Classifying vessels using broadband sonar: considerations for future autonomous support

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ABSTRACT

Submarine Command Teams often rely on sensor systems such as sonar to gain situational awareness when operating below periscope depth. Classifying different vessels using broadband sonar relies on the analysis of aural characteristics to build up a target motion solution for each sonar contact. This process is inherently uncertain, and misclassification can be potentially fatal, resulting in collisions between vessels and submarines. This paper offers suggestions for artificially intelligent support which could be created and provided through the analysis of historically collected information about fishing vessels transmitted via satellite. These suggestions were formed through an interview with a subject matter expert and the analysis of a report compiled about a collision that occurred between a Royal Navy submarine and fishing vessel in 2015.

KEYWORDS

Human Machine Teaming, Submarines, Uncertainty

Introduction

There have been a number of high-profile collisions involving submarines and fishing vessels since the turn of the millennium, some with fatal outcomes, such as the collision between the US Navy submarine, USS *Greeneville* and the Japanese fishing vessel *Ehime Maru* in 2001 (NTSB, 2005). Collisions are still the second most common type of submarine accident, accounting for 18% of accidents between 1946 - 2005 (Tingle, 2009).

With the Ministry of Defence envisioning future maritime platforms that incorporate artificial intelligence (AI) and increased levels of autonomy to increase safety and performance (UK Development Concepts And Doctrine Centre, 2018), identifying areas where these systems could have tangible application and benefit is an important task. Autonomy, when applied incorrectly to a problem, can actually increase workload and decrease reliance on a system (Bradshaw *et al.*, 2013) (Lee and See, 2004). Careful considerations must be made before incorporating such high-level autonomy into safety-critical environments in terms of how these technologies affect different roles and workloads within complex socio-technical systems.

This paper seeks to understand the activities and pitfalls of using broadband sonar to detect and classify different vessels at sea, with consideration given to how it may be improved upon using AI data analyses.

Information on the contact classification task was gathered through the conduct and subsequent analysis of an interview about sonar classification with an ex-Submariner, focusing on classification situations with high levels of uncertainty. This interview was used to produce a timeline of events within the task, together with a model for the sonar contact classification procedure. Submarine

collision incident reports compiled by the Marine Accident Investigation Board (MAIB) were reviewed to gain an understanding of the reasons for which submarine collisions occurred.

An Acci-Map was created using an MAIB incident report about a collision which occurred between a Royal Navy submarine and the fishing vessel *Karen* in the Irish Sea in 2015. Acci-Maps were developed by Rasmussen in 1997, with the purpose of generating proactive risk-management strategies for complex sociotechnical systems (Branford, Naikar and Hopkins, 2009) . The primary cause of the collision was determined by the report to be the mis-classification of the fishing vessel as a small merchant vessel.

From this understanding of the classification task and the reasons an incident involving misclassification can occur, two key areas are identified where the inclusion of AI data analysis may lead to better situational awareness and potentially less classification errors.

Problem scope

Submarines often operate surreptitiously, unable to engage in communication with those on land, and at depths that are undetectable from the surface. When dived, they are unable to rely on global positioning system (GPS) information or quick data transfer speeds. By nature, their activities are often covert; remaining undetected is always a primary objective. This results in infrequent returns to the surface to gather important external and tactical or strategic information. Unless the submarine is operating at surface level or periscope depth, no radio communication or visual information can be obtained. Therefore, the submarine relies on sensor systems such as sonar to provide information about its surroundings, and pre-mission planning to gain some understanding of the tactical environment.

Sonar Operators (SOs) interpret sonar recordings to detect, classify and track contacts when underwater. By analysing the aural characteristics of the sonar, SOs are able to identify contacts and their bearing. Using Target Motion Analysis (TMA) techniques and frequency analysis, a contact's engine size, number of engine shafts and propellers can be defined. This allows a contact to be classified as a military vessel, merchant vessel or fishing vessel, and a solution for its range can subsequently be calculated by the Officer of the Watch (OOW). The OOW may instruct the submarine to change direction or course in order to gain additional sonar information and to minimise the area of uncertainty around a contact's movements, to gain a clearer situational picture, or to increase distance between the submarine and a contact. An accurate TMA solution provides the OOW with a better opportunity to calculate precise range information for the contact, allowing the submarine to avoid collisions, by accurately predicting when a contact will reach the pre-defined Closest Point of Approach (CPA).

A Sonar Controller (SC) is in charge of communicating relevant information to and from the SOs to the OOW. The Sonar Controller, in essence, acts as an informational filter, providing summaries of activity and important information to the Command and Sonar teams. Typically, the OOW does not have a personal display but instead, can access any display from the Sound Room on a repeater screen.

From this description of the problem, it is clear that there are many parts of the task which incorporate levels of uncertainty. The task itself is inherently uncertain, as much of the analysis is based on unknown variables for course, range and speed, which must be inferred from the bearing and frequency information. Uncertainty can propagate very quickly through the solution and can

lead to incorrect classifications of contacts and therefore, incorrect TMA solutions which in turn could lead to collisions.

The OOW must create a mental three-dimensional tactical picture by constantly analysing the contents of various communications and information displays, constantly acquiring new information and updating his mental model from different information sources. Not only must the OOW rely on uncertain solutions for all contacts and actively use these to make crucial decisions, other constraints such as time, mission objectives and the need to remain covert can lead to eroded decision-making capability, through high stress and information overload.

Fishing vessels operating in European Union waters over twelve metres in length are required by law to carry Vessel Monitoring System (VMS) units, and over fifteen metres in length carry a class A Automation Identification System (AIS) transceiver (wwwgovuk and maib, 2015). AIS and VMS both use satellite tracking to transmit the location of vessels ('Understanding fishing activity using AIS and VMS data', 2012). This data is historically available. Services such as Global Fishing Watch collect and display this data mapped and in real time freely in the public domain, allowing it to be studied to better understand fishing patterns and behaviours (Global Fishing Watch, 2019).

The MAIB accident report for the *Karen* collision shows how, in spite of a rigorous procedural framework and readily available information about the concentration and types of vessel at the location of the accident, *Karen* and other ships at the submarine's location were misclassified. This resulted in a dangerous situation, with neither AIS nor VMS information accessed in the pre-mission planning phase.

This paper suggests that an autonomous agent could be used to warn the OOW and SOs when there is a high chance of misclassification, based on the validity of the logic behind the classification and through intelligent processing of historic AIS information. Since this information is already available, it is possible to analyse this historical data for areas of interest and use this to intelligently make predictions about the likelihood of encountering fishing vessels at certain times and locations. Such systems would then be able to display warnings, highlight areas of interest on displays or offer confidence ratings in classification, based on analysis of routes outlined in the mission planning stage.

Methodology

In order to gain a better understanding of the procedures and activities that make up the task of target classification using sonar, a two-hour interview was conducted with an experienced ex-Submariner (the Subject Matter Expert – SME). SME interviews are commonly used as a tool to gain understanding of complex social, technical and information systems and to inform suggestions of system design improvements (Barnes, 2003; Dominguez *et al.*, 2006; Kaempf *et al.*, 2006; Walker *et al.*, 2010). Although only one interview was conducted, it provided a strong basis for an understanding of the problem, covering many aspects of sonar operation in detail and establishing an operating procedure for creating an accurate solution for a contact. Future work will involve conducting further task analyses through SME interviews, as well as observations and analysis of standard operating procedures, which could confirm or disprove preliminary findings.

This interview focused on different aspects of uncertainty in sonar classification, providing a complete overview of the process and activities. The SME spoke at length about different classification scenarios and what techniques were employed to elicit more information about sonar

contacts, as well as the strategies used to suitably classify sonar contacts. This helped to give an idea of the flow of the information and uncertainty inherent within the task.

The interview allowed for the creation of a timeline of events for the general task of classifying a vessel using sonar. It also gave information about perceptions of fishing vessels, and what distinguishing features could be used to classify them, such as the presence of "trawl noise" - a noise that would indicate a vessel is trawling nets.

Cognitive Task Analysis (CTA) techniques were applied to the interview, which used Critical Decision Method (CDM) probes to elicit detailed information about the SME's experiences dealing with uncertainty during contact classification. These probes helped to identify common themes, strategies for dealing with uncertainty, attitudes towards classification, and preconceptions concerning fishing vessel behaviour during post-interview analysis. Thematic analysis was conducted on the interview transcript, broadly classifying its contents into activities involved with classification itself, rules for classification, strategies for dealing with uncertainty and attitudes towards fishing vessels.

In order to identify shortcomings in the classification process outlined during the interview, accident reports for incidents that involved submarine collisions over the last twenty years were analysed. There is a very limited amount of information about submarine accidents available in the public domain, and only accidents that were proved to have been caused by a submarine were considered, meaning cases where submarine involvement had not been confirmed were discounted. The *Karen* incident was chosen as the primary incident for analysis because a full report was available and misclassification was defined as a direct cause of the incident.

Acci-Maps can be used to better understand the causes of accidents and how they are related, the conditions, which when combined, could be dangerous. Rasmussen promotes the "systems approach" of accident analysis (Reason, 1995) whereby individuals are not blamed for errors where systemic failures and deficiencies are what provoked them (Branford, Naikar and Hopkins, 2009), allowing insight into how the system could be modified to prevent similar accidents in the future.

The diagram is split into six levels, allowing the activities to be understood in relation to the physical environment, and also in the context of mission and command objectives, and in relation to laws and regulatory bodies. The Acci-Map was generated through analysing the contents of the MAIB report and extracting the causes of the accident and how they were related. The events and causes were then classified by their place in the socio-technical hierarchy. Nodes were connected when they were considered to be related incident causes in the MAIB report or followed sequentially in the timeline of events.

Findings

During the interview, fishing vessels were described as "the most dangerous contact for a submarine". Often fishing vessels do not adhere to the designated fishing zones and behave unpredictably, stopping and starting engines to fish. This unpredictable behaviour was stressed in the interview. Sonar relies on a contact making noise and, without engine noise to analyse, a contact can be "crossed", leaving its position unknown. Knowledge of fishing areas, shipping timetables and routes are all used when trying to classify a vessel, and fishing vessels operating outside of these regulated areas are harder to predict. Their behaviour is not consistent, as would be the case for, for example, a merchant vessel using autopilot to travel in an established shipping lane. Fishing

vessels may not follow predictable patterns of movement, making them volatile contacts with high levels of uncertainty surrounding them.

There are certain tell-tale characteristics that distinguish a fishing vessel from other types of vessel. One mentioned earlier was the presence of "trawl noise", revealing a ship is trawling fishing nets. Trawl noise was highlighted as the most important noise to identify quickly during classification, as snagging fishing nets is inherently dangerous. This was stressed a number of times throughout the interview, showing the importance of the noise when classifying contacts. Secondary aural characteristics that could help distinguish between a small merchant vessel and a fishing vessel were mentioned but trawl noise was stressed to be the main distinguishing factor, which is an unreliable classifier in isolation because of the discussed unpredictability of fishing vessel contacts and their nets.

Although pre-mission planning was discussed during the interview and external information sources were mentioned, certain procedural issues such as the Fishing Vessel Safety Ship, VMS data and AIS data were not discussed. Shipping timetables and routes were mentioned as available resources that could be consulted in times when there was uncertainty around a certain contact or in the pre-mission planning stage. Their primary use was discussed in the context of identifying merchant ships or ferries, which have well documented routes and timetables.

The Acci-Map created about the *Karen* incident summarises the main actions and events that led to the collision and can be found as Figure 1. The busiest nodes in the map are highlighted in red – these are the key causes of the accident. It can be seen that the tactical and operational management layer and the physical process and activities layer contain most of the key causes of the incident. This suggests a breakdown between the activities surrounding classification and tactical command.

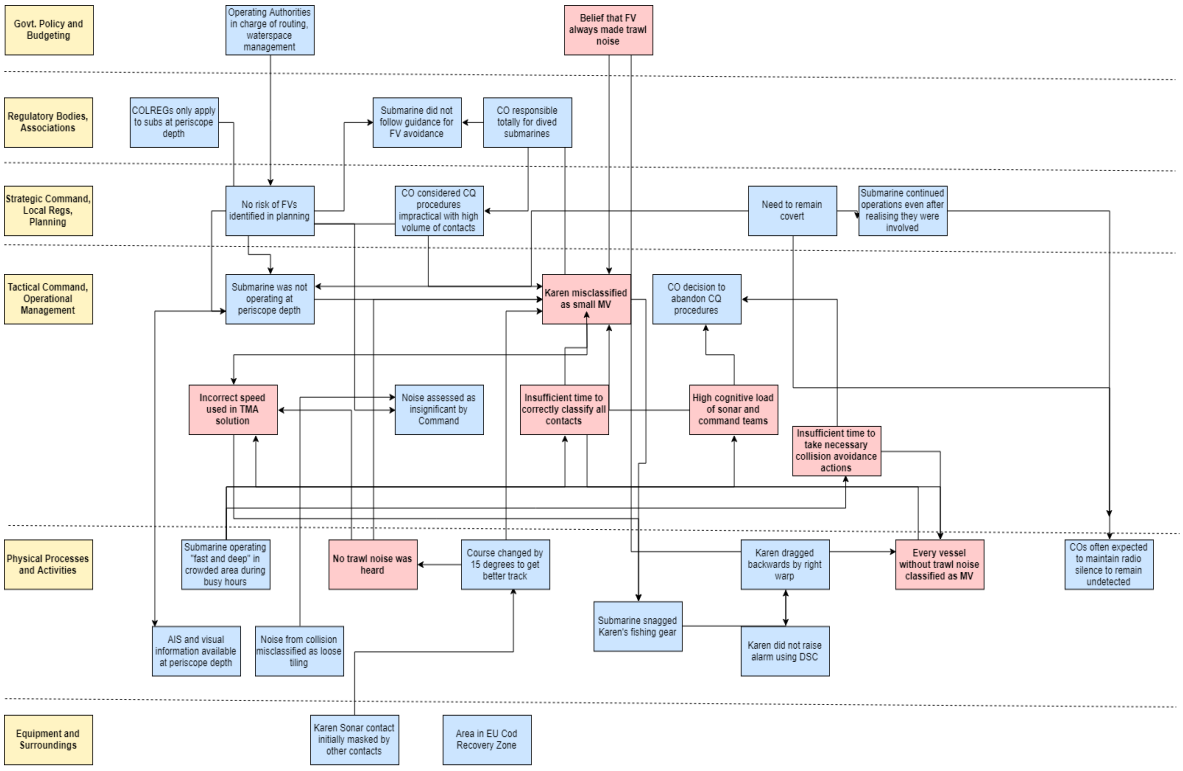

Figure 1: Acci-Map Constructed from the MAIB report of the incident involving the fishing vessel Karen in 2015

Looking at the Acci-Map, this incident occurred primarily because the *Karen* was misclassified as a small merchant vessel. This classification was mainly based on the lack of identifiable trawl noise. The high density of shared nodes in the lower half of the Acci-Map made it clear that this is not an incident that can be attributed to a lack of planning or procedure, but instead, carrying out tasks with high levels of uncertainty whilst experiencing a high cognitive load. These are the busiest areas of the Acci-Map – constraints on time meant procedure was not followed correctly, and the simplest classification solution was used even when incorrect, as many other fishing vessels were also mis-classified as merchant vessels. Artificially Intelligent support could be beneficial for this particular problem, especially when focused on reducing the cognitive load of the Command Team and providing pre-filtered, useful information that could aid with decision-making. Artificially intelligent systems are good at analysing and filtering high volumes of information with strong attention to detail and could be utilised to aid the Command Team by monitoring multiple contacts at once, creating a detailed tactical picture.

The SME interview, as well as highlighting the importance of trawl noise when classifying vessels, raised awareness of some secondary aural characteristics that could be used to further decrease uncertainty in the classification process. However, if the absence of trawl noise is the main classifier, this can lead to a negative confirmation bias; the absence of trawl noise is not an appropriate classifier for a small merchant vessel. Rather, the absence of trawl noise should indicate more investigation is needed to obtain an accurate classification of a contact.

The MAIB incident report stresses that the majority of the fishing vessels operating in the area of the accident had self-submitted AIS data prior to sailing, and that historical VMS data for the accident location showed similar levels of activity to the day of the incident. This implies that there could have been knowledge of the dense concentration of fishing vessels in the operational area prior to starting the mission, but this was not utilised effectively.

Fishing vessels' movements can be harder to predict and volatile, yet the information that is available about their routes was not discussed in the interview. This, coupled with their under-utilisation being a contributing factor in the *Karen* incident, leads the authors to believe that shipping information could be collected, analysed and utilised, both in pre-mission planning and during operations, to decrease uncertainty and give more detailed situational awareness.

Suggestions for Artificially Intelligent Support

From these analyses, certain parts of the process were identified that could be enhanced with some kind of artificially intelligent support. By comparing the method followed by the SME to the activities conducted when classifying the vessel *Karen*, two specific areas could be identified where additional informational support may have reduced the chances of an incident.

The author proposes that machine learning tools could be used to aid in pre-mission planning and vessel classification, by (a) highlighting areas of a chosen route that could have a higher volume of traffic at certain times, (b) providing statistical likelihoods of encountering fishing vessels for given times and locations, and (c) by flagging certain classifications as being unlikely based on the type and amount of vessels that are frequently seen in a given location during operations, as well as the aural characteristics used to classify the contact.

During the pre-mission planning phase, collection and analysis of AIS and VMS information for vessels in the vicinity of the planned route and the proposed times could be used to generate uncertainty statistics and prompts regarding vessel classification. The MAIB reports that nearly all

fishing vessels in the area had submitted accurate VMS information prior to them sailing. It also proposes that historical VMS data showed similar patterns of life in the operational area. An accurate assessment of the type of contacts present in the operating environment could be ascertained by reviewing this historical data, much of which is publicly available. Not only could this information be used to prompt the Command Team when there is a higher degree of uncertainty around contacts, it could also be used to engineer safer routes and establish what time of day was best to enter areas containing a higher concentration of fishing vessels when analysed during the pre-mission planning phase.

Tools like this stage could help reduce the Command Team's cognitive load during a task, as they would have a clearer starting picture of what kind of contacts to expect and where, in relation to the submarine's route. They could also be used to prompt SCs when a classification type seems statistically unlikely.

Using the absence of trawl noise to discount a fishing vessel classification, an example of negative confirmation bias, is not a suitable tool for classification, and a way of representing a level of confidence in the contact classification should be available to the OOW to be assured in making navigational decisions and CPA determinations based on this information. Machine learning tools could be used on sonar recordings to provide a certainty score for certain classifications, or by prompting Operators when a classification seems unlikely either based on the aural characteristics of the sonar recording, or because of the types of vessels most statistically likely to be encountered in certain areas.

Future Work

Based on these findings, designs for AI-based support both in the pre-mission planning stage and onboard the submarine are currently being developed through storyboarding and wireframing. Future work will involve conducting more interviews as well as task observations, possibly of currently serving Submariners undergoing tactical training, to gain a more detailed, accurate and broadly applicable understanding of the tasks involved in sonar classification. Further research analysing how Sonar Operators perceive sounds and what cognitive processes are used to understand and classify aural information may also be beneficial for creating usable and useful designs.

More detailed task analysis is required to assure the suggestions offered are relevant to current operational practices. Further investigations into the efficacy of the suggestions of support need to be conducted: this could be through interviews with additional SMEs and observations of planning and classification tasks to establish more substantial and rigorous user requirements.

The form the prompts and warnings could take also needs further exploration; the idea of having virtual crewmembers, or artificial speech-based agents, could reduce the level of training and cognitive load required to engage with these systems and improve usability and trust. Developing experiments with different forms of artificially intelligent support and testing for trust and usability are the next stages for this research.

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