The Human Navigation Element as a Statistical Parameter in the Information Aspect

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Abstract. The paper presents the results of a study on the topic of the human element in navigation, which is relevant for sailing. The relevance of the topic lies in the fact that this factor has a predominant influence on the safety of navigation. The main approach to the study of the human element is a psychological approach. This study uses the cybernetic approach based on concepts of the information theory, such as entropy. The object of the study is a complex dynamic control system, the main elements of which are the master, the vessel and the object of maneuver. The subject of the study is the human element of navigation in the Poisson notation, as the main determinant of a probabilistic state of the control system. The purpose of the study is to develop a probabilistic model for normalizing the human element of navigation from the standpoint of the cybernetic approach and a Poisson distribution of the random variable. The main hypothesis of the study is that the intermediate points of the trajectory of movement are the points at which the navigator makes decisions on controlling the movement of the vessel. The frequency of these points depends on many random reasons, including the human element. As a result of the study, the notion of the human element of navigation was formulated in the Poisson notation, and an evaluation criterion for the probabilistic state of the control system was proposed. The results are recommended to researchers in the field of automation of ship traffic control and specialists in creation of intelligent systems for controlling the movement of a marine vessel.

1. Introduction
Statistics show that one of the main causes of accidents on different modes of transport is the human element. According to average statistical data, it accounts for an average of 70–80% of accidents [1]–[3]. Similar statistics apply for water transport, where this figure reaches 90% [4], [5]. A series of serious sea accidents and disasters at the end of the last century forced the international maritime community to rethink the system of navigation safety. So, in 1997, the International Maritime Organization (IMO) adopted the resolution “Resolution A.850 (20). Human element vision, principles and goals for the organization (IMO)”. The resolution states: “The human element is a complex multidimensional issue that affects maritime safety and marine environmental protection. It involves the entire spectrum of human activities performed by ships’ crews, shore based management, regulatory bodies, recognized organizations, shipyards, legislators, and other relevant parties, all of whom need to cooperate to address human element issues effectively”.

The IMO resolution was a powerful incentive to conduct research on the problem of the human element. The urgency of this problem is currently due to the information redundancy of the officer of
the watch [6]. In this regard, the need to consider the human element is dictated in the framework of the implementation of the project e-Navigation IMO [7]. In addition, the urgency of the human element problem is enhanced by increasing the regulatory burden on the crew in accordance with the ISM Code, STCW, SOLAS, MARPOL and the requirements of the ISPS Code [8].

As a rule, in studies on this issue, the human element is considered in the psychological aspect, as a factor that takes into account the personal characteristics of the master. For example, in [9], [10] the role of the human element as a psychological component in ensuring safety and professional reliability in extreme conditions is investigated. [11] presented an overview of research in the following areas: fatigue, stress, health, awareness of the situation, teamwork, decision making, communication, automation and safety culture.

A psychological approach to the study of the human element is necessary, but it does not take into account that “The control system of a moving object (ship, vessel, plane) is man-machine and consists of a regulator, which also includes an operator (watch navigator, pilot), and an object of regulation, which is a moving object as an engineering structure” [12]. The inclusion of the master in the vessel control link as a regulator introduces significant problems, since there is a need to simultaneously take into account the personal characteristics of the master and the controllability parameters of the vessel. The rules that should guide the master, while making decisions, must be based on the natural laws of human behavior in the marine environment. However, the problem lies in the fact that so far there is not enough knowledge on these laws and the causal relationships of human-machine interaction. One of the ways to solve this problem can be the rationing (quantitative assessment) of the human element [12], [13], [14], [15]. For example, in [12] it is put: “... an attempt to ration the human element, that is, quantitative assessment of the degree of our confidence that its impact on the safety of the vessel will be minimized”.

Thus, the analysis of literary sources shows that a certain progress has been made in solving the problem of the human element in navigation. Nevertheless, this problem remains relevant and is still far from its final solution. The urgency of the problem is increasing and the human element is still a complex multi-dimensional problem that covers the whole spectrum of human activity at sea.

2. Materials and methods

In accordance with the hypothesis of this study, the authors believe that intermediate points of the trajectory of a vessel’s movement have a dual meaning: on the one hand, these are deterministic points of the kinematic trajectory, on the other hand, these are the points where the navigator makes decisions on controlling the movement of the vessel. Deterministic points of the kinematic trajectory of motion can be obtained by methods known in navigation as, for example, described in [16], [17]. The points at which the master makes decisions on controlling the movement of the vessel are the points where the frequency depends on many random reasons, including the human element. In this case, the issue naturally arises, how to select subjective reasons from a variety of reasons. The answer lies in the stochastic analysis of intermediate points and, above all, in the choice of the random variable X and the law of its distribution.

The random distribution of points in the field of the trajectory of motion must satisfy the following conditions:

1. The points are distributed statistically uniformly with the average density \( \lambda \) (the expectancy of the number of points per unit length).
2. Points are distributed independently of each other.
3. The probability of hitting a small area of two or more points is negligible compared to the probability of hitting a single point, i.e. dots appear singly.

Positioning the motion trajectory as a segment \( AB \) of length \( l \) and consider a discrete random variable \( X \) – the number of points that fall on this segment. Possible values of random variable will be:

\[
0, 1, 2, \ldots, m, \ldots
\] (1)
Since the points fall on a segment independently of each other, it is theoretically possible that there will be any number of them, that is, series (1) extends indefinitely. Then, the probability of hitting a single point on segment $AB$ will be low and the probabilities of the points will be equal. Under given conditions, low and equal probability of the events, the occurrence of some remarkable events, such as the ship’s movement to the intermediate point of the trajectory, can with a certain probability be correlated with the human element: the navigator in conditions of environmental uncertainty seeks to bring the ship to a given point. In the probability theory, the given conditions correspond to the law of distribution of a random variable, called the Poisson law.

It is noteworthy that this law was obtained and used by Poisson to study the probability of sentences in criminal and civil cases. In the book “Researches on the probability of sentences and verdicts in criminal and civil matters”, Poisson gives the following rationale for this law: “When a very large number of events are possible, a priori having equal and very low probabilities, the appearance of one of those that represent something notable should be very likely attributed to a special reason $C$, similar, for example, to the human will, and not the causality” [18, p. 11]. In this statement, the expression “human will” can be interpreted as “human element”. Hence, it follows that in the Poisson notation, the human element is a special reason for the appearance of random notable events that have an equal and low probability of a subjective nature.

Thus, as the random variable $X$ one can take the number of intermediate points (decision points) on the trajectory of movement, distributed according to the Poisson’s law. A rigorous mathematical proof that the distribution of $X$ on the line $AB$ obeys the Poisson law is given in [19].

According to the Poisson’s law, the probability that $X$ will take a certain value of $m$ is expressed by the formula:

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

where $a$ – some positive value, called the Poisson law parameter. The value $a$ in meaning is the average number of points per segment $l$.

The probability $R_1$ that $X$ will take a positive value, i.e. the probability that at least one point falls on the segment $l$ is:

$$R_1 = 1 - e^{-a}.$$

The probability $R_k$ that $X$ will take a value not more than the given $k$ may be found by the formula:

$$R_k = P_0 + P_1 + ... + P_{k-1} = \sum_{m=0}^{k-1} P_m.$$

The probability $R_k$ that $X$ will take a value not less than the given $k$ may be found by the probability of the opposite event:

$$R_k = 1 - (P_0 + P_1 + ... + P_{k-1}) = 1 - \sum_{m=0}^{k-1} P_m.$$

3. Results and discussion

Taking into account the accepted assumption that intermediate points of the trajectory have the value of decision points and are distributed randomly along the trajectory according to the Poisson law, the authors formulate and describe an algorithm for solving the problem of controlling the movement of the vessel. This algorithm with the solution of the control example is described in detail in [20].

4. Problem

A complex dynamic system “navigator, vessel, object of maneuver” is given. The main elements of this system are: the navigator is the subject of maneuvering, the vessel is the object of maneuvering,
the object of maneuver is a moving or stationary object with respect to which the vessel is maneuvering. The vessel operated by the master should approach the object of the maneuver for a specified distance or close. The trajectory and its parameters are known to the master.

It is required to:
1. Calculate the number of intermediate points of the trajectory for the case of maximum uncertainty and the best case for their planning (normalizing) by the criterion of a given probability.
2. Estimate the probabilistic state of the system by the number of planned intermediate points of the trajectory.
3. Assess the probabilistic state of the system when the vessel approaches the object of maneuver at the current intermediate points of the trajectory.

5. Solution
1. Calculation of the number of intermediate points of the trajectory for the case of maximum uncertainty and the best case when planning them by the criterion of a given probability.

The possible states of the considered system \( (X_n) \) by the number of planned intermediate points of the trajectory during the approach time (frequency of decision-making by the master) will be:

- \( x_1 \) – the number of intermediate points will take the value not greater than the specified \( k \);
- \( x_2 \) – the number of intermediate points will take the value not less than the specified \( k \).

In this case, obtaining the following state probabilities:

- \( x_1: R_{k1} = P_0 + P_1 + \cdots + P_{k-1} \);
- \( x_2: R_{k2} = 1 - (P_0 + P_1 + \cdots + P_{k-1}) \).

The number of intermediate points on the trajectory of movement will reach its maximum uncertainty (or taking into account the dual meaning of these points – the maximum uncertainty of decision making by the master will occur) with equiprobable states \( x_1 \) and \( x_2 \), i.e. one can write the following equation:

\[
P_0 + P_1 + \cdots + P_{k-1} = 1 - (P_0 + P_1 + \cdots + P_{k-1}),
\]

solving which one can obtain the value of the Poisson law parameter \( a \). The obtained value of the parameter \( a \) is, by definition, the mathematical expectation of the number of points in the Poisson distribution, or by the meaning – the average number of points per trajectory length.

In this case, the probability of \( x_1 \) and \( x_2 \) states will be equal to 0.5. To obtain a more reliable result, the “marginal” probability of the \( x_2 \) state is set, which will be assumed at the level of 0.99. Then, solving the equality

\[
R_{k2} = 1 - (P_0 + P_1 + \cdots + P_{k-1}) = 0.99,
\]

obtaining the value of the parameter \( a \) and, accordingly, the average number of points on the trajectory for a given “marginal” probability.

2. Estimation of the probabilistic state of the system by the number of planned intermediate points of the trajectory.

To go from the probabilities of the system’s states to the probabilities of the state of the system as a whole in terms of the number of planned intermediate points of the trajectory, introducing into consideration the generalized statistical indicator – entropy, widely used in the information theory. Because events \( x_1 \) and \( x_2 \) are independent, then the entropy can be calculated by the well-known Shannon formula:

\[
H(X) = - \sum_{i=1}^{n} p_i \log p_i
\]

where \( p_i \) – probabilities of possible states of the system.

In the case of equally probable events, the entropy of the system will reach a maximum value and will be equal to \( H(X) = 1 \). The maximum entropy value indicates the maximum uncertainty of the state
of the control system and can serve as the main criterion (a kind of “zero” of the rating scale) to estimate the probable state of the system “navigator, vessel, object of maneuver”.

3. Assessment of the probabilistic state of the system when the vessel approaches the object of maneuver at the current intermediate points of the trajectory.

The possible states of the $X_a$ system when the vessel approaches the object of maneuver at the current intermediate points of the trajectory will be:

$x_1$ – the vessel has reached the estimated intermediate point;

$x_2$ – the vessel has not reached the estimated intermediate point.

In this case, one obtains the following state probabilities:

$x_1$: $P_1 = 1 - e^{-a}$;

$x_2$: $P_2 = e^{-a}$.

Now finding the maximum uncertainty of the state of the system $X_a$, which appears when the system’s states are equiprobable, i.e. one can write the following equation:

$1 - e^{-a} = e^{-a}$.

After the transformations, getting:

$$a = \frac{1}{\log_2 e} = 0,6931.$$

With this value of the parameter $a$, the entropy of the system will reach the maximum value $H(X) = 1$.

6. Conclusion

So, the main conclusions of this study are as follows.

In the Poisson notation, the human element is a particular determinant of the occurrence of random notable events that have an equal and low probability of a subjective nature. A notable event is the result of the master’s target-oriented activity in controlling the movement of the vessel, for example, the vessel’s departure to a given intermediate point on the movement trajectory. When estimating the probabilistic state of the controlled system, a special Poisson determinant can be expressed by the amount of entropy per decision made.

In the aspect of the cybernetic approach, the human element of navigation is a statistical parameter of the Poisson distribution of a random variable, which measures the average amount of entropy of the probable state of the “navigator, vessel, object of maneuver” system per one decision made by the navigator.

The frequency of decision-making by the master in the performance of the control task must exceed the initial set frequency, which is based on experience and is set on the basis of practical considerations in accordance with the environmental conditions, rules of navigation and fishing. In order to ensure the best possible development of events in the process of solving the task of control, the number of intermediate points of the motion trajectory should about 2.5 times (according to the test case) exceed the original set value.

This conclusion in the interpretation of the cybernetic approach can claim to be one of the natural laws of human (navigator’s) behavior in the control of a complex system. In practice, this pattern is reflected in one of the principles of good marine practice: “Consider yourself closer to danger”. According to this principle, an experienced master needs to make decisions more often if the control task is higher in difficulty.

The results are recommended to researchers in the field of automation of ship traffic control and specialists in the creation of intelligent systems for controlling the movement of a marine vessel.

7. References

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