

Revealing success factors of safe ship operations of experienced captains to assess functional requirements of Maritime Autonomous Surface Ships using FRAM

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ABSTRACT

It is essential to reveal skills of experienced captains in order to define functional requirements of Maritime Autonomous surface ships (MASS). While textbooks, manuals, and laws define rules for captains and officers to follow, there are lots of other tacit knowledge, which are not written in documents, for safe ship operations. In this respect, it is essential to take into account complex dependencies among tasks/subtasks to build “an experienced captain’s model”. In order to accomplish this goal, we adopted a function-based modeling methodology which can support rich environmental factors for analyzing ship management operation.

In this research, we conducted the following two steps to identify functional requirements of MASS, i.e., 1) modelling the skills of officers of the watch (OoW) from literature reviews, 2) analyzing the actions of OoWs from the data acquired with gaze movements.

Firstly, we performed modellings of OoWs’ skills by utilizing FRAM. FRAM provides a way to describe how systems work in given working environment by using a characteristic functional representation of the systems as a diagram; each function of the systems is defined with six aspects, visually represented as a hexagon whose vertexes correspond to each of them, and eventually the systems are represented as a network of the six aspects. This representation provides complex dependencies among functions, and moreover, deeper insights about how the systems are successfully functioning. Secondly, we analyzed actions of OoWs observed in the simulator trials, using data obtained from an eye-tracker, videos, and a wearable device to measure heart rate variability. Then we have examined relationships between the variety of the OoWs’ actions and the heart rate variability. This study will contribute to define functional requirements of MASS for safety ship operations and assess the functions of MASS to develop.

1. Introduction

The design of Maritime Autonomous surface ships (MASS) requires functional requirement analysis. Class NK’s guideline, for instance, defined conceptual diagram of tasks and subtasks, which shows functions of onboard operations and works; tasks and subtasks can be classified into three groups: situation awareness, decision, and action (Class NK 2020). Also, Kutsuna (2019) identified tasks/subtasks to define basic requirements for Action Planning Unit (APU) of MASS. However, while those documents describe about requirements, such as rules or technical skills, for captains and officers, there are lots of other tacit knowledge, which are not written there, for safe ship operations. It is therefore difficult to identify specific functional requirements for the system design of MASS. In order to address the issue, the purpose of this research was to 1) identify functional requirements of safe ship operations based on literature reviews, 2) develop a model of OoWs’ tasks and technical skills, and 3) reveal tacit knowledge for ship operations based on action data analysis, whose data was obtained through a simulation-based experiment.

2. Modellings of OoWs’ skills

2.1 Method

Firstly, we performed modellings of OoWs’ skills. The relationships among those tasks/subtasks of OoWs are generally so complicated that it is difficult to literally describe how they successfully work; it is therefore essential

to consider such complex dependencies among tasks/subtasks and represent it as a model rather than literal descriptions. In this respect, we 1) firstly analyzed tasks of OoWs with literature reviews such as manuals, laws, regulations, and accident cases to identify the functions, 2) visualized tacit knowledge through interviews with several experienced OoWs, and 3) constructed Functional Resonance Analysis Method (FRAM) models to describe how the skilled OoWs are achieving safe ship operations.

2.2 Functional Resonance Analysis Method (FRAM)

FRAM (Hollnagel 2004, 2012) is a method to describe how systems work in given working environment by using a characteristic functional representation of the systems; each function of the systems is defined with six aspects and visually represented as a hexagon whose vertexes correspond to each of them. The systems are, consequently, represented as a network of the six aspects as shown in Figure 1(a) and (b). This representation provides complex dependencies among functions, and moreover, deeper insights about how the systems are successfully functioning.

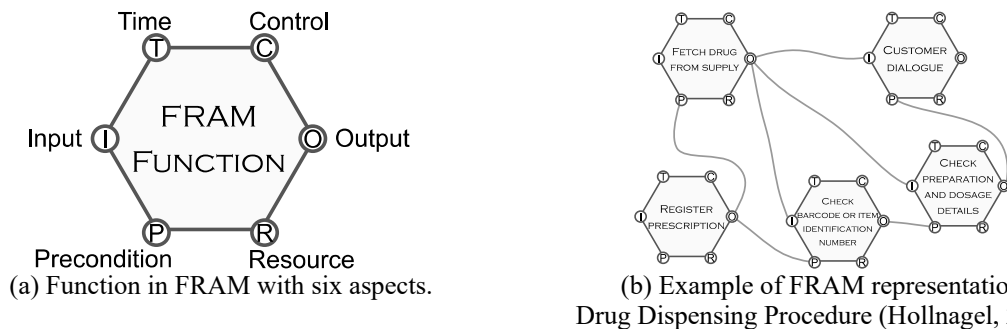


Figure 1 Functional representation in FRAM

2.3 Related works

FRAM has been applied to a variety of fields such as aviation, autonomous-driving or railway safety (Riccardo et al., 2018; Hirose et al., 2020; Fukuda et al., 2016), and it is also the case with the maritime safety. Adhita and Furusho (2021), for example, investigated ship-to-ship collision occurred in Surabaya West Access Channel (SWAC), Indonesia and concluded that the accident has occurred due to unintended dependency of several malfunctions, rather than a single failure of function of the ship operations. Smith et al. (2018) also built a FRAM model of arctic ship navigation, investigated a grounding accident of the Exxon Valdez case, and found additional safety recommendations that were not described in the accident reports. However, the primary focus of those cases is put on accident analysis although FRAM has recently been developed to pursue “why things go right” rather than “why things go wrong”, under the concept of Resilience Engineering (Hollnagel, 2006) and Safety-II (Hollnagel, 2017). FRAM is, therefore, not only a tool of accident analysis but also a method to find out success factors of target systems/operations and enhance their safety, contrary to the traditional approach trying to eliminate source of failures as much as possible. The purpose of our FRAM analysis is to investigate such success factors of great captain directly, based on the idea of Resilience Engineering and Safety-II.

2.4 FRAM modelling of ship operations

We initially analyzed tasks of OoWs with Class NK’s guideline (2020), Kutsuna (2019)’s list of tasks and subtasks of APU, and Nishizaki (2017) who analyzed navigators’ situational awareness. We also added functions based on manuals, laws, and regulations. Then we had interviews about ship operations with several researchers and captains to visualize tacit knowledge.

Then, we made a FRAM model of captains’ ship operations as shown in Figure 2. The model consists of very detailed tasks extracted from the documents such as “Open window” or “Refer to radar” as well as very complicated dependencies among them. The original model was then converted into another dimension of descriptions since it is so huge and complex that it is still difficult to analyze what it represents. Moreover, the functions existing in the original model shown in Figure 2 were grouped into several clusters, depending on their abstract goal or purposes; Figure 3 shows a cluster of “watch-keeping” as an example. The original FRAM model was consequently converted into another level of abstraction for further analysis as shown in Figure 4, representing the cognitive process of safe ship operations.

The developed FRAM model suggests the difference between traditional ideas about decision-making process and cognitive functions of human captains. According to Class NK’s conceptual diagram of the Automated Operation Systems (AOS), the flow of decision-making process: 1) Situation Awareness (SA), 2) Decision, and 3) Action. On the other hand, the FRAM model representing the cognitive process of safe ship operations suggests the ship operations by human captains do not necessarily follow such flow; the operation is composed of small

cognition loops trying to update their SA, Decisions, and Actions at multiple cognition levels frequently and simultaneously.

FRAM model showed three steps for planning based on the interviews of captains and other specialists: short-term planning, medium-term planning, and long-term planning. Short-term planning is the planning with the range of 1-2 nautical miles. Rules of laws such as Act on Preventing Collisions are applied. Medium-term planning is the one with the range of 4-6 nautical miles. This is the most important for collision avoidance as it is required to avoid encountered ships keeping the distance between own and the encountered ships for the safety. The effect of the medium-term planning was validated through a simulation-based experiment, and its result will be provided in the next section.

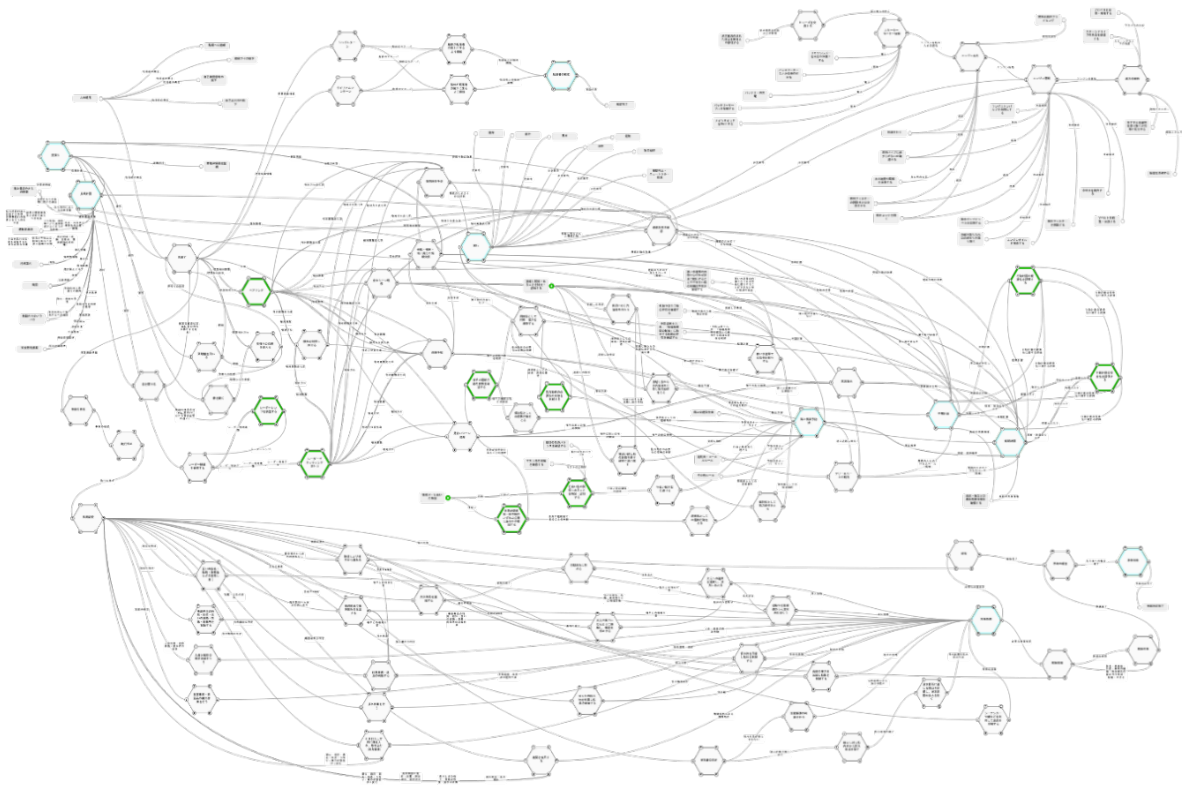


Figure 2 FRAM model of all functions of ship operation

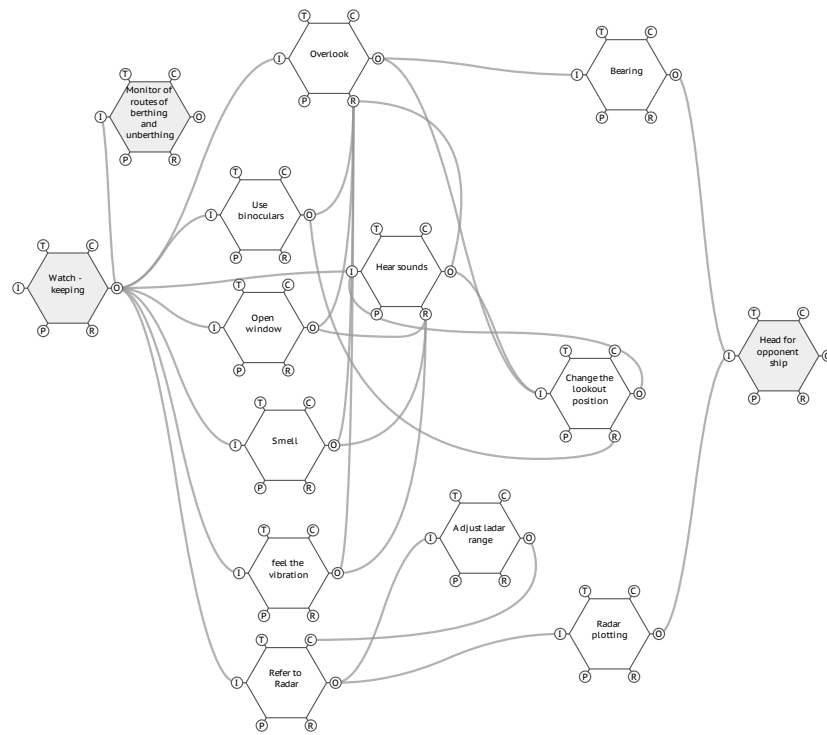


Figure 3 FRAM model of watch-keeping

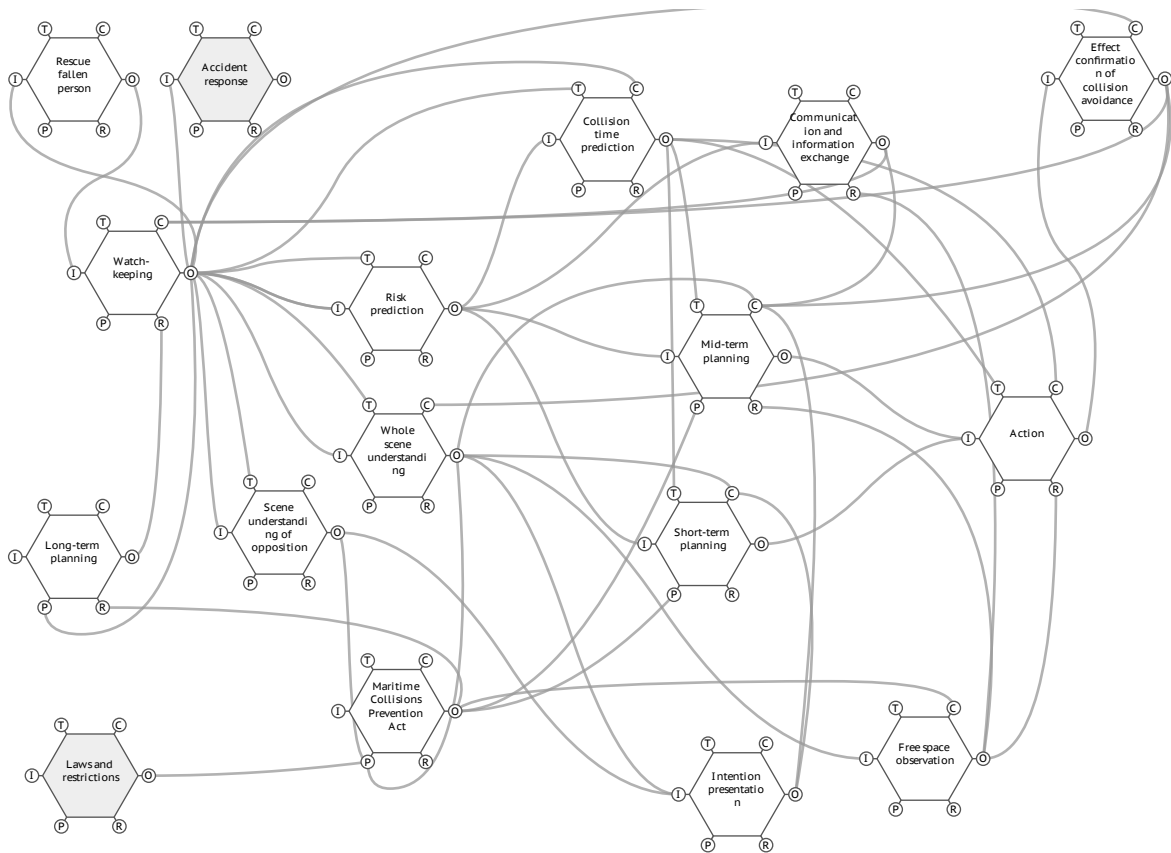


Figure 4 FRAM model of ship operation functions in the high abstraction level

3. Analysis of OoWs' actions

3.1 Method

We analyzed actions, observed in the simulator trials for collision avoidance, to verify and validate FRAM modelling, using the data of an eye-tracker, videos, and a wearable device to measure heart rate variability. In this research, we recorded five key actions of three captains who have different levels of experiences from gaze movements in time series: looking at nautical instruments, radars, outside from the bridge with their eyes, the outside with binoculars and taking bearing of target ships. We utilized the data of simulator trials with simulators of Marine Technical College (Murai 2022). The data was obtained with measuring devices of gaze movement and heart rate variability, videos, and voices in a bridge for three different captains, which have different experience years.

3.2 Validating the FRAM model

We validated the FRAM model by comparing functions of FRAM with the actions of captains, in which actions of captains were identified based on their conversations during the simulator trials. Table 1 shows examples of actions and corresponding functions in FRAM. The result found that all actions by the captains can be classified into the functions in FRAM model and validated our FRAM model comprehensively represents the simulation scenario.

Table 1 Examples of actions and corresponding functions in FRAM

Time	Voice of the captain	Functions in FRAM
14:52:37	Captain confirmed a crossing ship	Watch-keeping
14:54:03	Nearest ship C is 6 miles away, 12 knots, and 1 cable CPA. This is unavoidable in the current route.	Risk prediction Collision time prediction
14:54:25	Ship B is behind of the ship. It is also 12 knots and the distance between ship B and C is 2-3 miles.	Whole scene understanding
	Captain confirmed free space from the window and radar information	Free space observation
14:55:33	Captain confirmed a crossing ship. It is not able to see behind the ship.	Scene understanding of opposition
14:56:15	Ship C is 5.5 miles. We will start a route change for collision avoidance.	Mid-term planning
14:56:25	Starboard 10	Action
15:01:42	Captain saw the aft of the second ship.	Effect confirmation of collision avoidance
15:11:46	Captain is returning the course and going before the crossing ship.	Intention presentation

3.3 Analysis of avoidance routes

In the scenario of the simulator trials, there are three encountered ships crossing in front of the own ship, in which each captain made decision to avoid collisions. Figure 5 shows trajectories of the own ship and target ships. Two of three captains decided to move among three target ships while a captain made a slight detour to avoid collision with target ships. Although there is such a difference in the trajectory of ships, the distance where the Captain A and B made decision to start avoiding target ships were similar. First start point was between 4.84 and 5.46 nautical miles from the target ship to avoid. Second start point is between 3.96 and 5.99 nautical miles. The corresponding functions in our FRAM model are the mid-range plan and decision making. The distances match with the distance of the mid-range plan based on the experiences of captains.

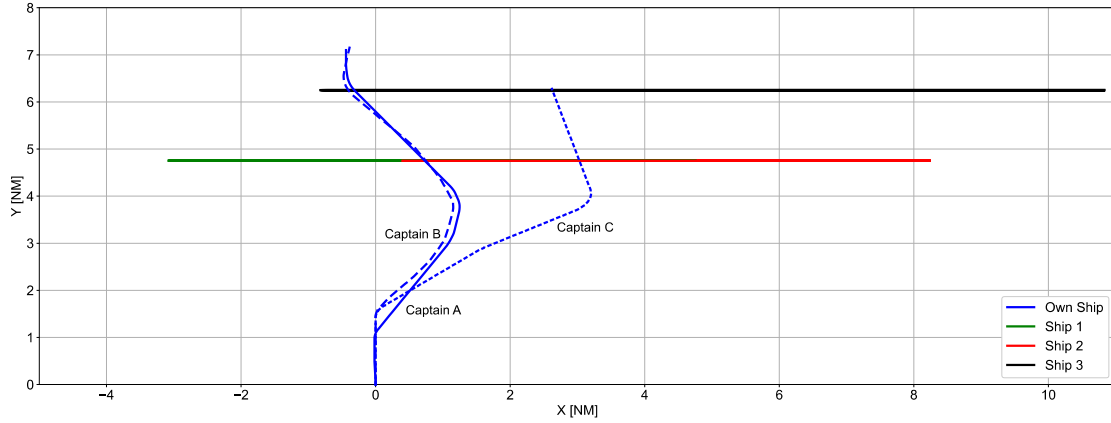


Figure 5 Trajectories of own ship and other ships in the training simulation

3.4 Analyzing actions from gaze movements

3.4.1 Statistical analysis of gaze movements

We compared the statistical data in actions of captain A and B, who performed similar trajectories in the trials. Table 2 shows the total time and number of times of each OoWs' actions during the trials. In this analysis, we divided the period into two phases: 1-1050s (first half) and 1051-2100s (second half) and visualized the changes in total time with heatmap. The result found that the following tendency of each captain: 1) while the number of times and duration time to look at the nautical instrument has dramatically increased from first half to second half in the case of captain A, the duration time to look at the instrument remained the same, and the number of eye-point transition has decreased in the second half phase in the case of captain B; 2) although the captain A was taking a bearing constantly regardless of the scenario phase, the captain B did not take a bearing in the second half phase; 3) both of captain A and B used the radar to monitor target ships for more time in first half and tended to watch from the window in second half; 4) the number of times in watching outside from the windows have increased in the case of captain A while the number has decreased with the increase of total time for captain B; the number of times and total time to use binoculars were decreased for captain A although the total time was increased for captain B. It means captain A noticed and understood the movements of target ships in early phase. Changes shown in the heatmap of the total time shows same trends for captain A and C; both captains spent more time to look outside from the window while the total time of using radar and binoculars decreased in the second half.

Table 2 Total time and number of times of each action

		Captain A			Captain B			Captain C		
		1 -1050 s	1051 -2100 s	Difference	1 -1050 s	1051 -2100 s	Difference	1 -1050 s	1051 -2100 s	Difference
Duration time to look at (s)	Instrument	6	29	23	15	15	0	28	38	10
	Bearing	97	86	-11	10	0	-10	65	37	-28
	Radar	472	267	-205	425	213	-212	481	261	-220
	Window	274	602	328	521	707	186	308	677	369
	binoculars	202	66	-136	80	115	35	169	37	-132
Number of times to look at	Instrument	3	11	8	7	4	-3	8	16	8
	Bearing	9	9	0	3	0	-3	11	9	-2
	Radar	42	44	2	33	32	-1	25	24	-1
	Window	44	58	14	41	40	-1	29	39	10
	binoculars	5	4	-1	5	5	0	9	2	-7

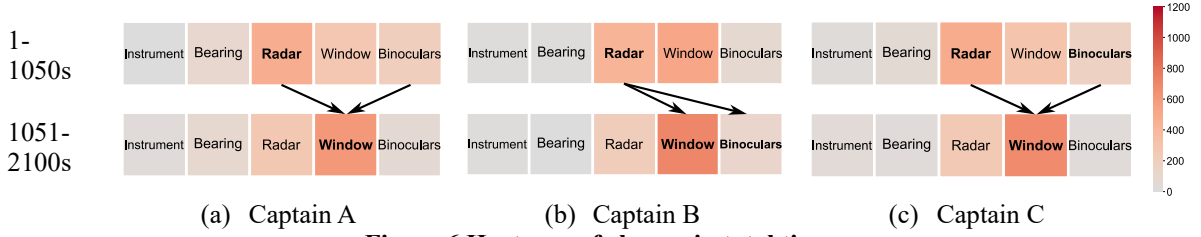


Figure 6 Heatmap of change in total time

3.4.2 Analysis of gaze movements

We visualized the transition frequency of gaze movements with heatmap as shown in Figure 7. In these figures, the origin of the eyepoint is aligned to the vertical direction, and the destination is aligned to the horizontal direction; each cell represents the frequency of gaze movements with a color scale. The result qualitatively shows that the gaze movement of all captains between window and radar was the most, and that of captain B was concentrated there rather than distributed across the heatmap matrix, for instance.

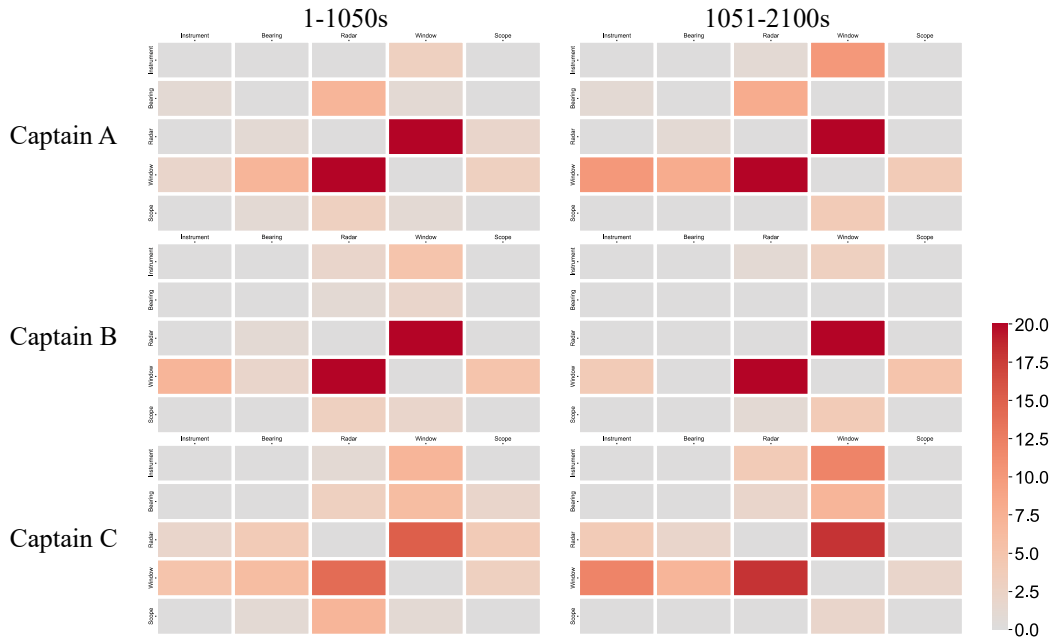


Figure 7 Heatmap of gaze movement

For further analysis of such tendency, we introduced a quantitative indicator called the information entropy (Shannon, 1948). The definition of information entropy and conditional information entropy are shown in Eq. (1) and (2), respectively; the value can be utilized for evaluating the variety of gaze movements, and the result is shown in Figure 8.

$$H(X) = - \sum_i p(x_i) \log_2 p(x_i), \quad x_i \in X \quad (1)$$

$$H(Y|X) = - \sum_{i,j} p(x_i, y_j) \log_2 p(y_j|x_i), \quad x_i \in X, y_j \in Y \quad (2)$$

Figure 8 shows the multiplot of the information entropy of gaze movement and LH/HF Ratio representing ratio of the low and high frequency power (LF/HF) to measure the condition of stress for captains (Malliani et al., 1994; Pagani et al., 1986); the entropy of gaze movement was calculated every 300 seconds and plotted with LF/HF Ratio at that time. In addition to these figures, the existence of route changes in each interval is shown in Table 3.

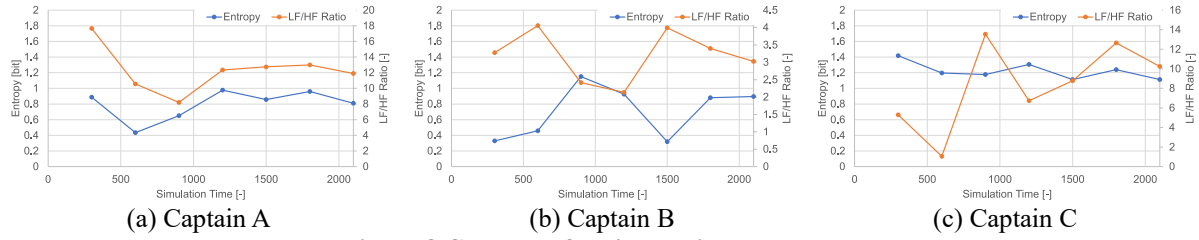


Figure 8 Changes of LF/HF ratio and entropy

Table 3 Existence of route change

Simulation time (s)	Captain A	Captain B	Captain C
0-300	○	-	-
301-600	○	○	○
601-900	-	○	-
901-1200	○	○	○
1201-1500	○	○	○
1501-1800	-	-	○
1801-2050	○	-	-

Firstly, we compared the data of captain A and B, who had similar routes. For both captain A and B, LF/HF ratio was the highest in the range when collision avoidance started: 0-300s for captain A and 301-600s for captain B. The ratio of captain A decreased from 300 to 900s and increased from 900 to 1200s. It corresponds to the existence of route change for collision avoidance. In terms of the entropy of gaze movement, captain A had constant entropy between 0.8 and 1.0 except for 600 and 900s while the entropy was not constant and high during the collision avoidance phase for captain B. Captain C had constant entropy for all phases.

4. Discussion

According to a theory of cybernetics, the variety of system controllers is the only possible way to cope with the variety of disturbances existing in the surrounding environment of the systems. The theory is known as the Law of Requisite Variety (LoRV) proposed by Ashby (1956) and has been discussed in the field of resilience engineering (Hollnagel et al., 2006) as well.

In this respect, the captain A and C was maintaining high entropy of gaze movement throughout the simulation sequence and decided the collision-avoidance strategy in the early phase. This tendency is also consistent with the FRAM model shown in Figure 4, suggesting that the safe ship operations by human captains consist of small cognition loops trying to update their SA, Decisions, and Actions at multiple cognition levels frequently and simultaneously. The result suggests that this is one of the success factors of mid-term planning, or moreover, success factor of captains.

The safe ship operation involves complex dependency among tasks and tacit knowledge. One possible way to automate such amazing skills of human beings is to understand and implement their nature. The insights obtained through this research will contribute to such activities and innovative development of MASS.

5. Conclusion

We modelled OoWs' ship operations with FRAM based on the analysis of literatures and interviews. The data analysis of simulator trials by three captains validated our FRAM model and revealed the tacit knowledge for successful ship operations with the analysis of gaze movements and calculations of information entropy. The important factors of tacit knowledge were 1) there are three phases for planning, and 2) experienced captain tend to complete collision avoidance in the mid-term planning with constantly high entropy. Those success factors will be important for the system design of MASS. This study will contribute to the safety analysis and system design of MASS.

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Reference

- (1) Adhita, I. G. M. S., and Furusho, M. (2021): Ship-to-ship collision analyses based on functional resonance analysis method. *Journal of ETA Maritime Science*, **9**(2), 102-109.
- (2) Ashby, W.R. (1956). *An Introduction to Cybernetics*. Chapman & Hall Ltd.
- (3) Class NK (2020): *Guidelines for Automated/Autonomous Operation on ships (Ver.1.0)*
- (4) Fukuda, K., Sawaragi, T., Horiguchi, Y., & Nakanishi, H. (2016). Applying systemic accident model to learn from near-miss incidents of train maneuvering and operation. *IFAC-PapersOnLine*, **49**(19), 543-548.
- (5) Hirose, T., Sawaragi, T., Nomoto, H., and Michiura, Y. (2021). Functional safety analysis of SAE conditional driving automation in time-critical situations and proposals for its feasibility. *Cognition, Technology & Work*, **23**(4), 639-657.
- (6) Hollnagel, E., Woods, D. D., & Leveson, N. (Eds.). (2006): *Resilience engineering: Concepts and precepts*. Ashgate Publishing, Ltd..
- (7) Hollnagel, E. (2017): *Safety-II in practice: developing the resilience potentials*. Routledge.
- (8) Kutsuna, K., Ando, H., Nakashima, T., and Kuwahara, S. (2019) What is Action Planning System (APS) for Manned Autonomous Navigation?, *Marine Engineering* **54**(2):210-214
- (9) Malliani, A., Lombardi, F., and Pagani, M. (1994). Power spectrum analysis of heart rate variability: a tool to explore neural regulatory mechanisms. *British heart journal*, **71**(1), 1.
- (10) Murai, K., Nishizaki, K., Kayano, J., Tamaru, H., Shoji, R., (2022): Quantitative Evaluation of Good Seamanship using Physiological Data to realize Maritime Autonomous Surface Ships, *Navigation*, **219**, 13
- (11) Nishizaki, C., Takemoto, T., & Kunieda, Y. (2017). A characteristic of a navigator's situation awareness for crossing ships. *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*, **11**(2).
- (12) Pagani, M., Lombardi, F., Guzzetti, S., Rimoldi, O., Furlan, R., Pizzinelli, P., ... & Piccaluga, E. (1986). Power spectral analysis of heart rate and arterial pressure variabilities as a marker of sympatho-vagal interaction in man and conscious dog. *Circulation research*, **59**(2), 178-193.
- (13) Riccardo, P., Gianluca, D. P., Giulio, D. G., and Francesco, C. (2018). FRAM for systemic accident analysis: a matrix representation of functional resonance. *International Journal of Reliability, Quality and Safety Engineering*, **25**(01), 1850001.
- (14) Smith, D., Veitch, B., Khan, F., and Taylor, R. (2018): Using the FRAM to understand Arctic ship navigation: assessing work processes during the Exxon Valdez grounding. *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation*, **12**(3).

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Shota Iino received his Ph.D. from University of Tsukuba. He has been researching on the safety analysis of space systems and machine learning based system in several fields such as automobile and Maritime Autonomous surface ships at IV&V Research Lab, Japan Manned Space Systems (JAMSS).

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