An Ontology-Based Approach to Representing and Analyzing Vessel Kinematic and Behavior

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Abstract. *For surveillance of maritime areas, detection of maritime anomalies is a major concern. In general, the approaches to detect anomalies in a maritime setting are based on formal knowledge representation. However, some representations do not take into consideration important aspects of agents and settings. This work aims at presenting an ontology-based approach to represent vessel kinematics and behavior in order to infer abnormal situations in maritime scenarios, based on semantic annotations of vessels' trajectories. The experiments carried out allowed us to obtain relevant inferences to detect anomalies, indicating its potential for practical use.*

Resumo. *Para a vigilância de zonas marítimas, a detecção de anomalias marítimas é uma grande preocupação. Em geral, as abordagens para detectar anomalias em um ambiente marítimo são baseadas na representação formal do conhecimento. No entanto, algumas representações não levam em consideração aspectos importantes dos agentes e configurações. Este trabalho tem como objetivo apresentar uma abordagem baseada em ontologia para representar a cinemática e o comportamento de embarcações, a fim de inferir situações anormais em cenários marítimos, com base em anotações semânticas das trajetórias das embarcações. Os experimentos realizados permitiram obter inferências relevantes para a detecção de anomalias, indicando seu potencial de uso prático.*

1. Introduction

The sea is an essential resource for the global economy, since it is the main transport mode for freight and goods between countries. Also, besides being an important transport mode, the sea also shelters natural resources such as fishing, oil, and minerals. In consequence, to secure the rights for sea use, maritime surveillance requires very efficient methods and tools, due to its high degree of importance.

For surveillance of maritime areas, various sensors are used to collect relevant data that need to be fused to support situational awareness, in which detection of maritime anomalies is a major concern. Examples of such anomalies are terrorism, drug and gun traffic, espionage, piracy, illegal fishing, military operations, and territorial violation [Martineau and Roy 2011].

Maritime surveillance can be proactive or passive. In proactive surveillance, sensors such as radars and sonars are used. In the case of passive surveillance, signal-receiver sensors such as AIS (Automatic Identification System) are used. Besides using data collected from sensors, maritime surveillance also uses analysis of visual data collected from certain points on land, from ships, patrolling aircrafts, and satellite.

In many cases, the approaches to detect anomalies in a maritime setting are based on the analysis of the kinematics and behavior of the involved agents by means of formal knowledge representation and reasoning. However, some representations do not take into consideration important aspects of agents and settings. I addition, data about maritime anomalies are sometimes scarce and difficult to collect, which complicates the study of such anomalies.

Concerning the type of data used by common approaches to detect anomalies, Martineau and Roy [2011] used the following two simple scenarios to illustrate the relevance of considering the use of contextual data:

- Scenario 1: the situation of a ship sailing at an above normal speed is not detected by the surveillance system as anomalous, because its speed is judged consistent compared to that of other nearby ships. Information on the type of vessel could be used by the system to contextualize data about vessel's speed.
- Scenario 2: the surveillance system classifies as an anomaly the behavior of a ship standing in a sea route for not having the information that it is a research vessel, and therefore might be performing some routine procedure.

One could represent the context of these example scenarios by adding a *type of vessel* attribute to a relational database containing the positions and speeds of vessels. Nevertheless, using a semantic model allows richer representations of more complex situations and the integration with ontologies of different domains.

Based on the above mentioned, the problem taken into account in the present work is the limitation in current approaches to detect anomalous behavior, and to represent and reason on data about vessel trajectories in different contexts. Thus, this work aims at presenting an ontology-based approach to representing the maritime domain and allowing inferences about vessel kinematics and behavior in order to detect abnormal situations in maritime scenarios based on semantic annotations of vessels' trajectories.

The rationale for this approach is that vessels' trajectories can be semantically annotated by marking spatio-temporal move and stop episodes. This way, the approach allows semantically rich representations of situations and provides ways of investigating the behavioral patterns of vessels.

The remaining parts of the paper are organized as follows. Section 2 presents some related works to put the proposed approach into perspective in relation to current literature. Section 3 presents the proposed approach for maritime anomalies detection. Section 4 presents the experiments carried out and the corresponding results. Finally, Section 5 presents the conclusion on the work.

2. Related Works

In this section, we present works described in the literature with two purposes. Firstly, we intend to describe those that provided us with inspiration for the present work. Secondly, we intend to provide a fair amount of similar works to ours aiming to put this work in perspective with what is happening in the field of maritime anomaly detection and semantic trajectory representation and reasoning.

2.1. Maritime Anomaly Detection

Martineau and Roy [2011] present an extensive review of the literature on the problem of detecting maritime anomalies. They revise common concepts related to the problem domain and split the anomaly detection process into seven phases: information and data acquisition; information and data fusion; situational awareness; anomalies detection; anomalies contextualization; threat assessment; and dissemination and presentation. Though it is not our purpose to go through all such phases, we summarize the important contribution by [Martineau and Roy 2011] as to provide a general framework for analyzing the problem of detecting maritime anomalies. Riveiro et al. [2018] present a more recent review of the state-of-the-art of research on Maritime Anomaly Detection. The authors analyze the contributions of publications related to data sources to vessel tracking, methods and systems for Maritime Anomaly Detection, user aspects in socio-technical systems, as well the current research challenges in the area. Zhen et al. [2017] combine two techniques, clusterization and Naïve Bayes classification, to classify vessels with anomalous behavior. They validate the proposed approach with real data of trajectories of ships collected from the AIS signal broadcasted by the ships.

PROGNOS [Costa et al. 2009, Carvalho et al. 2010] is a naval situational awareness prediction system. By using the PR-OWL language [Costa 2005], probabilistic ontologies were modeled to unite the expressiveness of OWL (Web Ontology Language) [W3C 2012] with the ability to represent uncertainties by Multi-Entities Bayesian Networks (MEBN) [Laskey 2008]. PROGNOS aims at preventing terrorist attacks. As the purpose of this work, PROGNOS also uses a simulation-based form of agents to simulate various situations containing vessels with normal and anomalous behavior in the context of terrorism. In such works, trajectory analysis is not a topic taken into consideration.

Garcia et al. [2011] present an approach to the construction of a maritime area surveillance system, in which an ontology-based context is a major feature. Through this approach, ontologies were built to represent the maritime domain, especially types of ships, port areas, and Semantic Web Rule Language (SWRL) [Horrocks et al. 2004] rules were defined to describe the types of expected behavior. One of the purposes of this system is the detection of anomalous behavior and threats from the application of navigation rules to ships near a port. To represent the spatial relationships between the entities, they used Region Connection Calculus (RCC) [Cohn et al. 1997], which is a logical theory that defines qualitative topological relations between two regions. The ontology shown in [Garcia et al. 2011] aims to model navigation rules in a maritime port area based on written rules that define, for example, speed restrictions of a vessel to go through a given maritime area. Unlike the approach to represent spatio-temporal trajectories used in the present work, the authors developed an ontology to represent only the spatial dimension, not mentioning any representation of temporal dimension in their ontology.

Some authors [Riveiro et al. 2008, Riveiro et al. 2009] show the efficient use of visualization tools through interactive graphical interface for maritime anomaly detection. They analyzed data from sensors using neural networks of the type self-organizing maps with a Gaussian mixture model. The process uses supervised learning in which the user interacts with each vessel alarm classified as abnormal, whom should indicate if one agrees with the abnormality displayed in the interface. Thus, dynamic parameters of vessels could be analyzed, among which speed and course. On the other hand, such approach has considered only parametric data of vessels, where neither the geographical context nor entities' relationships in scenarios were contemplated, thereby limiting the scope of the provided results.

Brax and Niklasson [2009] present an approach for detecting maritime anomalies using intelligent agents. Each system agent detects an anomaly in the static and dynamic data sets about vessels in specific simulated scenarios. First, simulations are performed without anomalies to train the agents to learn the normal vessel behavior patterns. Then, new simulations containing some vessel anomalous behaviors are performed to train the agents about abnormal behavior. So, this approach combines the use of data sets about position, course and speed of vessels and the information stored in a knowledge base, for the detection of anomalous situations. Despite the use of a knowledge base, the approach cannot handle the meaning of vessels trajectories for anomaly analysis.

In [Roy 2008, Roy and Davenport 2010], the results of a workshop on maritime anomaly detection are discussed. This workshop held meetings with experts in the maritime field, conducted for knowledge elucidation. Among the results obtained, the following information was useful as initial reference for building the ontologies used in this work: anomalies taxonomy; anomalous situation rules; types of analyzed areas, for example, fishing area and anchoring area; and types of activities performed by ships, such as fishing and piracy. In [Roy 2008] a draft ontology is presented and in [Roy and Davenport 2010] the architecture of a proof of concept is discussed. However, the authors do not represent the trajectories of ships as a sequence of episodes with defined semantics.

2.2. Semantic Trajectories

Spaccapietra et al. [2008] introduce a conceptual model for trajectories representation, in order to represent objects' trajectories in episodes of sequential motions of move and stop. The spatio-temporal trajectories model approach has the advantage of enabling associating regions in space and time used on the analyzed object in stop-move episodes. The motivation for this work, according to the authors, was the importance of enriching the trajectory data with semantic annotations in order to offer a more complete representation of these trajectories.

Yan [2011] presents an approach for trajectory analysis to facilitate the understanding of dynamic behavior of mobile objects through a semantic representation of trajectories. For experimenting with the approach, different datasets, such as trajectory data of cars, buses, people (data collected from the smart phone sensors) and migration of birds were used. In these experiments, Yan performed also the integration of data from a particular domain, a trajectory ontology and geographic data from specific locations. The main advantage of separately modeling these three distinct types of knowledge is the possibility of replacing or reusing them in other systems. Our work is based on the modular ontologic framework developed by Yan. We build and integrate a maritime ontology to the framework as the application domain ontology.

3. Approach to Representing and Analyzing Vessel Kinematic and Behavior

The purpose of the proposed approach is to offer a way to represent vessels kinematics and behavior in order to allow inferences about abnormal situations in a maritime scenario, based on semantic annotations of vessels' trajectories. Figure 1 depicts the approach's architecture.

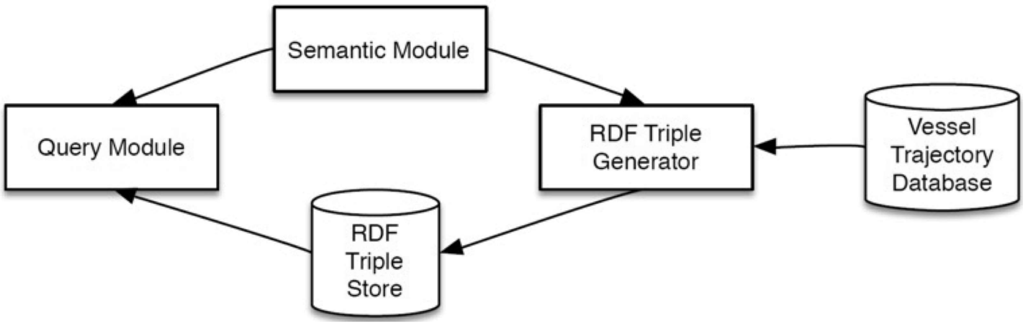

Figure 1. Architecture of the Proposed Approach.

3.1. Semantic Module

The Semantic Model is composed of three ontologies formalized in OWL 2 DL: maritime domain, trajectory, and Simple Event Model (SEM). The maritime domain ontology represents knowledge about vessels' categories and properties, and concepts related to the maritime environment. The trajectory ontology specifies relevant aspects related to vessels' trajectories, such as origin and destination ports. The simple event model ontology supports the representation of stop-move events. Besides such ontologies, logical rules written in SWRL were defined to allow inferences on vessels' behavior.

Figure 2 depicts the maritime domain ontology in the interface of Protégé [Musen 2015], which is based on naval regulation and the maritime anomaly taxonomy proposed by [Roy 2008]. The highlighted class *PREPS_Vessel* on Figure 2 represents the Brazilian fishing vessels that must send their position to the Brazilian government, according to their size and gross tonnage, as defined on regulations. We applied the knowledge-engineering methodology of [Noy et al. 2001], discussed at [Antoniou and Van Harmelen 2008], for the construction of the maritime ontology.

To build the maritime domain ontology, we extracted rules and definitions from regulations of the Brazilian Navy [Marinha do Brasil 2005, Marinha do Brasil 2013b] as references and also the expertise of one of the authors in planning and executing naval operations. The terms used in the ontology were taken from the vocabulary found in these regulations. The taxonomy of vessel types was drawn up based on the definitions from the reference documents.

As can be noticed in Figure 2, the main ontology's classes are: *Jurisdictional Water*, *Anomaly*, *Area*, *Activity*, and *Vessel*. The class *Jurisdictional Water* represents the legal classification of a sea region and its corresponding jurisdiction, including navigable waters, interstate waters, territorial waters, tributaries, and so on, as defined internationally by [United Nations 1982] and in Brazil by [Marinha do Brasil 2013a]. The Class *Anomaly* depicts the type of anomalies of interest. Only a few kinds of anomalies were

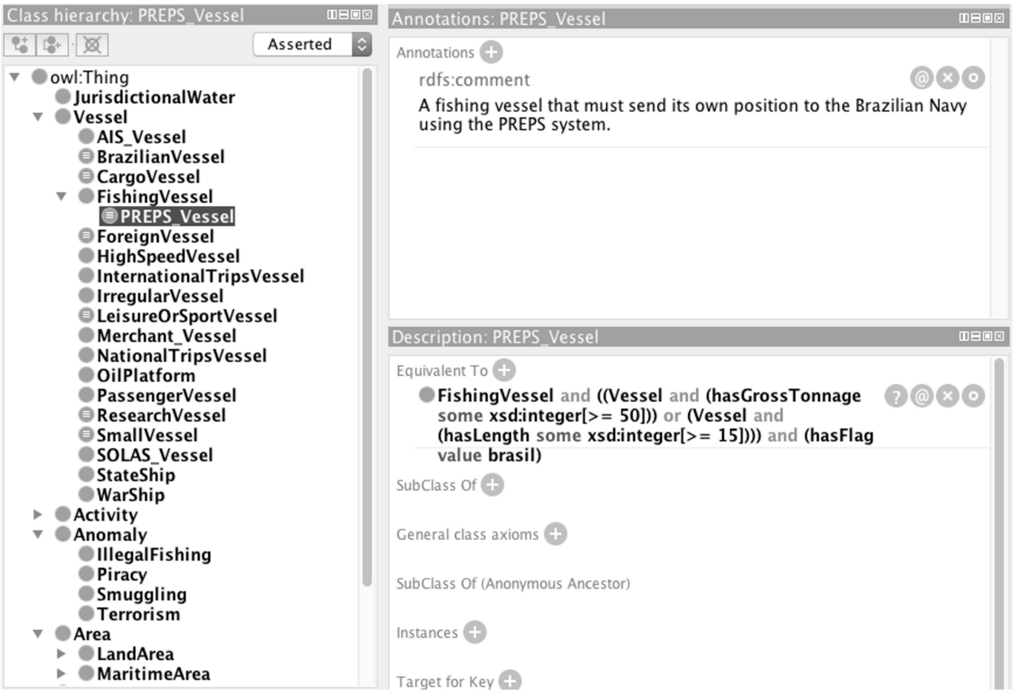

Figure 2. Maritime Domain Ontology.

considered in the present version of the ontology: smuggling, illegal finishing, and piracy. The class *Area* represents the kind of related maritime areas we took into consideration. The class *Activity* describes the type of activities vessels can perform. And finally, the class *Vessel* encompasses the type of vessels we used. It should be noticed that the main classes are not exhaustive, but present only the subclasses that allowed us to carry out the experiments to show the proposal's feasibility.

Figure 3 depicts the Trajectory Ontology, which is based on the works of [Yan et al. 2008, Yan 2011]. As can be seen in the figure, the Trajectory Ontology has a class named *Geo*, as defined by Yan, to represent geometry entities, as points, lines and surfaces. The class *BES* represents all the begins, ends and stops of a trajectory. The class *TimePoint* depicts an abstract entity that keeps the relationship of an instant in time and a place in space during the trajectory. The main classes that represent the episodes of a trajectory are the classes *Begin*, *End*, *Move*, and *Stop*.

The third ontology used was the Simple Event Model [van Hage et al. 2009, Hage et al. 2011]. SEM is intended to represent events in distinct domains. The SEM ontology main classes are *Actor*, *Event* and *Place*. Figure 4 depicts the SEM ontology in RDFS and RDF, illustrating an example of a sailboat anchoring that took place at an indicated geographic point in the territorial sea. Thus, we can describe, through RDF statements, an event, its actors, the place and the time period in which the event occurred, as well as other relevant properties of the event.

As described in the next section, for experimental purposes, the SEM ontology is used in this work to represent two types of events. *Vessels rendezvous* is defined as an event that occurs when the relative distance between two vessels is less than a given distance; and *Navigation in area* is defined as an event that occurs while a vessel sails

Figure 3. Trajectory Ontology.

throughout a given maritime area.

3.2. Query Module

The Query Module uses the SPARQL query language [W3C 2013] for querying the Triple Store about the anomalous situations of interest, attending the needs to identify anomalous situations inserted in the Triple Store accurately.

As described in the next section, for instance, we asked SPARQL queries related to illegal fishing, piracy and smuggling.

4. Experiments and Results

To submit SPARQL queries to the semantic model created, we first needed to generate synthetic data in RDF format to compose sets of assertions representing different situations. As mentioned earlier, it is not easy to obtain real data on anomalous trajectories. Therefore, we used two ways for generating RDF data to compose the Triple Store:

- Agent-based simulation, to generate statements in the form of RDF triples, to represent vessel trajectories. This technique allows to simulate the movement of agents (vessels) by a scenario with real geographical positioning data;
- Direct generation of RDF triples about situations containing synthetic trajectories of vessels but without taking into consideration geographical data, vessels position calculation and topology verification.

4.1. Agent-based Simulation

For the agent-based simulation experiments, we used the library MASON [Luke et al. 2005, Luke 2011] for multiagent-based simulation and its extension

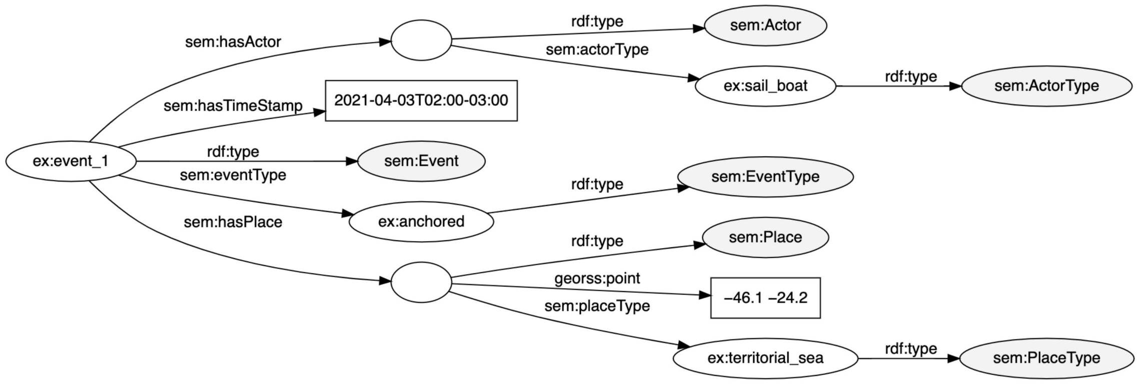

Figure 4. Example of an event represented in SEM ontology.

GeoMason [Sullivan et al. 2010]. To convert the trajectory data generated by the multiagent simulation into a RDF file, we used the framework Jena [Carroll et al. 2004]. Listing 1 illustrates the RDF description of a sample vessel's simulated behavior.

```
1  ex:stop1_ag5
2        trj:hasInterval
3               [ trj:hasFirstInstant ex:t191 ;
4                 trj:hasLastInstant ex:t211
5               ] ;
6        trj:hasPoint ex:p186 .
7
8  ex:move3_ag5
9        trj:from ex:stop2_ag5 ;
10       trj:to   ex:stop3_ag5 .
11
12 ex:p186
13       georss:point "−46.176 −24.270" ;
14       sea:isInsideArea
15              ex:area_1 .
```

Listing 1. RDF Description of part of a Vessel's Simulated Trajectory

In Listing 1, as indicated in lines 1 to 6, the agent *ag5* stopped at the point *p186*, during the interval *t191* to *t211*. The point *p186* is inside the *area_1*, as described in lines 12 to 15.

In addition, to perform the experiment we used geographic information stored in the shape file format files. The shapefiles used in the experiment were created and edited with the free software QGIS [Quantum GIS 2011]. Such a software takes advantage of the GDAL library [GDAL 2014] features, thus allowing viewing and editing georeferenced files of various formats, including electronic nautical charts of the raster type and the type vector on the S-57 standard [IHO 2000]. Raster charts contain georeferenced images, while vector charts store a collection of georeferenced geometries and additional data about their attributes.

Some points were created in the scenario to represent cities and ports and lines were created to represent vessels routes. These routes were intended to limit and guide the movement of the agents during the simulation. In future research we intend to model the agents with intelligent behavior, not just following routes. The behavior of an intelligent agent capable of making decisions related to the best path, watching and taking into account surrounding objects, will allow studies on the occurrence of behavioral patterns.

We simulated trajectories of fishing vessels leaving a port, going through and stopping inside a prohibited fishing area, and then returning to the same port. For the ontologies of the Semantic Module, classes' instances were generated by the simulation tool for three different scenarios: smuggling, illegal finishing, and piracy.

For all of these scenarios, we assumed that whenever a fishing vessel stops it is because it is doing a fishing activity. For these three scenarios, some queries related to illegal fishing were submitted.

Thus, on the basis of this premise, we could ask the following question to identify fishing vessels in a possible abnormal situation: Which fishing vessels stopped in any prohibited fishing area? This query then could be translated to SPARQL, as can be seen in Listing 2.

```
SELECT DISTINCT ?e ?a
WHERE {
   ?e   trj:hasTrajectory ?t.
   ?t   trj:hasStop       ?s.
   ?s   trj:hasPoint      ?p.
   ?p   sea:isInsideArea   ?a.
   ?a   a    sea:ProhibitedFishingArea.
}
```

Listing 2. SPARQL Query about Vessel Stop in Prohibited Fishing Areas.

Thus, other general questions related to fishing in prohibited areas were asked to the triple store in a very similar way. In addition, many other combinations could be asked. The approach is robust enough to accept queries with several temporal and spatial restrictions.

4.2. Strait RDF Triple Generation

As already mentioned, we also developed a tool to generate RDF triples for trajectories of different vessels. The tool was implemented in Java, using the library Jena. In this tool we used a Markov chain to generate trajectory episodes in terms of begin, move, stop, and end, such as used in [Spaccapietra et al. 2008]. Figure 5 depicts the possible trajectory episodes and the parameters $p_1, p_2, p_3, p_4, p_5, p_6$ that define the probabilities of each transition.

With the generated dataset, we asked queries related to fishing, piracy and smuggling. An example query we asked was the following:

Which vessels ran into each other in a common period of time, where one of them is a merchant vessel coming from a foreign port, the other is coming from a small port, the rendezvous point is in a suspicious smuggling area, and the stop duration is longer than 30 minutes?

Listing 3 presents this query in SPARQL syntax. We kept the three ontologies apart, giving a distinct namespace for each one to improve modularity and reuse: the *trj* namespace is a reference to the Trajectory Ontology, *sea* refers to the Maritime Domain

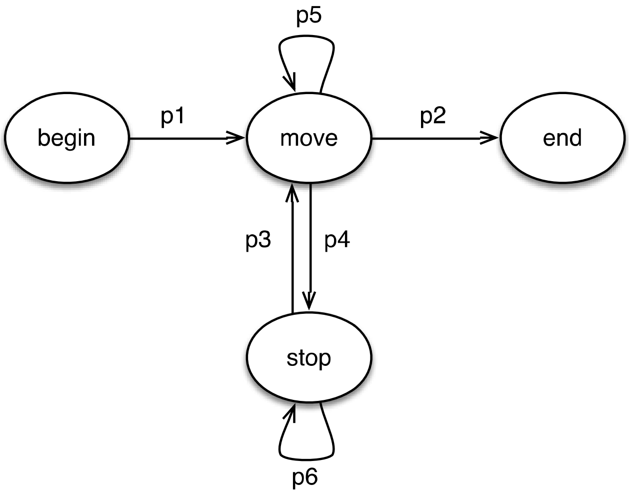

Figure 5. Markov chain to generate trajectory episodes.

Ontology, and *sem* refers to the Simple Event Model. Running this query, the reasoner returns a list of events that satisfied the query conditions, along with related vessels, places, and time periods.

```
SELECT ?event ?vessel1 ?vessel2 ?place ?time_first ?time_last
WHERE {
    ?vessel1 trj:hasTrajectory/trj:hasStop ?stop1 .
    ?vessel2 trj:hasTrajectory/trj:hasStop ?stop2 ;
             sea:portOfOrigin/a sea:ForeignPort.
    ?stop1 trj:overlaps ?stop2.
    ?event sem:hasActor ?vessel1 , ?vessel2 ;
       sem:hasPlace ?place;
       trj:hasInterval ?int_evt;
       sem:eventType sea:vesselsRendezvous.
    ?int_evt trj:hasFirstInstant/rdf:value ?time_first;
           trj:hasLastInstant/rdf:value ?time_last.
    ?place a sea:smugglingArea.
    FILTER (?vessel1 != ?vessel2)
    FILTER (?time_last - ?time_first > 30)
}
```

Listing 3. SPARQL Query to find ships with a smuggling trajectory pattern

Another example of a query for this dataset, related to suspicious smuggling behavior, that was correctly answered was the following: What vessel approach in high speed a merchant vessel and then stops?

4.3. Result Analysis

The multiagent-based simulation mechanism provided richer possibilities to represent detailed scenarios but at a higher computational cost. On the other hand, the random Markov chain mechanism provided more straightforward ways to represent anomalous situations but at the expense of more superficial scenario representations.

From a complementary perspective, both data-generation mechanisms supported the construction of data sets that allowed the proposed approach to make inferences about abnormal maritime situations to detect anomalies, indicating its potential for practical use.

We developed a proof of concept to study the feasibility of applying a maritime ontology as a module of the ontologic framework proposed by [Yan et al. 2008]. First, we build an ontology model with concepts and business rules from the maritime domain and then we execute queries to a knowledge base populated with data from simulated scenarios. Table 1 presents the number of OWL constructs of each ontology we used in this work. Note that for the study of this proof of concept, we build a small maritime ontology, representing selected concepts of the domain. Thus, the time and space complexity of the queries is a minor concern in this work.

Construct	Maritime	Events	Trajectory
Class	55	17	34
SubClass	44	14	28
Equivalent Class	8	0	0
Object Property	16	15	18
Data Property	13	7	5
SWRL Rule	11	0	0

Table 1. Number of constructs of each ontology.

5. Conclusion

The presented approach permits inferences about spatio-temporal trajectories of vessels in an anomalous situation. This study analyzed a small number of situations, which, however, were representative enough to show the potential of the proposed approach. Therefore, the approach can be applied to other types of anomalous situations, requiring only the descriptions in the corresponding semantic module.

As future work, we intend to refine the approach considering other practical aspects to be suggested by subject matter experts and use real data as much as possible. Another intention is to refine the approach to allow reasoning about what will happen according to present and historical situations. More specifically, we envisage the following works:

- Representation of the relative movement between vessels and other scenario objects: The integration of this representation with the ontology of semantic trajectories might provide richer trajectory representations. Van de Weghe et al. [2006] show the Qualitative Trajectory Calculus (QTC), a formalization to represent the qualitative analysis of trajectories. In [Cohn et al. 1997], a topology defining spatial relationships is presented. A study on this topology in conjunction with the QTC and the presented approach could enable rich ways of representing and analyzing vessels trajectories. Temporal relations, as *before*, *equal* and *overlaps*, are defined in [Allen 1983] to represent the relationship between two time intervals. The use of these time relations can provide a richer representation of events on the maritime domain;
- Application of the proposed approach to other domains, such as air traffic control, urban transportation analysis and analysis of people's moving patterns based on

data collected from mobile devices, and Unmanned Aerial Vehicle (UAV) trajectories analysis taking into consideration geographical, meteorological, and demographical data;

- Provide support for air accident investigation based on aircraft trajectories and geographical and meteorological data; and
- Ground the ontologies of the Semantic Module on a top ontology, in particular Basic Formal Ontology (BFO) [Arp and Smith 2008], as it provides classes related to the spatiotemporal domain, as the classes *spatiotemporal region* [1] and *temporal region* [2].

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