A Study on the Analysis of Navigators' Understanding of COLREGs :

Sailing Rule Interpretation and Ship Encounter Situations

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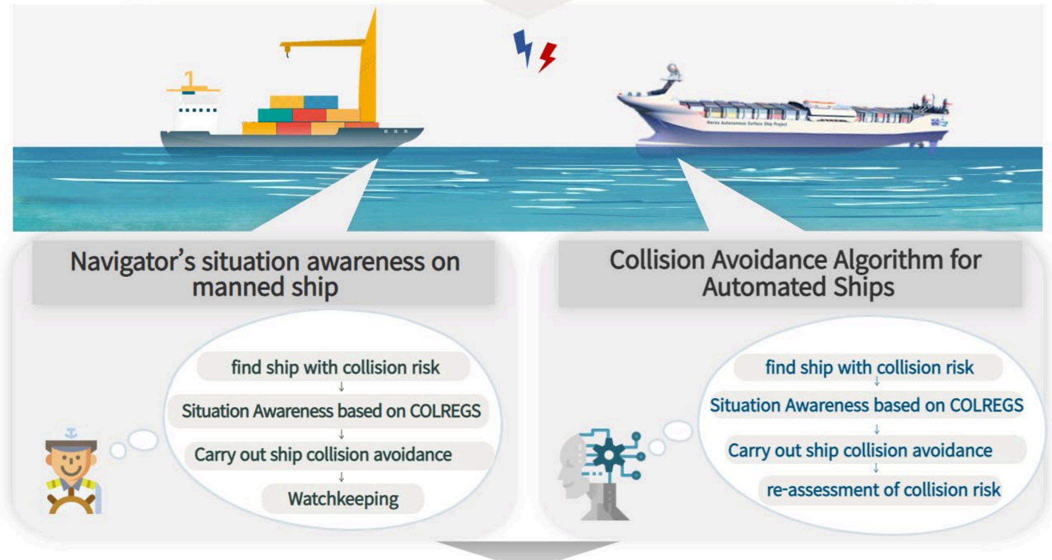
1 Introduction

1. Introduction

Background

When a maritime collision situation occurs between an automated vessel and a manned vessel, what should be done?



The difference in collision situation understanding between manned ship's navigator and collision avoidance algorithms in unmanned ships

Reserch Need

Necessity of Mechanical Analysis for Collision Risk Assessment System Based on Navigator Situational Awareness

Necessity of research on the difference between navigators and researchers in understanding COLREGS navigation

Research Goal

The purpose of this study is to present a method for resolving collision situations between unmanned and manned ships based on navigator's understanding.

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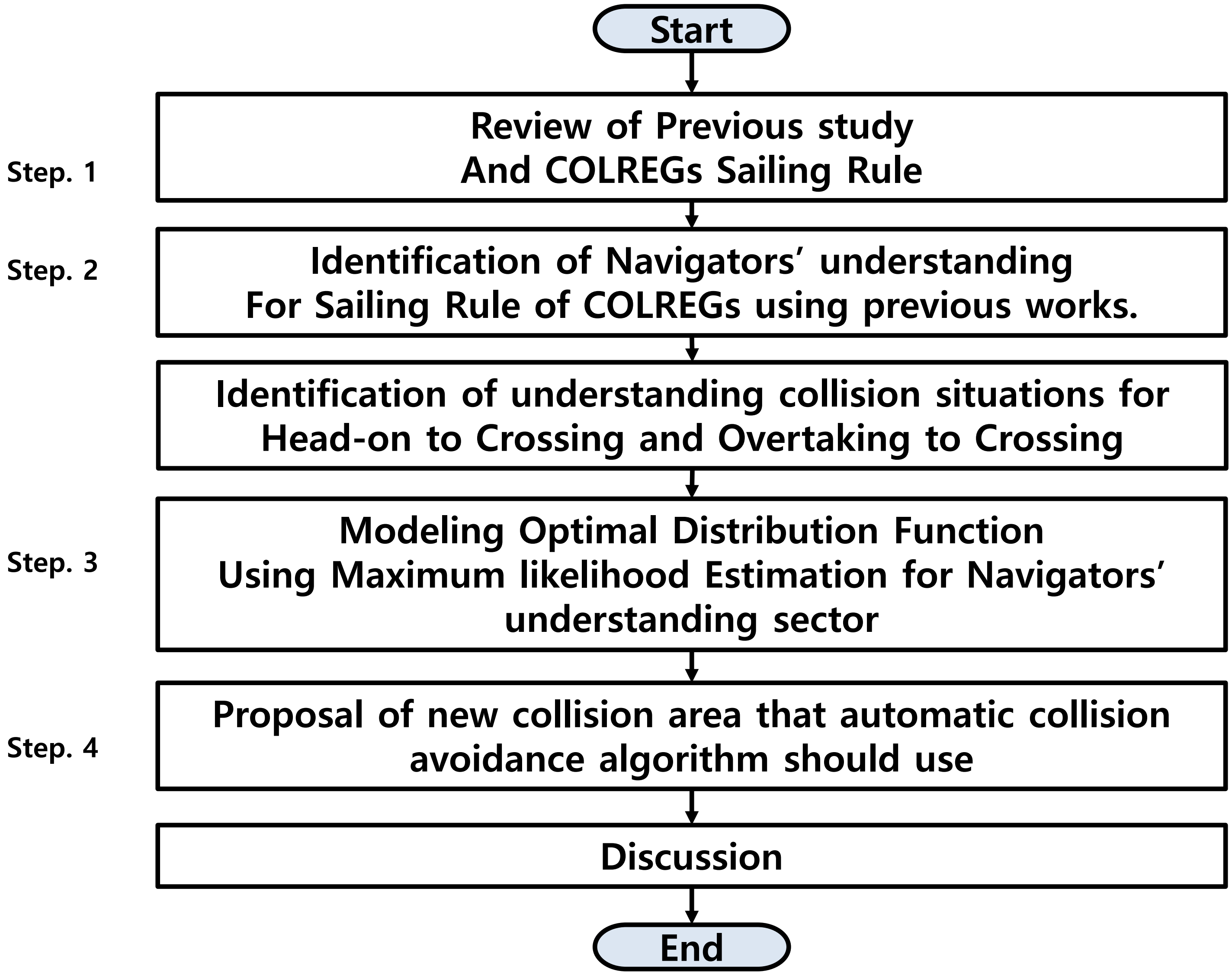
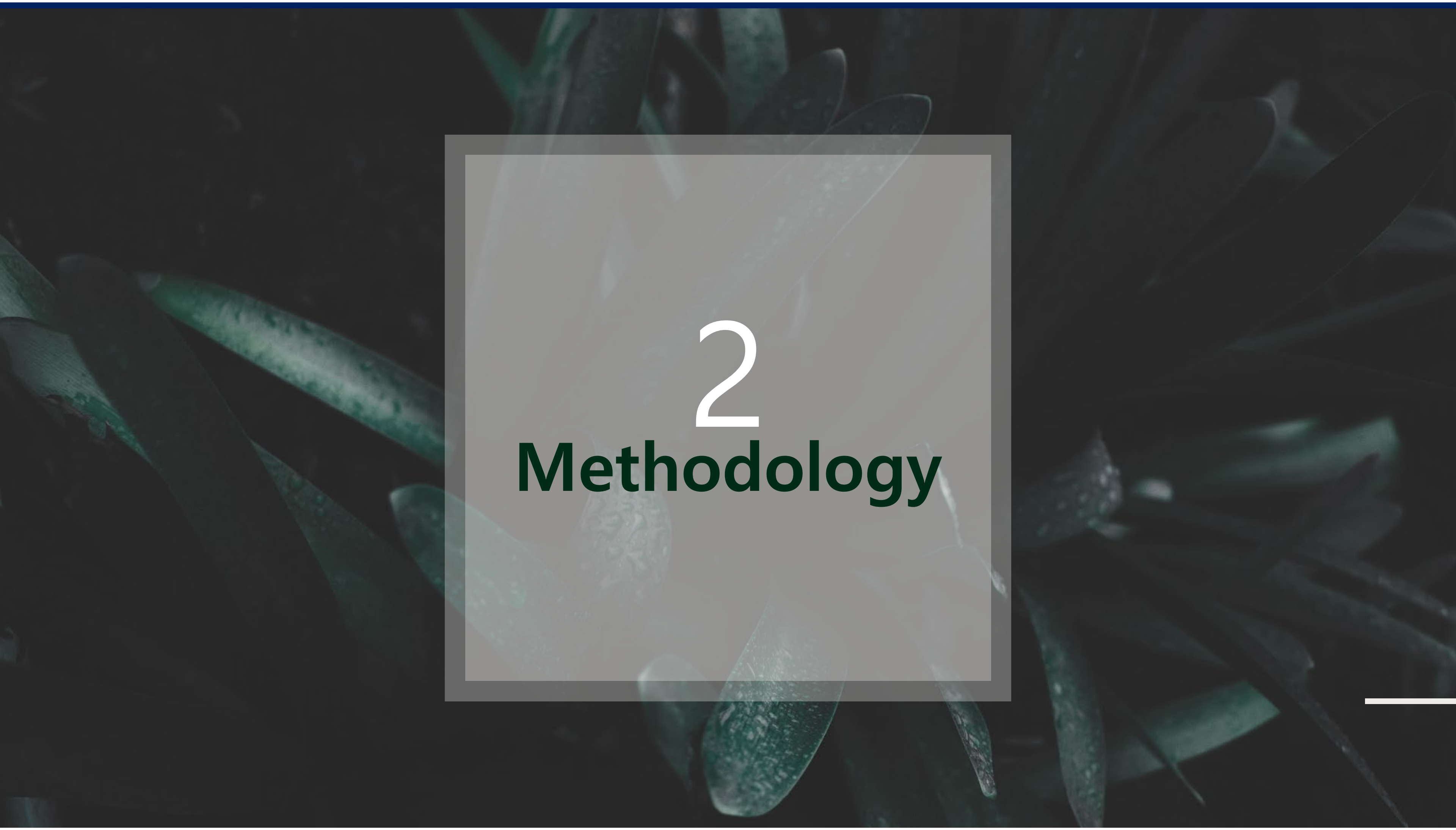

Start
Step. 1
Review of Previous study
And COLREGs Sailing Rule
Step. 2
Identification of Navigators' understanding
For Sailing Rule of COLREGs using previous works.
Identification of understanding collision situations for
Head-on to Crossing and Overtaking to Crossing
Step. 3
Modeling Optimal Distribution Function
Using Maximum likelihood Estimation for Navigators'
understanding sector
Step. 4
Proposal of new collision area that automatic collision
avoidance algorithm should use
Discussion
End



2 Methodology

- COLREGs have been written with general descriptions to be applied to situations as many as possible, and required decision-making that is determined according to the **practice of seamanship and maritime culture.**

- The Sailing rules of COLREGs used in decision making with visible situation are as follows.

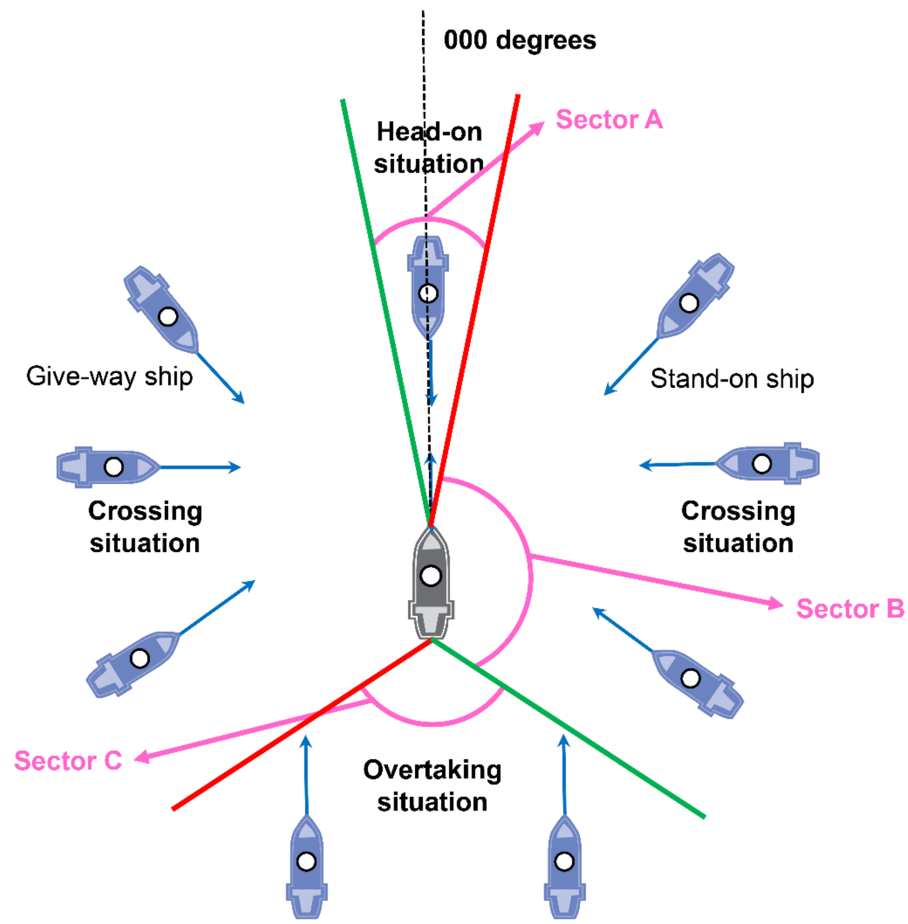
✓ Rule 13, Overtaking

✓ Rule 14, Head-on Situation

✓ Rule 15, Crossing Situation

✓ Rule 16, Action by Give-way Vessel

✓ Rule 17, Action by Stand-on Vessel



- For researchers, as a researches of reviewing the currently studied automatic collision avoidance algorithm, the head-on situation was normally set from 5 degrees to 45 degrees, and the crossing situation was set from 90 degrees to 180 degrees (Kim and Park, 2023)
- For navigators, we asked about understanding of sailing situations to navigator between Head-on and Crossing (HC), Overtaking and Crossing (OC) using ship's radar images.
- The survey was conducted by a total of 101 worldwide navigators, and 90% of the participants have experience boarding large ships of 5,000 tons or more.

Response to the questions about head-on and crossing situations (HC_Q1 to HC_Q11)	Response to the questions about overtaking and crossing situations (OC_Q1 to OC_Q10)
1. It is a head-on situation.	1. It is an overtaking situation.
2. It is likely a head-on situation.	2. It is likely an overtaking situation.
3. It is likely a crossing situation.	3. It is likely a crossing situation.
4. It is a crossing situation.	4. It is a crossing situation.

Ref. Kim and Park (2023), Understanding of Sailing Rule based on COLREGs : Comparison of Navigator Survey and Automated Collision Avoidance Algorithm, Marine Poilicy, 105894

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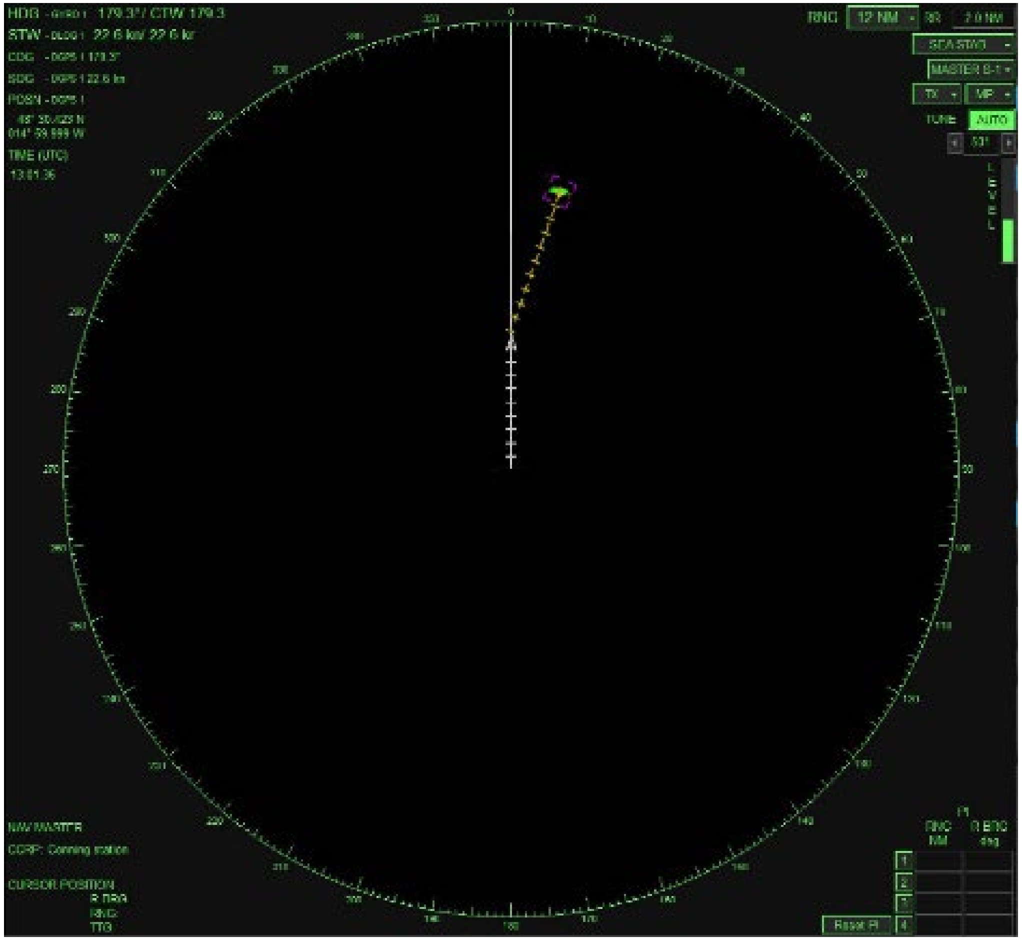
2. Methodology

- **How do you understand the following sailing situation? (using radar moving image)**



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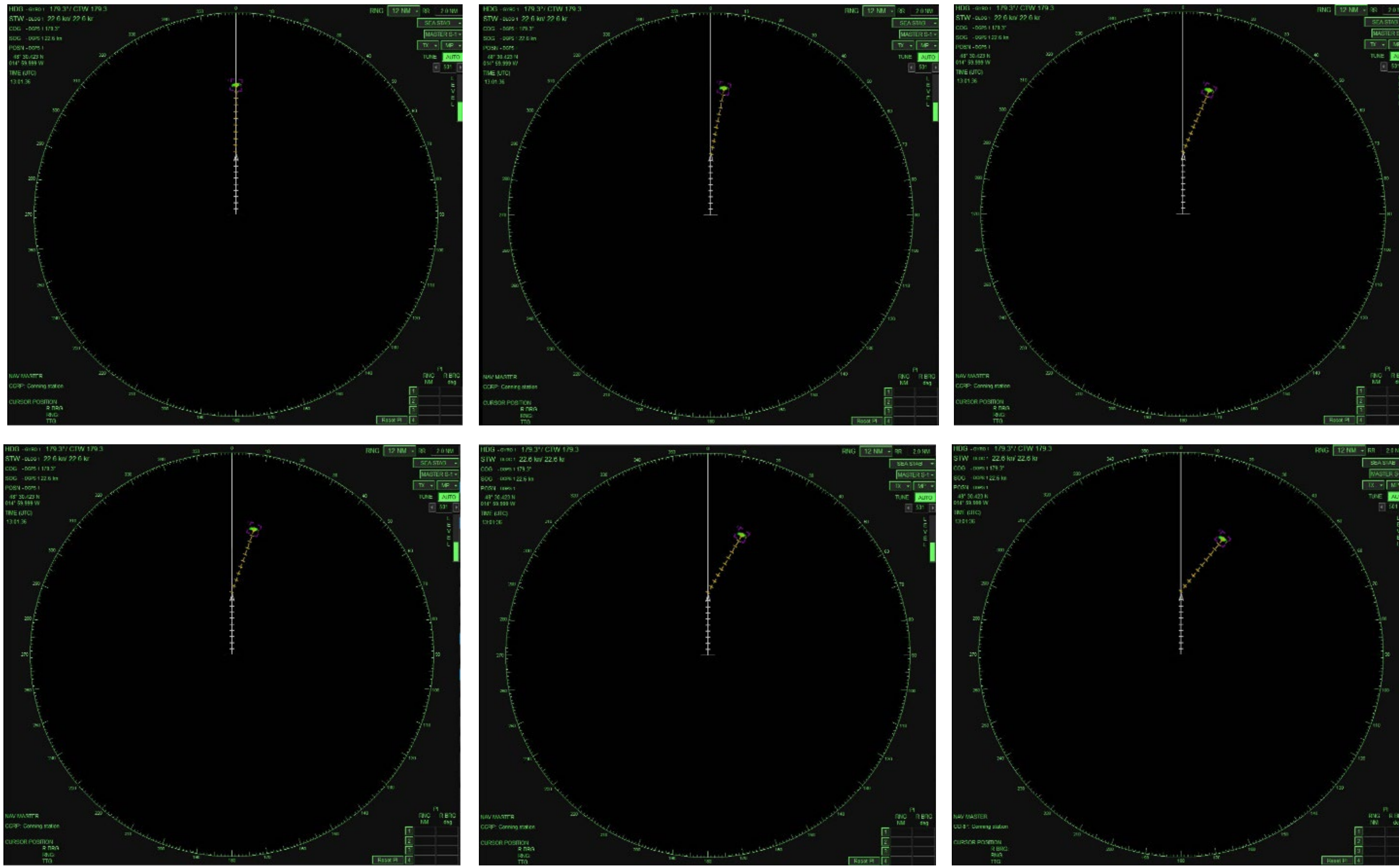
2. Methodology

- **How do you understand the following sailing situation? From 0° to 20 ° (every 2 °)**



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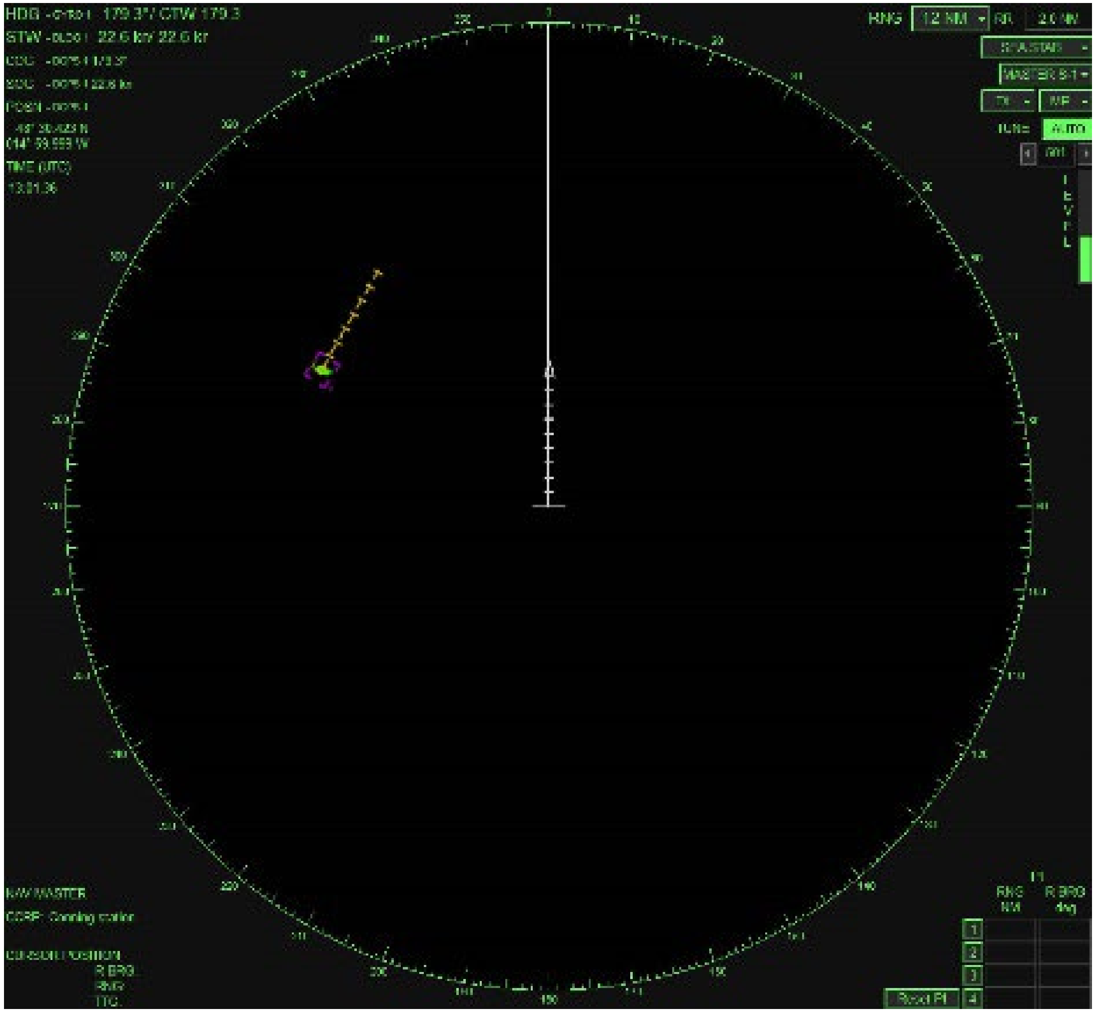
2. Methodology

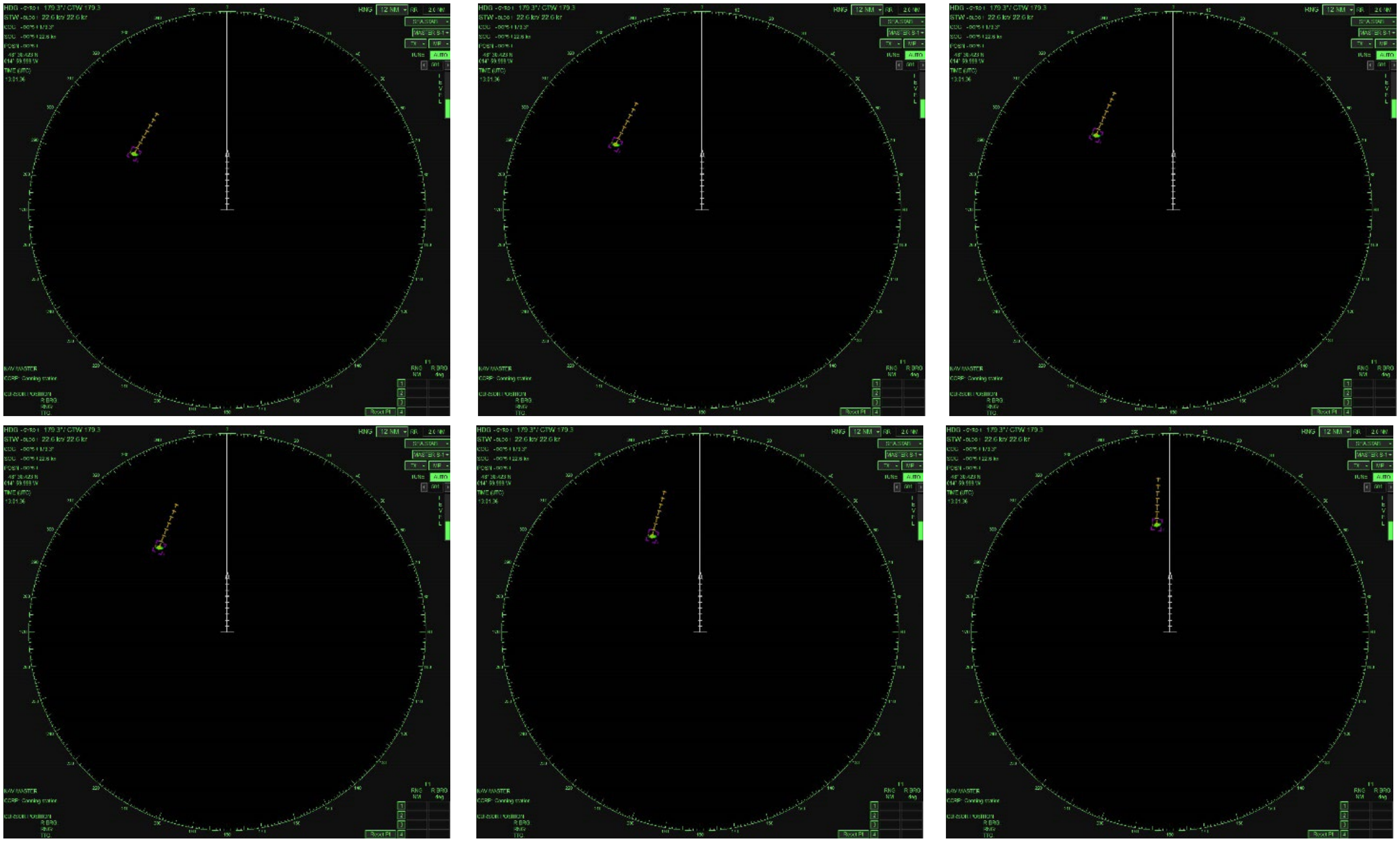
Overtaking-Crossing (OC) Situation

- **How do you understand the following sailing situation ? (using radar moving image)**



Overtaking-Crossing (OC) Situation

- **How do you understand the following sailing situation? From 90° to 180 ° (every 10 °)**



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- **Based on survey result, the Navigator Understanding HC & OC Sector is designated, a model that can distinguish collisions in the algorithm when a ship encounters it's needed.**
- **The modeling method is in order to fit the results of the navigator's understanding with the optimal distribution function, the Maximum Likelihood Estimation (MLE) technique was applied.**
- **A method of selecting the optimal function was applied through Goodness, which estimates model coefficients with low uncertainty..**
- **These methods are divided into two types: visual methods and numerical methods. Numerical methods calculate goodness-of-fit statistics and confidence limits to evaluate goodness-of-fit. Visual methods have advantages over numerical methods because the entire data set can be viewed at once and various relationships between the model and data can be easily displayed. Therefore, both methods were used in this study.**
- **Modeling was performed through MATLAB R2022a, and the models used were Gaussian distribution, log-normal, Sinusoidal, General Model Fourier1, and Exponential function.**

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Navigator's Understanding (HC & OC sector)

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3.1 Results of Navigator's Understanding for sailing rule

- **In a HC situation, a higher average means that the head-on situation is recognized as a crossing situation, and a higher standard deviation is interpreted as a decrease in confidence depending on the situation.**

- **A higher average in an OC situation means that the overtaking situation is recognized as a crossing situation, and the standard deviation is interpreted the same as HC.**

Question (°)	# 1	# 2	# 3	# 4	Average (SD)
HC_Q1 (000)	92	9	0	0	1.09(0.29)
HC_Q2 (002)	79	22	0	0	1.22(0.41)
HC_Q3 (004)	58	43	0	0	1.44(0.52)
HC_Q4 (006)	40	44	14	3	1.80(1.09)
HC_Q5 (008)	30	45	17	7	1.97(1.25)
HC_Q6 (010)	23	31	31	14	2.32(1.44)
HC_Q7 (012)	17	30	40	14	2.50(1.39)
HC_Q8 (014)	14	19	43	25	2.85(1.39)
HC_Q9 (016)	12	17	37	35	2.94(1.40)
HC_Q10 (018)	8	11	43	39	3.12(1.23)
HC_Q11 (020)	9	10	32	50	3.23(0.73)

Question (°)	# 1	# 2	# 3	# 4	Average (SD)
OC_Q1 (180)	73	28	0	0	1.28(0.63)
OC_Q2 (170)	69	30	2	0	1.37(0.58)
OC_Q3 (160)	32	50	14	5	1.92(1.12)
OC_Q4 (150)	27	48	19	7	2.06(1.24)
OC_Q5 (140)	19	52	23	7	2.18(1.21)
OC_Q6 (130)	13	45	33	10	2.40(1.27)
OC_Q7 (120)	14	46	28	13	2.40(1.30)
OC_Q8 (110)	10	48	25	18	2.50(1.33)
OC_Q9 (100)	11	40	30	20	2.58(1.34)
OC_Q10 (90)	8	35	33	25	2.84(0.85)

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- **Since navigators understand both HC situations from 006° to 012°, they set it as the HC sector, and this sector was designated as the HC sector for the navigators' understanding and modeled.**

- **Likewise, navigators understood the OC situation from 160° to 100° as other situations, so this sector was set as the OC sector understood by navigators and modeled.**

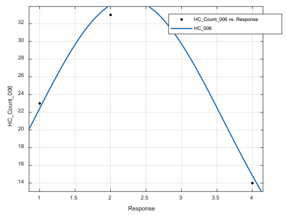
- **Using MATLAB's Goodness, the results of the numerical and visual methods for each result were presented.**

- **In numerical methods, the sum of square errors (SSE) measures the deviation of the total response variable value from the fitting to the navigator's response. If it is close to 0, it means that the random error component of the model is small and the fitting is more effective for prediction.**

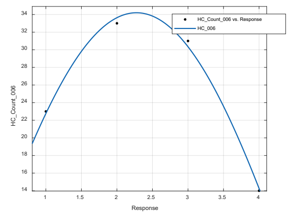
- **The closer the value of the Adjusted-R^2 of determination statistic is to 1, the better the fit. The root mean square error (RMSE) is an estimate of the standard deviation of the random components in the data, with values closer to 0 indicating a more useful fit for prediction.**

3. Navigator's Understanding

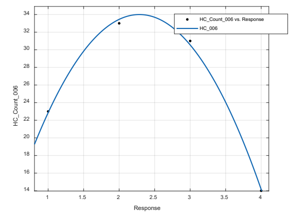
3.3 Result of Navigators' understanding HC modeling - Visual Method -



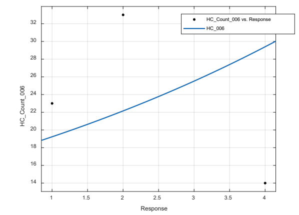
HC_Q4 Gaussian



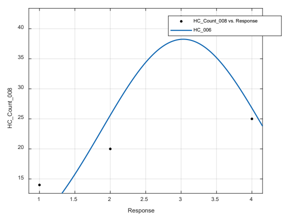
HC_Q4 Sinusoidal



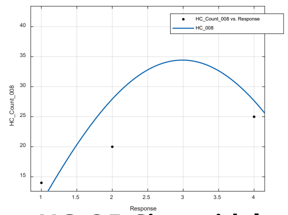
HC_Q4 Fourier1



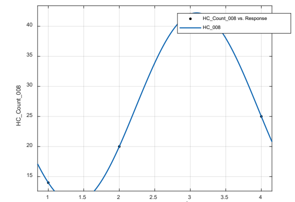
HC_Q4 Exponential



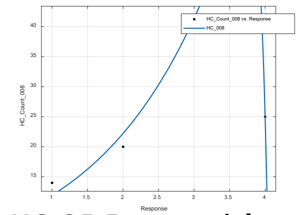
HC_Q5 Gaussian



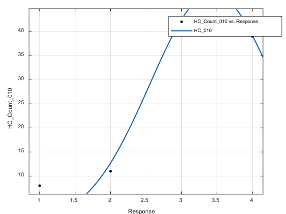
HC_Q5 Sinusoidal



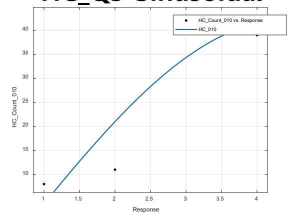
HC_Q5 Fourier1



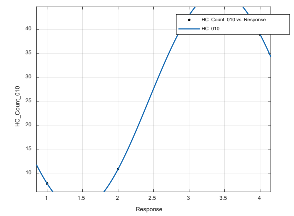
HC_Q5 Exponential



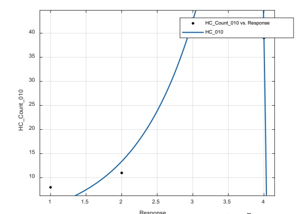
HC_Q6 Gaussian



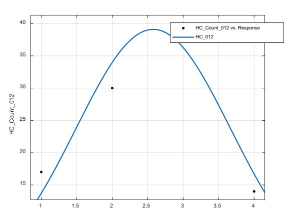
HC_Q6 Sinusoidal



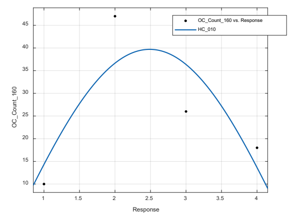
HC_Q6 Fourier1



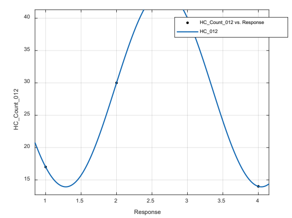
HC_Q6 Exponential



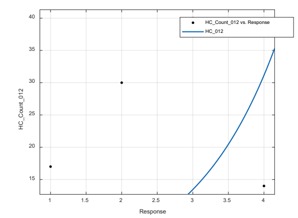
HC_Q7 Gaussian



HC_Q7 Sinusoidal



HC_Q7 Fourier1



HC_Q7 Exponential

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3. Navigator's Understanding

3.3 Result of Navigators' understanding HC modeling - Numerical Method -

	Fitting Model	SSE	R^2	Adjusted-R^2	RMSE
HC_Q4 (006)	Gaussian distribution	3.8950	0.9827	0.9480	1.97
	Sinusoidal	0.9656	0.9957	0.9871	0.98
	General Model Fourier1	**0.0001**	**1**	**1**	**0**
	Exponential function	399.1	-0.7755	-	-
HC_Q5 (008)	Gaussian distribution	84.2500	0.8062	0.4186	9.18
	Sinusoidal	138.4000	0.6817	0.0451	11.76
	General Model Fourier1	**0.0001**	**1**	**1**	**0**
	Exponential function	**9.597**	**0.9779**	**1**	**0**
HC_Q6 (010)	Gaussian distribution	51.5400	0.9487	0.8461	7.18
	Sinusoidal	198.2000	0.8027	0.4082	14.08
	General Model Fourier1	**0.0001**	**1**	**1**	**0**
	Exponential function	20.25	0.9788		
HC_Q7 (012)	Gaussian distribution	47.72	0.8902	0.6707	6.908
	Sinusoidal	53.99	0.8758	0.62750	7.348
	General Model Fourier1	**0.0001**	**1**	**1**	**0**
	Exponential function	1794	-3.127		

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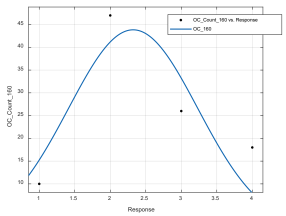
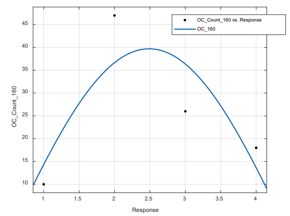
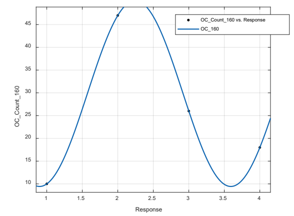
3.4 Result of Navigators' understanding OC modeling - Visual Method -



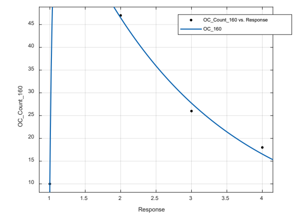
OC_Q3 Gaussian



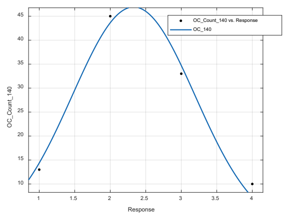
OC_Q3 Sinusoidal



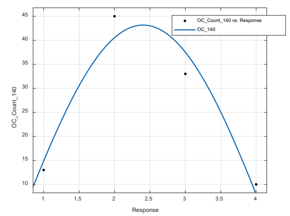
OC_Q3 Fourier1



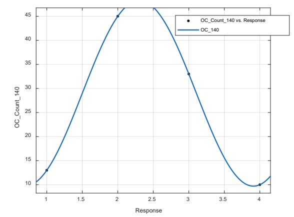
OC_Q3 Exponential



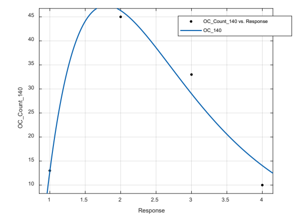
OC_Q5 Gaussian



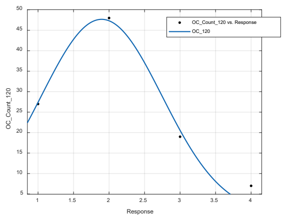
OC_Q5 Sinusoidal



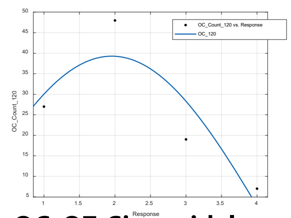
OC_Q5 Fourier1



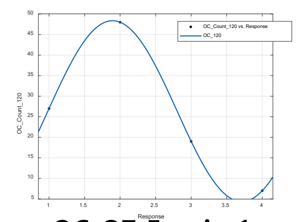
OC_Q5 Exponential



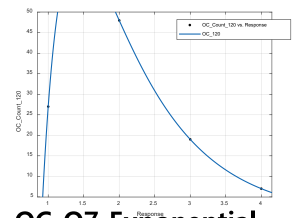
OC_Q7 Gaussian



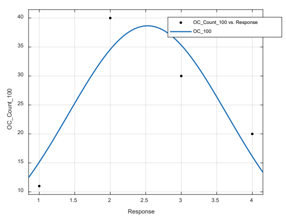
OC_Q7 Sinusoidal



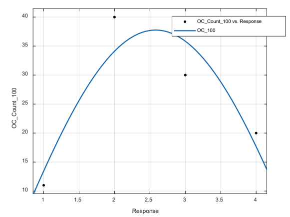
OC_Q7 Fourier1



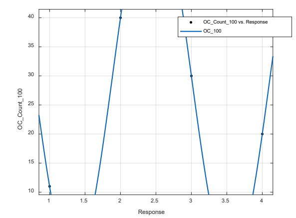
OC_Q7 Exponential



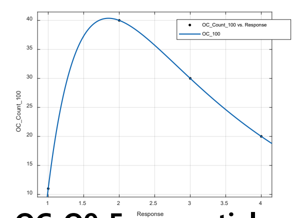
OC_Q9 Gaussian



OC_Q9 Sinusoidal



OC_Q9 Fourier1



OC_Q9 Exponential

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3. Navigator's Understanding

3.4 Result of Navigators' understanding OC modeling - Numerical Method -

	Fitting Model	SSE	R^2	Adjusted-R^2	RMSE
OC_Q3 (160)	Gaussian distribution	14.3200	0.9828	0.9484	3.78
	Sinusoidal	48.0300	0.9423	0.8270	6.93
	General Model Fourier1	**0.0001**	**1**	**1**	**0**
	Exponential function	5.384	0.9929		
OC_Q5 (140)	Gaussian distribution	213.4000	0.7187	0.1561	14.61
	Sinusoidal	252.2000	0.6676	0.0028	15.88
	General Model Fourier1	**0.0001**	**1**	**1**	**0**
	Exponential function	34.08	0.9591	1	0
OC_Q7 (120)	Gaussian distribution	25.6400	0.9713	0.9138	5.06
	Sinusoidal	189.8000	0.7874	0.3622	13.78
	General Model Fourier1	**0.0001**	**1**	**1**	**0**
	Exponential function	**0.0001**	**1**		
OC_Q9 (100)	Gaussian distribution	89.77	0.8093	0.4279	9.475
	Sinusoidal	80.18	0.8297	0.489	8.954
	General Model Fourier1	**0.0001**	**1**	**1**	**0**
	Exponential function	**0.0001**	**1**		

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Result

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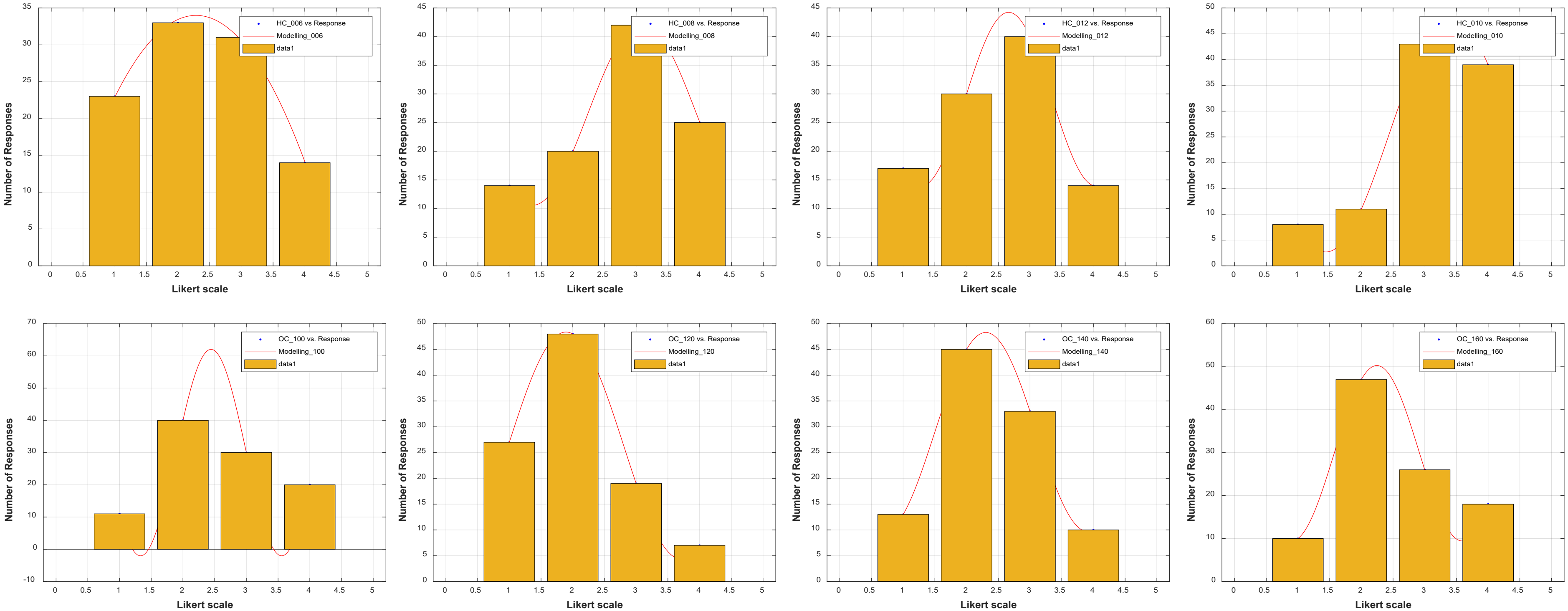
- **The navigator's understanding distribution function fitting results showed that General Model Fourier1 was the most suitable, and the optimal function results were shown in the HC sector (upper layer) and OC sector (lower layer).**

- **In the graph, you can see that there is no significant difference between the fourier function and histogram for which fitting has been completed.**



- **Since a model of the sector had to be developed, the variables for each angle were integrated and calculated.**

- **Navigators' understanding Modeling results for the HC Sector calculated coefficients based on the General Model Fourier1 formula below. The equation reflecting the coefficients is as follows.**

- $f(x) = a_0 + a_1 * \cos(x * w) + b_1 * \sin(x * w)$

  Coefficient of HC_Q4 a_0=19.94, a_1=−15.84, b_1=−8.517, w=2.235
  Coefficient of HC_Q5 a_0=26.40, a_1=26.40, b_1=−9.553, w=1.823,
  Coefficient of HC_Q6 a_0=25.28, a_1=14.82, b_1=−17.05, w=1.586
  Coefficient of HC_Q7 a_0=29.09, a_1=14.81, b_1=−3.244, w=2.278

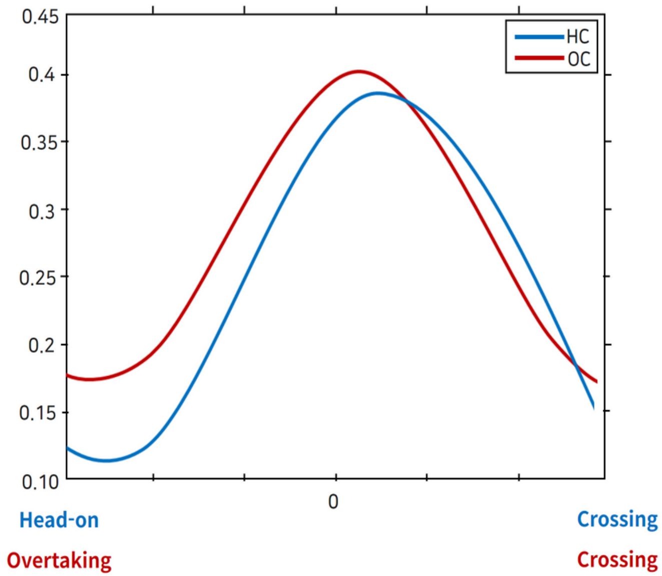
✓ **HC Sector Model : $f(x) = 25.18 + 10.05 * \cos(x * 1.98) - 9.59 * \sin(x * 1.98)$**

- **Navigators' understanding modeling results for the OC Sector are as shown below.**
- $f(x) = a_0 + a_1 * \cos(x * w) + b_1 * \sin(x * w)$

  Coefficient of OC_Q3 a_0=29.85, a_1=10.25, b_1=−17.65, w=2.333
  Coefficient of OC_Q5 a_0=29, a_1=−4, b_1=−18.88, w=1.955
  Coefficient of OC_Q7 a_0=26.36, a_1=−21.84, b_1=−2.781, w=1.727
  Coefficient of OC_Q9 a_0=30, a_1=26.1, b_1=18.56, w=2.824

✓ **OC Sector Model : $f(x) = 28.80 + 10.51 * \cos(x * 2.21) - 5.19 * \sin(x * 2.21)$**

- **The models of the HC Sector and OC Sector are drawn as follows.**
- **As you know, the sailing rules defined by COLREGs are three kinds of situations. In this study, we discovered the HC and OC sectors, which require navigators and researchers to understand these sectors.**
- **In current navigation with manned ships, the navigator's understanding is not a major risk. The reason is that when in this sector, it is tried to be resolved through a VHF call. However, when the Automated collision avoidance algorithm and a navigator meet this sector, a risk may arise as they classify the situation according to the meeting angle.**



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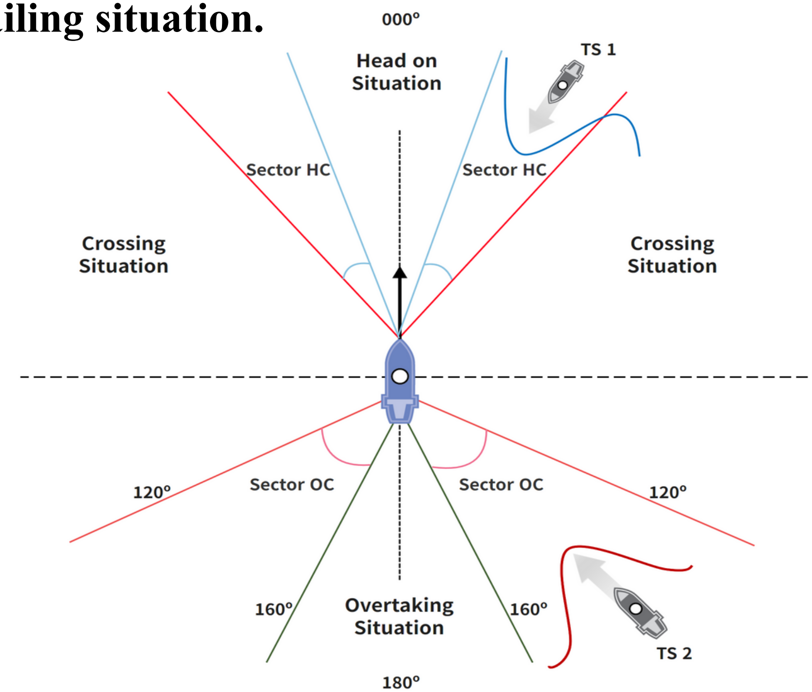
4.2 Proposal of Sailing Sector for automated algorithm using Navigators' HC and OC Sector Model

- **Adding the HC and OC Sector models to a situation based on COLREGs is shown in the figure below.**
- **This proposal can be summarized as follows: The automatic collision avoidance algorithm can be evaluated through the navigators' understanding HC & OC model of the navigator's understanding of the section.**
- **The algorithm determines the navigation application situation according to the output value of the navigator's understanding HC & OC Model, and determines how to avoid depending on the application of sailing situation.**



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5 Conclusion

5. Conclusion

- **This study identifies sectors that require understanding and develops a model to resolve the differences between the automatic collision avoidance algorithm of autonomous ships and the navigator's understanding of COLREGs Sailing Rule.**

- **A section that required the navigator's understanding of navigation was set, and the set section was defined as the HC & OC Sector for the navigator's understanding. And modelling method, the navigator's response to the sector was fitted with an optimal distribution function.**

1. Based on the navigator's response, the HC situation from 006° to 012° was set as the section requiring understanding, and from 160° to 100° was set as the section for the OC situation for modeling.
2. Navigators ' understanding Modeling results for the HC and OC Sector is the General Fourier1.
3. Algorithm determines the navigation application situation according to the output value of the navigator's understanding HC & OC Model, and determines how to avoid depending on the application of sailing situation.

- **This study can contribute to methods for avoiding collisions with manned ships, which are difficult to solve in current studies related to automatic collision avoidance. In the future, we plan to study the development of a collision avoidance system for model evaluation.**

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Thank you for your attention

- The head-on angle used in the researchers' collision avoidance algorithm applied to MASS was reviewed. (SCI journal paper only)
- Based on the literature review for situation of Head-on and Crossing & Crossing and Overtaking, this study was made to identify understanding collision situations.

Related work	Consideration of the COLREGs	Angle of Head-on Situation (°) (Sector A)	Angle of Crossing Situation (°) (Sector B)	Angle of Overtaking Situation (°) (Sector C)
Li et al., 2021	Yes	-	107.5	135
Pietrzykowski, Wielgosz, 2021	Yes	-	107.5	135
Stankiewicz and Mullins, 2019	Yes	-	107.5	135
Maza and Arguelles, 2022	Yes	-	112.5	135
Silveira et al., 2021	Yes	5	132.5	90
Chun et al., 2021	Yes	10	85	180
Hu et al., 2020, Lee et al., 2021, Liu et al., 2019, Mizythras et al., 2021, Rong et al., 2022	Yes	10	107.5	135
Szlapczynski and Szlapczyns, 2016, Yim et al., 2017	Yes	10	130	90

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Related work	Consideration of the COLREGs	Angle of Head-on Situation (°) (Sector A)	Angle of Crossing Situation (°) (Sector B)	Angle of Overtaking Situation (°) (Sector C)
Yuan et al., 2021, Zhang et al., 2015, Zhao and Roh, 2019	Yes	10	107.5	135
Zhai and Fu, 2021	Yes	10	130	90
He et al., 2017	Yes	11.4	106.8	135
Chen et al., 2015	Yes	12	119	110
Namgung and Kim, 2021	Yes	12	119	135
Sun et al., 2019, Shi and Zhen, 2022, Yim and Park, 2021	Yes	12	106.5	135
Hinostroza et al., 2019	Yes	12	168	12
Yu et al., 2022	Yes	15	105	135
Chai et al., 2017, Chen et al., 2018, Christian and Kang, 2017, Montewka et al., 2010, Rawson and Brito, 2021	Yes	20	160	20
Ma et al., 2021, Zhao et al., 2016	Yes	20	102.5	135

Related work	Consideration of the COLREGs	Angle of Head-on Situation (°) (Sector A)	Angle of Crossing Situation (°) (Sector B)	Angle of Overtaking Situation (°) (Sector C)
Benjamin et al., 2006, Bolbot et al., 2019, Pedersen et al., 2020, Woerner, 2016	Yes	30	97.5	135
Gerlandt et al., 2015, Du et al., 2021	Yes	45	132.5	50
Shaobo et al., 2020	Yes	45	90	135
Tam and Bucknall, 2013, Wang et al., 2020	Yes	50	87.5	135
Mou et al., 2020 , Ha et al., 2021	Yes	120	90	60
Lu et al., 2022, Du et al., 2022, Zhang et al., 2018, Huang et al., 2019	Yes	-	-	-
Xin et al., 2021, Liu et al., 2021	-	-	-	-

4. Result

4.1 Results of responses in the survey questionnaire

- **A total of 101 participant responded to the questionnaire, and they were classified according to age, tonnage, rank and experience.**
- **This survey was conducted over a period of 2 weeks, and was conducted non-face-to-face through Google foam.**

Age		Vessel tonnage		Rank		Experience	
Age	Number	Ton	Number	Rank	Number	Year	Number
20'	25	> 5k	10	Captain	7	> 1	4
30’	54	5k -10k	13	C/O	35	1–3	29
40’	17	10k–50k	29	2/O	44	3–5	27
50’	4	50k–100k	33	3/O	14	5–10	29
60’	1	100k <	16	Pilot	1	10 <	12
Total	101	Total	101	Total	101	Total	101

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