailing. Therefore, a deviation dX will cause different expenses C on deep water and in shallow waters. Setting the expenses function is free, but most rationally is to utilize the branches of quadratic functions, different for a port side deviation $h > 0$ and starboard side deviation $h < 0$:

$$C(h) = \left.\begin{array}{ll} C_0 + r_+ dh^2 & \text{if } h > 0 \\ C_0 + r_- dh^2 & \text{if } h < 0 \end{array}\right\}. \tag{10}$$

A risk estimation and probability of the accident-free sailing P can be made based on statistical data of passing vessels for definite water area analysis, or by analytical calculations [10]:

$$P = 1 - \exp\left(-\frac{D^2}{M^2}\right), \tag{11}$$

where D is minimum distance from the ship's hull to the nearest navigation danger taking into account the trajectory of motion and position of ship's hull on it; M it is a radial mean square ship's positioning error when sailing near a danger. The estimation of deviations from optimum trajectories which can be unimportant must take a place taking into account a real traffic and external indignations.

The second feature of navigator's preparation task is its complication [9]. Will consider forming of control for the Bridge Team of four persons. In this case, the command's injection and execution will be detained consistently by four dynamic systems (3). Therefore, the control is principally built as optimum with a prognosis, analysis of model and adjustment. Besides, if the functions of prognosis and analysis of model are attributed to the seniors in the Bridge Team, adjustment is executed as stabilizing of the command's parameters. This division does not depend on the automation level of a vessel. Thus, analyzing the activity of Bridge Team with the purpose of forming best training terms, it is necessary to review the decision of optimum control task with an asymmetrical quadratic objective function and set limitations. Such task provides the initial and eventual waypoints or trajectory in the case of tasks of piloting, and degenerates in a differential game with an indefinite opponent in the collision avoidance task. No less difficult is a task of maneuvering in a water area, where it is required to take the dynamic properties of ship and her circulation parameters into account.

For the first case, the control is related to the task of dynamic object optimum control with forming of control by the difficult dynamic system [11]:

$$\begin{aligned} &\mathbf{u}'_n(t), \eta'(t) \to \min J(\dot{\eta}(t), \eta(t), \mathbf{u}(t)), \\ &\dot{\eta} = A\eta + B\mathbf{u} + Q\mathbf{g}, \\ &\eta(t_0) = \eta_0, \qquad \eta(t_1) = \eta_1, \end{aligned} \tag{12}$$

$$\left.\begin{aligned} &\left.\begin{aligned} &\dot{\mathbf{x}}_1(t) = A_1\mathbf{x}_1(t) + B_1\mathbf{u}_1(t+\tau_{u1}) + Q_1\mathbf{g}_1(t) \\ &\mathbf{y}_1(t+\tau_{c1}) = C_1\mathbf{x}_1(t) \\ &\mathbf{u}_{2r} = \left.\begin{matrix} \mathbf{y}_{r1} & \text{if} & a(\mathbf{y}_1, \mathbf{y}^*_1) \ge 0 \\ \mathbf{0} & \text{if} & a(\mathbf{y}_1, \mathbf{y}^*_1) < 0 \end{matrix}\right\} \end{aligned}\right\} \\ &\vdots \\ &\left.\begin{aligned} &\dot{\mathbf{x}}_n(t) = A_n\mathbf{x}_n(t) + B_n\mathbf{u}_{n-1}(t+\tau_{un}) + Q_n\mathbf{g}_n(t) \\ &\mathbf{y}_n(t+\tau_{cn}) = C_n\mathbf{x}_n(t) \\ &\eta_{ir} = \left.\begin{matrix} \mathbf{y}_{rn} & \text{if} & a(\mathbf{y}_n, \mathbf{y}^*_n) \ge 0 \\ \mathbf{0} & \text{if} & a(\mathbf{y}_n, \mathbf{y}^*_n) < 0 \end{matrix}\right\} \end{aligned}\right\} \end{aligned}\right. \tag{13}$$

At the same time, the sailing limitations must be fulfilled:

$$\left.\begin{aligned} \boldsymbol{\eta}(t) \notin \varphi_+(\boldsymbol{\eta}) \\ \boldsymbol{\eta}(t) \notin \varphi_-(\boldsymbol{\eta}) \end{aligned}\right\} \tag{14}$$

Considerable and irregular delays make the feedback forming a complicated problem, and as a result, the task of optimum operation speed or optimization of the control expenses must be solved [12].

V. BRIDGE TEAM TASKS FORMALIZATION

The Bridge Team solves the followings basic optimization tasks:

1) *A route planning – a task of risks minimization.* The task of determination links multitude $(x_0, x_1)_i$ giving a minimum risk C for the set of acceptable values of ship's coordinate x and the set of limitations, formed by the sailing conditions $\varphi(x)$ is set:

$$\begin{aligned} &(\mathbf{x}_0^*, \mathbf{x}_1^*)_i \xrightarrow[i=\overline{1,n}]{} \min \bar{C}, \\ &\mathbf{x} \in X_d, \\ &X_d \cap \varphi(\mathbf{x}) = \varnothing. \end{aligned} \tag{15}$$

2) *A task of planned course alterations* is an isoperimetric task with the chosen control resource [13]. The aim and limitations in a form of a functional lead to a task with limitation of equality type and Lagrange method application. In this case for the aim functional and limitations:

$$\begin{aligned} J\{x(t), \dot{x}(t), t\} &= \int_{t_0}^{t_1} F(x, \dot{x}, t)\,dt, \\ I\{x(t), \dot{x}(t), t\} &= \int_{t_0}^{t_1} \psi(x, \dot{x}, t)\,dt = 0, \end{aligned} \tag{16}$$

the functional of Lagrange is generated:

$$\begin{aligned} \tilde{L}\{x(t), \dot{x}(t), t\} &= \lambda_0 \int_{t_0}^{t_1} F(x, \dot{x}, t)\,dt + \lambda_1 \int_{t_0}^{t_1} \psi(x, \dot{x}, t)\,dt \\ &= \int_{t_0}^{t_1} \{\lambda_0 F(x, \dot{x}, t)\,dt + \lambda_1 \psi(x, \dot{x}, t)\}\,dt \\ &= \int_{t_0}^{t_1} L\{\lambda, x, \dot{x}, t\}\,dt. \end{aligned} \tag{17}$$

The necessary condition of optimum contains the requirement of a zero variation of Lagrange functional: $\delta L(\lambda, x, x', t) = 0, t \in 0(t_0, t_1)$, that gives the pair of terms:

$$\begin{aligned} &\delta J\{x(t), \dot{x}(t), t\}_x = 0, \\ &\delta J\{x(t), \dot{x}(t), t\}_\lambda = 0 \leftrightarrow \int_{t_0}^{t_1} \psi(x, \dot{x}, t)\,dt = 0. \end{aligned} \tag{18}$$

The solution of the achieved system allows to find an extremal if taking into account the boundary conditions. The heading angle φ is changing in the case of gyration. Taking into account the mathematical model of a vessel for the change of heading angle $\Delta\varphi$ can write down:

$$\left.\begin{aligned} \Delta\varphi &= \int_0^T \frac{d\varphi}{dt}\,dt \\ C &= \int_0^T \left(\frac{d^2\varphi}{dt^2} + a_1 \frac{d\varphi}{dt} \right) dt \end{aligned}\right\} \tag{19}$$

Consequently, the functional of Lagrange, in this case, looks like:

$$L = \int_0^T F(\varphi, \dot{\varphi}, C_0, \lambda)\,dt = \int_0^T \left[\left(\frac{d\varphi}{dt} + C_0 \right)^2 + \lambda_0 \varphi \right] dt. \tag{20}$$

After the use of Euler's condition get:

$$\begin{aligned} &\varphi(t) = \frac{1}{4}t^2 + c_1 t + c_2, \\ &\left.\begin{aligned} &\varphi(0) = 0, \\ &\varphi(T) = \Delta\varphi. \end{aligned}\right\} \end{aligned} \tag{21}$$

Thus, receive a trajectory, which minimizes the expenses, included in the risk assessment.

3) *A task of deviation* (Pontryagin's task) is formed by an optimum response speed of the linear system [15], [16]. In this task it is required to transfer the linear system from one state to another for the shortest time. This task is put as a task of Lagrange in general case:

$$\begin{aligned}&(\mathbf{x}',\mathbf{u}',t') \to \inf J(\mathbf{x},\mathbf{u},t) = \int_{t_0}^{t_1} f_0(\mathbf{x},\mathbf{u},t)dt,\\ &\frac{d\mathbf{x}(t)}{dt} = \dot{\mathbf{x}} = \mathbf{f}(\mathbf{x},\mathbf{u},t),\\ &\dim \mathbf{x} = \dim \mathbf{f} = n,\\ &\mathbf{x}(t_0) = \mathbf{x}_0, \qquad \mathbf{x}(t_1) = \mathbf{x}_1.\end{aligned} \tag{22}$$

The objective functional has the special convex properties (strictly convex, i.e. quasiregular or regular) and requires complete controllability limitations from the dynamic system. Thus, get the task of the convex programming. The convex conditions allow to apply the theorem of Kuhn-Tucker for Lagrangian:

$$L(\mathbf{x}',\mathbf{u},\boldsymbol{\lambda}') \le L(\mathbf{x}',\mathbf{u}',\boldsymbol{\lambda}') \le L(\mathbf{x},\mathbf{u}',\boldsymbol{\lambda}'). \tag{23}$$

Taking into account the identity of extreme properties of Langrangian and Hamiltonian, let us write down the condition of Kuhn–Tucker in terms of Hamiltonian:

$$H(\mathbf{x}',\mathbf{u},\boldsymbol{\lambda}') \le H(\mathbf{x}',\mathbf{u}',\boldsymbol{\lambda}') \le H(\mathbf{x},\mathbf{u}',\boldsymbol{\lambda}'). \tag{24}$$

Further form direct and dual tasks with the division of state and control variables. The condition of convex for determination of three unknowns gives four connections. Consequently, it is possible to simplify a task, eliminating the “inconvenient” connections.

Pontryagin Principle of a maximum:

$$\left.\begin{aligned}&\frac{\partial H}{\partial \mathbf{x}} = -\frac{d\boldsymbol{\lambda}}{dt}\\ &\frac{\partial H}{\partial \boldsymbol{\lambda}} = \frac{d\mathbf{x}}{dt}\\ &\frac{\partial H}{\partial \mathbf{u}} = \mathbf{0}\end{aligned}\right\}$$

$$\begin{aligned}&\mathbf{x}' \to_{u=u'} \min H(\mathbf{x}',\mathbf{u}',\boldsymbol{\lambda}')\\ &\mathbf{u}' \to_{x=x'} \max H(\mathbf{x}',\mathbf{u}',\boldsymbol{\lambda}')\end{aligned} \tag{25.1}$$

Principle of Bellman:

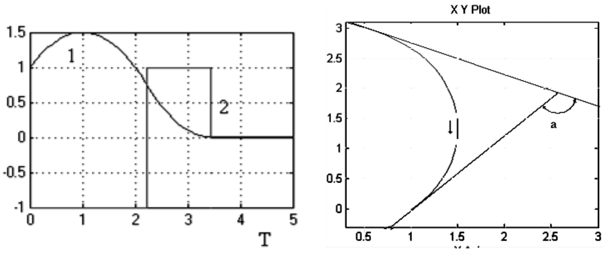
$$\left.\begin{aligned}&\frac{\partial H}{\partial \mathbf{x}} = -\frac{d\boldsymbol{\lambda}}{dt},\\ &\mathbf{u}' \to_{x=x'} \max H(\mathbf{x}',\mathbf{u}',\boldsymbol{\lambda}'),\\ &\frac{\partial H}{\partial \mathbf{u}} = \mathbf{0}.\end{aligned}\right\} \tag{25.2}$$

Thus achieved a principle of maximum of Pontryagin on an optimum route plan, where at an optimum control Hamiltonian arrives at the maximum. As the task is turned to the standard task of optimum operation speed of the linear system, it is possible to use the known solution [16], [17] to describe the turn angle φ_0 at gyration:

$$\begin{aligned}&\frac{d^2\varphi}{dt^2} = k_9 u, \qquad |u(t)| \le 1,\\ &u_1' = \begin{cases}\text{if } t \in (0,t_1), & u' = -u_m, \quad t_1 = \sqrt{\dfrac{\varphi_0}{k_9}},\\[2ex] \text{if } t \in (t_1,t_k), & u' = +u_m, \quad t_2 = 2\sqrt{\dfrac{\varphi_0}{k_9}}.\end{cases}\end{aligned} \tag{26}$$

On a Figure 3a the graphs of speed of turn land controls 2 are shown. On a Figure 3b the trajectory of a ship is shown at an optimum speed operation control.

Thus, the task of navigator at the urgent course alterations is very complicated and requires determination of three moments: wheel-over time, gyration-starting time and time of control cease (easing the rudder).



(a) (b)

Fig. 3. The control diagrams and trajectory of ship at an optimum speed operation control: (a) a diagram of speed of turn 1, and controls 2; (b) trajectories of gyration with minimum time

4) *Task of course-keeping* (task of Bellman) [17], supposes minimization of quadratic function for the linear system:

$$I(\mathbf{u}) = \int_{t_0}^{T} [\varphi^T(t)P(t)\varphi(t) + \mathbf{u}^T(t)Q(t)\mathbf{u}(t)]dt + \varphi(T)^T R\varphi(T), \tag{27}$$

where matrices are positively certain. Utillizing the control stationary condition find the form of optimum control:

$$\frac{\partial H}{\partial \mathbf{u}} = \mathbf{0} \to B^T(C\varphi + C^T\varphi) + 2Q\mathbf{u}^* = 0 \to \mathbf{u}^* = -Q^{-1}B^TC\varphi. \tag{28}$$

The achieved expression allows to find an optimum control for every current $y(t)$, however $C(t)$ matrix is unknown and can be found from the Riccati’s equation solution:

$$\frac{dC}{dt} + CA + A^T C - CBQ^{-1}B^T C + P = 0. \quad (29)$$

Thus, the solution of this task is the adaptive proportional adjustment.

5) *A task of collision avoidance* is a game with risk minimization and indefinite strategy of an opponent. A risk C of decision-making is here minimized at the expected actions of ship, presenting a danger. Realization of risk minimization strategy leads to the sequence of steps, realizing an optimum-safe trajectory.

VI. BRIDGE TEAM SIMULATOR STRUCTURE

Relying on the tasks considered higher, it is possible to form the structure of training complex of Bridge Team (Fig. 4).

A training complex consists of: visualization complex 1, where an external situation is designed, workplaces of members of Bridge Team 2 – 4, data bases of vessels' models dynamics 5, navigation database 6, bases of indignations models 7 and workplace of instructor 8 [18].

To generate the basic navigation tasks, as shown above, the different mathematical facilities are needed. Route planning task 9 requires not only a navigation set and legend but also statistics of passing the route, which allows a navigator to estimate risks as a basic criterion. The task of course keeping additionally requires the use of ship's dynamic model, which is formed from the separate module 5.

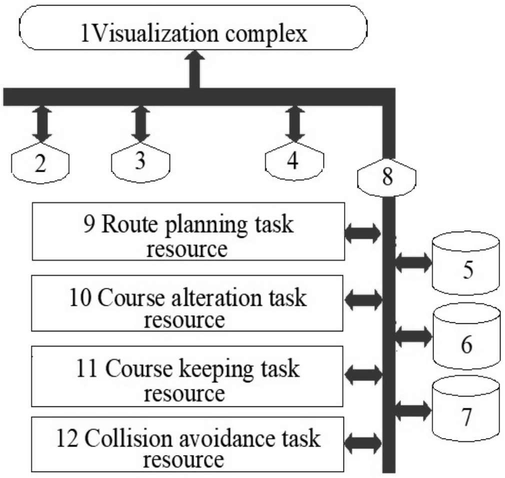


Fig. 4. Bridge Team simulation training complex structure

More complicated problem of vessels collision avoidance requires not only work of all Bridge Team but also the proficiency of navigator. This task is supported by separate software block 12. The necessary arrays of the navigation facilities, models of vessels and models of indignations contained in bases 5–7. The place of instructor is segregated with its system of assessment and control 8. Actions of instructor practically not have limitations, but the rules of assessment are formed on his expert opinion. Accordingly, for the observance of adequacy of scenario to the real sailing conditions, this module requires upgrading.

VII. CONCLUSIONS

The Bridge Team simulation training is an efficient facility to decrease the influence of "human factor" on water transport incidents level.

The functionality of existing soft and hardware means of training complexes fully satisfies the requirements of IMO model courses and Ukrainian legislation. However, these regulations do not contain any strict procedures to create the exercises scenarios and the principles of students' assessment. Such a situation does not allow to improve the level of Bridge Team training automation and to facilitate an automated unbiased competence assessment.

A method of Bridge Team competence assessment, based on safe sailing probability function and minimum risk is suggested. The represented formalized form of the main navigation tasks allows to calculate the risk function for different scenarios and to build an estimated losses function on each leg of a preliminary route.

The existing structure of Bridge Team training complexes does not allow to use fully the resources of it's data bases and overloads the instructor. Therefore it shall be upgraded using the suggested solutions.

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П. В. Каштальян, С. О. Рожков. Математичне та інформаційне забезпечення системи управління для підготовки команди ходового містка

Незважаючи на значні зусилля і ресурси, що витрачаються на програмні, технічні та організаційні засоби підготовки штурманів, необхідно підвищувати рівень навичок штурманів, знайомити їх з функціями і обмеженнями суднового устаткування, забезпечити узгоджене співробітництво між членами команди ходового містка. У даній статті розглядається проблема підвищення безпеки морських перевезень за рахунок підвищення якості підготовки судноводіїв на тренажерах. Було проведено критичний огляд модельних курсів ІМО і їх використання для задач навчання на тренажерах судноводіїв. Більшість з них засновані на модельних курсах, розроблених Міжнародною морською організацією (ІМО) з метою стандартизації та уніфікації навчання команди містка відповідно до конвенції STCW 1978/2010. Були класифіковано основні навігаційні завдання, представлені їх формалізовані кінцеві рішення. Оскільки стала часу і час затримки не залежать від рівня відповідальності рішення, їх можна розглядати як характеристики певного члена команди суднового містка. Ці описи визначаються в простих експериментах по реакції на визначення часу відомих сигналів, і можна отримати модель поведінки команди містка в залежності від ризиків прийняття рішень і зовнішніх збурень. Було запропоновано використовувати функцію ймовірності безпечного плавання в якості критерію компетентності штурмана. Важливим моментом в статті є перехід від часткових критеріїв оцінки роботи штурмана до оцінки середнього ризику в якості єдиного критерію, який дозволяє реально оцінити перспективу використання конкретного екіпажу судна. Реалізація стратегії мінімізації ризику призводить до послідовності кроків, які реалізують оптимально безпечну траєкторію. Був запропонований принцип максимуму Понтрягіна по оптимальному плану маршруту, щоб завдання було обернено в стандартну задачу оптимальної за швидкістю роботи лінійної системи. Визначено структуру оптимального рішення для тренування команди містка. Була запропонована структура навчального комплексу, яка складається з комплексу візуалізації, де проектується зовнішня ситуація, робочі місця членів суднового містка, бази даних динаміки моделей суден, навігаційна база даних, бази моделей збурень і робоче місце інструктора.

Ключові слова: тренажерна підготовка; команда ходового містка; попередня прокладка; оптимальний маршрут; тренажерний комплекс; сценарій вправи; прийняття рішення; оптимальне управління.

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П. В. Каштальян, С. А Рожков. Математическое и информационное обеспечение системы управления для подготовки команды ходового мостика

Несмотря на значительные усилия и ресурсы, затрачиваемые на программные, технические и организационные средства подготовки штурманов, необходимо повышать уровень навыков штурманов, знакомить их с функциями и ограничениями судового оборудования, обеспечить согласованное сотрудничество между членами команды ходового мостика. В данной статье рассматривается проблема повышения безопасности морских перевозок за счет повышения качества подготовки судоводителей на тренажерах. Был проведен критический обзор модельных курсов ИМО и их использования для задач обучения на тренажерах судоводителей. Большинство из них основаны на модельных курсах, разработанных Международной морской организацией (IMO) с целью стандартизации и унификации обучения команды мостика в соответствии с конвенцией STCW 1978/2010. Были классифицированы основные навигационные задачи, представлены их формализованные конечные решения. Поскольку постоянное времени и время задержки не зависят от уровня ответственности решения, их можно рассматривать как характеристики определенного члена команды судового мостика. Эти описания определяются в простых экспериментах по реакции на определение времени известных сигналов, и можно получить модель поведения команды мостика в зависимости от рисков принятия решений и внешних возмущений. Было предложено использовать функцию вероятности безопасного плавания и критерий компетентности штурмана. Важным моментом в статье является переход от частных критериев оценки работы штурмана к оценке среднего риска в качестве единого критерия, который позволяет реально оценить перспективу использования конкретного экипажа судна. Реализация стратегии минимизации риска приводит к последовательности шагов, которые реализуют оптимально безопасную траекторию. Был предложен принцип максимума Понтрягина по оптимальному плану маршрута, чтобы задача обратилась в стандартную задачу оптимальной по скорости работы линейной системы. Определена структура оптимального решения для тренировки команды мостика. Была предложена структура учебного комплекса, которая состоит из комплекса визуализации, где проектируется внешняя ситуация, рабочие места членов судового мостика, базы данных динамики моделей судов, навигационная база данных, базы моделей возмущений и рабочее место инструктора.

Ключевые слова: тренажерная подготовка; команда ходового мостика; предварительная прокладка; оптимальный маршрут; тренажерный комплекс; сценарий упражнения; принятие решения; оптимальное управление.

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