An Integrated Reconfigurable System for Maritime Situational Awareness

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Abstract. Nowadays the maritime operational picture is characterised by a growing number of entities whose interactions and activities are constantly changing. To provide timely support in this dynamic environment, automated systems need to be equipped with tools— lacking in existing systems—for real-time prioritisation of the application tasks (missions), selection and alignment of relevant information, and efficient reasoning at a situation level. In this paper, we present METIS—an industrial prototype system for supporting real-time, actionable maritime situational awareness. In particular, we focus on the innovation of METIS, which lies in the employment and integration of several state-of-the-art AI technologies to build the overall system's intelligence. These include reconfiguration of multi-context systems, natural language processing of heterogeneous (un)structured data and probabilistic reasoning of uncertain information. The capabilities of the system have been demonstrated in a proof of concept, which is deployed as a situational awareness plugin in the Tacticos command-and-control platform of our industrial partner. The principles exploited by METIS are giving valuable insights into what is considered to become the next generation of situational awareness systems.

1 INTRODUCTION

Around 2000 ships are daily active off the coast of the Netherlands. While most of them behave normal a few ships may be engaged in illegal or irresponsible activities such as smuggling, illegal fishing, and dumping garbage to the sea, whose consequences can be devastating in terms of human life losses, financial costs or damage to the environment.

Situational awareness[6] systems have emerged to provide the operator, e.g., of a coast guard, with a constantly updated picture of the situation in a maritime area of interest to facilitate timely human decision-making. Most of the early systems were only capable of collecting low-level sensor data (e.g., from coastal radars or satellite images) to generate ship tracks based on which the operator was expected to recognize abnormal patterns or behaviour, and make decisions. Recent systems (see Section 5) have been extended with an intelligent model aiming to automatically identify and prompt a warning for such abnormalities.

Nowadays, the maritime operational picture is characterised by a growing number and diversity of entities (e.g., ships, crew members,

owner companies), whose interactions and activities are constantly changing. To provide timely support in this dynamic environment, automated systems need to be equipped with tools—lacking in existing systems—for real-time prioritisation of the application tasks (missions), selection and alignment of relevant information, and efficient reasoning at a situation level.

The innovative system we developed within the METIS project addresses this need by employing and integrating the following state-of-the-art artificial intelligence (AI) approaches for building the overall system's intelligence:

1. non-monotonic multi-context logic for *configuration* of the work of the system's components in terms of relevant inputs and outputs to provide cost-effective data collection and interpretation,
2. natural language processing tools for *collection & semantic alignment* of maritime-related data obtained from heterogeneous and (un)structured sources,
3. first-order probabilistic logic for *interpretation* of noisy, incomplete and dynamic data to provide timely predictions about the identity of entities (low-level attribute reasoning) and about their behaviour (high-level intent reasoning).

To allow autonomous and continuous running of the METIS system, the communication between its components is provided by a data distribution infrastructure. Finally, the interaction with the operator is supported by an advanced user interface that displays a tailored operational picture of the current situation.

In this paper, we present the functionality of the METIS system by highlighting the information flow and its individual intelligent components. In Section 2, we describe the problem domain and a typical scenario from it to demonstrate the challenges that human operators face in their daily practice and to later illustrate the work of the system's components. In Section 3 we present the overall information flow of the METIS system and we provide an overview of the relevant state-of-the-art AI techniques exploited in the core functionality of the intelligent components. In Section 4 we briefly describe the integration of the system into the product line of *Thales Nederland B.V.*, the industrial partner of the project. Finally we discuss related work in Section 5 and conclude the paper in Section 6.

2 MARITIME OPERATIONAL PICTURE

Consider the port area of Amsterdam, Europe's number 4 transhipment port, which sees more than 5200 ocean-going ships and approximately 40000 inland navigation ships per year.[7] Typically the entry

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[6] en.wikipedia.org/wiki/Situation_awareness

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[7] www.portofamsterdam.nl/docs/nl/Factsheets/2013/factsheet werk 2013_EN.pdf

of a ship into the port area is being detected by a coastal radar or by the messages broadcasted by the Automatic Identification System (AIS) transmitters on-board of the ship (for ships of 300 gross tonnage and more, engaged on international voyages). The AIS messages contain important ship's identity information such as MMSI (unique nine-digit code), IMO (unique number assigned to large sea-going merchant ships), name and type (e.g., cargo, passenger), as well as provide kinematic (movement) and voyage information. Since the AIS messages are sent by the ship, they may contain errors or be missing at all, especially if the ship has a reason to hide its identity, e.g., when the ship is involved in smuggling.

Currently, two main operational tasks for a decision-support system, as in the context of METIS, can be identified. The first one requires the identification of the ship entering the port area by verifying the truthfulness of its AIS information. This can be done by consulting various traditional sources such as the commercial ship database *IHS Fairplay* (`www.ihs.com`), intelligence reports, and tactical chats, as well as non-traditional sources such as ship tracking websites (*marinetraffic.com*, *myship.com*), and news items about ship events.

The second task is monitoring the behaviour of the ship in the context of the sea zone the ship enters or manoeuvres in it to detect illegal or dangerous activities. The following table presents for various typical sea zones the potential threats with respective hallmarks of ship's behaviour that can be used for threat detection:

zone type	threats (hallmarks)
Exclusive economic zone	smuggling (360° turns, rendezvous)
fishing zone/protected habitats	environmental pollution (dumping garbage)
coastal shipping lanes	collisions (proximity of two ships)
port security perimeter	smuggling (history of involvement)

A (fictive) scenario

The maritime operational picture shows a ship moving towards the Amsterdam port entry point, entering an environmentally protected area. The last transmitted AIS message by the ship provides the following identity information:

name	IMO	MMSI	type	flag
"Marion"	5254448	246187000	passenger	NLD

To verify the ship's identity, the operator performs additional searches in IHS Fairplay (IHS) and marinetraffic.com (MT) based on the ship's self-identification by its name, IMO and MMSI, and it finds the following information:

source	name	IMO	MMSI	type	flag
IHS	"Marion K"	8026282	304336000	passenger	ATG
MT	"Marion"	—	246187000	tanker	NLD
MT	"Angelique V"	5254448	221049559	passenger	NLD

Clearly the information obtained is contradicting suggesting that the ship may try to hide its identity. By examining further relevant news articles based on the AIS data, the operator finds both history of environmental pollution and collision, which raises the attention level for possible environmental hazard and for reckless sailing. Later, the ship enters the security perimeter of the harbour and comes into proximity of another vessel resulting in a rendezvous impeachment for possible smuggling involvement.

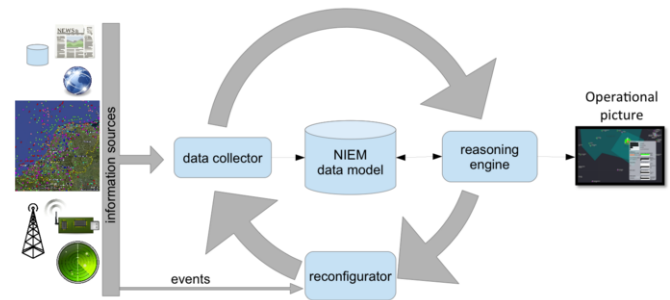At this point, questions about the ship's true identity and intents will arise such as:

Figure 1. The information flow in the METIS system

Q1: What is the true name and IMO of the ship?
Q2: Is there a high risk for environmental hazard?
Q3: Is the ship involved in smuggling?

It is not plausible in practice to obtain timely answers to these questions by a manual examination of sources and mental reasoning over contradicting and uncertain information. Therefore, the METIS system pursues automation of these tasks for real-time operator's support.
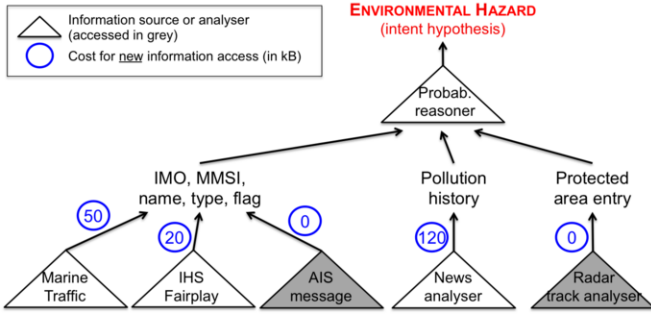
3 THE METIS SYSTEM

3.1 Information flow

Figure 1 depicts the general information flow in the METIS system. Upon entry of a ship into the area of interest, METIS picks up the ship's self-identification AIS messages and passes it to the system's *reconfigurator*, which given the mission context (e.g., smuggling, collision, piracy) determines a system configuration—a set of heterogeneous information sources (e.g., local/remote databases, ship tracking websites, news sources) and computational resources. This configuration together with the ship's identity information are used subsequently by the *data collector* to retrieve additional relevant ship's information. The retrieved information is aligned into a semantic unambiguous information model based on the *National Information Exchange Model* [4] (NIEM)—a standard in the maritime domain. The aligned information together with the output from kinematic analysers (e.g., detectors of 360° turns or rendezvous events) is further passed to the *probabilistic reasoning engine*, which provides assessment of the true ship's identity and intents such as smuggling, environmental hazard, piracy. If there is a lack in confidence with respect to certain intent hypotheses, i.e., high probabilities for threats, the reconfigurator iteratively considers the available information sources and the current resource constraints to steer further information retrieval and obtain best possible assessment of the situation, which is finally *visualised* in a (mission) operational picture to support operator's awareness and decision-making.

Following this flow of information, we now explain and illustrate, on basis of the scenario from Section 2, the functionality of each intelligent component within the METIS system.

3.2 System reconfigurator

To assess the risks a ship poses, the METIS system relies on a number of heterogeneous external information sources. These can fail, or

Figure 2. METIS information retrieving and processing components as a definite stratified multi-context system.

become inaccessible over time, and accessing them can incur non-negligible resource or even financial costs (e.g., network bandwidth, pay-per-request, communication channel costs, etc.).

Hence, the task of the METIS system reconfigurator is to compute relevant and resource-saving query plans (alternative ways to answer a query of interest) depending on mission goals and costs. To do so, the reconfigurator models the METIS' structure as a *non-monotonic multi-context system* (MCS), a logic framework introduced in [1] with precursor works tracing its origins back to [5]. A multi-context system comprises a number of knowledge bases, opaque contexts, each encapsulating a body of information, together with a corresponding mechanism for semantic interpretation of the information and reasoning with it. In METIS MCS, the set of contexts comprises the active information-processing components of the system—information sources and reasoning components (analysers). The flow of information among the contexts is regulated by a set of MCS bridge rules, which model the information exchange between the contexts within the system.

The *grounded models* of such multi-context systems and their further decomposition to fragmentary possible justifications of queries correspond to different query plans. The reconfigurator exploits these correspondences and determines the repertoire of the currently relevant system configurations—sets of information sources and processors to engage. Finally, for each such a configuration it computes an incurring cost and selects one maximising the coverage of the available information sources, while at the same time satisfying the system-wide resource constraints. A formal description of the underlying theoretical principles of cost-aware reasoning in multi-context systems and reconfiguration thereof is given in [13].

Consider the scenario from Section 2. As the ship has entered a protected area of the Amsterdam port, METIS is switching its focus so as to determine whether the ship might impose an environmental hazard (intent hypothesis). Figure 2 depicts a fragment of the METIS structure relevant for reasoning about this intent, which is modelled as a multi-context system. The triangles represent individual contexts and correspond to the individual information sources and reasoning components of METIS capable to derive valuation of higher-level information about the ship. Each information-source context is further annotated with the cost of accessing it. Here, the cost corresponds to the estimated size of data transfer involved in the information retrieval. The arrows represent some of the bridge rules of the multi-context system and depict the input/output flow of information between the contexts. To simplify the exposition, we include only the probabilistic reasoner in the hierarchy; in reality, the structure can be more involved.

To derive a valuation of the intent 'environmental hazard', the METIS system can (1) cross-validate the AIS data by accessing the additional sources IHS Fairplay (IHS) and marinetraffic.com (MT), and thus check whether the ship tries to hide its identity or (2) check news items for history of pollution events the ship may have been involved in. Hence, the reconfigurator creates two configurations with the associated cost, which are suitable for the next step of the system's work:

Config.#	Description	Inform. sources/analyser	Cost
C1	Cross-validate AIS data	AIS, radar, IHS, MT	70kB
C2	Check history of pollution	AIS, news-analyser	120kB

Suppose that the constraint on the configuration cost is 120kB per information retrieval per ship. The reconfigurator will select **C1** to be the next system configuration as it satisfies the constraint on data transfers and it is cheaper to execute. Hence, **C1** is passed to the METIS data collector to gather information from the associated sources and analysers. All the collected information is passed to the probabilistic reasoning engine, which analyses it and predicts a high chance for the ship hiding its identity. Thus the chance for the hypothesis environmental threat will increase, which, later on, will lead the reconfigurator to select **C2** as the subsequent system configuration to be passed further to the data collector and the reasoning engine.

3.3 Data collector

The data collector component of the METIS system is tasked with the retrieval of information about ships under investigation from heterogeneous third-party sources, such as websites, social media, external databases or newspapers. Such information is not semantically aligned, complete or fully reliable but it can provide valuable signals enhancing, corroborating and complementing the information retrieved from traditional maritime sources, such as radars, or AIS messages, exploited also in the METIS system.

By implementing natural language processing techniques, this component has an important capability to automatically detect valuable clues inside large bodies of unstructured documents, such as newspapers, tactical chat logs, or intelligence reports, that might indicate or confirm suspicious behaviour in the past. In particular, we exploit the notion that documents can be represented as vectors in a multidimensional space, based on the terms (words) they contain [18]. Using these vectors, it is possible to distil 'salient terms' from a set of articles with respect to the entire text corpus. This essentially highlights words the reasoner or operator might be interested in, while suppressing words that occur frequently throughout the corpus, which are essentially noise.

Once a request for a newspaper investigation is received by the component, an internal search engine, filled with approximately 25,000 maritime-related press releases from the Press Association, is queried for all documents that possibly describe an event involving the ship of interest. Special care is taken to carefully exclude documents about ships with similar names (e.g., *Queen Mary* is specifically excluded when investigating *Mary*). The term vectors for the found documents are then compared with a random sample from the rest of the corpus, and salient words are calculated using the Rocchio Relevance Feedback technique[16]:

$$\overrightarrow{T_s} = \left(\frac{1}{|D_r|} * \sum_{\overrightarrow{D_j} \in D_r} \overrightarrow{D_j} \right) - \left(\frac{1}{|D_{nr}|} * \sum_{\overrightarrow{D_k} \in D_{nr}} \overrightarrow{D_k} \right) \quad (1)$$

where $\overrightarrow{T_s}$ is the vector of salient terms, D_r is the set of term vectors of related documents, and D_{nr} is the set of term vectors of sampled non-related documents. This essentially calculates *the query that would have been asked to a search engine in order to get the highest number of relevant documents and the lowest number of irrelevant documents*, which in the current context represents a weighted list of terms specific to the ship of interest.

These words are then compared to a predefined set of indicator words, each tagged with a *risk category*, to find words hinting towards events of interest. The set of words and categories can be fully customised depending on the mission and/or domain. WordNet[11] is used to account for the hyper- and hyponymic relation between words, resolve synonyms, and to calculate word ambiguity. Examples of risk categories and indicator words are given below:

Risk category	Indicator words	Hyponyms
Criminal activity	Wrongdoer, Transgression	Delinquent, Criminal, Crime, Terrorization
Thievery / Piracy	Thief, Seize	Pickpocket, Plunderer, Pirate, Commandeer, Hijack
Smuggling	Smuggle, Smuggler	Traffick, Gun-Runner, Rum-Runner
Collision / Reckless behaviour	Run into, Accident	Rear-end, Collide, Broadside, Collision
Environmental hazard	Spill, Waste, Pollute	Spillage, Pollutant, Sewage

The weights of the matching words are then summed for each risk category to obtain an *evidence score* for each category, which are then passed to the reasoner.

Consider the scenario where the news analyser is invoked by the reconfigurator with **C2**, and retrieves all documents that mention "Marion". These documents contain words such as *collide*, *captain*, *port*, *offload*, *waste* and *passenger*. After normalizing, it finds that *passenger*, *collide*, *offload*, and *waste* are particularly distinguishing for the set of retrieved documents. After comparing these terms with the indicator words, it turns out *offload* and *waste* are both indicators for the *environmental hazard* category, while *collide* serves as an indicator for *reckless behaviour*. The two categories, along with their scores are passed to the reasoner.

A detailed description of this component, along with a case study and task-oriented evaluation is described in [8].

3.4 Probabilistic reasoning engine

The goal of the probabilistic reasoning engine in the METIS system is twofold. First, it performs automatic fusion of the information reported from various sources about the ship's attributes such as IMO, name and type, to best possibly predict their true values. Second, it makes a prediction about the behaviour of the ship in terms of threats such as smuggling or collision, which will be used as a warning to the operator. The engine performs high-level situation reasoning by fusing heterogeneous information obtained from the data collector as well as from (low-level) kinematic analysers (e.g., proximity of two ships).

We constructed the reasoning engine manually using expert knowledge about the relationships between ships, their (identity) attributes and behaviour. Given the heterogeneous nature of and uncertainty in the reported ship information, as well as the dynamic number of sources and ships observed, we have opted for *first-order probabilistic logic* as a modelling technique. Its advantages lie in the combination of powerful knowledge representation provided by first-order logic rules and explicit expression of uncertainty in terms of probabilities. In particular, we have used a logic programming language

extended with discrete random variables to handle probabilistic uncertainty known as *distributional clauses* [6].

The core of the reasoning engine is the knowledge base $\mathcal{KB}$, which represents the following two types of knowledge:

Prior information about ship's attributes, intents or the occurrence of an event. For example, the prior probability of 1% that a ship is colliding is represented as:

$$\mathbf{attr}(Ship, isColliding) \sim \{0.01 : true, 0.99 : false\}.$$

Here $\mathbf{attr}(Ship, Attr)$ is a random variable representing the value of attribute $Attr$ of ship $Ship$.

Generic relationships between entities (ships), their attributes, intents and the information about them reported from various sources. The relationships can be deterministic:

$$\mathbf{attr}(Ship, protected\_area\_violation) \leftarrow$$
$$\mathbf{attr}(Ship, inside\_protected\_area)$$
$$\mathbf{attr}(Ship, shipType) = passenger.$$

or probabilistic:

$$0.9 : \mathbf{attr}(Ship, in\_proximity) \leftarrow \mathbf{attr}(Ship, isColliding)$$
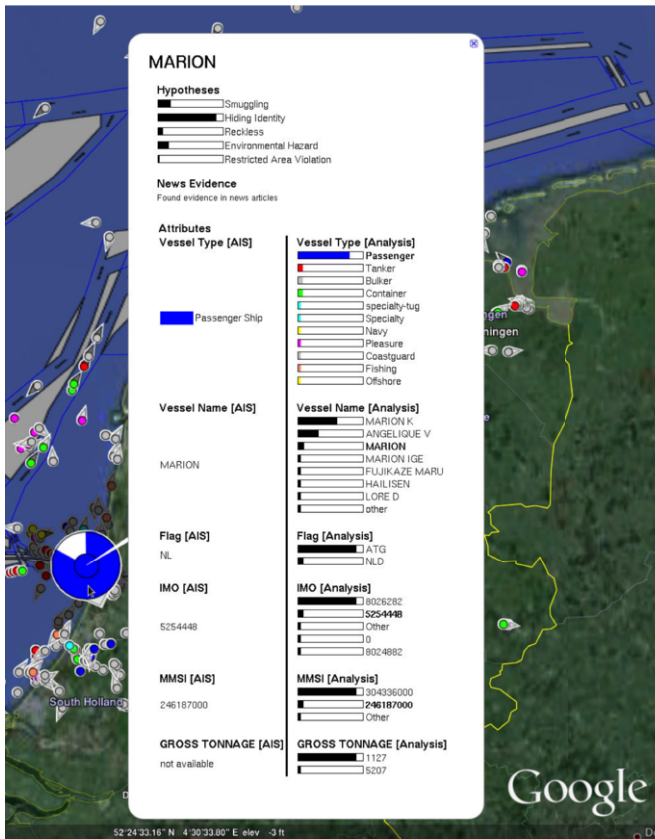$$0.6 : \mathbf{attr}(Ship, in\_proximity) \leftarrow \mathbf{attr}(Ship, rendezvous)$$

The last two rules state that there are two reasons why a ship is in a proximity with another ship: due to a collision (90%) or a rendezvous (60%). Although the chance is small, these two causes for proximity may co-occur, hence the probabilities do not sum up to one.

A strong feature of the reasoning engine is its capability to perform an information fusion by modelling the relations between the information reported from various sources (in one or more records) and the true entity's attributes:

$$\mathbf{rec\_attr}(Rec, Attr) = Value \leftarrow$$
$$\mathbf{error}(Rec, Attr) = false, \mathbf{about}(Rec) = Ship$$

Here, $\mathbf{rec\_attr}(Rec, Attr) = Value$ is a random variable representing the value $Value$ of the attribute $Attr$ reported by record Rec, whereas $\mathbf{error}(Rec, Attr)$ is a binary random variable indicating whether the value reported for attribute $Attr$ by record Rec is erroneous. The random variable $\mathbf{about}(Rec)$ represents the ship of interest the information record Rec is about. The rule states that when there is no error in the reported attribute value then this is the ship's true attribute value. The case when the reported information is erroneous is modelled by other rules, defining a probability noise distribution for the attribute.

When the METIS system is operating, a set of facts $\mathcal{F}$ is being created for one or more ships of interest with the information obtained from the data collector. This set is subsequently used together with $\mathcal{KB}$ to perform *reasoning*, i.e., answer questions of interest–called *queries* Q–that are imposed by the reconfigurator (or eventually the operator, e.g., **Q1-Q3** given in the scenario in Section 2). Answering such questions means to compute the success probabilities of Q, which is done by summing of the probabilities of all possible choices for the random variable values under which Q can be derived. Exact inference is performed by translating the distributional clauses to Problog2 [14]. An earlier version of the reasoning engine with a detailed description of the language used and experimental results to test its performance is presented in [10].
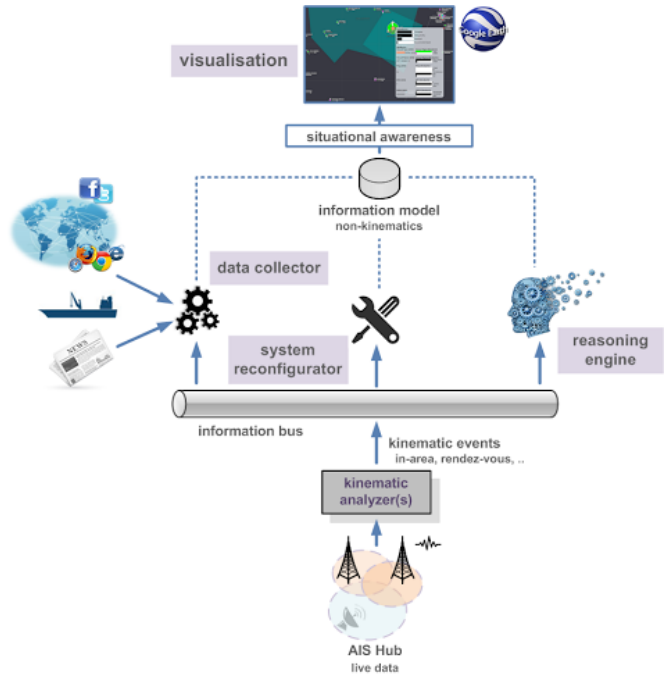
Figure 3. A screenshot with the results from the Metis system on the scenario.

Figure 4. The general architecture of the METIS system.

To conclude the running scenario, by instantiating the configuration **C2**, the reconfigurator exhausted the space of available options, and hence it stops the reasoning cycle. The results obtained about the ship of interest are shown on the METIS operational picture; see Figure 3. Next to the intent predictions, the system shows also the ship information from the AIS message as well as the probability distribution obtained from the reasoning engine per ship's attribute. Despite the high probability for hiding identity, the ship does not impose further high risk for environmental hazard and the operator does not consider taking an action for now. With the following ship's entry in the port security perimeter and the detection of its proximity to another ship, the METIS system enters into a new reasoning cycle by shifting the focus of its intelligent components on 'smuggling' as an intent hypothesis.

4 PROTOTYPE AND FUTURE IMPACT

The METIS system is realised as proof of concept, and deployed as a plugin, for the Thales's command-and-control industrial platform Tacticos. The system's general architecture is depicted in Figure 4 and described in details in [7]. To ensure integration and valorisation opportunities every six months, METIS plugin deliveries are integrated in the latest Tacticos baseline.

A 24/7 system, driven by live AIS data distributed by the AIS Hub (`www.aishub.net`) and continuously (re)deployed with the latest state-of-the-art METIS technologies, started begin 2014 to continuously monitor all ship activities within the Dutch Exclusive Economic Zone. To give an insight in the system performance we give a

short summary of its results from a recent operation. For the period May 18–21 the METIS system has monitored around 9400 ships. Information about vessels from sources such as AIS, IHS Fairplay and Press Association is constantly collected and fused to reason about vessel's identity and intents such as reckless behaviour, smuggling and environmental hazard. The process of data collection and reasoning takes on average a few seconds per vessel, affirming the real-time operation of the METIS system. For 99% of the monitored ships, the system reported an alert rate of less than 10% for any of the intents. For the remaining ships, 0.94% had an alert rate of up to 41% mostly due to a high (prior) chance for reckless behaviour. Only for two ships, the alert rates were of 78% and 92% due to news evidence about reckless behaviour. Further examinination of the latter ships will show whether the alert is correct. These first results already demonstrate the potential of the system to filter out a significant part of the ships entering a monitoring area. In the course of 2014, we will improve (i) the data collector by adding timeliness on the event extraction mechanism and (ii) the reasoning engine by representing and reasoning about temporal changes in vessel information. We expect these enhancements to show a real operational value in the 24/7 system, which we consider a prerequisite for an anticipated final field trial.

The METIS system pursues a shift from 'mental reasoning' to 'automated reasoning'. The immediate consequence for the operator is the relief from the burden of dealing with all ships to dealing with only those ships that really matter. This great operational advantage comes, however, at the expense of capturing domain knowledge into the system in an easy and intuitive way. For Thales the novel technologies exploited by METIS are giving valuable insights into what is considered to become the next generation of situational awareness systems.

Future valorisation and successful industrialisation of the METIS innovations require that the rules in the reasoning engine and the

strategies of the reconfiguration can be brought into the system by operational experts. They have the domain knowledge, comprising all hallmarks for the various threats, that must be captured in rules, and they have the mission knowledge that steer the configuration of the system so as to best support the mission at hand. These operational experts are, however, ignorant of any of the utilised METIS technologies. To bridge this gap, we plan to create intuitive abstractions from the METIS technologies, which allow input in a domain specific language, and translates this input into the technical language of the METIS components.

5 RELATED WORK

There has been a great interest in the development of intelligent systems for maritime surveillance tasks in the last years. Early works focused on the detection of a single threat only, such as the use of semantic web tools for piracy surveillance [19], and case-based reasoning for forecasting oil spill [9]. Later systems were developed for a broader application of predictive situational awareness. Such a system is PROGNOS [2], which similarly to the METIS system employs a first-order probabilistic logic formalism, called Multi-Entity Bayesian Networks, to represent and reason about dynamic and uncertain information in the domain. An ontology-based knowledge management module is used to define mission-specific reasoning parts. However, the system lacks capabilities for configuring relevant input/output depending on application goals and costs, as done in the METIS system.

A recent system uses Markov Logic Networks (MLN) [15], another probabilistic logic formalism for the detection of anomalies represented as simple events (deviations in the low-level input data) or complex events (logical combinations of simpler observations) [17]. In contrast to probabilistic logic, as used in the METIS system, in MLN a weight is added to each logic rule and its meaning is determined only in combination with weights of other rules. This makes the uncertainty representation and interpretation of the rules less intuitive for domain experts.

Another system for situation awareness that deals with the interpretation of uncertain and missing information is presented in [12]. The reasoning engine is based on dynamic Bayesian networks while a situation recovery component provides the final decision-making. The disadvantage of the employed tool, however, is its propositional nature that does not allow dealing with a varying number of entities as existing in the maritime domain. In [3], the authors report about the GeMASS system that uses genetic algorithms to discover knowledge from historical AIS and local port management data about common and exceptional events of ships' kinematic behaviour.

6 CONCLUSIONS

We presented innovative research on the METIS project that pursuits the enablement of the next generation information centric systems-of-systems for actionable situational awareness. The novel intelligent capabilities of the METIS system have been built by employing state-of-the-art AI technologies, which allow automated reconfiguration, collection and reasoning of heterogeneous and uncertain information to deliver actionable knowledge in real-time to the operators. The METIS technologies are integrated and validated into a demonstrable proof of concept in the command-and-control platform of our industrial partner, setting a new benchmark for situational awareness systems.

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