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Grey Relational Analysis of Environmental Influencing Factors of Autonomous Ships' Maneuvering Decision-Making

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***Abstract*—The natural environmental factors that typically affect the safe environment of maritime traffic are weather conditions and ocean conditions, specifically, wind, current, and waves. The environmental influence factors affect the ship's navigation and the crew's decisions by affecting the ship's maneuverability, along with the skill and mentality of the crew. In addition, autonomous ship maneuvering decisions are influenced by several factors, and it is especially important to distinguish the crucial influencing factors for efficient selection of the corresponding maneuvering decisions. At the same time, the autonomous ship maneuvering decision factors are a typical "grey system", which is suitable for the research by grey relational analysis. Therefore, this study mainly focuses on the concept of human-like maneuvering for the autonomous ship. Based on the actual crews' operational data from full-task handling simulation platform, we proposed a grey relational analysis model to prioritize the environmental influencing factors, thus to analyze the decision-making mechanisms for specific ship maneuvering scenario. This method can mine the key factors which affect maneuvering decisions and provide guidance for an autonomous ship-assisted or automatic maneuvering system and promotes the application of autonomous ships.**

***Keywords*—marine safety, grey relational analysis, grey system theory, autonomous ships, quantitative assessment, decision-making**

I. INTRODUCTION

With the development of modern science and technology, especially the rapid development of technologies and theories such as big data, internet of things, information technology and artificial intelligence, the global industry is moving in the direction of informatization and intelligence. For the shipbuilding industry, with the wide application of network technology and information technology, the electrical systems such as ship automation, control, and communication navigation have gradually matured, and the level of autonomous ship has been rapidly improved. The development of autonomous ships has been technically feasible. Besides, the ship market is suffering a long-term excess capacity, the world's major shipping companies have to focus on the improvement of the efficiency and safety of their fleet. At the same time, marine accidents occur frequently, in which collisions and damages caused by personnel mistakes account for more than 80% of marine accidents Rothblum [1].

As autonomous ships have outstanding advantages in improving the operational efficiency, safety, management decision-making efficiency, the researches for autonomous ships have become an inevitable direction for shipping development. However, the improvement of the degree of automation of ships has a certain gap from the ships with automatic perception, subjective analysis, and intelligent decision-making.

The accuracy of autonomous ship maneuvering decisions is directly related to the safety of water traffic. In the process of autonomous ship human-like decision-making, the officer on watch (OOW) maneuvering decision-making is often stimulated and influenced by multi-source information, for instance, the other ships in specific waterway, the natural environmental factors [2]. In addition, the natural environment is an important factor affecting the safety of waterborne traffic [3], specifically, wave, wind, current, etc. Therefore, it is necessary for maneuvering decision-making knowledge to be automatically obtained and expressed along with higher decision-making knowledge effectiveness.

In addition, due to the limited information processing capacity, the OOW cannot concurrently achieve knowledge acquisition and representation of the multi-source information so that maneuvering decisions can be carried out accurately and quickly, which could lead to water traffic accidents. At the same time, under high-intensity work pressure, the OOW cannot always ensure to make correct decisions timely when facing changing factors in a navigation environment. Therefore, the automatic acquisition and representation of maneuvering decision-making are essential in ensuring accurate and rapid maneuvering decisions and water traffic safety.

The decision-making problems in the real world are often grey (the data/information that is known partially). The grey system theory, proposed is one of the most widely used models of grey system theory. As an effective pattern recognition method, it is mainly used to analyze the proximity of the dynamic grey process development situation, determine the primary and secondary factors in the grey system, and control the main factors affecting the system [4]. Grey relation analysis does provide techniques for determining an appropriate solution for real-world problems. Through the research on some known information, the system can be accurately understood [5]. The grey relational analysis method does not require too much sample size and does not require a typical distribution law during analysis. The grey relational analysis method could capture the impact of the relationship between the crucial factor and influencing factors in the system regardless of whether the system has adequate information [6]. The results are consistent with the qualitative analysis results, so the method has wide practicality [7]. As a systematic analysis technique, the grey correlation analysis is a quantitative comparative analysis method. By calculating the correlation between the target value and the influencing factors, and the ranking of the relevance, the main factors affecting the target value are sought [5, 6]. After more than 20 years of development, the grey system theory has penetrated into many scientific research fields and has been confirmed and developed. It provides a new way to solve system problems in the case of poor information [8]. In order to analyze the system behavior of grey systems with uncertain information, the grey system theory develops a series of comprehensive analysis methods of grey systems, such as grey correlation analysis [9, 10]. It is applied to many research domains, for example, it was adapted to study the research output and growth of countries [11], and it has also been used to effectively study air pollution [12] and subsequently used to investigate the nonlinear multiple-dimensional model of the socio-economic activities' impact on the city air pollution [13]. Lu et al. used grey relational analysis to evaluate the problem of road traffic safety measures [14]. Kelvin et al. proposed a grey model-based smoothness predictions; the results showed that the model provides promising results and is useful for evaluating the riding quality of pavement performance [15]. Lilly Mercy et al. proposed a multi-response optimization algorithm to study the mechanical properties in self-healing glass fiber reinforced plastic using grey relational analysis; the results showed that lesser microcapsule size and concentration with medium catalyst concentration gave better mechanical properties [16].

The autonomous ship human maneuvering decision factors studied in this paper constitute a typical "grey system". It is suitable to study with grey relational analysis method. The main influencing factors are identified by analyzing the influencing factors of autonomous ship maneuvering the decision. In addition, autonomous ship maneuvering decisions are influenced by many influence factors; In our case, the main propose is to select the crucial influence factors from all the decision-making factors, thereby establishing the decision-making model efficiently for our subsequent research of autonomous ship human-like decision-making algorithm. In this study, the analysis model of decision-making factors of ship maneuvering based on the theory of grey relational analysis is established, aiming at clarifying the influence degree of influencing factors on ship maneuvering decision, finding out the dominant factors influencing autonomous ship decision-making, and recognizing the decision-making mechanisms for different ship maneuvering behaviors in specific scenario, so as to provide the theoretical basis for the accurate and rapid autonomous ship maneuvering decisions and water traffic safety.

II. METHODOLOGY

A. Grey Relational Analysis

Grey relational analysis (GRA) is an analytical method based on the microscopic or macroscopic geometric approach to determine the influence degree between factors or the contribution of factors to the primary system. It is mainly the analysis of a development situation, that is, the quantitative analysis of the dynamic development process of a system, which is represented by the proximity of the geometric shape of the curve, judging by the degree of correlation (usually determined by the relational coefficient as (3)-(9), reveals the influence degree between reference series and comparative series). In addition, the GRA can also be regarded as a dynamic quantitative comparison procedure of the relative changes in the factors between/in systems over time.

B. The Proposed GRA Model

1) Data preprocessing

Since there are differences in the dimension and magnitude of each factor in the ship's maneuvering decision system. In order to facilitate data processing, the original data needs to be standardized, the dimension or the order of magnitude needs to be eliminated, and the data series need to be transformed into a comparative series due to the inconsistent dimension of various factors.

Assume X is a grey relation factor set (discrete series), $X_0 = \{x_0(k) \mid k = 1, 2, \cdots, m\}$ as a reference series, representing the ship maneuvering decisions, which is the combination of Telegraph and Rudder Order (TRO) of the experimental ship in the research of our paper. $X_i = \{x_i(k) \mid k = 1, 2, \cdots, m\} (i = 1, 2, \cdots, n)$ as comparative series, representing the environment influencing factors, such as wind, current, and waves. Thus, the correlation mechanisms of the reference series and comparative series can be utilized to recognize the influential mechanism of different factors for autonomous ship maneuvering.

In the analysis and calculation process of the GRA, since the standardization method may genuinely reflect the relevance of the influencing factors to ship maneuvering decisions. Therefore, the standardization method is utilized to explore the results of the interaction between ship maneuvering decisions and various environment influencing factors.

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$$X_0' = \left\{ \left[x_0(k) - \frac{1}{m}\sum_{k=1}^{m} x_0(k) \right] / S_0 \mid k = 1,2,\cdots,m \right\} \tag{1}$$

$$X_i' = \left\{ \left[x_i(k) - \frac{1}{m}\sum_{k=1}^{m} x_i(k) \right] / S_i \mid k = 1,2,\cdots,m;\ i = 1,2,3,...,n \right\} \tag{2}$$

where *X'₀* is a non-dimensionalized reference series; *X'ᵢ* is a dimensionless comparative series; *S₀* and *Sᵢ* are the standard deviation of the reference series and the comparative series, respectively.

The original data series can be described by

$$X' = \begin{pmatrix} X_0' \\ X_1' \\ X_2' \\ \vdots \\ X_\omega' \end{pmatrix} = \begin{bmatrix} x_{01}' & x_{02}' & \cdots & x_{0m}' \\ x_{11}' & x_{12}' & \cdots & x_{1m}' \\ x_{21}' & x_{22}' & \cdots & x_{2m}' \\ \vdots & \vdots & \ddots & \vdots \\ x_{\omega 1}' & x_{\omega 2}' & \cdots & x_{\omega m}' \end{bmatrix} \Rightarrow \begin{bmatrix} TRO \\ Influence\ Factor\ 1 \\ Influence\ Factor\ 2 \\ \vdots \\ Influence\ Factor\ \omega \end{bmatrix}$$

where ω is the number of influencing factors.

2) Range analyzing

First, calculate $\Delta_i(k)$, that is, the absolute value of the difference between the reference series and each sub-series at each point:

$$\Delta_i(k) = \left| x_0(k) - x_i(k) \right| \tag{3}$$

among them, $k = 1,2,\cdots,m$; $i = 1,2,\cdots,n$.

Then find the two-level maximum range and the two-level minimum range. First, calculate the first-level maximum range and the first-level minimum range:

$$\Delta_i(\max) = \max_k \Delta_i(k) \tag{4}$$

$$\Delta_i(\min) = \min_k \Delta_i(k) \tag{5}$$

Then calculate the second-level maximum range:

$$\Delta_{\max} = \max_i \max_k \Delta_i(k) \tag{6}$$

Similarly, the second-level minimum range is given by:

$$\Delta_{\min} = \min_i \min_k \Delta_i(k) \tag{7}$$

3) Relational coefficient calculating

The relational coefficient is used to measure the geometric difference between the comparative series and the reference series at each point. The relational coefficient of X_i to X_0 is:

$$\xi_i(x_0(k), x_i(k)) = \frac{\Delta_{\min} + \rho \cdot \Delta_{\max}}{\Delta_i(k) + \rho \cdot \Delta_{\max}} \tag{8}$$

where $\xi_i(x_0(k), x_i(k))$ represents the correlation coefficient between the comparative series X_i and the reference series X_0 at point *k*; ρ is a resolution ratio, in $(0,1)$, if ρ is small, the greater the difference between the relationship coefficient, the stronger the ability to distinguish, and ρ usually takes a value of 0.5 [17]; $k = 1,2,\cdots,m$; $i = 1,2,\cdots,n$.

4) Relational Grade Ranking

Calculating the traditional grey relational grade according to:

$$\gamma_i = \frac{1}{m}\sum_{k=1}^{m} \xi_i(x_0(k), x_i(k)) \tag{9}$$

where $k = 1,2,\cdots,m$; $i = 1,2,\cdots,n$.

When determining the relational grade, each sub-series of Y1-Y8 is compared to the reference series of TRO. Hence, the relationship between each sub-series and the reference series is sorted. Thereby, the main maritime traffic safety influencing factors of the autonomous ship maneuvering decisions in the specific navigational scenario are prioritized and identified. The framework of our proposed model is shown graphically in Fig. 1 that briefly illustrates the environmental influencing factors of autonomous ship maneuvering decisions prioritizing procedure for the proposed GRA methodology.

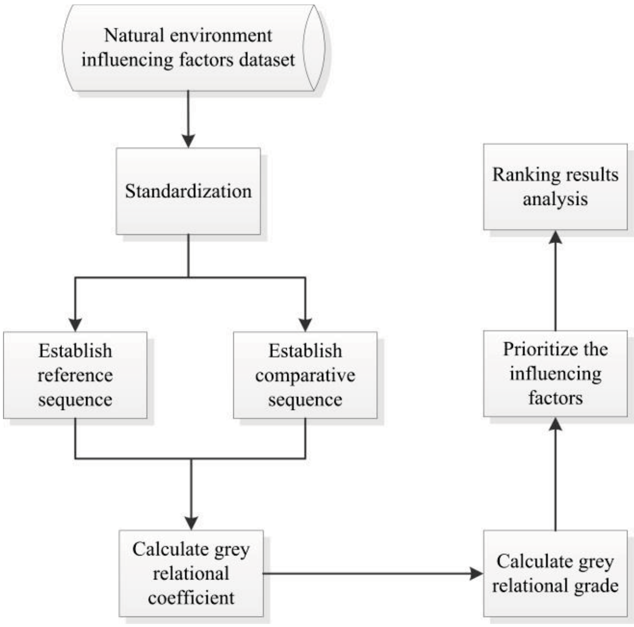

Fig. 1. The framework of the proposed model.

III. DATA ACQUISITION AND PROCESSING

We collect the data from the simulator of Navi-Trainer Professional 5000, which conforms to the IMO STCW78/10 convention and the Det Norske Veritas (DNV) from the Maneuvering Simulator Laboratory. In addition, we use the Shanghai Waigaoqiao wharf as the scenario for our case study. The ship is downstream of the berthing into the port. The scenario and initial and end boundary line are shown in Fig. 2.

The operational data from the experienced seafarers (96 people, 32-45 years old, unlimited navigational class seafarers, skilled maneuvering level) are collected as our experimental data. The environment and ship control of ship maneuvering information are recorded. For instance, environment (wind, current, etc.), control (rudder order, marine telegraph). Table I lists the category of environment influencing factors, and some of the training samples are shown in Table II.

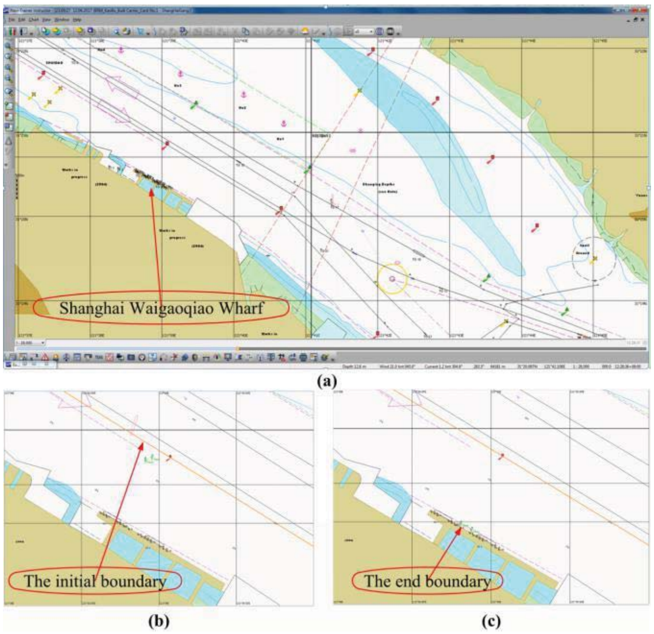

Fig. 2. The designed experimental scenario.

TABLE I. THE CATEGORY OF ENVIRONMENT INFLUENCING FACTORS

Influencing factors	Meaning	Units
Y1	Current direction	Degrees
Y2	Current speed	Knots
Y3	Relative current direction	Degrees
Y4	Relative wave direction	Degrees
Y5	Relative wind direction	Degrees
Y6	Relative wind speed	Knots
Y7	Water depth	Meters
Y8	Wave height	Meters

TABLE II. ORIGINAL DATA OF THE STUDIED AREA (PARTIALLY)

No.	X		Y1 (Degrees)	…	Y8 (Meters)
	Rudders Order (Degrees)	*Telegraphs Order (%)*			
1	-1.0000	50.0000	316.7000	…	0.0759
2	-1.0000	50.0000	316.7000	…	0.0760
3	-1.0000	50.0000	316.7000	…	-0.0902
4	-1.0000	50.0000	316.7000	…	-0.0384
5	-1.0000	50.0000	316.7000	…	0.0992
6	-1.0000	46.2955	316.7000	…	0.0652
7	-1.0000	40.0000	316.7000	…	-0.0542
8	-1.0000	40.0000	316.7000	…	-0.0647
9	-1.0000	40.0000	316.7000	…	0.1324
10	-1.0000	40.0000	316.7000	…	0.0271
11	-3.3119	40.0000	316.7000	…	-0.1328
12	-11.2792	40.0000	316.7000	…	-0.0734
13	-11.9016	40.0000	316.7000	…	0.0854
14	-11.0000	40.0000	316.7000	…	0.1700
15	-11.0000	40.0000	316.7000	…	0.1074
16	-11.0000	40.0000	316.7035	…	0.0003
17	-11.0000	40.0000	316.8000	…	0.1176
18	-11.0000	40.0000	316.8000	…	-0.0401
19	-11.0000	40.0000	316.8000	…	-0.0600
20	-11.0000	40.0000	316.8000	…	-0.0100
…	…	…	…	…	…

The OOW maneuvers the ship by operating a multi-dynamic process of different telegraph and rudder orders to change ship's speed and direction. It should be noticed that the principle of the rudder angle and the propeller speed are defined based on the data collected from the simulator and the navigation experience. In this paper, we utilize the standardization principle proposed by Xue et al. [18] for output maneuvering decision-making factor. Then the 64 possible maneuvering decisions based on various standardization principle of speed control (propeller state) and course control (rudder angle) are analyzed.

IV. RESULTS

In our experiment, we select X and the related parameters Y1-Y8 to apply the proposed model. The values of X form the reference series, which are the 64 possible maneuvering decisions. Y1-Y8 are the environment influencing factors, and their values constitute the comparative series. In addition, we collect a total of 20,534 samples as our data set.

A. *Standardizing of the original data set*

In this paper, X presents the percentage of the number of each maneuvering decision of X1-X8 in a total number of the data set records. Limited to space, Table III lists only a part of multiple measured data which standardized according to the principle of standardization of maneuvering decision-making influencing factors proposed by Xue et al. [18].

TABLE III. DATA SET WITH THE PRINCIPLE OF STANDARDIZATION

No.	X		Y1 (Degrees)	…	Y8 (Meters)
	Standardized	*Proportion*			
1	X2	0.0300	316.7000	…	0.0759
2	X2	0.0300	316.7000	…	0.0760
3	X2	0.0300	316.7000	…	-0.0902
4	X2	0.0300	316.7000	…	-0.0384
5	X52	0.0196	316.7000	…	0.0992
6	X52	0.0196	316.7000	…	0.0652
7	X4	0.2955	316.7000	…	-0.0542
8	X4	0.2955	316.7000	…	-0.0647
9	X4	0.2955	316.7000	…	0.1324
10	X36	0.0098	316.7000	…	0.0271
11	X35	0.0062	316.7000	…	-0.1328
12	X35	0.0062	316.7000	…	-0.0734
13	X35	0.0062	316.7000	…	0.0854
14	X3	0.0818	316.7000	…	0.1700
15	X3	0.0818	316.7000	…	0.1074
16	X3	0.0818	316.7035	…	0.0003
17	X3	0.0818	316.8000	…	0.1176
18	X3	0.0818	316.8000	…	-0.0401
19	X3	0.0818	316.8000	…	-0.0600
20	X3	0.0818	316.8000	…	-0.0100
…	…	…	…	…	…

B. *Applying the proposed model*

The GRA method can quantitatively describe the similarity and consistency degree between each comparative series and reference series. It uses relational grades to complete the matching order of influencing factors. According to the ranking criteria of the grey relational grade, the greater the grey relational grade of the comparative series, the greater the relevance of the comparative series to the reference series, and the higher the ranking of the influencing factors. This way, we obtain the original data series. Then, we use the standardization methods to explore the results of the interaction between ship maneuvering decisions and various influencing factors.

TABLE IV. THE EXTREME VALUES OF OUR DATA SET

Influencing factors	Standardization	
	Δ_i(max)	Δ_i(min)
Y1	2.677718534	0.001937135
Y2	2.607298241	0.002782460
Y3	4.896570329	**4.70016E-05**
Y4	6.238392243	0.000341300
Y5	5.742657263	0.000149654
Y6	2.699055325	4.80284E-05
Y7	6.230599999	0.000794324
Y8	**8.023167652**	0.000179697

From Table IV and (3) to (7), we can get the extreme values, $\Delta_{\max} = \mathbf{8.023167652}$, $\Delta_{\min} = \mathbf{4.70016E-05}$, and we can calculate the grey relational coefficient based on the (8), the results are shown in Table V.

TABLE V. THE GREY RELATIONAL COEFFICIENT (PARTIALLY)

Influencing factors	Grey Relational Coefficient			
	No. 1	***No. 2***	***No. 3***	**…**
Y1	0.766663139	0.766663139	0.766663139	…
Y2	0.690255906	0.690255906	0.690255906	…
Y3	0.861719986	0.862217653	0.862435769	…
Y4	0.826977031	0.827699531	0.828813001	…
Y5	0.428520347	0.428202661	0.427817446	…
Y6	0.987824725	0.987213279	0.986913605	…
Y7	0.892423518	0.892423518	0.892423518	…
Y8	0.705490029	0.705429329	0.959407739	…

Using (9) and the results of grey relational coefficient from Table V, the priority ranking results of our proposed model are obtained, as shown in Table VI.

TABLE VI. RANKING RESULTS OF OUR PROPOSED MODEL

Influencing factors	Our proposed model	
	Grey relational grade	***Rank***
Y1	0.799355343	7
Y2	0.801680362	6
Y3	0.814649312	2
Y4	0.819897374	1
Y5	0.804557741	5
Y6	0.813601720	3
Y7	0.806096141	4
Y8	0.796465909	8

The rankings of ship maneuvering decision-making environment influencing factors are shown in Table VI, ranking result: Y4 > Y3 > Y6 > Y7 > Y5 > Y2 > Y1 > Y8. The ranking results of our proposed model are visualized in Fig. 3.

The result is corresponding to the judgment/operation of experienced seafarers in the real word shipping: when the seafarer (OOW) maneuvering the ship inbound the port, they need to pay more attention to the environment influencing factors of relative wave direction, relative current direction, relative wind speed, water depth, relative wind direction, etc., so as to ensure the safety of ship and cargo. Therefore, the results indicate that our proposed model can identify the influencing factors of autonomous ship maneuvering decisions under real word maritime traffic safety context.

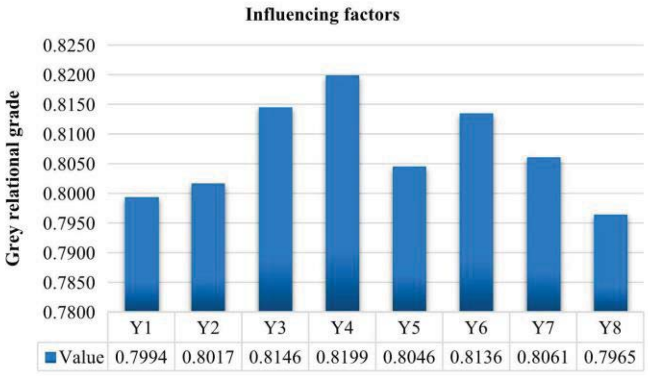

Fig. 3. The ranking results of our proposed model.

V. CONCLUSION

This paper proposes a prioritizing model for the environment influencing factors of autonomous ship maneuvering decision-making using grey relational analysis theory. Based on the actual operational data of the experienced seafarers, a reference series is established by using the combination of ship telegraph and rudder orders which directly corresponding to the control of a ship. Moreover, the standardization principle of ship maneuvering is introduced, and an innovative inference model is proposed, this model can recognize the main decision-making factors of ship maneuvering from multi-source environment influencing factors, so as to study the decision-making prioritization for maritime traffic safety in specific ship maneuvering scenario accurately and efficiently.

In further research, we will explore more about the optimization method for the prioritization of influencing factors for autonomous ship maneuvering decision-making. In addition, we need to combine the expert knowledge to further compare and analyze the effectiveness and accuracy of this method.

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