Using a Data Fusion-based Activity Recognition Framework to Determine Surveillance System Requirements

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***Abstract*— A technique is proposed to extract system requirements for a maritime area surveillance system, based on an activity recognition framework originally intended for the characterisation, prediction and recognition of intentional actions for threat recognition. To illustrate its utility, a single use case is used in conjunction with the framework to solicit surveillance system requirements.**

Keywords: Requirements definition, activity recognition, threat assessment, data fusion, maritime surveillance.

I. INTRODUCTION

Surveillance systems play an important role in the management, control, monitoring and policing of maritime resources. These resources include fish stocks, sea ways (access), environmental and conservation sensitive areas, oil and diamond fields, recreational areas, harbours and harbour approach zones amongst others. Various sources of surveillance, safety and monitoring information are available for the maritime environment, to include:

- Automatic Identification System (AIS) [1]
- Vessel Monitoring System (VMS) [2]
- Space System for the Search of Vessels in Distress / Search and Rescue Satellite Aided Tracking (COSPAS-SARSAT) [3]
- Ship-based radars
- Land-based radars
- Satellite-based optical and radar sensors

New applications using these systems are emerging employing data fusion techniques to provide better information to authorities to manage maritime resources. An example is the Vessel Detection System (VDS) [4] developed by the European Commission. In principle it compares VMS vessel positions with positions estimated from satellite-based imagery to determine if vessels are breaching regulations or treaties. It can also detect if a vessel is intentionally disabling or tampering with its VMS system. New concepts are also being evaluated which include the use of high altitude airships (HAAS) serving as platforms for surveillance sensors [5]–[8].

Due to the wide spectrum of stakeholders and end-beneficiaries, requirements for maritime surveillance systems are diverse and difficult to capture rigorously and comprehensively. A technique is proposed to prevent the haphazard identification of surveillance system requirements but to allow for a systematic approach to cover both sensors and other data sources.

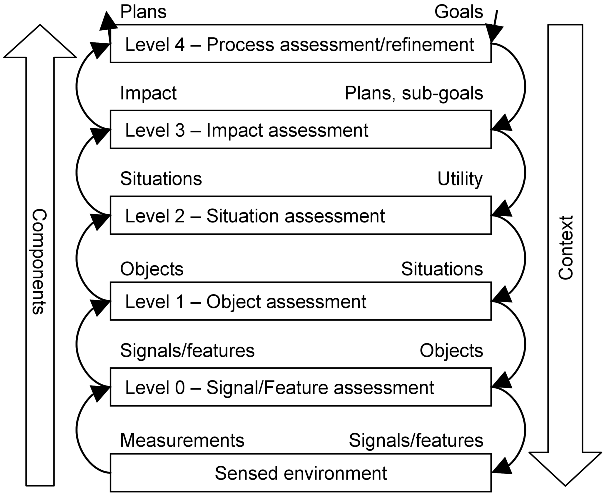

Fig. 1. Logical flow across the Data Fusion Levels (Adapted from [9])

Techniques to solicit and identify system requirements stem from the systems [10], [11] and software engineering [12] communities. Bray [13] reports that a natural language, fact-based information modelling approach to explicitly model information requirements works well. To some extent the data fusion model originally proposed by the Joint Directors of Laboratories (JDL) [14] and subsequently revised [9], [15], [16], can also be used to identify system requirements. The JDL data fusion model is aimed at serving as a common framework of understanding for the data fusion community, As such, it can be used to identify the level(s) of fusion required for a specific purpose, the applicable fusion techniques and the sensing requirements to make the system feasible. Figure 1 depicts the characteristic logical flow across levels, as adapted from [9]. The logical flow across levels is applicable in both directions: From lower to higher levels to determine the components required as input to a certain level and from higher to lower levels to provide context.

Keithly [17] suggests a methodology to evaluate the value of data fusion in terms of information requirements. The methodology rests on the calculation of the satisfaction of decision-makers' information needs and the value of such information to the decision outcome. Information needs and needs satisfaction are abstracted into measures of the needed and achieved resolution of entity identity, location, tack, activity, capability and intent states.

Ménard [18] suggests a use case template-based technique to infer the intent of maritime vessels. Use case templates are problematic when trying to capture anomalous behaviour. Templating techniques can incur unacceptable detection and false alarm performance; i.e. subject to both

- Type 1 errors (e.g. calling a fishing boat a threat) caused by the difficulty in defining boundary conditions for of normal behaviors; and
- Type 2 errors (e.g. ignoring a threat that is disguising its activity as fishing) caused by lack of observability of significant dimensions of threat behaviors.

The present paper does not argue against any of the traditional requirements definition techniques but rather presents an alternative technique which shows promise for application in the maritime surveillance domain.

The paper provides an overview of an activity recognition framework adapted for the maritime environment. In subsequent sections it illustrates how use cases can be used, together with this framework, to identify surveillance system requirements and concludes with the identification of future refinements and research.

II. ACTIVITY RECOGNITION FRAMEWORK

Steinberg [19] proposed a threat assessment framework for the characterisation, detection and prediction of threat scenarios. The framework is intended to accommodate all types of threats, from actions of individual agents to those of terrorist organisations or nation states. Indeed, the threat assessment framework has been revised to recognise any intentional behaviour rather than just threats or threat intent, and is referred to as an activity recognition framework [20]. This is a level-3 data fusion process, as defined by the JDL Data Fusion Model [9], [15], [16]. The revised framework specifically allows for the recursive generation and refinement of situation and activity hypotheses.

As illustrated in Figure 2, the activity recognition framework fuses three elements - Capability, Intent and Opportunity - to estimate or predict the likelihood of an action.

- Capability assessment provides indicators of potential actions, in terms of the availability of physical and informational means to carry out various actions.
- Intent for actions is characterised in terms of a decomposition of an agent's high-level objectives and the utility of various situational states relative to those objectives. The assessment can involve both technique-driven methods (i.e. explaining the purpose of observed activity) and goal-driven methods (i.e. seeking means to assumed ends).
- Opportunities for action can be characterised by an evaluation of constraints imposed by the accessibility and vulnerability of targets to such actions.

The feasible types, opportunities and intent are used to generate activity hypotheses which are evaluated to provide action likelihood and outcomes.

To apply the activity recognition framework in a maritime surveillance environment, it must address a diversity of vessel intentions: hostile, friendly and neutral. The framework has been focused to consider single entities, such as a single maritime vessel out on the open seas. It is expected that future development will extend it to cases of coordinated activity among multiple entities.

Figure 3 shows the adapted activity recognition framework with the capabilities, intent and opportunity elements populated for a maritime environment. For illustrative purposes the modifications are biased towards illegal, unreported and unregulated (IUU) fishing activities. Note that all sub-elements have been populated as well.

To illustrate: Capabilities which were originally defined by design, development and deployment sub-elements are still used as such, but whereas design was indicated by theory and technology capabilities in the original framework, it is now indicated by the fish species a vessel is capable of catching. Similarly development is now indicated by equipment such as cranes, stores and ice making capabilities and deployment capabilities by range, crew and open seas abilities.

Opportunities are translated to the maritime environment by including surveillance and enforcement vulnerabilities, access to restricted and prohibited fishing grounds, capacity for total allowable catch and fish stock levels.

High level objectives in the intent category are indicated by the inclination to conduct IUU fishing, misreporting and intentional tampering with AIS or VMS equipment. Means decomposition is achieved by analysing market information (to be able to land catches) and implicate partnering vessels. Desirability includes aspects such as breeding areas, prohibited fish species (but with high market demand and prices) and fish stocks (availability).

As already mentioned, diverse stakeholders and end-users exist in the maritime environment. An activity recognition framework should therefore be populated for each discipline, application area or user area.

The original framework (Figure 2) is applicable for naval applications, with adaptation to specific threats categories. In the enforcement arena it should be adapted to include threats such as piracy, and for the environmentally concerned authorities it should be extended to include threats such as oil spills and other ecological disasters. A library of activity recognition frameworks are then constructed and used in conjunction with use cases to identify surveillance system requirements. The next section shows how use cases are used in conjunction with populated frameworks.

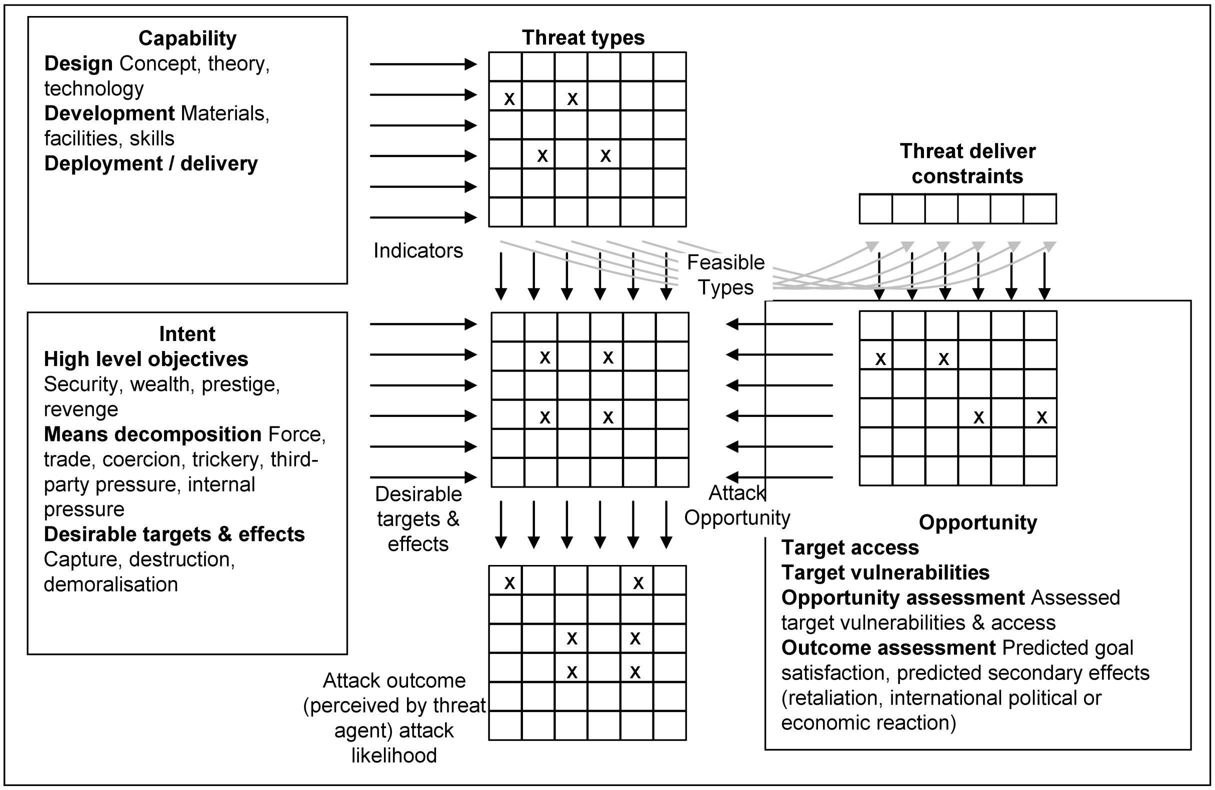

Fig. 2. A high-level activity recognition framework (From [20])

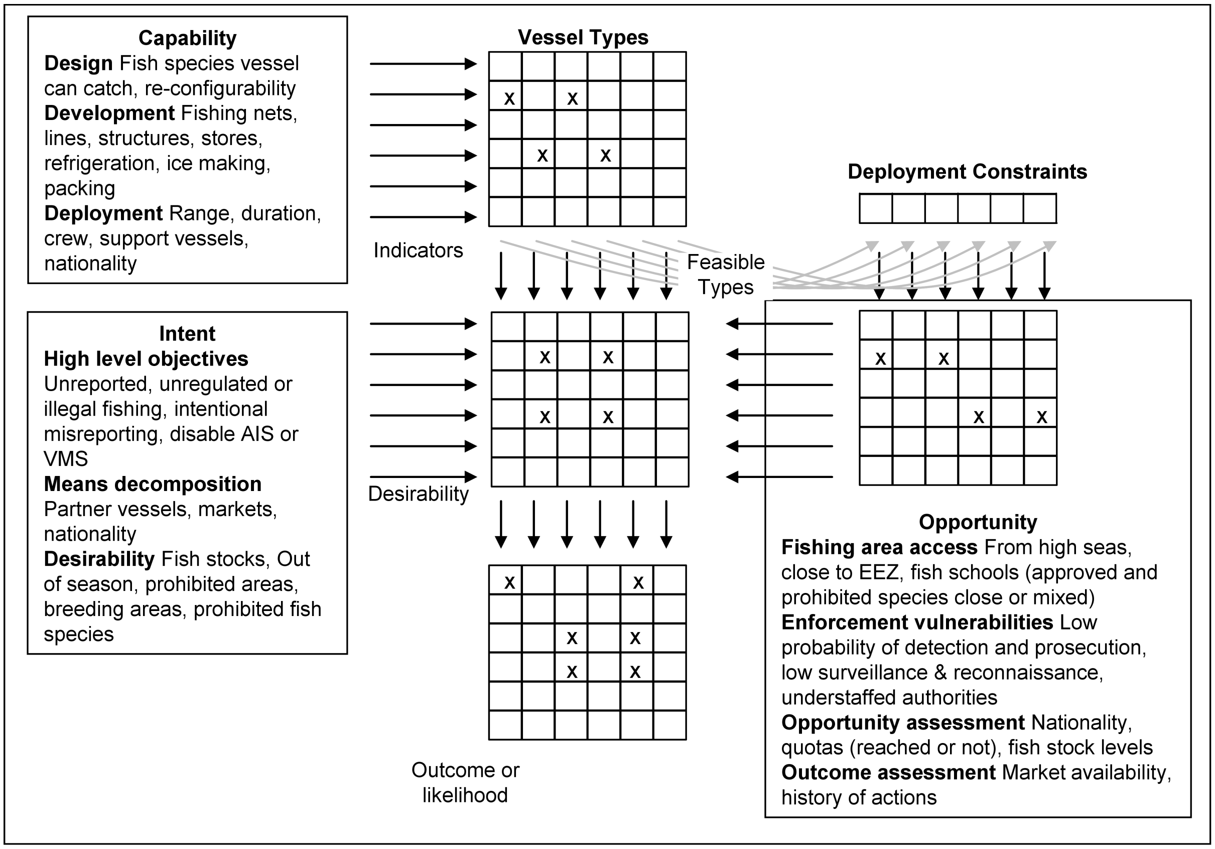

Fig. 3. Modified activity recognition framework for maritime applications (Adapted from [20])

III. APPLYING THE FRAMEWORK

A. Use Cases

Use cases [12] are valuable means of capturing transactions between users and systems. In the maritime surveillance environment, a marine vessel can be considered as a ”user” and the surveillance system as the ”system” the ”user” interacts with. Another possibility is an enforcement official, as ”user”, interacting with a persistent area surveillance system console, the ”system”. To illustrate how a use case, in conjunction with the activity recognition framework, can be utilised to define surveillance system requirements consider an example scenario in the following subsection.

B. Example IUU Fishing Scenario

A commercial fishing trawler departs from a national port to steam to open fishing grounds [6]. The vessel’s captain indicates that Hake will be caught and that the company for which the fish are caught has capacity left in its total allowable/licensed catch. Well aware of the fact that a closed area for fishing has to be passed *en route* to the open fishing grounds, the captain steams such that the vessel passes through the closed area. The closed area is defined landwards of the 110m depth line, declared by the fishing authorities as a protected area for Hake breeding and juvenile Hake. Not withstanding this restriction the captain trawls for Hake in the closed area. Typical trawling patterns are followed to deploy and recover fishing nets. When the net is full, the vessel turns into the wind and slows down due to the drag of the full net in the water. A fisheries enforcement agent detects that the fishing vessel is steaming in a recognisable pattern at a speed of 2-3 knots (typical trawling speed) in the closed area. Returning to the port, upon interrogation, the captain claims technical problems, hence the slow speed in the closed area, and that the Hake landed has been caught in the open fishing grounds which was also steamed through at the trawling speed. The enforcement agent does not have sufficient evidence to take the case further, as her only source of surveillance data is VMS data captured at a very slow rate (hours between updates).

C. Use Cases and Activity Recognition Output Reverse Engineering

From the above scenario, multiple use cases may be identified from different points of views; e.g. those of the enforcement agent or the trawler captain. To define surveillance requirements, the use cases of importance are from the fisheries enforcement agent’s point of view, as those will drive requirements such that sufficient evidence could be collected to challenge the legality of actions by the ship captain. Assuming the vessel is busy with illegal fishing practices and reverse engineering the output, vessel types (capabilities), opportunities and intent have to be populated to achieve such a result.

When populating elements (opportunities, capabilities and intent) and sub-elements (design, means, access, etc.) with the mechanisms to determine or estimate values, confidence factors should be introduced. The different confidence factors are used in the fusion processes to give more weight to more accurate (or trusted) data and information sources. An example is where a vessel type is estimated from satellite images or obtained from VMS data. Although the latter is more reliable, the two sources can be used in combination:

- The VMS data can confirm satellite image-based position detections, or *vice versa*;
- The satellite images can be used to detect that a vessel has tampered with its telemetry systems (VMS/AIS) such that it report incorrect positions;
- The satellite images can be used to detect that a vessel does not have active or compliant telemetry systems.

D. Vessel Capabilities

In terms of capabilities, the design, deployment and development sub-elements have to be estimated from information and data sources. To establish that a vessel is engaged in illegal fishing activities, basic criteria should be met:

- It is a vessel capable of catching fish in larger, rather than smaller, quantities (commercial viability);
- The vessel is able to endure longer stays on the open seas. In the example scenario this is not a definite requirement, although the vessel’s captain will want to at least create the perception;
- The vessel should be capable of storing catches until it returns to port.

To determine the above vessel characteristics - which can be deduced from the vessel type - different sources of information can be employed. In the test scenario case, surveillance systems might not be necessary, as the vessel type should be available from the harbour master, shipping register, AIS or VMS systems. However, should these sources be outdated, false information supplied upon registration or it is a foreign vessel accessing closed fishing areas from outside the EEZ, rather than from a local port, other surveillance capabilities would be required. In these cases vessel type and capabilities could be estimated from surveillance data:

- The vessel’s length and width can be used to narrow down vessel types which can be compared with a database of commercial fishing vessels [21]. This requires optical imaging or synthetic aperture radar sensors, both typically satellite or HAAS-based [22], [23].
- The Kelvin wakes of the vessel can be used to detect hull shape, speed and direction [24], [25]. From this possible vessel types could be estimated. To detect Kelvin wakes, optical or Synthetic Aperture Radar (SAR) sensors can be used, again satellite or HAAS-based.
- From a persistent maritime surveillance system, vessel tracking data can be used to determine capabilities by for instance classifying steam paths for types of ships. High resolution optical or SAR imaging of maritime vessel can also allow the detection of vessel size or even superstructures on the vessel. This involves automatic pattern recognition techniques [26].

E. Vessel Opportunities

In the example scenario ample opportunities exist for the vessel to undertake illegal activities:

- Fishing area access: The closed area (landwards of the 110m depth line) is easily accessible. No physical barriers exist to prevent fishing in these areas;
- Enforcement vulnerabilities: Patrols are inadequate to monitor closed areas or detect illegal activities in progress. Surveillance capabilities are limited to VMS position reports at intervals of up to hours which could be requested by an enforcement agent;
- Opportunity assessment: The fishing permit holder has capacity left in terms of its total allowable catch. Fish stock levels are high enough to justify the cost of an open seas fishing effort;
- Outcome assessment: The estimated total cost per unit effort is low when catching fish within the 110m depth line. The time at sea is reduced, reducing crew costs and fuel costs. Catchments can also be landed earlier, thus cost recovery is quicker.

All of these opportunities are not directly measured or detected by a surveillance system but rather are based on information and management data sources. The requirement therefore is to integrate (fuse) such sources with surveillance system outputs. During this step other data sources are identified.

F. Vessel Intent

Intent - translated to vessel intent for the maritime application - is indicated by high level objectives, means decomposition and desirability:

- High level objectives - It is the intention of the captain to catch fish within the closed area. Reporting is correct in terms of fish species and weight caught, but not where it was caught.
- Means decomposition - No partner vessels are required, and the vessel has all the means necessary to catch Hake in both the open and closed areas. Market demand for Hake is high, both locally and internationally.
- Desirability - Fish stock levels are sufficient in both open and closed areas. The total cost per unit effort is the driving factor for catching Hake landwards of the 110m depth line, as it is more cost effective.

The above aspects do not have direct maritime surveillance implications but rather imply that external data and information sources should be integrated. The purpose of high level objectives in the activity recognition framework is to either provide corroborating evidence for illegal actions, to indicate that motivation exists, or indicate that motivation for illegal actions lacks.

The two sub-elements of the intent element, means decomposition and desirability have been translated to indicate if the high level objectives can be achieved and if they are worthwhile achieving.

The means decomposition implies partner vessels. Detecting these requires surveillance techniques to resolve vessels in close proximity, determine if vessels interact on the open-seas and predict vessels on intersecting paths. This requires a tracking capability with appropriate update rates and resolution to detect interacting vessels.

The desirability of catching fish in closed areas is related to information regarding market demand for fish (high prices) and lower cost (closed area is closer to the coast than the open area). The consolidated requirement for intent is therefore to have adequate maritime surveillance and tracking capabilities, but integrated with information sources, including fisheries market information, landing registers and fisheries control means (open and closed areas, etc).

G. Vessel Constraints

The example scenario does not contain any constraints that suppress the opportunities for a vessel to fish illegally. Constraints that may be included are meteorological conditions that endanger fishing or even leaving a port; and the vessel's knowledge (or perception) of enforcement, surveillance and monitoring in the area. These aspects do not impact directly on surveillance requirements, but again, requires the integration of other information sources such as weather reports, etc.

An indirect consequence of identifying constraints is that the constraints can modulate requirements for other elements of the activity recognition framework. If an area is known for severe sea states, constraints will indicate that only larger vessels can trawl in the area - this will then impact on the minimum size of vessel to be detected when estimating vessel capabilities.

H. Prioritisation and Probability of Occurrence

Some of the activity recognition elements, such as vessel intent and opportunities, are not directly observable, but must be inferred. Therefore, they do not directly incur surveillance system requirements. Nonetheless, they are used to prioritise requirements and influence future decision processes. Vessel intent and the part of use cases that cover it, point to the probability that a certain action or intention (use case) will occur - If a number of use cases are found where the vessel captain has the intention to fish illegally, e.g. within the 110m depth-line, it shows that priority should be given to surveillance system requirements that enables the detection or prediction of fishing within the 110m depth-line.

IV. CONCLUSION

All elements of the proposed activity recognition framework have been used to identify surveillance requirements for a single use case. This served as an example only and would in practice be refined further and result in additional surveillance requirements. The same process will be followed for all the identified use cases, resulting in a complete list of surveillance requirements. Combining the probability that a specific use case would occur and its impact would serve to prioritise firstly the use cases and secondly the urgency and importance of certain surveillance requirements.

Although the framework works well to define high-level requirements and provides direction for development of a surveillance system, a further analysis will be necessary to refine specific requirements. In some cases it is already possible, such as to be able to detect a vessel of minimum size.

V. FUTURE WORK

A systems-level simulation will be constructed to test and evaluate the proposed framework. The simulation environment contains all relevant entities, including a steam path model, optical and radar sensors on satellite and air ship platforms, AIS base stations and information sources such as sea state, weather conditions and harbour master reports. Experiments with a data fusion system to detect IUU fishing will be defined to evaluate surveillance requirements.

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