Proc. of International Waterside Security Conference 2010

Object-Oriented Sensor Data Fusion for Wide Maritime Surveillance

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Abstract— **The objective of maritime surveillance is to reach a level of situation awareness which allows the timely detection and prevention of events threatening maritime security and environment. Due to the heterogeneous mix of platforms and sensor technologies in use today, there is a need for powerful sensor data fusion architectures. This article introduces an object-oriented approach for the fusion of object observations produced by arbitrary heterogeneous sensors. Different scenarios and sensor configurations as well as fusion algorithms can be evaluated by a simulation tool. The benefits of the architecture are highlighted for an illegal immigration scenario.**

Keywords- maritime domain awareness; maritime picture; object-oriented world model; surveillance system

I. INTRODUCTION

The challenge of advanced surveillance systems is not to collect as much sensor data as possible, but rather to process and present them in an intelligent and meaningful way to give a sufficient information support to some human decision maker. The mental state of a decision maker is often referred to as *situation awareness*. The most commonly used definition of situation awareness was provided by Endsley in [1]:

> "Situation awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future."

In her article, she also distinguishes between the term situation awareness, as a state of knowledge, and the term situation assessment, as the processes used to achieve that state. Furthermore, situation awareness is the major basis for decision making and can therefore be interpreted as the mental state of a decision maker.

Endsley's definitions are directly applicable to the maritime domain. The main goal of maritime surveillance is to support situation awareness, or more specific, maritime domain awareness through building a maritime picture and providing a basis for further decisions, e.g. intervention actions or sensor planning. The executed decisions directly affect the elements in the environment and have influence on their perception again. Therefore the connection between the three components of situation awareness and the decision component can be visualized by a cycle as already depicted by Endsley in [1] and adapted in Figure 1.

However, the maritime picture is not only a visualization of a map and ship detections. The maritime picture can be viewed as a mean of collecting all information about the current situation at sea, which also includes the comprehension of specific object states or relations between objects, and furthermore the projection of the current situation in the future. In Figure 1, the maritime picture can be interpreted as the result of the three processes perception, comprehension, and projection. The focus of the maritime picture is on supporting the maritime domain awareness of a decision maker as best as possible.

Several problems arise when the observed area for generating a maritime picture is very large. First of all, there are many different objects that can behave in many different ways. There are for example tankers, which normally follow the shipping routes, or small pleasure boats, which follow a more random route. But, however, almost all of the observed ships are expected to behave normal, which means that they do not want to hide their intentions or, in other words, are cooperative. Another problem is that not every ship in a wide maritime area can be observed all of the time. Every sensor used for the detection of ships has a limited range either in space or in time. For example satellite images can provide

Figure 1. Situation awareness cycle

This research is partially supported by the WIMAAS project (Wide Maritime Area Airborne Surveillance) co-funded by the European Commission under the Seventh Framework Programme (http://www.wimaas.eu).

pictures over a wide area, but the temporal resolution is quite low, as the images are only a snapshot at a certain time. Video cameras on an airborne platform provide a high temporal resolution but only small areas can be observed by them.

As one can imagine, a decision maker needs more than the fused information gathered by several heterogeneous sensors and visualized them in a map. A decision maker needs automatic support by guiding his focus of attention, either on a certain area or on a certain object that behaves abnormal. The challenge in supporting maritime situation awareness by means of a maritime picture is therefore not only to know about every kind of activity that is going on in the whole area, but also to differentiate between relevant and irrelevant activities. In wide maritime surveillance, the focus lies in the detection and localization of non-cooperative ships, e.g. ships that hide illegal immigrants on board and distinguish them from the normal traffic in a certain area.

The paper is structured as follows. Section II gives an overview of the related work in situation awareness, data fusion, world modeling and in maritime anomaly detection. Section III describes the assumptions made for the surveillance environment. In Section IV, the sensor data fusion architecture used for generating the maritime picture is presented in detail. In Section V the Simulation of an example-scenario is described and it is shown how the simulation can support the evaluation of the fusion modules. The paper finishes with a conclusion and outlook in Section VI.

II. Related Work

Endsley introduced in [1] a theoretical model of situation awareness and it is the most widely used model today. She developed the model based on its role in dynamic human decision making and stated that individuals with good situation awareness will have a greater likelihood of making appropriate decisions in complex environments. Working with heterogeneous sensors, the theories of multi-sensor data fusion [2] offer a powerful technique for supporting situation awareness. A lot of data fusion models have been developed and compared to Endsley's situation awareness model [3], whereas the most dominant model is the JDL model [4].

The *object-oriented world model (OOWM)* was developed in [5] and is an approach to represent the relevant information extracted from sensor signals, fused into a single comprehensive, dynamic model of the monitored area. The basic ideas have been published in [6], whereas a detailed description of the architecture can be found in [7]. An application of the OOWM to the maritime domain is described in Section V. One challenge in a maritime surveillance system is the management and planning of the sensor data acquisition, where one has to deal with heterogeneous sensor platforms and sensor types [8]. Signal-processing methods like object detection and classification, e.g. on the basis of infrared image sequences [9], play an important role in the whole system. But low-level fusion issues like position fusion, identity estimation, multi-target tracking [10] or track association [11] are building then the basis for supporting maritime domain awareness in a maritime surveillance system. More advanced systems also support high-level functions such as situation assessment as described in general in [12]. Situation assessment in the maritime domain is often referred to as anomaly detection. Existing approaches in anomaly detection are rule-based [13], probabilistic like Bayesian networks [14] or they involve the user directly in the anomaly detection process by means of visual analytics [15].

III. Surveillance Environment

When designing a surveillance system, it has to be clarified first, where the detections come from. In the following, we assume that there is one *ground control station (GCS)* that is responsible for a specific area, namely the area where activities on the sea and surveillance missions take place. All information collected from various types of sensors is sent to the ground control station, either preprocessed or in raw format. The ground control station is responsible for the fusion of all sensor information, which result builds the basis for the maritime picture. This concept is a system of system approach [16] and is highlighted in Figure 2.

For our approach we assume, that there are real activities happening outside in the sea during a spatio-temporal section of the real world. Such activities can be divided into legal and illegal activities, whereas the legal activities consist of normal background traffic including cooperative boats and the illegal activities consist of non-cooperative boats with an illegal intention like drug trafficking or carrying illegal immigrants over a border on the other hand. The challenge in the ground control center is then to separate the illegal from legal activities by means of surveillance resources and highlight them in the maritime picture.

Thus, the planning of a surveillance mission is a critical point as further results like the detection of an illegal activity are strongly dependent on a sufficient mission planning. By a mission we mean the tasking of different platforms for the surveillance of an area or object of interest. A mission can in general be associated to a mission class, for example routine surveillance, targeted surveillance or search mission.

Mission planning includes not only the definition of the mission objective and its duration, but also the selection and tasking of available platforms and its sensors to fulfill the mission objective. Several conditions influence the selection and tasking process. Firstly, the platform and sensor selection is strongly dependent on the environmental conditions (e.g. weather condition or sea state). Secondly, platforms for

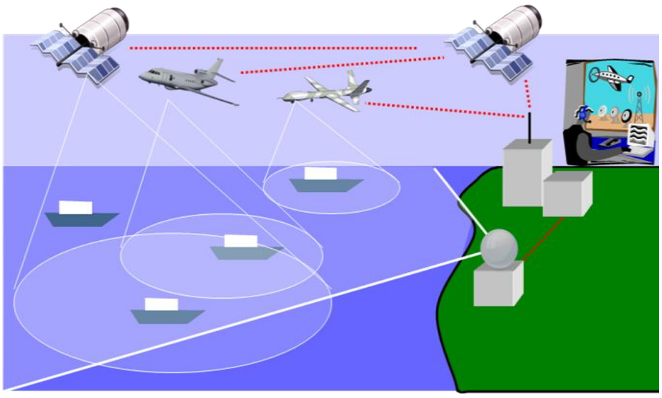

Figure 2. System of Systems Concept

maritime surveillance systems are of various types and have therefore different characteristics. They can be located on ground like coastal radars or AIS[1] antennas or on the water like buoys or patrol vessels. They can be used as surveillance resources but are often limited in their spatial range as they cannot be used beyond the line of sight. Platforms in space like satellites provide information acquisition for wide areas, but a big disadvantage is their high revisiting time. A more flexible opportunity offer aerial platforms like UAVs[2], as their flight plan can also be adjusted during the flight.

IV. Sensor Data Fusion Architecture

The requirements for the fusion architecture are derived from the analysis of threat scenarios (e. g. illegal immigration) and possible configurations of both stationary and mobile sensor systems. The central part of the fusion architecture is a consistent representation of the real world. As our approach is object-oriented, we call our representation the *object-oriented world model (OOWM)*. Its objective is the fusion of object observations that have been collected from multiple and heterogeneous sensors and platforms and it serves therefore as an information source for application-level modules like visualization and more high-level methods like track analysis or behavior recognition. To account for uncertainty introduced by inaccurate signal-processing and incomplete sensor coverage of the area of interest, a probabilistic representation is chosen. The OOWM system and its connection to application-level modules, signal-processing modules and sensor deployment in the context of a maritime surveillance system are highlighted in Figure 3.

As the objective of the OOWM to deal with object-oriented information, it is assumed that there are signal-processing modules located between the sensor deployments and the OOWM. These modules are responsible for extracting object detections and feature measurements from raw sensor data, e.g. the detection and localization of ships or even tracks of ships, estimation of the size, heading or speed. This way, any sensor technology can be integrated as an object observation provider.

The object information that can be derived from the modules is of course dependent on the sensor capabilities. In the maritime domain, some sensors like the AIS receivers are even able to deliver the identification number of the ship (e.g. the ship identification number defined by the IMO[3] or the MMSI[4] number) or its origin and destination.

In order to serve its objective, the OOWM has to perform several challenging tasks, which are highlighted in the following:

- *Information Representation and Distribution*

  An application independent representation of objects, its features and uncertainty about their assessment has to be developed. To distribute object information to high level applications, a unified access and query mechanism has to be established.

- *Data Association and Tracking*

  For each new object observation, it has to be decided if it corresponds to a new object or represents updated information about a previously observed object.

- *Data Fusion*

  If the data association states that the object observation belongs to previously assessed information of the same object, the older and the newer information have to be fused in order to have a consistent representation.

- *Information Aging and Management*

  First, it has to be managed, whether objects which have not been observed for a longer time period can be removed from the object representation. Secondly, it has to be decided if information that does not belong to a previously observed object justifies the existence of a new object.

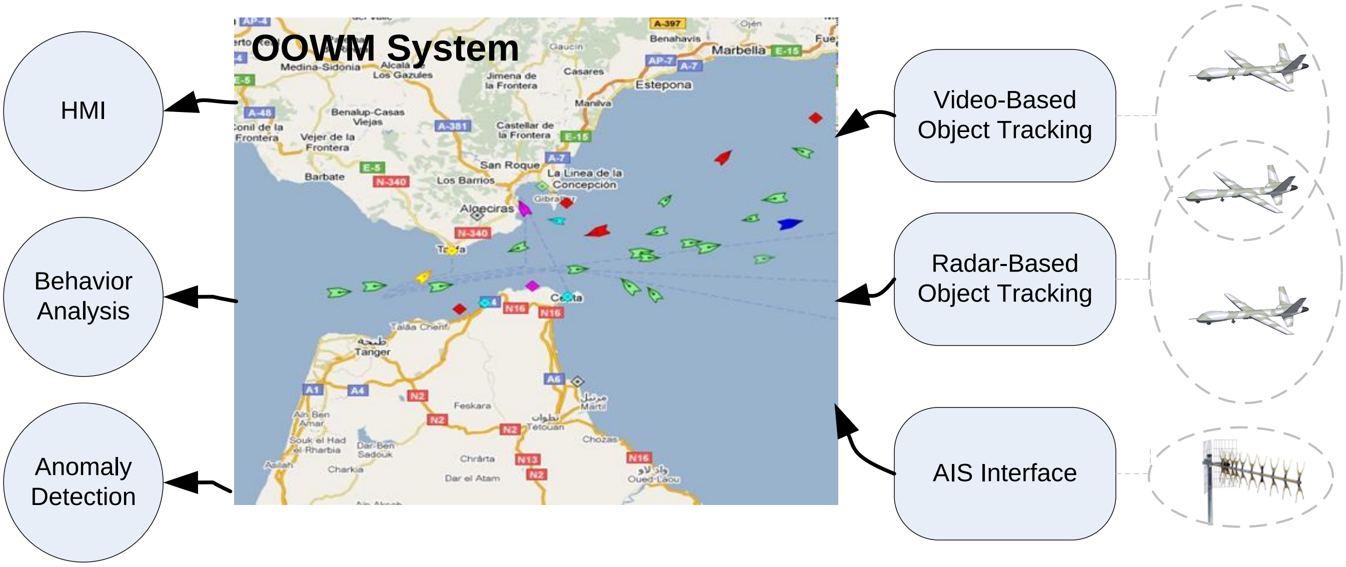

Figure 3. The OOWM System and its connection to application-level modules, signal-processing modules and sensor deployment

[1] Automatic Identification System
[2] Unmanned Aerial Vehicles
[3] International Maritime Organization
[4] Maritime Mobile Service Identity

As the OOWM is the basis for higher-level fusion methods like situation or intention recognition and thus is the critical element for supporting situation awareness, algorithms for solving the highlighted tasks have to be selected carefully. The choice of the algorithms and the settings of the parameters depend not only on the sensor properties, but also on the application domain and the properties of the objects under surveillance. Algorithms for data association, fusion and tracking are encapsulated as software modules, in order to be able to extend the system with improved algorithms and application-specific fusion algorithms. Sensor coverage and age of information is explicitly modeled and updated using the knowledge about the current positions and footprints of stationary and mobile sensor platforms.

The main benefit of the object-oriented and probabilistic representation is the establishment of a generalized object representation, which is designed to be independent of application and signal-processing modules. The generalized representation enables the independent development of new modules on the application-level as well as on the signal-level. The system is implemented as a service-oriented architecture.

Figure 4 shows a more detailed view inside the architecture of the OOWM that tries to solve the above listed challenges. The sensor services on the right side depict the signal-processing modules that extract object information out of raw sensor data. These object information are sent to the observation bus and transferred to the observation interface. It should be mentioned that the sensor services do not have a fixed location as they can be applied in the GCS or on board of a UAV.

The first step in the fusion chain is the data association. The decision if a new object observation belongs to a known object is based on various attributes of the object. If one known attribute of the object is a unique identifier of the object, then the data association states no problem. But if only the position of an object is known, the data association turns out to be a multi-target-tracking problem with an unknown number of targets. Various methods exist for solving this problem, whereas the most common methods nearest neighbor, are JPDA[5] or MHT[6], see e.g. [2], [12] or [17] for further information and references.

If the data association states that the object is previously known, the information about the object has to be updated with the new observations. This is done by the fusion manager that consists of several fusion modules. For updating position and speed attributes, the well-known Kalman-filter ([2], [12]) is used. Static attribute values like the size of a boat are enhanced by the Bayesian fusion method. If the data association states that a new object has been detected, the instance manager creates a new object instance. The instance manager is also responsible for removing object instances that have not been observed for a longer time. Thus, the object-oriented representation is always cleaned from false-instantiations or objects that are no longer present in the surveyed area.

The object-oriented representation is the main part of the OOWM. The represented objects are described by their attributes which are modeled as degree of beliefs [5]. If the type of an object is not determined at instantiation time, it can be dynamically estimated and updated by a classification module. This module classifies the object by matching its attribute characteristics to predefined object prototypes, for example by the length value of a boat (a tanker is in general much longer than a pleasure boat).

Higher-level modules can access the object-oriented representation via an interface. These modules try to assess the current situation on a higher semantic level and are therefore able to query for or subscribe to certain categories of events. An example of such a high-level module could be a Bayesian network that subscribes to the attribute information of one specific boat and classifies its behavior as normal or abnormal, as it is done in [14]. The results of such high-level services greatly enhance the awareness of the current situation and they can furthermore be used as an input for new mission plans.

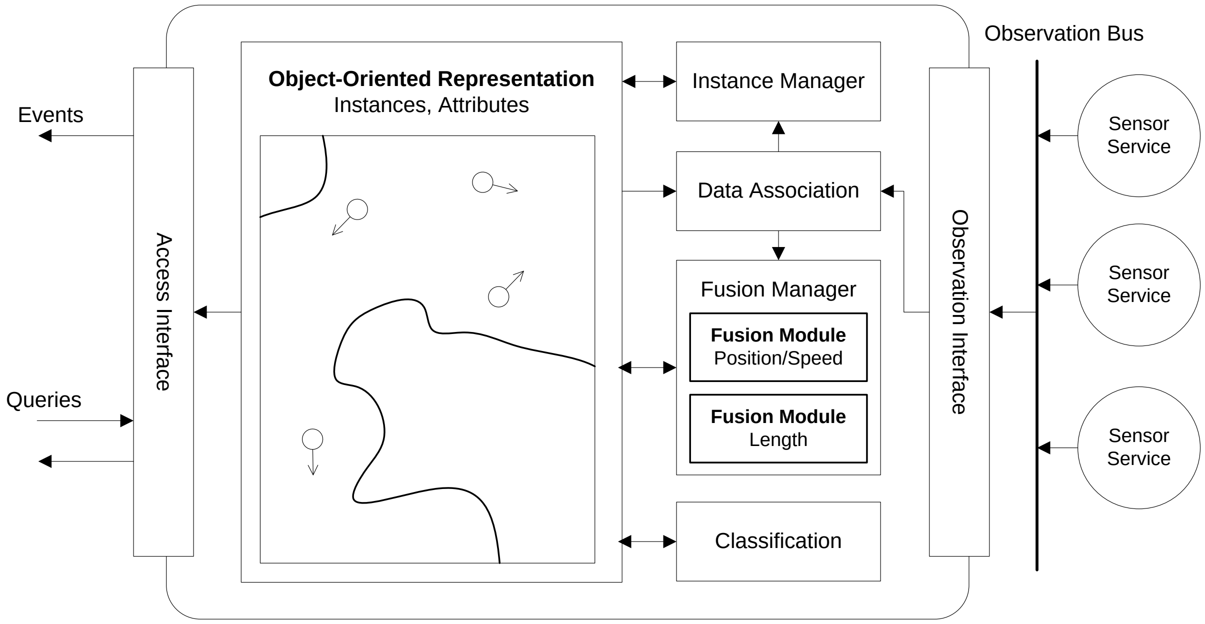

Figure 4. The OOWM System architecture

[5] Joint Probabilistic Data Association
[6] Multiple Hypothesis Tracking

V. STEP SCENARIO SIMULATION

The acquisition of real-data and ground-truth in the maritime domain is expensive and access to previously recorded data is often restricted. An alternative approach for evaluation of fusion results is simulation of sensor data. Therefore a scenario simulator has been developed, for investigating state-of-the-art methods for multi-target tracking and data association. Using the simulator, complex scenarios can be defined and in each scenario, different sensor configurations as well as data fusion and situation recognition methods can be evaluated.

Ship tracks representing the ground truth data are designed by connected line segments, whereas every vertex is annotated with the ships speed. Moreover, a time offset related to the starting point of the simulation can be set. Background traffic, or in other words, tracks from cooperative ships have been designed based on shipping routes and their ship information was adopted from AIS data available on the web site of the marine traffic project [18]. In addition to the cooperative ships, six ships with an illegal intention have been added to the simulation scenario. The illegal intention of the five small boats, starting from the coast of Tunisia is to drop off illegal immigrants on the island of Lampedusa. They take a direct course to the island, staying close together in a group. Another boat with illegal immigrants on board starts at the Libyan coast and also takes a direct course to Lampedusa. It is assumed that the boat from Libya is a larger motorboat and is therefore faster than the five boats from Tunisia. Additionally, several surveillance resources have been configured, namely two UAVs, one with a base location on Lampedusa and the other on Malta. The STEP[7] scenario simulation window, in which the scenario configuration takes place, is displayed in Figure 5.

The simulator is able to produce object observations and feature measurements in predefined multi-target multi-sensor scenarios. The fused observations are visualized in the STEP view window that is depicted in Figure 6 and 7. When staring the scenario simulation in the STEP scenario simulator as described above, the sensors start their simulation of observations and the functions in the STEP view window can be used. If a boat is in the footprint of a sensor, an object detection is sent to the observation interface of the OOWM. The data association, and either the fusion manger or the instance manager make their decisions and their result is sent to the object oriented-representation. Either the attributes, which are mainly the position and the speed, of a previously detected ship are updated or a new instance of a ship is created. In Figure 6, the circular footprint of the sensor located on a UAV is visualized. Inside the footprint, the detections of some ships can be seen. By zooming in, one can see that five ships have been detected and some of their last positions are highlighted, see Figure 7.

If the type attribute of the ship is unspecified, the classification module tries to classify the ship based on its other attributes. By selecting one boat inside the STEP viewer, its attributes are listed on the left side of the viewer, as depicted in Figure 7. Furthermore, several situation assessment services can be initialized. The operator can draw a polygon inside the viewer to create an area, where he wants to know what is going

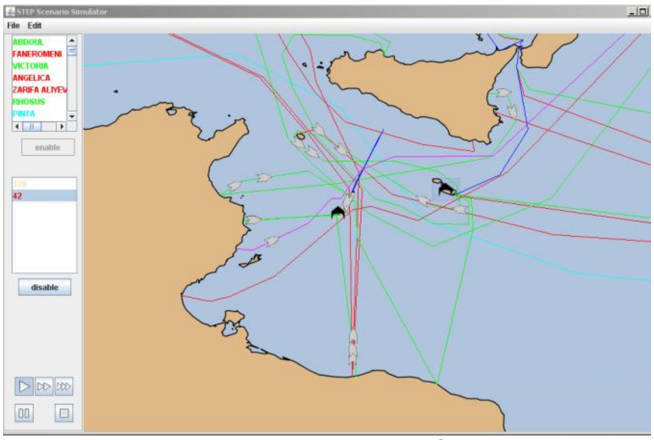

Figure 5. STEP Scenario Simulation

on. This area assessment gives an alarm for every object that has been detected inside. For each area, several constraints can be added. These constraints are formed as simple rules (greater, smaller, equals, etc.) with respect to some attribute value and the rules can be combined by logical conjunction or disjunction. For example, for the detection of the illegal immigration boats, one can exclude boats with a very high speed, very large size, and heading towards Tunisia or Libya. As a result, the detected boats in the area assessment that fulfill the rule are highlighted in the STEP viewer and an alarm is generated. The main benefit of the architecture is that the situation assessment services are completely independent of the platforms or sensors used for the detections. Due to common fusion algorithms, adding more platforms and sensors enhance the estimation of the attributes of the detected objects.

If an alarm is generated by the system, the decision maker has to decide how to act. One possible action is to send another surveillance resource there for confirming the suspect. This could be another UAV, equipped with a visual or infrared camera on board, sending high-resolution images or videos to the GCS. Therefore, the STEP view offers the possibility to

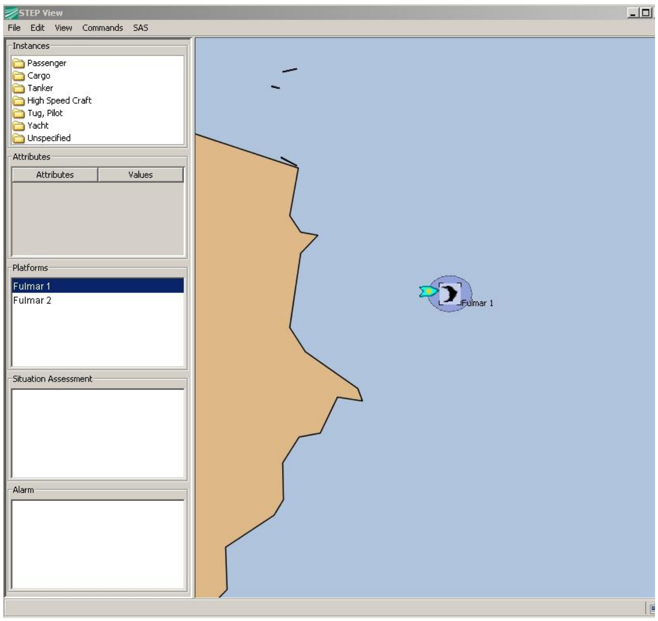

Figure 6. STEP View

[7] Sensors, Targets, Events, Platforms

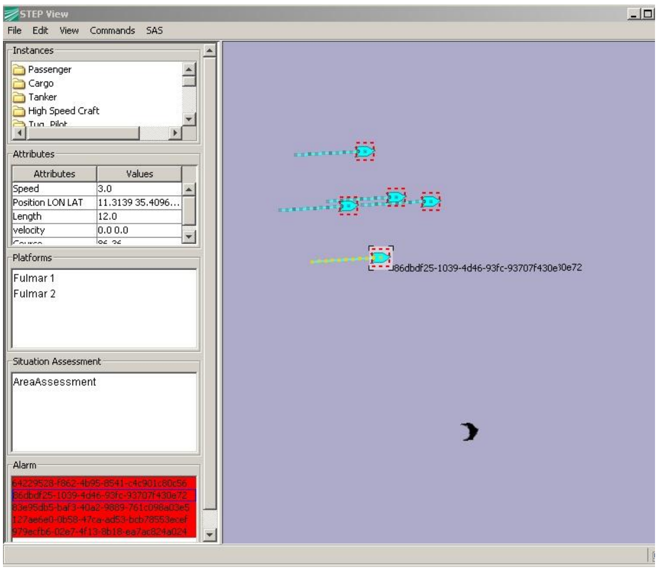

Figure 7. Tracking Visualization

select a platform and plan its flight route. The route of the UAV can be planned in several ways. Firstly, waypoints can be chosen and the UAV is visiting them one after the other. Secondly, a rectangle area can be drawn which marks an area that the decision maker wants to have surveyed completely. The UAV is planning then its own route inside this area, whereas the area will be completely covered by the sensor footprint. Thirdly, it is also possible to select an already detected object, for example a boat that has generated an alarm. The UAV is moving then to its designated target and follows it as long as no other tasks are made. It is therefore possible to re-task a platform during its operational flight and change its flight route interactively during the simulation.

VI. Conclusion and Outlook

In this article, we introduced an object-oriented sensor data fusion architecture for the fusion of object observations produced by arbitrary heterogeneous sensors, as it is the case in maritime surveillance. The resulting object-oriented representation of the activity in the area of interest serves as a basis for higher-level situation assessment algorithms and for the visualization of the situational picture.

The proposed sensor data fusion architecture, namely the OOWM and its realization in a simulator environment is a first step towards a surveillance system as it can be used in a ground control station for supporting maritime situation awareness. Different ground truth scenarios and sensor configurations can be simulated. Basic fusion algorithms for object detections have been included and its estimation results are displayed in a viewer. Simple rules serve as a situation assessment service, which can be adjusted and used for the detection of boats with certain attributes in certain areas. The use of the complete system was shown for an illegal immigration scenario.

A future development will be to generate more background traffic and to include more different platforms and sensors into the STEP scenario simulator. Other illegal activity traffic will be added to the scenario, for example a hijacking situation, which includes complex behavior between several boats and evolves over time. Furthermore, more advanced data association, tracking and situation assessment methods will be included. The rule-based situation assessment service is a first step towards a maritime picture. However, for sufficient awareness in the maritime domain, the timely detection of complex situations that evolve over time is a key factor.

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