Entropy As an Assessment Factor of the Current State of Vessel When Approaching an Object of Maneuver

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Abstract. The paper describes a method for assessing the current state of a vessel as an element of a complex dynamic system when approaching a mobile object. As an evaluation criterion, it is proposed to use the maximum value of the entropy of the “vessel – the object of maneuver” system with the equality of probabilities of possible states of this system. The relevance of the study is due to the need to improve the classical methods of analysis and solving the problems of the vessel’s approach to the object of maneuver. Classical deterministic methods often prove ineffective if the object of maneuver performs unpredictable random actions in relation to the maneuvering vessel. Such objects include, for example, mobile shoals of fish or other vessels operated by inexperienced navigators. The purpose of the study is to justify the method of assessing the current state of the vessel when approaching the object of maneuver on the calculated deterministic trajectory. The solution of the control example confirmed the possibility of using the entropy of the “vessel – the object of maneuver” system as a universal estimation parameter of vessel’s current state when approaching an object of maneuver. The materials of the paper can be of practical and theoretical interest for specialists in the field of automation of ship movement control, navigators of merchant and fishing ships.

1. Introduction

Safety is one of the key problems of sea navigation. To solve it, a whole complex of measures and tasks has been developed and implemented to create the ways, methods and means for controlling the movement of the vessel and to create automated navigation systems on their basis. The relevance of the safety of navigation is reflected in [1]. When solving problems of vessel movement control at large distances and within the water areas of ports, deterministic methods are developed and used. On their basis, automated vessel traffic control systems have been created both within the water areas of ports [2, 3] and when navigating on the high seas [4].

However, in cases where a vessel is approaching a mobile object (an object of maneuver), there are a number of unresolved tasks, primarily related to assessing the current state of the vessel to determine the degree of danger or efficiency of the approach process. Such cases include: divergence of ships, maneuvering to occupy a given position relative to the object of maneuver, rapprochement with the shoal of fish or the targeting of fishing gear on the shoal.

As a rule, the approach is carried out along a trajectory, the coordinates and parameters of which are calculated by known mathematical algorithms, i.e., in these cases, deterministic methods of approach and guidance of the vessel are used. These include [5]:

[1] Fadyushin, S. G., Vereshchagina, E. A., Rudnichenko, A. K. Entropy As an Assessment Factor of the Current State of Vessel When Approaching an Object of Maneuver. IOP Conf. Series: Earth and Environmental Science 272 (2019) 022120. doi:10.1088/1755-1315/272/2/022120
1. Methods with a fixed direction of the velocity vector relative to the bearing line: the chase method, the method of the constant angle of anticipation.

2. Methods with a changing direction of the velocity vector relative to the bearing line: the method of parallel approach and the method of proportional approach.

A generalization of these methods is the method of proportional navigation [6]. The law of proportional navigation connects the angular velocity of rotation of the bearing line with the angular velocity of rotation of vessel’s velocity vector through a proportionality factor, which is called the navigation constant. When implementing this method, it is necessary at each moment to measure the angular velocity of the bearing line to the object of maneuver and compare it with the angular speed of rotation of vessel's velocity vector. Methods of guidance of a vessel and fishing gear on a moving shoal of fish are highlighted in [7, 8, 9, 10].

Classical deterministic methods often prove ineffective if the object of maneuver performs unpredictable random actions in relation to the maneuvering vessel. Such objects include, for example, mobile shoals of fish or other vessels operated by inexperienced navigators. The publications of the authors [11, 12], which describe the interaction of a vessel with a moving shoal of fish, are devoted to the control of the “vessel – fishing gear” system. The human factor affecting the safety of navigation is paid much attention by the International Maritime Organization (IMO) [13]. This problem is dealt with in [14, 15].

The current state of a vessel when approaching an object of maneuver, as a rule, is estimated by the parameters of the deterministic trajectory: the calculated values of the bearing and the distance, i.e., in fact, not the current vessel’s state is estimated, but its location on the approach trajectory. Therefore, there is a problem of choosing a comprehensive parameter and an evaluation criterion for the current state of the vessel. As such parameter in this research, it is proposed to use one of the basic concepts of information theory - entropy. Earlier in [16, 17, 18, 19] it was shown that entropy can serve as a comprehensive universal evaluation criterion of purposeful human activity. The activity of the navigator on the movement of the ship can also be attributed to this category (purposeful human activity). Using entropy to assess the current state of a vessel, it is thus possible to take into account the influence of the human factor on the safety of navigation.

Thus, the relevance of the study is due to the need to improve the classical methods of analysis and to solve problems of convergence of the vessel with the object of maneuver to ensure the safety and effectiveness of vessel control. The main objective of the study is to justify a comprehensive universal parameter and the corresponding criterion for assessing the current vessel’s state when approaching the object of maneuver. As an estimation parameter, the entropy of the “vessel - object of maneuver” system is considered by the criterion of maximum value when the probabilities of possible states of the system under study are equal.

2. Materials and Methods

The method of proportional navigation is a key one, and depending on the control law it can be interpreted as the chase curve approach, with a constant anticipation and parallel approach angle. When approaching using this method, it is necessary to constantly measure the angular velocity of the bearing line to the object of maneuver and compare it to the angular velocity of rotation of vessel’s velocity vector. In practice, the trajectory of motion is divided into separate sections and the courses from one intermediate point to another are calculated for each section. To control the movement at intermediate points, the distance to the object of maneuver and the bearing on it are calculated. This is a deterministic method of approach, not taking into account the influence of random factors.

To assess the current state of the vessel, taking into account random factors, let us consider the probability of the vessel leaving the calculated intermediate point. As a random variable $X$, the authors take the number of points on the bearing line that the vessel can occupy, depending on the distance to the object of maneuver, i.e., assuming that at the calculated point the bearing remains unchanged, and the distance can change randomly. From the probability theory it is known that such a distribution of $X$
obeys the Poisson law. The proof of this statement in the general case for a line parallel to the abscissa is given in [20].

According to the Poisson law, the probability that a random variable $X$ will assume a certain value of $m$ is expressed by the formula

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

where $a$ – a certain positive value, called the parameter of the Poisson law.

Value of $a$ by its meaning is the average number of points per segment $l$, and can be calculated as $a = \lambda l$ (\(\lambda\) – density of distribution of points on the bearing line). The probability that the value of $X$ will take a positive value, i.e., at least one point will fall on the segment $l$, is calculated by the formula

$$P_1 = 1 - e^{-a}.$$

So, taking into account the kinematic model of a vessel’s approach to the object of maneuver and the statement proved in [20] on the random distribution of the intermediate points of the trajectory on the bearing line according to the Poisson's law, one can formulate the problem of estimating the current state of the vessel.

2.1 Problem

Given a complex dynamic system, consisting of a vessel (object of maneuvering) and a mobile object (object of maneuver). The vessel must approach the object of maneuver for a specified distance or close. Approach occurs by the method of proportional navigation. The vessel’s trajectory is calculated and its parameters are known to the navigator, including the bearing and the distance to the object of maneuver at each intermediate point. Current intermediate points are randomly distributed on the bearing line passing through the vessel and the object of maneuver, according to the Poisson law. It is necessary to assess the state of the vessel when approaching the object of maneuver at the current intermediate points of the trajectory.

2.2 Solution

To solve the problem, the authors use the statement on the distribution of a random variable $X$ in accordance with the Poisson law and the basic concepts of information theory.

Consider the physical system $X_a$ - "vessel – the object of maneuver" at the moment when the vessel reaches the next intermediate approach point on a given trajectory. Possible states of the $X_a$ system are:

- $x_1$ – the vessel reached the calculated intermediate point;
- $x_2$ – the vessel did not reach the calculated intermediate point.

In this case one obtains the following probabilities of states:

- $x_1$: $P_1 = 1 - e^{-a}$;
- $x_2$: $P_2 = e^{-a}$.

Let us determine the maximum uncertainty of the state of the $X_a$ system. Obviously, the system $X_a$ will reach its maximum uncertainty, when the entropy of this system will also be maximum. From the theory of information, it is known that the maximum entropy is attained for equiprobable states of the system, i.e., one can write the following equality:

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

After the transformations, one obtains:

$$a = \frac{1}{\log_2 e} = 0.6931.$$

With this value of the parameter of the Poisson law, the entropy, which can be calculated from the formula,
will be equal to the maximum value, i.e. in this case, 1.

Thus, the main criterion for assessing the current state of the system “vessel – the object of maneuver” and, accordingly, the current state of the vessel will be as follows:

\[ H(\mathcal{X})_{\text{max}} = 1. \]

The value of \( a \) by its meaning is the average number of points per segment \( l \) of the bearing line and is calculated by the formula:

\[ a = \lambda l. \]

Then, it is possible to calculate the distance to the object of maneuver at which the entropy of the system “vessel – the object of maneuver” reaches a maximum value and will be 1:

\[ l = \frac{a}{\lambda}, \]

where \( \lambda = \frac{l}{l_0} \); \( l_0 \) – estimated distance to the object of maneuver.

The current value of the parameter of the Poisson law can be calculated from the formula:

\[ a_i = \lambda l_i, \]

where \( l_i \) – current distance to the object of maneuver.

Then, taking into account the density equation \( \lambda \) one obtains

\[ a_i = \frac{l_i}{l_0}. \]

The current value of the entropy of the system “vessel – the object of maneuver” with probability of states \( x_1 \) and \( x_2 \), may be calculated from the formula (1). Meantime, for \( x_1 \) the probability of state will equal

\[ p_1 = 1 - e^{-a_i}, \]

for \( x_2 \)

\[ p_2 = e^{-a_i}. \]

3. Results and Discussion
To verify the adequacy of the described method of assessing the current state of the vessel in reality, the authors will solve the following example problem.

3.1 Example
A vessel is approaching a mobile object using the method of proportional navigation. The approach trajectory is calculated and the approach parameters are known. At one of the intermediate points, according to calculations, the approach distance should be 1,000 meters. When the vessel reaches the calculated bearing line value, the actual distance value is equal to 800 meters. It is required to assess the current state of the vessel.

3.2 Solution
1. Now, calculating the distance to the object of maneuver, at which the entropy of the system “vessel – the object of maneuver” will reach a maximal value and will be \( H(\mathcal{X})_{\text{max}} = 1 \) at \( \lambda = \frac{1}{1000} \) point/meter and \( a = 0.6931 \):
2. Calculating the current value of the Poisson law parameter at \( \lambda = \frac{1}{1000} \) point/meter and the current value of distance to the object of maneuver \( l_i = 800 \) meters.

\[
l_i = \frac{a_i}{\lambda} = \frac{1}{1000} \times 800 = 0.8 .
\]

3. Calculating the probability of state \( x_1 \) of the system “vessel – the object of maneuver”:

\[
p_1 = 1 - e^{-\alpha} = 1 - e^{-0.8} = 0.5506 .
\]

4. Calculating the probability of state \( x_2 \) of the system “vessel – the object of maneuver”:

\[
p_2 = e^{-\alpha} = e^{-0.8} = 0.4493 .
\]

5. Calculating the current value of entropy of the system “vessel – the object of maneuver”:

\[
H(X)_i = - \sum_{i=1}^{n} p_i \log p_i = - \left( 0.5506 \times \log_2 0.5506 + 0.4494 \times \log_2 0.4494 \right) = 0.9925 \text{ binary units},
\]

### 3.3 Conclusion

After the calculations, one obtains: \( l_i > l_{\text{max}} \), \( H(X) < H(X)_{\text{max}} \). Therefore, the current state of the system “vessel – the object of maneuver” and the vessel may be considered satisfactory. Vessel may continue approaching the object of maneuver taking into account the correction of the approach error.

### 4. Summary

The main results of the study are as follows:

– a method is proposed for assessing the current state of a vessel on the basis of calculating and analyzing the entropy of the system “vessel – the object of maneuver”;

– a justification of the estimated criterion of current vessel’s state as the maximum value of entropy of the system “vessel – the object of maneuver” is given, with the probabilities of possible states of this system being equal.

The proposed method makes it possible to determine the minimum distance to the object of maneuver, at which the entropy of the system “vessel – the object of maneuver” reaches its maximum value. The current value of entropy gives navigators an opportunity to keep continuous control over the movement of the vessel.

The solution of the control example confirmed the possibility of using the entropy of the system “vessel – the object of maneuver” as a universal estimation parameter of the current vessel’s state when approaching an object of maneuver.

The obtained results are recommended for use for specialists in the field of automation of ship movement control, navigators of merchant and fishing vessels.

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