Assessment of the decisions made by the marine vessel navigator

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Abstract. The paper deals with interdisciplinary scientific research that lies in cognitive psychology, information technology and navigation, and is devoted to the relevant topic of navigation - vessel navigator’s decision-making. It reflects the results of theoretical research on the formalization of certain aspects of human mental activity in relation to solving navigation problems. The specific nature of this paper lies in navigator’s inclusion into the ship management which leads to the need in simultaneous consideration of psychological characteristics and ship manageability characteristics. Thus, navigator’s decisions are subjective and consequently difficult to formalize. The purpose of the research is to formalize, i.e. to mathematically describe the quantitative assessment of navigator’s decision-making. Author’s method of probabilistic sense evaluation is used in this research. The semantic space structure, which channels navigator’s decision-making, is represented as the model of a semantic prism. The results are adapted to the concepts of navigation and may be of interest to specialists in ship traffic control automation, artificial intelligence, creation of intelligent control systems and navigation safety.

1. Introduction
Regardless of the fact that high technologies are widely used on modern sea vessels, human error still remains a key issue in navigation safety and is considered the most common cause of incidents in shipping. Statistics show that 75-96% of marine accidents are caused by human error. [1]. According to the IMO website, life safety and security at the sea, marine environment protection and more than 90% of the world trade depend on the professionalism and competence of seafarers, i.e. on the human factor [2].

A lot of scientific research has been devoted to solving the problem related to the human factor. Navigator’s ability to act in extreme navigation situations and difficult sailing conditions is being studied [3, 4]. The role of the human factor as a psychological component in ensuring navigator’s safety and professional reliability in extreme, complex emergency conditions is being studied as well. The paper [5] provides an overview of the human factor in the field of such characteristics and features of behavior as fatigue, stress, health status, situation awareness, collaboration, decision-making, communication, automation and safety culture. The human element (factor) is taken into account when conducting research in the field of ISPS code [6] and in e-Navigation IMO project [7].

Despite the progress, the problem of the human factor in shipping is still far from being resolved. Perhaps the reason is that the research often does not consider “control system of a mobile object (ship, vessel, aircraft) as a human - machine cooperation. It consists of a controller, that includes the
operator (log boatmaster, pilot), and the controlled object, which is a mobile object, an engineering structure” [8]. Navigator’s inclusion into the ship management as a technical controller leads to a number of significant problems, as it requires simultaneous consideration of psychological characteristics and ship manageability characteristics.

One of the ways to solve these problems is to normalize (quantify) the human factor "... an attempt to normalize the human factor, i.e. quantitative evaluation of our confidence degree in minimization of human factor impact on vessel safety, may be of great interest" [8]. Research is already being conducted in this scientific area. For example, the paper [9] provides a justification for the quantitative evaluation method in terms of human factor influence on navigation safety. This method is the basis for preventive regulation of the human factor in the navigation process.

Decisions made by the navigator may cause erroneous actions which could lead to an immediate accident. These actions sometimes represent an active negligence in navigation safety standards and good maritime practice. Such negligence is obvious and can be attributed to the main cause of the accident [10]. Therefore, when analyzing and evaluating the decisions, correct classification of causal accident factors becomes particularly important. Paper [11] provides the classification of human errors at sea. The author believes that the most important errors are those in human decision-making "Errors, as the first sub-category of the Unsafe acts is represented by three types of possible human errors - skill-based, decision and perceptual. Examples includes mistakes such as safety check list error, critical-thinking failure or wrong hearing of verbal order» [11].

The problem of human decision-making is one of the most important problems in management theory and practice of complex dynamic systems and objects, such as a marine vessel. The purpose of this study is to mathematically describe (formalize) the quantitative assessment of navigator's decision-making. The specificity of the study lies in the fact that the navigator is mainly a person who has certain personal characteristics. Therefore, the study was performed in the context of psychological concepts and adjusted to solving navigation problems.

2. Materials and Methods
The mathematical description of navigator's decision-making assessment is based on such concepts of psychology as sign, denotation, meaning, intention, which form the structure of the semantic space. The meaning of these concepts: sign, denotation and sense is described in the work of G. Frege "Sense and denotation" [12]. The author investigates the related phrase "meaning - sense" in his paper. The denotation (meaning) of a sign is, in the broadest sense of the word, a certain thing, which the symbol denotes and makes an assertion about. Sense is the way of representing a denotation that binds symbols together. Concepts introduced by G. Frege formed the basis for the figurative representation of semantic reality as a flat figure — a semantic triangle, the vertices of which are sign, denotation and sense.

In abstract mathematical concepts, G. Frege's semantic triangle is a semantic space structure in the plane. Its structure-forming elements are sign, denotation and sense. If you add intention to these elements, you can use a rectangular coordinate system to formally represent the structure of the semantic space. In this system, sign, denotation and sense are single coordinate vectors (orts) that form the basis. The intention is the vector of the semantic space. When the intention vector is decomposed by the basis, the structure of the semantic space can be represented as a rectangular parallelepiped (semantic prism).

In navigation concepts interpretation of sign, denotation, sense and intention have the following implications:
- sign — trajectory point, at which the navigator makes a decision;
- denotation - entropy in "navigator - vessel - maneuver object" system;
- sense — a statistical parameter that shows the decision-making efficiency;
- intention — navigator's vision, his plan of action.

Trajectory points have a dual implication: on the one hand, they are deterministic points that form the trajectory, on the other hand, they are the points at which the navigator makes decisions.
concerning the movement of the vessel. The frequency of these points depends on a variety of random causes, including the human factor. Random distribution of these points along the trajectory meets the following requirements:

1. Points are distributed evenly in terms of statistics.
2. Points are distributed independently of each other.
3. The probability of two or more points falling into a small area is negligible compared to the probability of a single point.

In the probability theory, given conditions correspond to the law of a random variable distribution - Poisson's law. According to this law, the probability of the value $X$ (the number of points) taking a certain value $m$ is expressed by the formula

$$P_m = \frac{a^m}{m!} e^{-a} (m = 0, 1, ...),$$  \hspace{1cm} (1)

where $a$ — the parameter of Poisson's law (the average number of points per trajectory segment $l$).

Then, regarding the conditions for random distribution of points along the trajectory and formula (1), we can use a well-known K. Shannon's formula to calculate the entropy required for determining denotation and sense:

$$H(X) = -\sum_{m=1}^{m} p_m \log_2 p_m,$$  \hspace{1cm} (2)

where $p_m$ — the probability that the number of points will get the value $m$.

Sense (a statistical parameter that shows decision-making efficiency) is calculated using the method described in the article [13]. The calculation method is based on the fact that entropy difference $\Delta H$ as a random variable uses an exponential distribution law, the parameters of which estimate sense value. Entropy difference is calculated using the formula

$$\Delta H_i = \left| H(X)_{i-1} - H(X)_i \right|$$  \hspace{1cm} (3)

Differential entropy $H(\Delta H)$ is used to estimate sense value as a parameter of a random variable exponential distribution law. Research shows that the greater the $H(\Delta H)$, the more sense there is, and vice versa [14]. This pattern is used to quantify sense value as a psychometric criterion $M$:

$$M = H(\Delta H).$$

The method of sense evaluation is based on calculating the value $\Delta M_s$, thereby we compare and analyze the values of psychometric criteria in navigator's original plan $M_s$ and probabilistic plan that corresponds to the current situation, $M_p$:

$$\Delta M_s = M_s / M_p.$$

The higher the value $\Delta M_s$, the more sense the original plan has, and vice versa. If sense value decreases and becomes less than 1, the original plan should be revised.

Mathematically, the intention - navigator's action plan - can be represented as a vector $\vec{G}$ decomposed into single vectors $\vec{a}, \vec{b}, \vec{s}$, respectively, sign, denotation and sense:

$$\vec{G} = g_s \vec{a} + g_s \vec{b} + g_s \vec{s}$$  \hspace{1cm} (4)

where $g_s, g_s, g_s$ — intention coefficients (coordinates) along the corresponding axes that show an average number of bits per interim trajectory point.
The distance between the intention vector end in the original plan $\vec{G}_0$ and the intention vector end in current situation $\vec{G}_j$ determines the distance between current situation estimation and standard situation estimation and is expressed as a vector $\vec{\gamma}_i$. The smaller the module $|\vec{\gamma}_i|$, the closer the situation is to the standard one. When the value of the standard situation module $|\vec{\gamma}_0|$ is set and the module $|\vec{\gamma}_i|$ is compared to it, the situation is recognized as corresponding to the standard one.

$$|\vec{\gamma}_i| \leq |\vec{\gamma}_0|$$

This allows the navigator to evaluate the decision and take a reasonable action to manage the vessel.

3. Results and Discussion

As an example, let’s consider an abstract (The above example illustrates the results obtained and does not describe any specific situation) situation when the vessel approaches a maneuver object (see Figure 1), similar to the one described in [15].

**Figure 1.** Kinematic vessel trajectory when approaching the maneuver object (the original plan of navigator’s actions). S – vessel; O – maneuver object.

Vessel trajectory is divided into three sections of different lengths (see Figure 2). The first section: $S_0 – S_2$, second: $S_3 – S_7$, third: $S_8 – S_{15}$. Uneven distribution of points along the trajectory serves as an
indirect evidence that navigator made his decisions at these points, the density of which grows as distance to the maneuver object decreases.

Figure 2. Current situation when the vessel is approaching the maneuver object. S – vessel; O - maneuver object.

4. Solution
1. Using the formula (2), we calculate system entropy (denotation) "navigator – vessel – maneuver object" for each trajectory section. To do so, we use the formula (1) to determine the probabilities of the corresponding points.

The first section:

\[ P_3 = \frac{a^3}{3!} e^{-a} = 0.223618; \]

second section:

\[ P_5 = \frac{a^5}{5!} e^{-a} = 0.152814; \]

third section:

\[ P_8 = \frac{a^8}{8!} e^{-a} = 0.011867; \]
Finding the entropy (denotation):

\[ H(X) = - \sum_{i=1}^{m} p_m \log_2 p_m = -0.97328 \text{ bit/symbol}. \]

2. In order to determine the effectiveness of navigator's decisions (sense), we calculate the entropy values for each trajectory section using the formula (2).

Entropy of the first section:

\[ H(X)_1 = - \sum_{i=0}^{2} p_3 \log_2 p_3 = -0.48321 \text{ bit / symbol}. \]

Entropy of the second section:

\[ H(X)_2 = - \sum_{i=3}^{7} p_3 \log_2 p_3 = -0.41415 \text{ bit / symbol}. \]

Entropy of the third section:

\[ H(X)_3 = - \sum_{i=8}^{15} p_8 \log_2 p_8 = -0.07591 \text{ bit / symbol}. \]

Finding the entropy differences by the formula (3):

\[ \Delta H_1 = [\Delta H(X)_1] - [\Delta H(X)_2] = 0.06906 \text{ bit / symbol}. \]

\[ \Delta H_2 = [\Delta H(X)_2] - [\Delta H(X)_3] = 0.33824 \text{ bit / symbol}. \]

We find the differential entropy of the exponential distribution in entropy difference (Shannon entropy differences) mindful of current situation \( H(\Delta H) \) and the corresponding psychometric criterion \( M_s \):

\[ M_s = H(\Delta H) = -0.591353 \]

We find the differential entropy of the exponential distribution in entropy difference (Shannon entropy differences) mindful of current situation \( H(\Delta H) \) (For a probabilistic situation, the probabilities of points are randomly distributed in the following order: \( P_8, P_2, P_3 \)) and the corresponding psychometric criterion \( M_p \).

After performing calculations for the new order of probability distribution using the same formulas as for the current situation, we obtain the differential entropy of the exponential distribution in entropy difference for a probabilistic situation:

\[ M_p = H(\Delta H) = -0.591352 \]

We calculate the value of \( \Delta M_s \) in current and probabilistic situations: \( \Delta M_s \):

\[ \Delta M_s = \frac{M_s}{M_p} = \frac{-0.591353}{-0.591352} = 1.0000017 \]

3. Regarding the results obtained, the intention vector (4) for the current situation will be:

\[ \overrightarrow{G} = \overrightarrow{a} + 0.9732800\overrightarrow{b} + 1.0000017\overrightarrow{s}, \]

where the coefficient \( g \) is assumed to be equal to 1, i.e. one point is assumed to be equal to 1 bit.

The intention vector in the original plan is based on the same formulas as in the current situation. Let's assume that
\[ \vec{G}_0 = \vec{a} + 0.9832800 \vec{b} + 1.0000007 \vec{s}. \]

4. Using the formula known in analytical geometry, we calculate the distance between the end of the intention vector in the original plan \( \vec{G}_0 \) and the end of the intention vector in the current situation \( \vec{G}_j \).

\[ |\vec{y}_i| = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2} = 0.01 \]

5. We compare the resulting module value \( |\vec{y}_i| \) with the set module value \( |\vec{y}_{r0}| \), which is calculated based on existing navigation standards and good maritime practice. Let's assume \( |\vec{y}_{r0}| = 0.02 \). In this case, condition (5) is written as:

\[ 0.01 \leq 0.02 \]

Since the condition is met, we can conclude that current situation corresponds to the standard one, i.e. the navigator makes correct decisions in this situation.

5. Conclusion

As a result of the research, the semantic space structure in the spatial coordinate system is described as an abstract mathematical object — a semantic prism. The main structural elements of the semantic space are sign, denotation, sense, intention.

In the interpretation of navigation concepts, structural elements have the following implications:

- sign — trajectory point, at which the navigator makes a decision;
- denotation - entropy in "navigator - vessel - maneuver object" system;
- sense — a statistical parameter that shows decision-making efficiency;
- intention — navigator's vision, his plan of action.

Transition from psychology concepts to navigation concepts allowed us to adjust mathematical description of the semantic space structure in the psychological aspect to the mathematical quantitative assessment description of navigator's decision-making using a practical example. As a result, a mathematical model for evaluating navigator's decision-making is obtained.

The results may be of interest to specialists in ship traffic control automation, artificial intelligence, creation of intelligent control systems and navigation safety.

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