Evading Low Pressure In High Pressure Engagements

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Synopsis

Ship Signature Management Systems (SSMS) aims to support the crew on board of naval vessels with real time information on the susceptibility of the ship in relation to various threats. The underwater acoustic signature is relevant for various underwater threats and a dominant contributor to this signature is propeller cavitation.

Within SSMS a Cavitation Management System (CaMaS) is being developed. CaMaS consists of two main parts: cavitation monitoring and an advice function. Based on the output of on board installed accelerometers combined with algorithms cavitation can be determined. The online-assessed cavitation status shall be stored in a dynamic database as function of the sea and platform conditions. Artificial Intelligence (AI) and self-learning technology will be applied to deliver the operator advice to avoid cavitation.

A demonstrator on board a navy vessel is installed to incrementally develop an SSMS and its CaMaS-functionality. For the CaMaS demonstrator accelerometers have been placed on the hull plates above the propeller where multiple algorithms were tested to detect cavitation giving relevant results. The operator has a major role in the development of the functionalities and its Human Machine Interface.

CaMaS is dual use technology; it can be exploited for naval applications as well by commercial shipping to satisfy the developing international regulation of undersea noise. This paper describes the development of CaMaS and presents the unclassified results regarding full-scale experiments on board of various vessels.

Keywords: AI; HMI, Cavitation Inception, Susceptibility, Signature Management, Undersea Noise Pollution.

1. Introduction

While performing their mission, naval vessels operate in a three dimensional threat environment. Our surface vessels and submarines are threatened from space, air, and surface as well as from below the sea surface. Different threats will exploit a range of our platform's signatures. Knowledge and ability to adapt the vessel's signatures are crucial to survive an encounter. Over decades, the engineer's goal was to reduce signatures. New threat challenges make it necessary to adapt the signatures to the threat and environment by means of real time Ship Signature Management System (SSMS) functionalities. Next to the impact of signature reduction and management on survivability, there is also a crucial impact on the mission effectiveness of a platform.

The functionalities of an SSMS are to generate operational awareness for the ship's operators with respect to their signatures and provide information on the counter detectability by adverse sensors. An SSMS has the objective to generate situational understanding with an increasing focus on Maritime Information Warfare.

SSMS monitors the platform's own signatures in order to detect and report signature anomalies, recommend options for signature reduction, allow mission planning from a susceptibility point of view and supports soft kill operations by providing advice for optimal launch timing and separation manoeuvres. By supporting the ship's operators in changing the signature dynamically (i.e. war and peacetime modes), it will avoid or retard detection, classification, identification, tracking and engagement of the platform by an adversary, and thus provides a tactical and operational advantage in a combat scenario.

To fulfil the functionalities, an SSMS consists of different partial systems. Each partial system consists of a model of the ship, the propagation of the signature through the environment and the processing by the adversary's sensors. These modelling pipelines use real time platform-information, METEO information and e.g. vibration, magnetic, electric and thermal data RT recorded by on board sensors.

Within the partial acoustic system, CaMaS is being developed on board of a demonstrator to decrease the acoustic signature and increase survivability in high pressure engagements of the Naval vessel.

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2. Survivability & Signatures

The last decades, the threat has evolved significantly, challenging our warships and submarines. Figure 1 depicts an overview of space-, air-, surface-, subsurface- and seabed based threats. These threats exploit different and combinations of signatures. An overview of the most relevant signatures for our above water platforms and submarines are given in Figure 2.

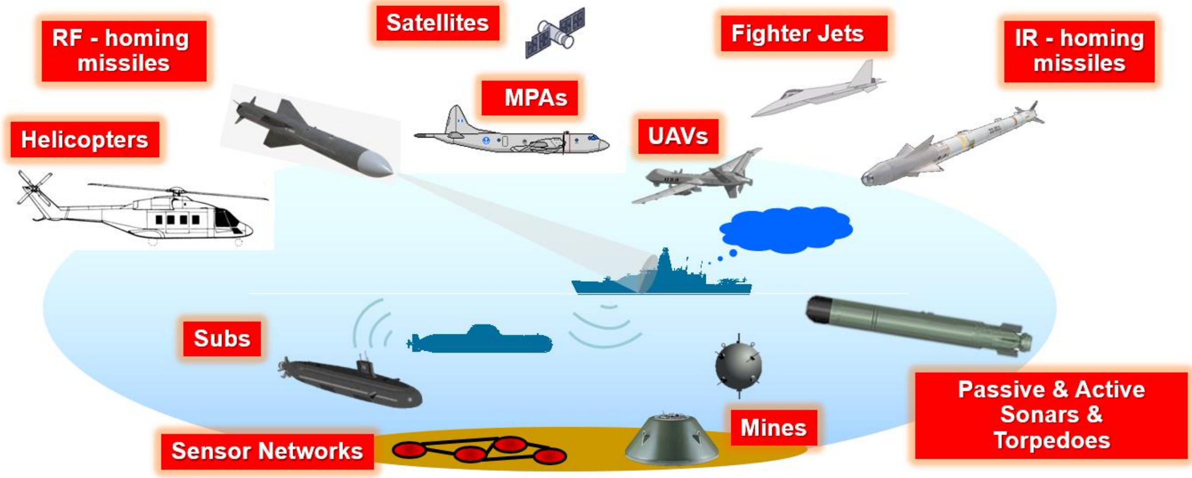

Figure 1: Overview of “Red on Blue” threat systems

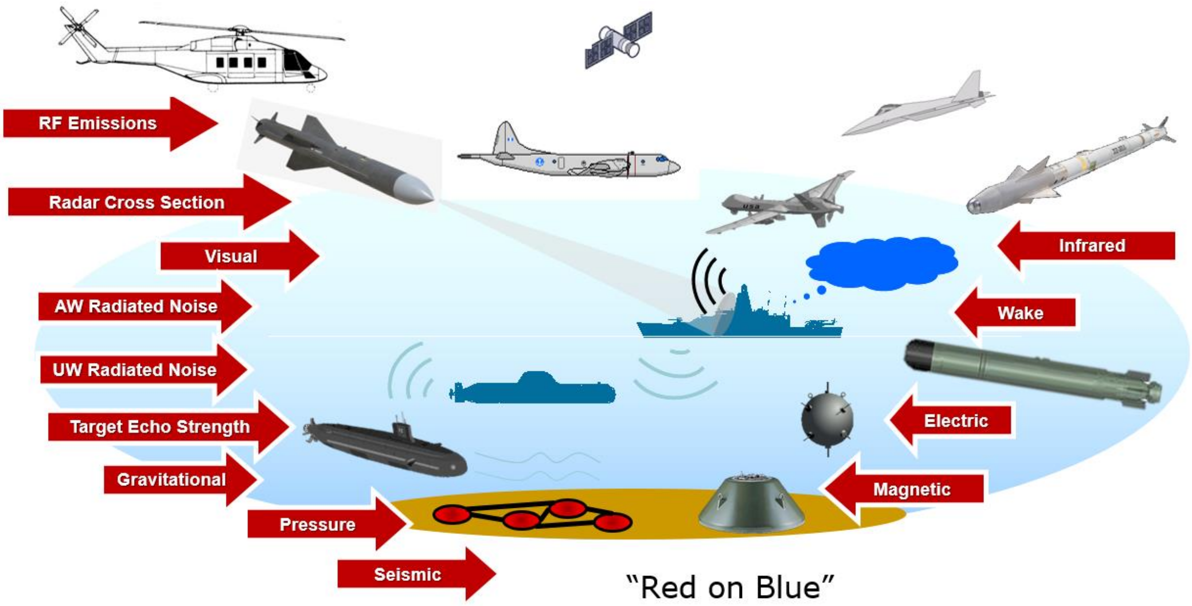

Figure 2: Relevant Signatures for above water platforms and submarines.

Threats have become more and more sophisticated in terms of e.g. velocity, agility, sensor technology and Digital Signal Processing, with AI as an upcoming technology.

In case of propeller cavitation generated noise, which is a significant contributor of Underwater Radiated Noise (URN), the relevant related threats are for a surface vessel are e.g.: submarine and torpedo sonar systems, mine threat and underwater sensor networks.

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In (Galle, 1997 & 2002) and (Galle et al. Witberg, 2002) it was advocated to counter these threats with an integral survivability approach. Two main Survivability factors i.e. Susceptibility and Vulnerability were introduced, see

Figure 3.

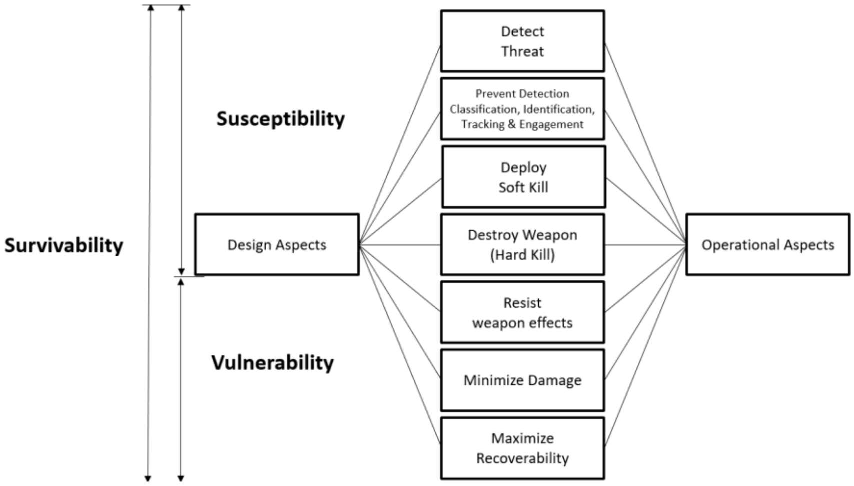

Figure 3: Survivability a combination of Susceptibility and Vulnerability

Where susceptibility is the inability to avoid weapon effects and vulnerability the inability of the warship to withstand weapon effects.

In former decades reducing the susceptibility was mostly focused on the reduction of signatures and the deployment of hard kill and soft kill systems. Reduction of the level of a signature will lower the detection and lock-on range, next to this it will support the deployment of soft kill systems i.e. in the distraction and seduction role.
Improvements on threat side urge the capability to manipulate the signatures. Advances of technologies in the signature domains in combination with growth in computing power enable to determine and manipulate own platform's signature in real-time.

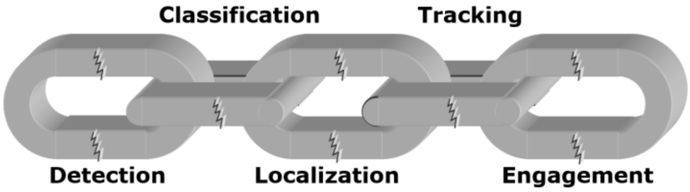

Figure 4: The adversary's Kill-Chain

Real-time signature reduction and signature management are key factors for survivability in order to be able to disrupt or retard the observe-orient-decide-act, the well-known OODA-loop, of the opponent. This is performed by destruction of the kill chain of the adversary, see Figure 4.

3. Ship Signature Management System (SSMS)

To assist the operators on disrupting the adversaries kill chain an SSMS will be deployed on future naval platforms. The Royal Netherlands Navy's future platforms will be equipped with an Integrated Mission Management System (IMMS). The IMMS is a distributed computing server architecture for hosting various mission supporting applications such as the SSMS, see also Figure 5. This approach allows for deeper integration by sharing the HMI and data, avoiding traditional "stovepipe" architectures and creating an constant look and feel.

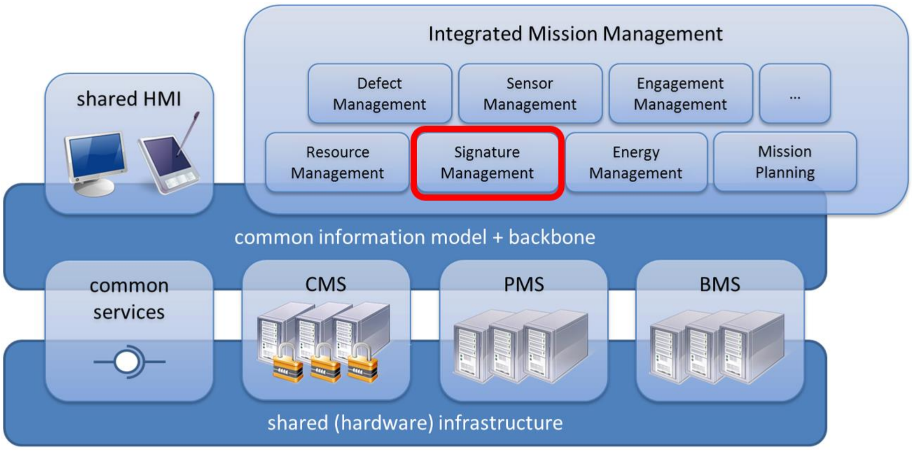

Figure 5: Signature Management as an application within the Integrated Mission Management System

To be able to fulfil the various functionalities of a Ship Signature Management System the modelling "chain" of a Signature-, Propagation- and Susceptibility-model has a central role as can be seen in Figure 6. The architecture is modular and flexible to allow for extension of the system to other signatures or future upgrades of individual modules (Fehr, M. et al., 2014) and (Janssen J. Dr. et al., 2018).

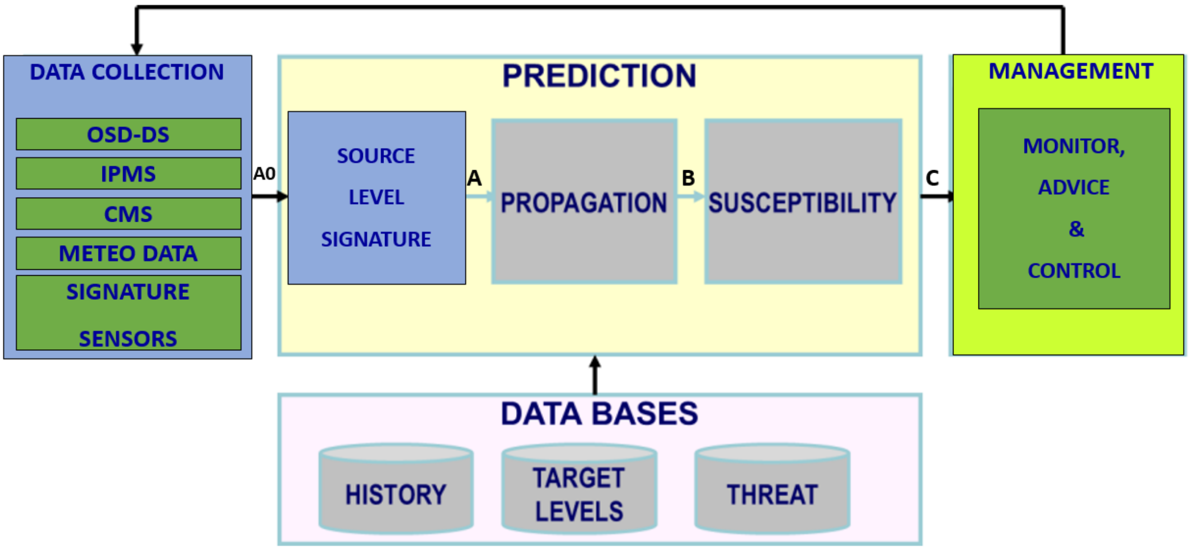

Figure 6: Principle SSMS Architecture

An accurate understanding of the physics of the various signatures, the propagation through the environment and interpretation by an adversary's sensor are required. The models require data to be able to give a relevant real time estimation of the susceptibility and perform its monitoring, advice and control functionality. This information is mostly already available on-board of modern naval platforms i.e. data from its Own Ship Data Distribution System (OSD-DS), Integrated Platform Management System (IPMS), Combat Management System (CMS) and a METEO data provider. Special attention is required for the additional so-called "signature sensors", these sensors

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are specifically placed to gather more information on the current platform’s signature state. These sensors consist of temperature sensors to monitor temperatures of the superstructure and exhaust plume for the infrared signature, magnetometers for the magnetic signature and accelerometers to determine the acoustic signature of the platform.

3.1. ***Demonstrator project: “Project S”***

The Royal Netherlands Navy decided to develop the modules of the SSMS. To be able to develop the system a demonstrator platform is required for gathering validation data, model development and operational feedback. Therefore, the air-defence and command Frigate HNMLS Tromp was selected as platform for the installation and integration of the required hardware and software. A server has been installed with interfaces to the platform systems for platform data and is connected with a laptop in the command centre for user interaction and displaying the resulting output. The ship has been equipped with accelerometers mounted on the girders and hull throughout the ship for monitoring the acoustic signature. The system will be extended by installation of magnetometer and temperature sensors during the planned three year duration of the project.

Figure 7: HNMLS Tromp (1) hosting Project S, the Ship Signature Management Demonstrator Project. Distributed data acquisition modules (3) and accelerometers (4) have been installed and interfaced to a server (2) running the demo-SSMS software.

4. Cavitation

Cavitation is known to be the dominant contribution of the overall URN when the ship speed is above the cavitation inception speed. Cavitation occurs when the pressure on the propeller drops below the local vapour pressure. The first occurrence of cavitation is called: cavitation inception and the corresponding ship velocity the: cavitation inception speed (CIS). A necessary condition for cavitation is the presence of nuclei in the water that break up the bond between the water molecules.

Cavitation may occur at different positions on the propeller blades, struts and rudder. This leads to different types of cavitation (sheet/vortex/bubble), see Figure 8. Propeller sheet or tip-vortex cavitation are the two types of cavitation that occur at the lowest speed and therefore determine the cavitation inception speed. Other types of cavitation may occur in off-design conditions.

All types of cavitation generate noise. When the external pressure around a cavitation bubble starts to increase, the bubble will enter its collapse stage. The collapse of cavitation leads to a rapid reduction of cavitation volume and it is therefore a very efficient noise source.

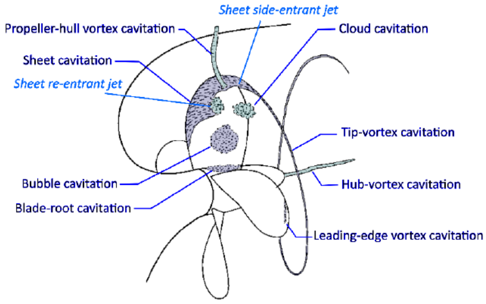

Figure 8 Types of cavitation [1]

4.1. Operation relevance regarding cavitation for naval vessel

As cavitation is the dominant contribution the acoustic signature of the vessel, avoiding cavitation is of outmost importance in high pressure engagements. Evading low pressure on the propeller blades is important for frigates during anti-submarine warfare (radiated noise regarding detection but also for the own sensor performance of towed sonar) and for submarines to be able to perform their missions surreptitiously.

4.1.1. Detection range

In case propeller cavitation, the URN increases significantly starting at high frequencies. When cavitation develops further, it will dominate the whole frequency range, see Figure 9.

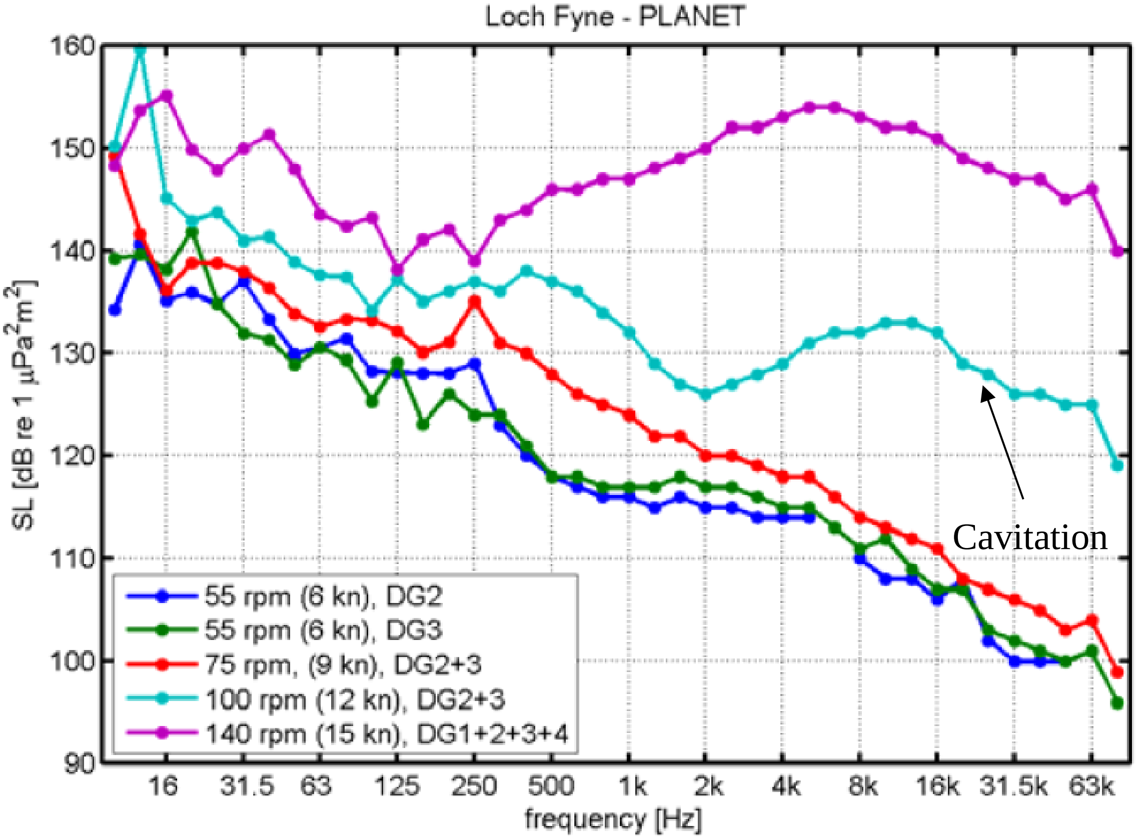

Figure 9 : Acoustic measurement of RV Planet (de Jong, 2016)

Cavitation noise as part of URN, can be detected by passive sonars. The detection range can be determined be means of the passive sonar equation (Urick, 1983):

$$SL - PL = NL + DT \quad [1]$$

where SL is the Source Level of the ship, PL is Propagation Loss by the environment, NL Noise Level and DT is the Detection Threshold of the sonar. Assuming spherical spreading of the source, see Figure 10, the detection range can be determined by:

$$PL = 10\, Log_{10}\, r^2 = SL - NL - DT = \Delta SL \rightarrow r = 10^{\frac{\Delta SL}{20}} \quad [2]$$

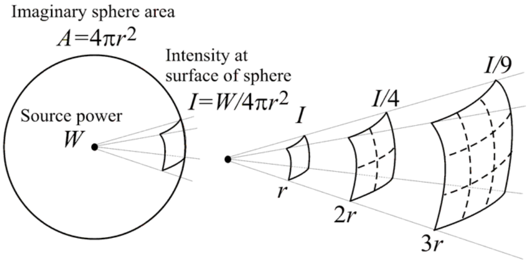

Figure 10: Spherical spreading of a point source (Urick, 1983)

When the acoustic signature is increased by 10 dB due to cavitation, the counter detection range or mine safe depth decreases approximately with a factor three.

4.1.2. *ASW relevance*

In the domain of operational analysis, the counter detection range is seen as Measure of Performance (MoP) or level-1 indicator. This MoP can be used to bring the analysis on a higher level to convert it to operational information i.e. a level-2 indicator or Measure of Effectiveness (MoE).

An example was presented by (Audoly, 2022) on the effect of propeller CIS on Anti-Submarine Warfare (ASW) operations. The influence of CIS on ASW effectiveness was determined. The probability of the ASW-Frigate, while self being undetected, to detect a submarine in an area using its active sonar was chosen as MoE. A representative ASW scenario with a generic ASW-Frigate searching a generic submarine with sprint and station/drift tactics was taken, as depicted in Figure 11. During the station phase the ASW-Frigate was deploying its active sonar and during the sprint phase the submarine used its passive sonar.

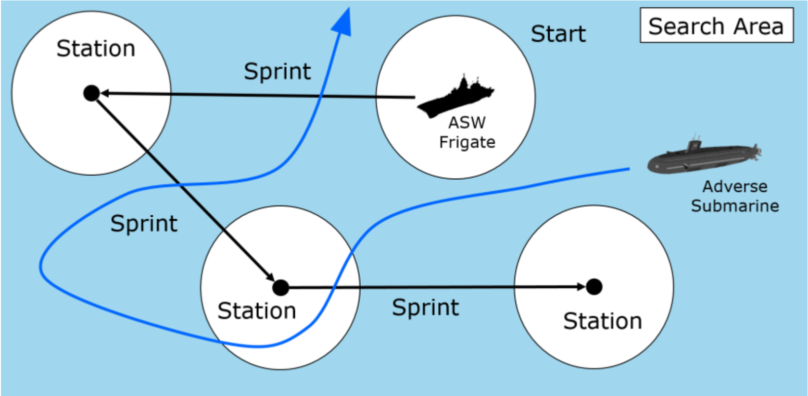

Figure 11: A generic ASW scenario with an ASW-Frigate searching a submarine with sprint and station tactics (Audoly, 2022)

The MoE-results of this analytical assessment are given in
Table 1, which shows that increasing the CIS can have a significant impact on ASW operations.

Table 1: Impact of CIS on ASW Effectiveness (Audoly, 2022)

CIS	Relative MoE
Nominal	100%
Nominal + 2kt	117%
Nominal + 4kt	123%

4.2. Commercial influence

Avoiding cavitation is not only important for naval vessels but also be relevant for commercial vessels. Underwater noise from vessels can have a negative impact on the marine environment and vulnerable marine mammals. Furthermore, cavitation may impose reduced comfort on board of ships due to the resulting inboard noise and vibrations.

5. Cavitation Management System (CaMaS)

Propeller cavitation inception speed depends on a lot of variables such as:

- Propeller pitch;
- Shaft rpm;
- Ship speed through water;
- Nuclei (water quality);
- Sea State (SS);
- Mannering (rudder motions leading to drift and yaw rate)
- Heading;
- Current and wind;
- Propeller fouling and maintenance.

The CIS varies strongly based on the operational condition of the vessel and it is difficult to predict in high pressure situations. Therefore, within the partial acoustic SSMS a Cavitation Management System (CaMaS) is being developed to predict the CIS such that maximum sailing speed can be sailed avoiding excessive increase in URN. Data from various sources is gathered to feed a cavitation detection algorithms. The cavitation status should be online displaced to the operators on-board of the naval vessel. The real time cavitation status shall be stored in a dynamic database as function of the sea and platform conditions. AI and self-learning technology in combination with the dynamic database, is planned to be applied to deliver the operator advice to avoid cavitation. Various advises can be given to avoid cavitation such as decreasing propeller rpm, limit the rudder angle, change pitch of the propeller or change course (if possible) with respect to the incoming waves. Creating a map of cavitation status vs. conditions can help to predict the suspected cavitation status beforehand.

Another foreseen functionality of CaMaS will be an autopilot. Based on the dynamic cavitation database in combination with AI and self-learning technics, the operator should be able to change course by just adjusting the desired heading of the vessel and the CaMaS autopilot will perform the request without cavitation by regulating the rpm, pitch angle and or rudder angle accordingly.

The last foreseen functionality of CaMaS is a peace time mode. By intentionally causing low pressure in low pressure engagements (propeller cavitation), it is possible to hide/mask the real signature and acoustic identifiers of the vessel. This might be applied when the naval vessel is entering a foreign harbour.

A schematic schema of the input, process and functionalities of CaMaS, is shown in the Figure 12.

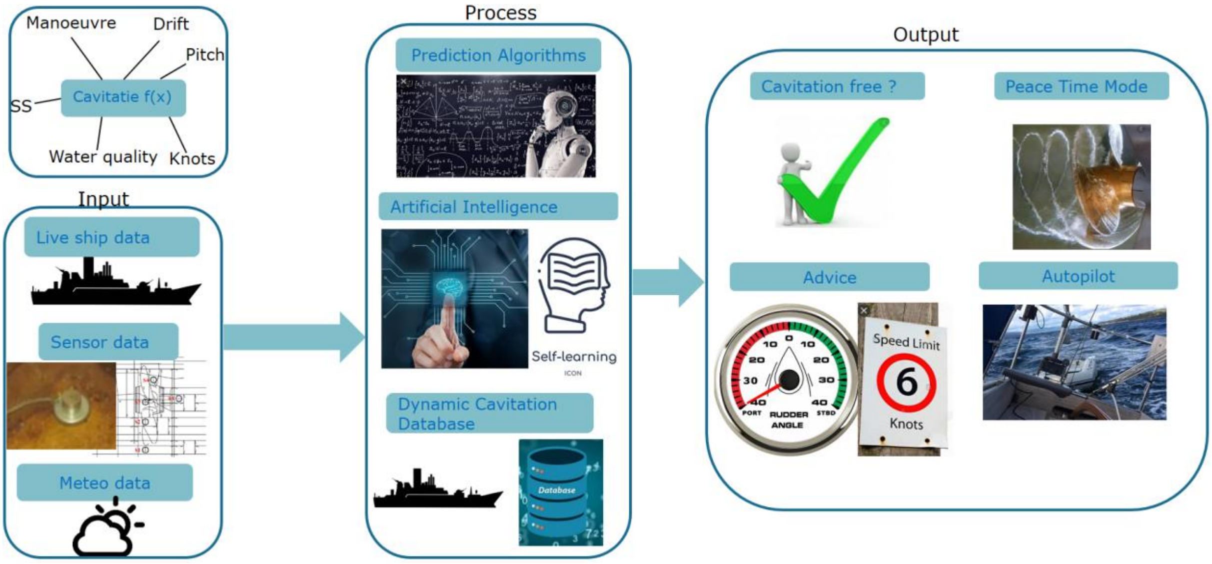

Figure 12: Process flow of CaMaS in its foreseen end state.

The above described process and functionalities of CaMaS will be incrementally implemented. It is not possible to develop and implement this at once on board of a naval vessel. Within the duration of Project S, it is the author's proposal to develop a CaMaS v1.0 as a solid foundation. The functionalities of the CaMaS v1.0 are chosen such that it is realistic to develop and implement on board of the demonstrator within those three years.

CaMaS v1.0 will have live ship data and data from accelerometers positioned above the propellers as input. The process still consist of a cavitation prediction algorithms but the dynamic database is replaced by a static database. The static database describes trend lines of accelerations for limited environmental conditions and two propeller pitch angles are considered. The static database will generated using data of full-scale trials, model tests and CFD calculations. Using this database, an advice can be given to the ship operator regarding ship speed and rudder angle. Furthermore, the database will be used as reference for the cavitation status of the propeller to check for anomalies or environmental conditions not in agreement with those considered in the database. A process flow of the input, process and functionalities of the CaMaS v1.0 is shown in the Figure 13.

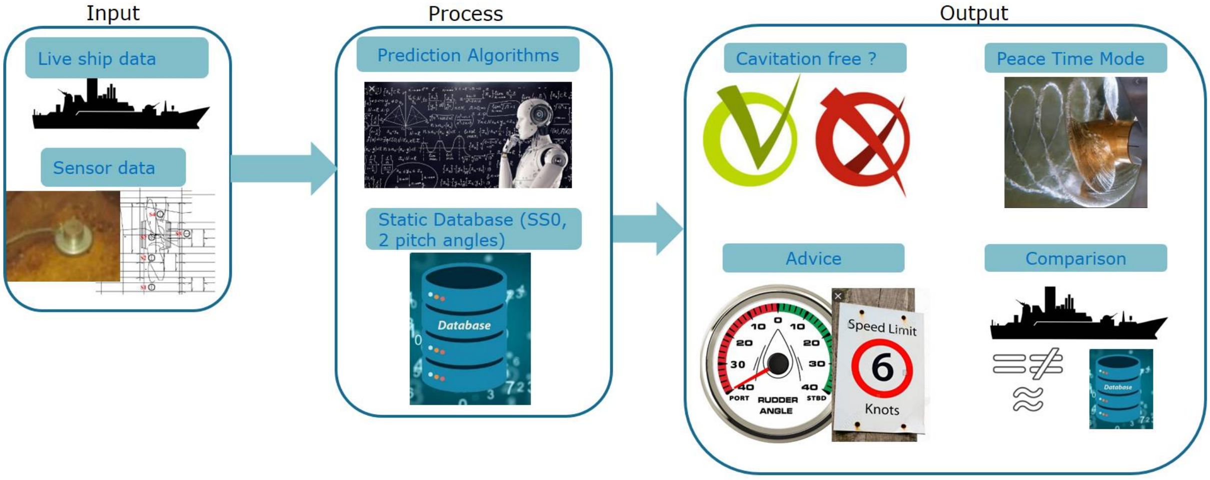

Figure 13: Process flow of CaMaS v1.0.

6. Cavitation determination

Within Project S, accelerometers were placed above the propeller to collect full-scale data to be able to develop and test multiple algorithms to detect cavitation. Development of cavitation detection algorithms making use of on board accelerometer data has been the subject of various studies (Gilroy 2022). This section describes analysis performed on: Nautilus and Zr.Ms. Tromp. As acoustic data from operational warships are classified the data cannot be shared.

6.1. *Threshold analysis*

At the end of 2021, the diving support vessel Nautilus of the Royal Netherlands Navy was instrumented with accelerometers above the propeller. In cooperation with MARIN, a study was performed related to detection algorithms by using the unclassified gathered data of a full scale measurement of the diving vessel the Nautilus.

6.1.1. Nautilus

The Nautilus is one of the four diving support vessels of the Royal Dutch Navy. The Nautilus came into operation in 1992 and its hull has been extended by 10 meters in 2008. The Nautilus is mainly used as platform for diving activities. The main particulars are given in table 2.

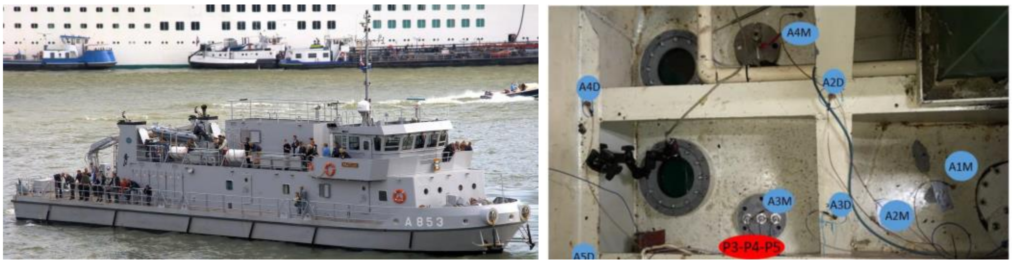

Figure 14: The Nautilus and accelerometers placed on the Nautilus

Table 2: Main particulars of the Nautilus

Parameter	**Nautilus**	**Unit**
Length overall	38	m
Breadth moulded	8.5	m
Draught	1.5	m
Transverse wind area	30	m^2
No. propellers/blades	2/4	-
Propeller diameter	1	m
Installed power	2x279	kW

To determine a possible threshold value from the on-board accelerometers, multiple velocity sweeps were executed in a three day period. During the velocity sweeps, the accelerometers, rpm and torque were monitored and logged. From this data, a spectrum analysis was made with trials of day two and three, see Figure 15. The spectrum analysis, has a similar shape as the URN measurement of the Plant, Figure 9. However it is hard to determine the CIS as the acceleration level (La) of 4.5 knots at day three are higher than the La of 5.0 knots at day two. This is probably caused by the different weather conditions, see Table 3. As the draught of the Nautilus is only 1.5 meter and the transverse area is quite large, the Nautilus is very sensitive to wind and waves which results into rudder motions.

When the spectrum analysis of the velocity sweep of day three is considered, it can been seen that the acceleration level increases with the vessel velocity. The La difference between velocity 4.5 and 5.4 is a couple of dB from 200 HZ. The La difference between velocity 5.4 and 6.3 is much higher. It is clear from this spectrum analyse that the propeller is cavitating at a velocity of 6.3 knots. It is unclear if the increment of acceleration levels at 5.4 knots is due to cavitation or other noise sources.

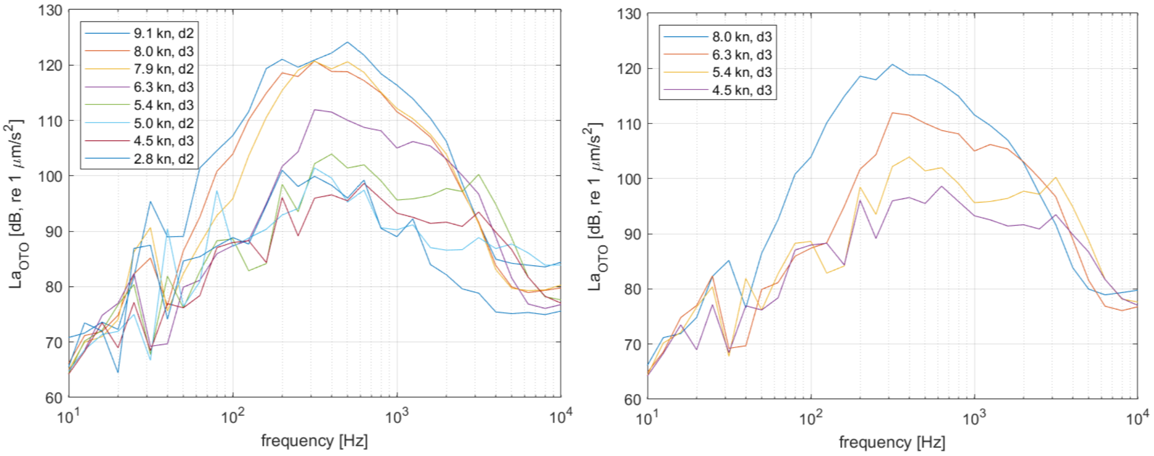

Figure 15: Spectral analysis of day 2/3 and only 3

Table 3: Weather condition during full scale trials.

Day 1	**Wind**	**Wave**
1	5-6 bft W	0.6 m
2	3-4 bft W	0.4 m
3	4 bft SW	0.3 m

In Figure 16, the acceleration levels (La) for one third octave band with centre frequency 1 kHz are plotted versus the Vs for all three days. A clear jump in La is seen between 97 dB and 104 db. This suggests that the propeller is cavitating. The variation in La below the 97 dB is most likely caused by background noise (i.e. rudder movement and machinery noise). Considering only the runs of day three in westwards direction, it seems that cavitation occurs at 6.4 knots and not at 5.4 knots. A possible threshold value would then be 98 dB.

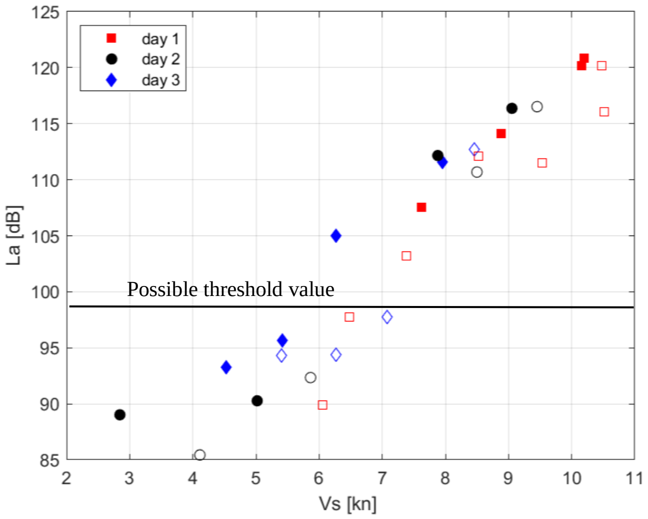

Figure 16: Acceleration level per 1/3 octave band with centre frequency of 1 kHz. Open symbols are trials in the eastwards direction and closed symbols are in westwards direction.

6.2. DEMON

An alternative explored cavitation detection algorithm is: DEMON (Detection of Envelope Modulation On Noise) (Chung 2011). With DEMON you can show at which frequency the amplitude of the signal is modulated. When cavitation occurs, the sound/vibrations due to cavitation is modulated by blade passing frequency, as the cavity collapse typically on at one specific location in the propeller disc. Differences between blades will show additional peaks at the shaft rate frequency and harmonics thereof.

With the available data of the Nautilus, a first effort with the DEMON analysis was done. At 5.4 knots, DEMON shows for the first time large spikes at the expected blade passing frequencies. These spikes insinuate modulated noise and thus cavitation, see Figure 17. The DEMON results shows that cavitation occurs sooner as was concluded with the spectral analysis of the accelerometers.

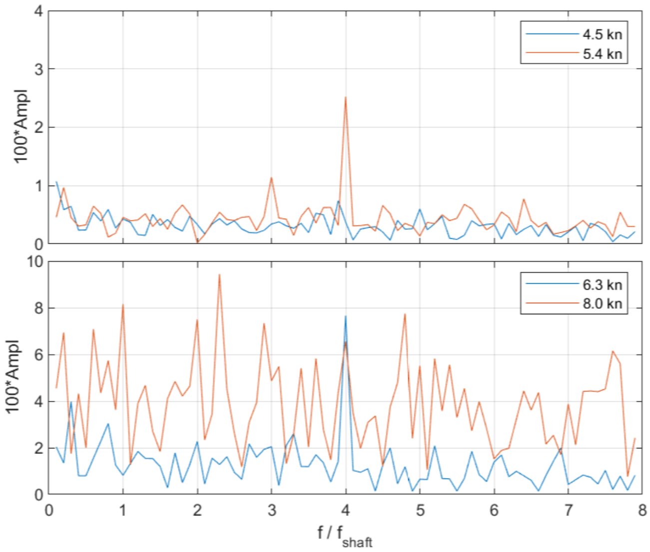

Figure 17: DEMON analysis of Nautilus data

Based on the first preliminary analyses, both the threshold analyse and demon algorithm can detect cavitation but give different results regarding CIS. More experience and testing trials are required to be able to validate the algorithms and compare robustness and accuracy.

6.3. Project S

6.3.1. Algorithm

As it was expected that the Zr.Ms. Tromp will show less scatter in La in non-cavitating conditions, it was decided to develop a first threshold algorithm for CaMaS based on on-board accelerometers in a frequency range that is the most relevant for cavitation. This frequency range is ship dependent.

A first threshold algorithm is developed as the energetic average of the power spectrum La(k) in 1/3 octave band for a certain frequency range:

$$L = 10 * log_{10}\left(\frac{1}{\Delta x}\sum_{k=x}^{x+\Delta} 10^{L_a(k)/10}\right) \text{ in dB} \qquad [3]$$

When L is plotted in time, small spikes of +/- 3 dB are visible and sometimes larges pikes of +/- 10 dB in non-cavitation conditions. This can be considered as background noise from other noise sources like machinery or result of rudder induced vibrations. Therefore it was decided to add the exponential time average L_{avg} of the last 15 seconds. An example is shown in the Figure 18, where at 110 seconds, the propeller rpm was increased significantly to cause propeller cavitation, which is clearly identifiable in de L_{avg} parameter.

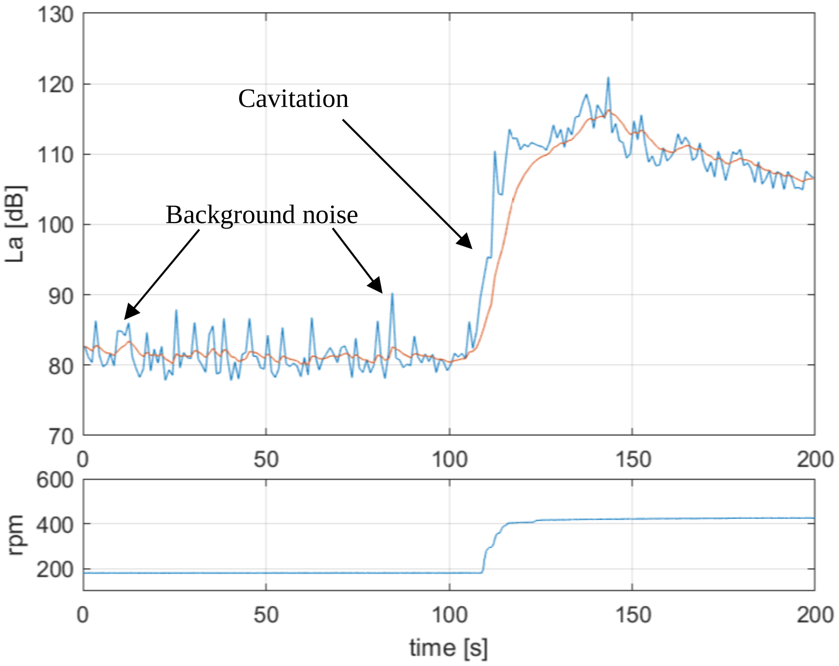

Figure 18: Test data of the Nautilus which shows the L in blue L_{avg} in red.

6.3.2. *Cavitation monitoring graph*

After the development of a threshold algorithm, a first cavitation monitoring graph was implemented on the demonstrator. On a local webpage on the Project S server, L and L_{avg} are plotted in time for the past 15 min and updated every second (Similar graph compared to Figure 18). Based on the analysis of the Nautilus it was decided to add two threshold lines on the monitoring graph, + 4 dB and + 8dB (preliminary values) above a reference vibration value L_{avg} in non cavitating conditions. When L_{avg} crosses the first threshold, there is possible cavitation and when the +8dB line is crossed, there is certainly propeller cavitation. The reference vibration level was determined through a velocity sweep.

Multiple velocity sweep trials were performed to determine the reference vibration level (baseline vibration level in non cavitating condition). In non-cavitation condition, L_{avg} should be constant, as the machinery noise is the dominant factor for the vibrations. Once the propeller starts to cavitate, the L_{avg} value increases significantly. The determined cavitation inception speed was compared to the cavitation inception speed determined by the acoustic trials at Heggernes Noise Range a few years earlier. The two methods showed good correspondence. During the velocity sweep the helmsman determined cavitation inception at the same rpm as was determine by the algorithm.

These results are preliminary as it is a first order algorithm and the velocity sweeps were performed in a very calm water (SS0-SS1) so there was limited distortion. The robustness of the algorithm has not been tested yet.

Since the results of the demonstrator are classified, the results and the graph of the velocity sweeps are not shown.

6.3.3. *Cavitation detection gauge*

The cavitation monitoring graph was discussed with the operators during the sea trials. The concept of CaMaS v1.0 was well received. The monitoring graph with the adjustable reference levels, was also embraced. However, this graph gives a lot of information and it is hard determine the cavitation status in a split second. Therefore, the operators prefer a gauge with traffic light colours that shows the cavitation status. Green depicts that the propeller is cavitation free, orange that there is incipient cavitation and red means developed cavitation. The purple line in the gauge is the actual L_{avg} value. The implemented gauge is shown in the Figure 19.

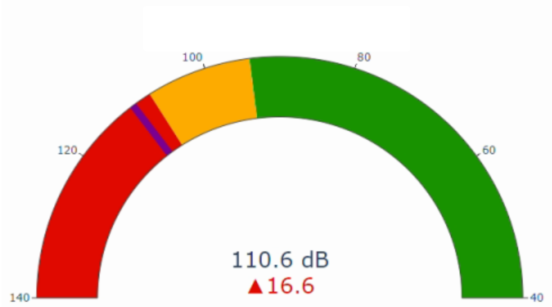

Figure 19: Cavitation detection gauge implemented on board of the demonstrator (arbitrary values)

In June 2022 the gauge has been added to the CaMaS software next to the cavitation monitoring graph. In the near future, the gauge will be integrated into the Combat Management System for operational use. The monitoring graph, will stay on the Project S server such that the crew can get more detailed information when needed or the adjust the reference levels.

7. Roadmap

In three years' time, a first version of CaMaS will be installed on the demonstrator. The planning is to implemented roughly every six months an update, such that CaMaS v1.0 can be realised in a total of 6 steps:

1: Develop an threshold algorithm and implemented a monitoring graph;
2: Develop and implement a cavitation detection gauge;
3: Update cavitation detection algorithm that is robust and reliable;
4: Implement first version of static database and advice function;
5: Update the current functionalities based on feedback of the operator;
6: Add the comparison functionality and peace time mode.

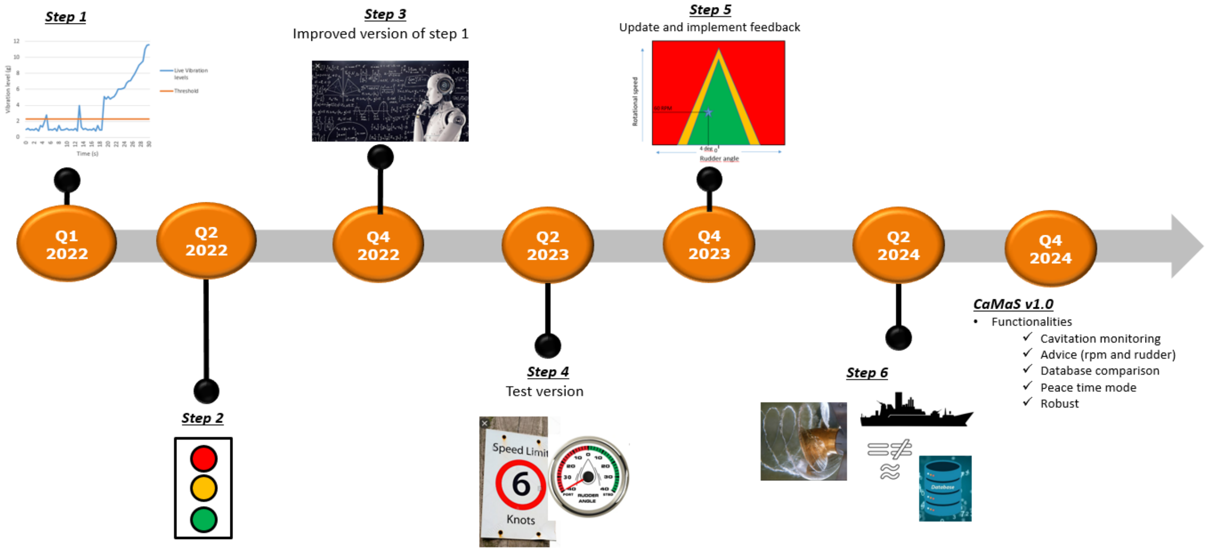

Figure 20: Schematic roadmap of CaMaS v1.0

Conclusions

Within the SSMS, CaMaS is being developed. A demonstrator on board a navy vessel is installed to incrementally develop an SSMS and its CaMaS-functionality. A first order threshold algorithm was developed and implemented in the demonstrator together with a monitoring human machine interface. The first preliminary result showed that the cavitation inception can be determined with the algorithm and is in line with the cavitation inception speed determined from the acoustic range. However the robustness of the gauge has not been tested yet, and more sophisticate algorithms will be tested in de future on the demonstrator.

Based on the feedback of the crew, a cavitation detection gauge has been developed and implemented in the Project S software. In the next 2.5 years, every six months an update will take place such that at the end of 2024 a CaMaS v1.0 with all its functionalities is implemented and tested on the demonstrator.

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List of Acronyms

ASW	Anti Submarine Warfare
CaMaS	Cavitation Management System
CIS	Cavitation Inception Speed
COSIMAR	Continuous Operational Signature Monitoring Awareness and Recommendation
CSSM	Centre for Ship Signature Management
DEMON	Detection of Envelope Modulation On Noise
DMO	Defence Materiel Organisation
IMMS	Integrated Mission Management System
IPMS	Integrated Platform Management System
MARIN	Maritime Research Institute Netherlands
MoE	Measure of Effectiveness
MoP	Measure of Performance
OODA	Observe Orient Decide Act
Project S	Ship Signature Management demonstrator project on board of HNMLS Tromp
SS	Sea State
SSMS	Ship Signature Management System
TNO	Toegepast Natuurwetenschappelijk Onderzoek
OSD-DS	Own Ship Data Distribution System
URN	Underwater Radiated Noise