Silent safety: assessing cavitation-prevention procedures on board naval surface ships

Steinke, J.; Band, G.P.H.; Ketterij, R. van den

Citation

Steinke, J., Band, G. P. H., & Ketterij, R. van den. (2025). Silent safety: assessing cavitation-prevention procedures on board naval surface ships. doi:10.14339/STO-MP-IST-205-41-PDF

Silent Safety: Assessing cavitation-prevention procedures on board naval surface ships

Julian Steinke
Cognitive Psychology
Leiden University
Leiden, The Netherlands
ORCHID ID: 0009-0007-7249-9057

Guido P.H. Band
Cognitive Psychology
Leiden University
Leiden, The Netherlands
ORCID ID: 0000-0003-0408-0039

Robert van de Ketterij
Section of Military Technological Sciences
Royal Netherlands Military Academy
Den Helder, The Netherlands
ORCID ID: 0000-0003-1774-3997

Henk de Weerd
Royal Naval Institute
Royal Netherlands Military Academy
Den Helder, The Netherlands
HC.d.Weerd@mindef.nl

Abstract—**In modern naval warfare, the submarine poses one of the largest threats to surface ships, naval or civilian. Cavitation has been identified as a large contributor to underwater radiated noise and is used to locate surface ships. It has come into focus as a topic for noise prevention and thus decreasing the detectability of a naval vessel. This study aims to map the processes that are currently used to prevent cavitation to identify the involved crew members and functions, and to estimate the workload within the system. We performed a Functional Resonance Analysis (FRAM) based on observational data from high-fidelity simulator runs and exercises on an active frigate. The model generated shows the current process towards moving without cavitating and identifies possible failure points of the system. It also enables us to identify how to make the process more resilient. We argue that an interface taking over some of the functions that are estimating cavitation inception would aid the crew in its decision-making process and lower the cognitive load.**

I. INTRODUCTION

There are multiple reasons to minimize Underwater Radiated Noise (URN). Not only does it have a significant negative impact on sea life [1], [2], [3], [4], it can also compromise safety in conflict situations. Anti-submarine warfare (ASW) is one of the most important parts of modern naval warfare, as submarines offer the opportunity for covert movements of conventional ordnance as well as nuclear weapons. The advantage of detecting an adversary before they detect you applies in any war domain, and the maritime domain is no exception. Listening for URN with passive sonar has been one of the most used methods to detect enemy vessels and subsurface weapons since the development of the hydrophone [5], [6], [7]. Especially submarines rely on passive sonar as it does not reveal their own location, thus maintaining the submarines' major advantage in stealth. With multiple hydrophones on the hull, the source of URN can be accurately triangulated, providing a submarine with the location of a surface ship without the use of active sonar or having to rise to periscope depth [6].

Cavitation has long been identified as a major cause of URN with ships in general [8]. Cavitation in a maritime context specifically refers to propeller cavitation. This is defined as the vaporization of water due to the difference in water pressure caused by the propeller blades moving through the water [9], [10], [11]. The water vapor forms bubbles trailing the propeller and will eventually implode. The implosion causes a shockwave and thus sound. In addition, this acoustic cavitation causes URN on a broad spectrum making it very detectable with hydrophones [12].

Ship designers have strived to reduce URN since decades, especially through improvements in propeller design for decades, especially in propeller design [12], [13], [14]. As it is almost impossible to prevent cavitation when a propeller is spun on maximum rotational speed (usually indicated in revolutions per minute (RPM)) [15], blades are designed to be as efficient as possible. Submarine propellers have long been highly optimized and, as a result, their designs are usually guarded as state secrets.

Cavitation of surface ships has been researched for some time because of its eroding effect on material [11], [16], and its negative impact on maneuverability [17]. URN emissions specifically caused by cavitation have only recently come into focus for naval research for surface ships. Usually, a vessel(-class) is evaluated on its cavitation inception speed (CIS) and this value is treated as a constant. However, CIS depends on many different factors including the hull design and -deterioration, sea state, currents, previous maneuvers, salinity, and blade-angle or pitch of the propeller [12], [18], [19], [20], [21], [22], [23]. With the CISCON project of which this study is a part, we aim to develop tools to predict cavitation and aid crews in adapting their speed in accordance with the actual CIS.

Given the various variables influencing CIS, a number of methods to control CIS are suggested by research. They can be divided into three categories; fixed, passive, and active. This study will focus on active methods. These include those, that the crew can apply while operating. If accessible, adjusting the pitch angle of the propeller blades will change the CIS as the angle of attack of the blades affects the thrust without having to change the rotation-speed of the propulsion unit [24], [25]. The other method is reducing the RPM of the propeller. This approach is also universally applicable in contrast to adjusting the pitch angle.

By comparison, passive methods are about monitoring factors that cannot be influenced by the crew, like environmental factors and wake of other vessels. Fixed methods are applied either during the construction phase or refitting, for example the already addressed design of the propeller and the hull itself. Both categories offer no methods suited for this project, because the crew cannot react to variations in CIS while steaming.

We chose adjusting RPM to remain under CIS as the focus point of this study. This active method is applicable to any vessel and does not require special equipment like variable pitch propellers or adjustments to the hull. However, the crew will have to receive information about the current CIS in real time. Any display of this requires the introduction of a new human machine interface (HMI). It is important that the HMI is designed and integrated with a high degree of usability.

Determining the necessary information to transfer by the HMI and the procedures to prevent cavitation with it will be the subject of future research. Before the design process can start, it is important to understand the surroundings of such a possible interface as it introduces additional safety-relevant data in an existing workflow. It is therefore essential to investigate the current network of information processing and to understand the work pressure on board. First, the location of a future HMI has to be determined, as the physical location will determine the frame of the information network. After preliminary discussions with four commanding officers within the Royal Netherlands Navy (KM), it was decided that the bridge would be the target environment of such a system, as it is from here where the propulsion unit of vessel primarily receives input. This determines the environment of the bridge as the frame for this study. Therefore, we will first and foremost consider the crew on the bridge and their process of preventing cavitation.

The bridge presents a high-pressure high-risk work environment during a mission, with a sustained high cognitive load and high probability of causing operator fatigue over time [26]. As a high-alert state onboard can take many days, operator fatigue only becomes more significant. Any new interface, especially safety-critical infrastructure, therefore has to be installed on the bridge and integrated in the command structure in such a way that it minimizes the increase of the cognitive load of the crew.

It is necessary to first understand the current procedures on board a naval vessel when it comes to preventing cavitation. This baseline has to be established to ergonomically integrate a new system where it is needed and to present necessary information regarding cavitation to the appropriate crew member(s). This study has the aim to establish this baseline by mapping the current procedures on the bridge that are used to sail without cavitating in the frame of anti-submarine warfare. Secondly, we want to investigate the resilience of the overarching system and identify elements that could be aided by an HMI.

The specific goals of this study are to (1) Identify the relevant human agents in preventing cavitation, (2) map the information processing flow and (3) map how the sub-processes interact, (4) identify sources of high variability in the system, and (5) identify where a future HMI would ideally be integrated into the current processes. Given this list of goals, we chose to perform the functional resonance analysis method (FRAM) by Hollnagel [27]. The analytic hierarchy process method (AHP) has also been considered, but is not fit for this study, as it has the purpose of understanding a chronological decision-making process. FRAM however, reveals the system in nominal performance and illustrates sources of workload. In addition, AHP does not show variability, which is especially value in planning the introduction of an additional interface in the future.

In addition, FRAM characterizes up to six aspects per function which may be connecting nodes. Time (T) indicates temporal conditions to carrying out a function. This could for example be a specific time of day that this function could only be executed or a specific sequence. Control (C) describes supervision or regulation. Inputs (I) are aspects that start the execution of the function, as wells as something that is transformed by performing the function. Output (O) on the other hand is the result of the functions' execution, i.e. the product. Preconditions (P) are the aspects needed to be in place start-up the function, but they will not start the execution itself. Resources (R) are aspects that are used or consumed by the function.

II. METHOD

This study utilized an overt observational design in two phases. The first phase of data collection was performed in a simulator environment. This full-bridge simulator was chosen as it enabled the observation of multiple crews in highly replicable scenarios. The exercises were performed by officers in training during their final practical simulator runs before entering the fleet as a junior officer. This enabled the observation of ASW fully in accordance with doctrine. So far, there is no research about possible divergences from "by the book" procedures in active service. Therefore, the second phase occurred on board an active frigate with varying exercises. This phase allowed the observation of an experienced crew in the naturalistic environment and thus with possible workarounds that would not occur in the simulator runs. It allowed for the observation of the bridge in the context of the entire ship. Both phases will be explained separately in the following sections.

A. Phase one

1) Participants: The simulator study observed three crews of officers in training. Each crew comprised of two lookouts, a helmsman, a map officer, and an officer on watch, resulting in three groups of five participants each (N=15). Due to the necessary protection of the individual participants and the observation of the crews as one unit, the individual demographics were not recorded.

2) Materials: The study utilized the Ship handling simulator of the Royal Netherlands Naval College located in Den Helder. The simulator includes a high-fidelity bridge replica of a full-scale frigate. This bridge is placed in a 360 degrees projection of the digital environment made in VirtualShip Maritime Simulator by General Dynamics Information Technology. The crew was recorded with four fixed cameras, multiple microphones, as well as through a recording of the entire simulation run. The debrief was recorded with a camera and microphone.

3) Procedure: The crews were fully informed about the observation and the purpose of this study by the researcher. After informed consent was given, the crews were briefed on their mission by their commanding officer for this specific simulator run. The crews received information about the mission before the run and had to prepare a plan as part of their training program.

The scenario consisted of a combined anti-submarine exercise together with another frigate for support. The mission was to escort a high-value asset in the form of a freight ship through a narrow straight with reports of enemy submarines in the area of operation. The crews had to protect the oiler, avoid and control civil vessels, look out for a submarine, and either deter or destroy the enemy force. Each session was scheduled for an hour, but ran until completion. The first session was completed after 81 minutes, the second after 67 minutes, and the third after 69 minutes.

After the run had been completed, the crews exited the simulator and convened for a debrief of the mission. During this debrief, they evaluated their performance during the run and the success of the mission. The researcher had the opportunity to ask any remaining questions that had not been addressed during the debrief so far. After the debrief, the participants were thanked for their cooperation and received a debrief-letter with information about the processing of their data, information about the study, and contact details of the researchers.

B. *Phase two*

1) Participants: Phase two of the observations was conducted on the bridge of a Karel Doorman-class frigate of the KM. Participants included multiple shifts on the bridge varying in number of personnel at a given time depending on the requirements of the specific mission. In total, 18 personnel participated and were observed on the bridge (N=18). The observed stations and functions were officer on watch, helm, lookout(s), map officer, navigational officer, communications operator, communications operator for the command center, as well as the first officer and the commander of the vessel.

2) Materials: Three action cameras were installed on the bridge windows in order to record the crew without compromising classified information on displays. One midship, one starboard, and one port, so that the entire bridge could be captured.

3) Procedure: The entire crew was informed about the data collection in advance. This already gave crew members the possibility to indicate no consent beforehand. Every crew member was also fully briefed and asked for informed consent when they entered the bridge during an observed exercise.

Multiple exercises were conducted and recorded during the five days of observations. These included torpedo firing exercises, submarine investigations, navigational exercises, point-defense exercises, cavitation measurements, and fleet exercises.

As the crew was rotating continuously on their shift schedule, debriefing of the crew members was not possible on site. A debriefing letter was distributed by the first officer after the observations were completed.

C. *Analysis*

Given these objectives, the FRAM was fitting for this study, as the resulting model would deliver a synthesis of the nominal processes on board that are involved in sailing without cavitation. The functions were formulated by reviewing all recorded footage. The model was then built with the FRAM Model Visualizer by Rees Hill [28].

The predefined frame for the FRAM included only the functions on the bridge. However, multiple highly relevant functions are performed by agents physically located in a different location. Therefore, the model includes two physical locations, i.e. the bridge and the command center.

III. RESULTS

In total, 24 functions are involved in the FRAM model (Table 1). The predetermined frame for the analysis was the bridge and the command center, that is, the executing and the monitoring processes in the model. The analysis regarded all functions within this frame that are involved in the process of achieving the goal-function *move efficiently without cavitation.* 18 functions are defined as the core functions, as these are always present.

TABLE I. FUNCTIONS AND VARIABILITY OF THE FRAM MODEL

CCO[b]	Engage in ASW methods	ASW doctrine, Frequent speed change required,	
CCO	Inform bridge (about detected	Possible contact position	
CCO	Decide to prevent cavitation	CCO instructs sonar to monitor cavitation,	
CCO	Communicate parameters (of	OOW[b] has parameters, Parameters via relay directly on	
CCO	Inform bridge about cavitation (that has been	OOW gives command to reduce speed, Cavitation information via relay	
External[d]	Inform about potential of enemy submarines in the	External threat assessment	Intelligence about the enemy might be inaccurate or incomplete.

Lookout	Look out for surface threats	Combat cancels quiet state	Threats could be missed, nullifying the output
Lookout	Inform about surroundings	Room for maneuver	
Sonar officer	Monitor sub-surface	Possible contact via sonar	A threat may be detected too late
Sonar officer	Listen for cavitation	Cavitation detected through passive sonar, Additional task for sonar	Cavitation might be recognized too late due to other sounds underwater, i.e. sea-state, sea life, traffic, or listening for threats
OOW	Commence sub-surface investigation	Sub surface investigation yields no result	The investigation can take a too long time based on accuracy of maps used.
OOW	Conclude high likelihood of submarine	Internal threat assessment	
OOW	Varying Speed (with irregular changes as required by ASW doctrine)	Variation in speed required for ASW	Chosen vector may not be possible due to traffic, obstacles, CIS
OOW	Varying course (with irregular changes as required by ASW doctrine)	Maneuvering causes CIS to drop, Change in own vector	Chosen vector may not be possible due to traffic, obstacles, CIS
OOW	Keep under CIS	Cavitation prevention ,Limitations on rudder angle, Limitations on RPM	Precision of actual CIS may be off, as CIS is influenced by many variables unknown to the OOW
Specialist[d]	Inform about external communication	Detections by other vessels, Maneuvers by other vessels	
Specialist	Enable direct communication on bridge required by mission	Communications on bridge, ECDIS/map officer on bridge, CC/weapons on bridge	
Specialist	Inform about geodata, own and other vessels	Vectors, Seabed information	
Specialist	Facilitate loop between OOW and CC[e]	OOW has parameter, Warning about cavitation if needed	
System	Increase sub threat level	Reduce detectability	Threat assessment can be incomplete. Information might not reach the vessel.
System	Quiet State	Passive sonar used for monitoring cavitation ,CCO acknowledges URN prevention, Active Quiet State	
System	Prevent blinding the crew at night	red light and negative luminance displays	
TD[f]	Maintain systems	Wear and tear, Running systems	

[a] Command Centre Officer

[b] Officer On Watch

[c] External roles include any broadcast of information towards the vessel

[d] Specialized personnel that is placed on the bridge, if the mission demands it

[e] Command Centre

[f] Technical Department

Depending on the mission profile, additional agents and thus additional functions can be present on the bridge. The entire model is shown in figure 1 color-coded per role.

The officer on watch (OOW) is the commanding agent on the bridge. They determine course, speed, and interaction with the environment within the boundary parameters given

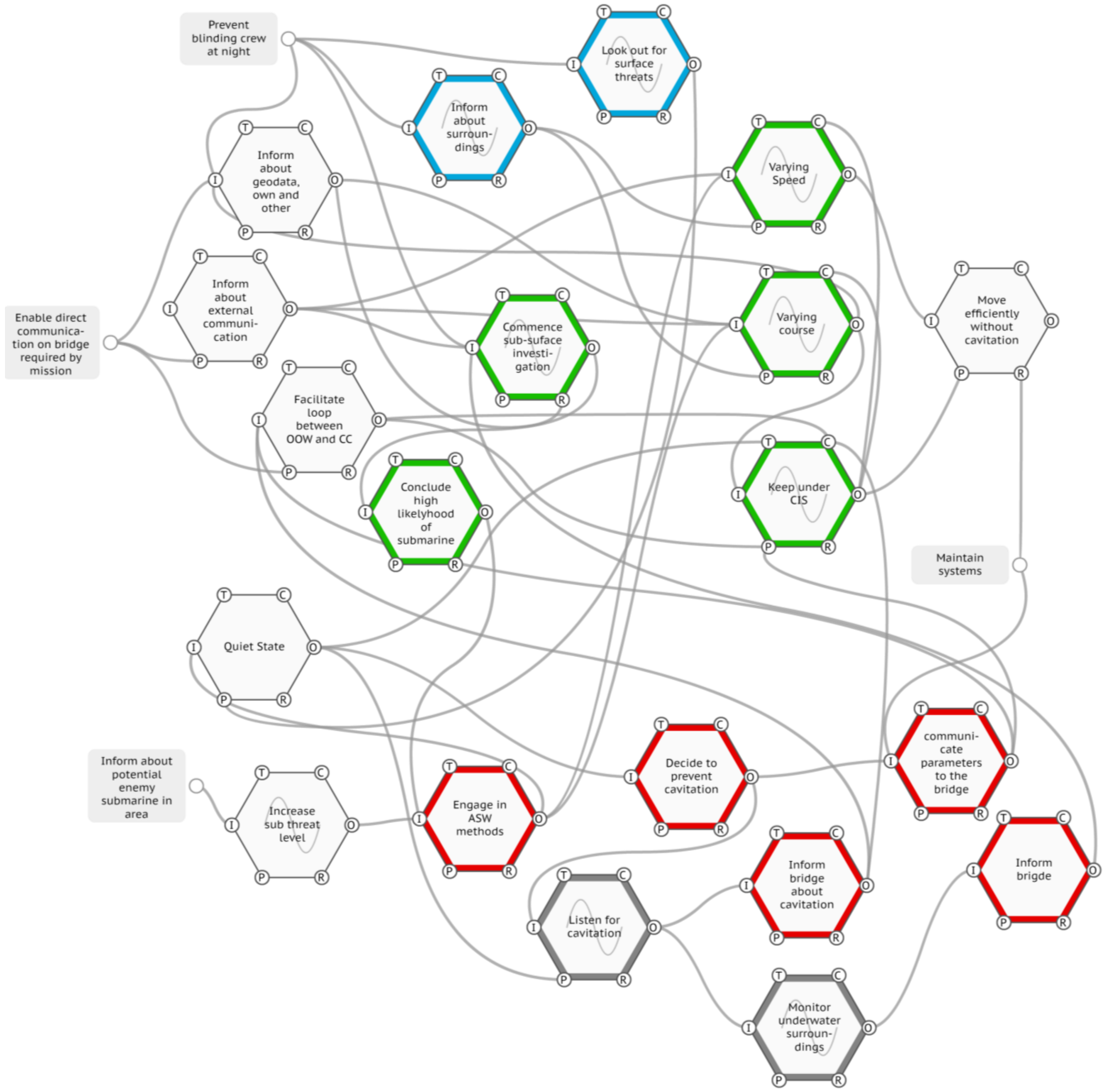

Fig. 1. Visualisation of the FRAM model.Functions are represented as hexagons with each aspect in one corner, i.e. Input, Time, Control, Output, Resources, Precondition. Functions performed by the lookout are shown in blue, by the officer on watch in green, by the command center officer in red, and by the sonar operator in grey. Variability in a function is indicated by a sinus-wave within a hexagon.

by the command center officer. The bridge shows a lot of variability in general, but most is either within the OOW's functions, or influences the OOW directly. In addition, the OOW's functions show a high number of connections with other functions. This interconnectedness and significant variability within the functions performed by the OOW within a high-pressure high-risk environment place most of the functional load on the OOW.

The lookout, often more than one, provides the OOW with information about the direct surroundings of the vessel. The outputs of their functions are limiting factors for the vectors the vessel can take. It is also their task to keep track of the direct surroundings independently, thus aiding the OOW's cognitive load.

The sonar operator performs two functions relevant to the model. As the passive sonar monitors underwater sound, they are involved in the search for underwater threats. In addition, they are also the first station to detect cavitation caused by the vessel. The variability indicated at those two functions are first and foremost a direct result of those two functions interacting. As the operator focusses on subsurface threats, they cannot focus on cavitation – and vice versa.

The command center officer (a specific role within the KM) performs multiple functions, but most of them are within a linear process with little variability. Preventing cavitation is for the most part tied to actively sailing the ship and that is not the role of the crew in the command center (CC). The Command center officer's (CCO) functions are therefore about determining the parameters of sailing without cavitation. The CCO is has no active role in the continuous process of preventing cavitation.

Additional functions are grouped as unassigned. These include functions performed by crew members who are only on the bridge if required. If these agents are not present on the bridge, they share the information with the bridge via a dedicated phone line. In essence, additional personnel will be placed on the bridge to have a direct means of communication towards the OOW instead of via the phone. A radio operator will be present if a lot of communication within a fleet is needed. A dedicated officer will keep track of maps and radar if the vessel has to operate in a complicated space, interact with traffic, or both. This could also necessitate the presence of a navigations officer who will work together with the OOW. A dedicated communicator for the CC can also be placed in the bridge, introducing an additional person in the CCO-OOW link.

IV. DISCUSSION

This study set out to map the processes that are currently in place on the bridge of naval ships to prevent cavitation. The FRAM model shown in this paper presents this process in the frame of the bridge and the adjacent functions in the command center enables us to identify various points of attention in this safety-critical process. As already stated, the CCO occupies a lot of functions, but most of them are linear and/or their outputs are not subject to variability. In essence their role is to set the parameters of steaming without cavitating.

The OOW on the other hand occupies functions with a high number of inputs, factors, and variability. In addition, this model has to be viewed in the context of the bridge. The prevention of cavitation is not the only task of the OOW, yet it causes a significant cognitive load. The additional personnel that will be placed on the bridge if demanded by the mission profile increases the complexity of the process as it on the one hand shortens the lines of communication, but on the other hand increases the number of inputs for the OOW by doing so. Furthermore, as the OOW now has the possibility to hold incoming information on standby, the variability increases as response time to cavitation information from the CC can take longer.

Functions performed by the lookout are in place to aid the situational awareness of the OOW and the bridge as a whole. The lookout actively calls out changes in the environment as well as potential threats to the vessel. This verbal stream information ensures that the OOW receives the information, because acknowledgement or readback is required. In addition, as the call out is happening on the bridge, the situational awareness of all crew members on the bridge is raised. The lookout is also able to raise concerns about a planned vector, as they are aware of the environment of the ship and thus able to check whether the planned course is possible.

The sonar operator is the first agent in the system to detect cavitation. However, while listening for cavitation of the vessel itself, the operator is not able to listen for other threats. Especially during ASW, this mutual exclusivity can present a failure point. In addition, passive sonar is a single failure point for the entire system. If it fails, cavitation detection falls to other, less sensitive sensors.

A significant amount of variability in this model can be identified. Incoming information can vary in both accuracy and timing as it is processed by the operators and systems interpreting the information before it gets forwarded to the OOW. In addition, the frequent variation in the vessel's vector dictated by ASW doctrine induces variability in the system, because previous maneuvers and the planned next vector influence CIS. In fact, the model shows continuous feedback between the vector (i.e. speed and course) and CIS. It is important to note that all processes described above are not happening in a vacuum. Especially the OOW has a large responsibility and varying other tasks that are unrelated to cavitation. The high degree of variability presented in this model can also be affected by other processes on the bridge and the ship at large. Although this study focused on cavitation-prevention, the observations revealed some of these interactions in part. Any incoming information for the OOW, for example external communication or other vessels changing course, does require a certain amount of capacity and will therefore affect the cognitive workload of the OOW.

The second goal of this study was to identify where and how a human machine interface displaying information about cavitation would fit in this process. The function with the most connections and the largest amount of total variability is "Keep under CIS". This function should either be taken over by a human machine interface or at the very least be assisted by one. The proposal is a system that takes all the information that is currently being processed by the OOW and processes it for them. This would also enable the integration of a CIS that is continuously adapting to environmental factors.

The crew could be provided with alle relevant information regarding CIS in one place, for example pitch-angle, RPM, speed, sea state, etc., or with a visualization of CIS with a real time plot with a so-called cavitation bucket. However, the fidelity of such a system cannot be based on the results of this study. Whether the displayed information should be one single value for CIS or show more detail is to be investigated in further research.

There is a clear distinction between the data gathered by observations in the simulator and on board the active ship. The simulator study revealed the communication streams on the bridge and the amount of cognitive load for the OOW. It was possible for the participants to review and reflect on specific actions they took. The observations in the naturalistic environment expanded the model, as multiple different missions were observed. This led to the integration of the additional personnel in the model. It also revealed the variability of the environmental factors, as some missions took place at night or in a higher sea-state. In conclusion, the combined approach of a simulator study and observations in the naturalistic environment can be recommended for this type of research, as indicated by this study.

V. CONCLUSION

Our study delivers an overview of the current processes that are in place on naval vessels of the Royal Netherlands Navy to prevent cavitation during ASW missions. It shows a high amount of variability in the functions occupied by the

OOW, which causes concern with a safety critical objective as cavitation prevention. We argue that the different streams of information that are currently being processed by the OOW could be processed by a HMI to decrease the cognitive load of the OOW. This approach could also introduce adaptive CIS into the overall processes on board without significantly raising the workload while decreasing the variability in the process.

VI. LIMITATIONS AND FUTURE RESEARCH

The model presented in this paper is only directly applicable to the KM, as every navy has variations in their organizational structure. For example, the function of command center officer in the roles considered in this study is unique to the KM. However, the overall process is by definition tentatively comparable to other NATO forces.

Even though the number of participating crews for the very rigid system. In addition, comparable studies using the FRAM utilize the same or even less crews. It is nevertheless important to verify the model during a full ASW exercise, which has already been scheduled as a follow-up study. The model generated in this study will form the basis for the development of a HMI which will aid the crew in preventing cavitation during ASW missions.

VII. ACKNOWLEDGMENTS

The completion of this study would not have been possible without the outstanding collaboration with the following people:

The staff of the Royal Netherlands Naval College, who facilitated the collection of data during examinations of officers in training and shared their facilities with us.

The crew of the Zr. Ms. Van Amstel for welcoming this research project on board without hesitation and for their enormous enthusiasm and support during and after the data collection.

This study is part of WP3 of the Cavitation Inception Speed CONtrol project funded by the NWO file number KICH1.VE02.20.002. The study was approved by the ethical committee of Leiden University under reference numbers 2023-06-13-G.P.H. Band-V2-4788 and 2023-08-21-G.P.H. Band-V1-4948. This paper was originally submitted for the NATO Science and Technology Organization Symposium (ICMCIS) organized by the Information Systems Technology (IST) Panel, IST205-RSY – the ICMCIS, held in Koblenz, Germany, 23-24 April 2024.

REFERENCES

[1] M. Andersson, L. K. G. Persson, I. Lagenfeld, and G. Ljundahl, “Displacement effects of ship noise on fish population,” 2015.

[2] M. Andersson, K. Lucke, M. André, T. Folegot, E. Baudin, and L. K. G. Persson, “Criteria for bioacoustic sensitivity in maritime areas,” 2015.

[3] K. Lucke and M. André, “Masking effect of white noise and simulated shipping sound on lowfrequency auditory perception in harbour porpoises (Phocoena phocoena),” 2015.

[4] M. Solé, M. André, and M. Van der Schaar, “Cephalopod tolerance thresholds of low frequency sounds,” 2015.

[5] T. Lowell, “Fighting the Submarine,” *Popular Mechanics*, pp. 19–27, Jul. 1929.

[6] S. Pasupathy and W. J. Alford, “Range and Bearing Estimation in Passive Sonar,” *IEEE Trans Aerosp Electron Syst*, vol. AES-16, no. 2, pp. 244–249, 1980, doi: 10.1109/TAES.1980.308961.

[7] K. V. Vinutha, K. Vinutha, and T. Yuvaraja, “Under Water Mine Detection Using Sonar,” *J Comput Theor Nanosci*, vol. 15, no. 6–7, pp. 2150–2152, 2018, doi: 10.1166/JCTN.2018.7426.

[8] J. P. Jalkanen *et al.*, “Modelling of ships as a source of underwater noise,” *Ocean Science*, vol. 14, no. 6, pp. 1373–1383, Nov. 2018, doi: 10.5194/OS-14-1373-2018.

[9] J. P. Franc and J. M. Michel, “Definition,” in *Fundamentals of Cavitation*, Springer Science & Business Media, 2006, pp. 1–5. Accessed: Sep. 06, 2023. [Online]. Available: https://books.google.nl/books?hl=de&lr=&id=QJOQYa_oo24C&oi=fnd&pg=PA1&dq=cavitation+definition&ots=2jIzAS_wAaA&sig=wiYbBudr5o8xKyPjmRKvNWFZ6uA#v=onepage&q=cavitation%20definition&f=false

[10] E. Herbert, S. Balibar, and F. Caupin, “Cavitation pressure in water,” *Phys Rev E*, vol. 74, no. 4, 2006, doi: 10.1103/PhysRevE.74.041603.

[11] E. P. Rood, “Review—Mechanisms of Cavitation Inception,” *J Fluids Eng*, vol. 113, no. 2, pp. 163–175, Jun. 1991, doi: 10.1115/1.2909476.

[12] S. D. Sharma, K. Mani, and V. H. Arakeri, “Cavitation noise studies on marine propellers,” *J Sound Vib*, vol. 138, no. 2, pp. 255–283, Apr. 1990, doi: 10.1016/0022-460X(90)90542-8.

[13] A. Vrijdag, D. Stapersma, and T. van Terwisga, “Control of propeller cavitation in operational conditions,” *Journal of Marine Engineering & Technology*, vol. 9, no. 1, pp. 15–26, 2010, doi: 10.1080/20464177.2010.11020228.

[14] S. J. Jeong, S. Y. Hong, J. H. Song, H. W. Kwon, and H. S. Seol, “Numerical method to determine the cavitation inception speed of a submarine propeller based on the noise obtained from bubble dynamics,” *Ocean Engineering*, vol. 245, p. 110464, Feb. 2022, doi: 10.1016/J.OCEANENG.2021.110464.

[15] S. Gaggero *et al.*, “Efficient and multi-objective cavitating propeller optimization: An application to a high-speed craft,” *Applied Ocean Research*, vol. 64, pp. 31–57, Mar. 2017, doi: 10.1016/J.APOR.2017.01.018.

[16] G. Kuiper, “Chapter 4 Physics of cavitation:CAVITATION INCEPTION,” in *Cavitation in Ship Propulsion*, 2012, pp. 17–27.

[17] Y. H. Lee, C. Y. Yang, and Y. C. Chow, “Evaluations of the outcome variability of RANS simulations for marine propellers due to tunable parameters of cavitation models,” *Ocean Engineering*, vol. 226, p. 108805, Apr. 2021, doi: 10.1016/J.OCEANENG.2021.108805.

[18] B. Taskar, S. Steen, and J. Eriksson, “Effect of waves on cavitation and pressure pulses of a tanker with twin podded propulsion,” *Applied Ocean Research*,

vol. 65, pp. 206–218, Apr. 2017, doi: 10.1016/J.APOR.2017.04.005.

[19] D. Savitsky, "Hydrodynamic Design of Planing Hulls," *Marine Technology and SNAME News*, vol. 1, no. 04, pp. 71–95, Oct. 1964, doi: 10.5957/MT1.1964.1.4.71.

[20] A. Stück, J. Kröger, and T. Rung, "Adjoint-based Hull Design for Wake Optimisation," *Ship Technology Research*, vol. 58, no. 1, pp. 34–44, 2011, doi: 10.1179/STR.2011.58.1.003.

[21] M. V Trevorrow, B. Vasiliev, and S. Vagle, "Directionality and maneuvering effects on a surface ship underwater acoustic signature," *Article in The Journal of the Acoustical Society of America*, 2008, doi: 10.1121/1.2939128.

[22] A. Pustoshny and S. Kaprantsev, "AZIPOD Propeller Blade Cavitation Observations During Ship Maneuvering," Jan. 2001, Accessed: Sep. 19, 2023. [Online]. Available: https://resolver.caltech.edu/CAV2001:sessionB9.002

[23] M. Yusvika, A. R. Prabowo, D. D. D. P. Tjahjana, and J. M. Sohn, "Cavitation Prediction of Ship Propeller Based on Temperature and Fluid Properties of Water," *Journal of Marine Science and Engineering 2020, Vol. 8, Page 465*, vol. 8, no. 6, p. 465, Jun. 2020, doi: 10.3390/JMSE8060465.

[24] D. Bertetta, S. Brizzolara, S. Gaggero, M. Viviani, and L. Savio, "CPP propeller cavitation and noise optimization at different pitches with panel code and validation by cavitation tunnel measurements," *Ocean Engineering*, vol. 53, pp. 177–195, Oct. 2012, doi: 10.1016/J.OCEANENG.2012.06.026.

[25] J. H. Spence and R. W. Fischer, "Requirements for Reducing Underwater Noise from Ships," *IEEE Journal of Oceanic Engineering*, vol. 42, no. 2, pp. 388–398, Apr. 2017, doi: 10.1109/JOE.2016.2578198.

[26] R. Scott and T. Lamb, "Human Factors in Ship Design: Preventing and Reducing Shipboard Operator Fatigue," 2006. Accessed: Sep. 23, 2023. [Online]. Available: http://www.manningaffordability.com/s&tweb/PUBS/Fatigue/fatiguepaper.html

[27] E. Hollnagel, "FRAM: the Functional Resonance Analysis Method," p. 9, 2012.

[28] R. Hill, "GitHub - functionalresonance/FMV_Community_Edition: FMV - FRAM Model Visualiser." Accessed: Feb. 07, 2024. [Online]. Available: https://github.com/functionalresonance/FMV_Community_Edition