Detection and Tracking of Non-Cooperative Vessels

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ABSTRACT

Harbor areas and high-traffic shipping lanes near coasts are specific causes of high risk because at these regions a high number of vessels of various sizes are concentrated within a limited space. The persistent surveillance (24 hours / 7 days) of the sea surface is hampered by the occurrence of small vessels, falling below the requirement to carry automatic identification systems (AIS). Non-cooperative objects, ranging from vessels with defect AIS-transponders to smugglers and potential terroristic attacks, complete the scenario, resulting in missing, wrong, or spoofed positions and ID signals.

In addition to automatic identification systems used for larger and cooperative vessels, active and passive radar systems and optical sensors should be considered. Especially harbor areas and shipping lanes of limited spatial extent are well suited for the supplementary surveillance by means of radar and optical systems, as these scenarios allow for the necessary permanent installation of sensor equipment.

The Fraunhofer IOSB has long-term experience regarding the automatic surveillance of the sea surface based on optronic sensors, especially IR sensors. In the course of these studies, several measurement campaigns at various climatic regions have already been conducted, using different active and passive optronic sensors, cooled as well as uncooled, and operating at various spectral bands. The captured scenarios cover mainly asymmetric threats, e.g. small boats and swimmers, for which suitable detection, tracking and classification algorithms have been successfully developed.

The Fraunhofer FKIE has long-term experience regarding fusion of data from heterogeneous sensors and information sources such as Automatic Identification System (AIS), Vessel Traffic Services (VTS), maritime & coastal radar (active and passive), Long Range Identification and Tracking Systems (LRIT), Satellite based AIS (Sat-AIS), Satellite based Earth Observation, Airborne Remote Sensing, emitter localization (DoA, TDoA, FDoA).

Combining AIS, radar, and optical sensor systems in an integrated security concept especially for ports and regional maritime security systems allows for several new scenarios: cooperative vessels can be tracked and guided; non-cooperative vessels can be detected as such – concerning the mere AIS transponder behavior – and further inspected by optical systems and suitable vision algorithms. But even the inverse problem can be tackled: vessels detected and tracked within the images from optical sensors can be rechecked for matching AIS transponder signals. In such a way, defect AIS transponders and wrong or spoofed AIS signals can be detected.

1.0 INTRODUCTION

For the security and safety of vessels of any type it is required that the responsible persons on board are aware of all other stationary and moving ships in their surroundings. The persistent surveillance (24 hours / 7 days) of the sea surface is hampered by the occurrence of small vessels, falling below the requirement to carry automatic identification systems (AIS). Non-cooperative objects, ranging from vessels with defect AIS-transponders to smugglers and potential terroristic attacks, complete the scenario, resulting in missing, wrong, or spoofed positions and ID signals.

This paper is focused on new sensor-based techniques for the automatic detection, tracking and identification of non-cooperative objects. These techniques shall not replace, but augment the existing techniques for the monitoring of cooperative vessels. After a short overview on cooperative detection and tracking, we show the capability gap, i.e. we introduce non-cooperative vessels and other situations, were additional techniques shall be applied.

For the detection, tracking and identification of non-cooperative vessels, different sensors and algorithms have to be used. Generally, a sensor optimized for the detection of objects in a wide field of regard is not very useful for the detailed analysis, classification and identification of the detected objects. Thus, a multi-sensor approach is preferred. First, we show various methods based on the use of a specific type of sensor: RADAR-based systems and passive and active optronic systems. For optimized and robust performance under varying conditions combined systems shall be used, consisting of multiple sensors and sensor data fusion algorithms.

1.1 Multi-Intelligence All-Source Information Fusion

Automated or semi-automated systems for detecting and tracking non-cooperative vessels will provide officers on all levels of hierarchy, as well as decision support systems, with a vast amount of data. To prevent human users, or actuators involved from being overwhelmed by the continuously streaming data and information and to optimize its use for the manifold and various decision tasks, it is necessary that only the right piece of high-quality information, relevant to a given situation, is transmitted at the right time to the right user or component and appropriately presented. The development of sophisticated software and data processing technologies and algorithms are mandatory e. g. for under clutter detection and the identification and tracking of small vessels.

One main objective is the robust and reliable information fusion, which includes information sharing and information exchange software and data base architecture aiming at the automatic detection of anomalies. Dedicated data and information fusion algorithms provide the informational elements for producing an appropriate situation picture, according to the respective level of command, responsibility, and type of function to be supported. Only if this is given, the data streams will support goal-oriented decisions and coordinated action planning in practical situations and on all levels of decision hierarchy. The latest modern trends and features are: robustness, scalability, flexibility, high availability, standardization.

1.2 Advanced Unmanned Sensor Platform Technology

VTOL UAV. The maritime scenarios considered (harbor areas, high-traffic shipping lanes) the consideration of unmanned aerial sensor platforms for patrol missions is required. VTOL UAV as versatile sensory platform is able to supply airborne support with sensory equipment as a payload. Such platforms are capable of positioning the respective sensors in any required position by allowing access to confined areas, offering low-altitude operation, and stationary hovering. The autonomous system allows reliable and accurate geo-positioning of the respective sensors, therefore giving full control and situational awareness.

Multiple Sensor Buoys, as an independent maritime surveillance system, cover, for example, un-cooled thermal imager and hydrophone sensors, particularly for the monitoring of small boats and of non-cooperative vessels. It is considered to be an autonomous system with low investment and low life-cycle costs. Existing systems can be further improved by covering additional sensor systems like an innovative microphone system and ESM sensors. The first allows meeting the requirement to detect low-flying aircrafts at an early stage; the latter one gives the possibility to detect any kind of radio communication device in a certain region around the buoy. This allows early detection of communication activity indicating smuggling activity. Additionally, the power management of the buoy may be improved to enable even longer autonomous operation.

Autonomous Masts. The general concept of the buoy can be transferred to a platform called 'autonomous mast'. Within this mast platform, power management and wireless communication is incorporated, similar as for the buoy. This allows autonomous operation at coastal lines with no infrastructure, for instance on archipelagos at Turkish Islands. The same sensor systems can be used except the hydrophones.

2.0 DETECTION AND TRACKING OF COOPERATIVE VESSELS

Existing methods for the acquisition of cooperative vessels often lead to the disparity of different surveillance systems used and therefore no single system has the complete overview of all vessels or other maritime objects within a certain area. In addition, sensor performance is often limited and not all ships or other objects can be detected seamlessly during all conditions (24/7, all-weather, all-sight). The information that is being collected by the installed systems is often not detailed enough to identify threats or infringements. This is especially true for small vessels, as may be used for e.g. drug smuggling, illegal immigration or terrorism.

The installed cooperative reporting and messaging systems that are already established along the European coast line provide external information, completing sensor information from non-cooperative objects. Information from these reporting systems can be integrated and fused with information from further public data sources (e. g. internet), such as legal and open source databases, but also commercial databases. All available appropriate information can be used to check for inconsistencies and to detect abnormal behavior to find suspicious vessels and to concentrate further detailed surveillance on suspicious objects.

In the following we provide an overview of mainly deployed cooperative (technical and administrative) reporting systems, used for maritime surveillance:

AIS – Automatic Identification System is mandatory on the basis of IMO's (International Maritime Organization) SOLAS (Safety Of Life At Sea) convention [1]. As systems get upgraded, AIS (including Satellite based AIS, Sat-AIS) and radar positions of ships are displayed in a fused way on the same screen. In several regions (Baltic Sea, Northern Sea and in the Mediterranean), neighboring countries for example are collaborating to maintain a regional AIS network.

VMS - Vessel Monitoring System is a system on fishing vessels for monitoring and control of fishing vessel operations. VMS is relatively far advanced in operational data sharing between countries, but at the same time quite restricted in any sharing outside the fisheries sector.

LRIT - Long Range Identification and Tracking (LRIT) is a global messaging system for security and SAR purposes that is regulated by IMO. Additionally the development of the so-called Space-AIS has to be taken into account. Although it is not an IMO system, this system forced by the US will provide additional information for vessel traffic surveillance in a wider range.

GMDSS - Global Maritime Distress and Safety System enables communications to/from ships in relation to emergencies. Using ship-mounted equipment and protocols, ships can alert authorities on shore as well as other ships in the vicinity in case of an emergency.

SafeSeaNet is a system to exchange information between maritime authorities to help prevent pollution and accidents at sea. SafeSeaNet is 24/7 available and respects confidentiality. The way it works is that all data about vessels and traffic are stored in databases.

ISPS Code - International Ship and Port Facility Security is a system to detect security threats and take preventative measures against security incidents affecting ships or port facilities used in international context.

The systems mentioned above, provide a basis for an information sharing environment that is based on existing and legacy systems. Due to different approaches in the past, most of the systems provide solutions only for specific domains. Considering integration and exchanging of information these systems are quite restricted. Data and information acquisition and sharing is difficult today, even almost impossible since the interfaces of the different systems are poorly developed and are mostly not developed to exchange information.

3.0 NON-COOPERATIVE VESSELS

An increasing number of vessels are equipped with AIS (presently worldwide more than 70000 ships). However, depending on their size and function, many vessels are not required to use AIS. Most recreational and fishing boats are not equipped with AIS; some military vessels will probably not operate their AIS. Smugglers, pirates and terrorists (see Figure 1 left) are not interested to unveil their operations and therefore it cannot be expected that they use AIS correctly. It is more likely that such non-cooperative vessels do not transmit any information, or they transmit spoofed signals, such as wrong identities, positions or destinations. Besides vessels, there are also other non-cooperative objects which might be of interest, such as swimmers and floating obstacles like lost containers and icebergs.

Finally, even in the case of cooperative objects, the IDs, positions and further static and dynamic features received in AIS messages are not fully reliable. According to [2], up to 50% of AIS messages contain errors. Figure 1 right shows a screenshot view of a typical AIS service tool providing a map with the positions and further features of cooperative vessels. It is obvious, that the positions of two vessels are wrong, because they are marked at positions inside the city, far away from any water area.

Figure 1: Examples for missing and wrong or spoofed position signals.
Left: Pirate boat, unlikely to cooperate (image source: Bundeswehr).
Right: Two vessels with obviously wrong AIS positions (screenshot from www.portmaps.com).

A large variety of heterogeneous sensors is relevant to detecting and tracking of non-cooperative vessels. The most important sensor classes are characterized in the following:

Radar systems: general comments. The main advantage of radar sensors is their all-weather and all-sight capability, which allows system operation under fog, mist, haze, rain and snow-conditions during day and night. This feature is especially important for law enforcement, as mostly such weather conditions are looked at for unauthorized landing attempts, border crossing, and other criminal activities. According to the requirements concerning a higher resolution, there is a need for the deployment of novel types of radar technologies, since commercial maritime radar systems have not the necessary resolution to detect small objects on the sea level with the required accuracy.

Passive radar systems. A particularly innovative approach is the deployment of passive radar systems for the detection of moving object under all-weather-conditions. Passive radar systems using illuminators of opportunity allow observation of moving targets at low cost without permission of frequency bands [3]. Due to the availability of multiple illuminators which are abundantly available along coastal areas, improved performance can be obtained by fusing results from multiple bi-static configurations with a single receiver. Passive radar enables in particular surveillance capabilities where active transmission of radar signals is unwanted, i.e. near politically sensitive borders. Moreover, the dense coverage of coastal areas with GSM base-stations makes GSM passive radar particularly suitable for coastal surveillance [4].

Mm-wave active radar systems. Mast-borne mm-wave radar systems along blue borders provides the necessary resolution to detect, identify and to track small boats, vehicles, or persons on foot as required for detecting and tracking non-cooperative vessels. In addition, mm-wave enhanced Synthetic Aperture Radar (mmSAR) achieves high sensitivity to small scale patterns. This feature is important for the evaluation of indirect signatures on the sea surface, like the Kelvin wave from a boat, which can be detected up to hours after the boat was at a certain place. It can be shown, that millimetre wave radar is very well capable to image small items like wooden boats on sea also under higher sea states. The millimetre wave enhanced Synthetic Aperture Radar can be carried by maritime UAV platforms.

Emitter localization sensors. An important aspect is covered by considering sensor systems that are able to detect electromagnetic signal transmitted from maritime objects of interest such as communication, radar, or transponder (e.g. AIS) signals. A variety of emitter location principles are applicable in this context, such as DoA (Direction of Arrival), ToA (Time of Arrival), TDoA (Time-Difference of Arrival), or FDoA (Frequency-Difference of Arrival). Typically, smaller or larger networks of emitter localization sensors have to be considered. Which particular principle is best suited, strongly depends on the situation considered. Since the structure of AIS signals is known, the Time of Arrival related to AIS signal can be estimated resulting in rather accurate estimates of the actual positions of AIS transponders. If the position reported by the body of the AIS message differs from the ToA estimate of its position, a clear indication of an “anomaly” is given. The information provided by FDoA measurements is based on Doppler-shifted received frequencies and thus requires relative motion between the transmitter to be located and the sensor platform, i.e. this location principle is best suited within the context of moving Unmanned Aerial Systems (UAS).

Optronic systems: general comments. Optronic or electro-optical systems comprise one or more optical sensor in the wavelength from ultra-violet over the visual up to the far infrared spectrum (i.e. approx. from 0.2 µm to 15 µm) and electronic components ranging from the electronics necessary to generate images to fully automatic image processing systems including object detection, tracking, and classification. The main advantage of optronic systems is their high spatial resolution in terms of angular positions relative to the sensor. This allows detailed analyses of objects and reliable separation of multiple objects which are close to each other. The maximum achievable angular resolution is in the order of 0.1 mrad, depending on the used wavelength, other sensor parameters, the object distance, and the atmospheric conditions. As humans are trained to use their eyes and their visual system, i.e. to look at and to analyze images, the data gained by optronic sensors is very well suited to be understood by humans. Thus, imagery from optronic sensors can be used for automatic detection and tracking, and also handed over to humans for further analyses and for final decisions.

Passive optronic systems. The main advantage of passive systems is that they do not emit any radiation. Passive optronic sensors take advantage of available light (mainly from the sun) and of the radiation emitted by the observed objects. Sensors with short wavelengths are more sensitive to the component reflected from the sun light, long wavelengths are better suited for measuring the self-emitting radiation of objects at normal temperatures. Long-range high-performance infrared sensors with high sensitivity can detect temperature differences as low as 0.1 K, independently from daylight.

Active optronic systems. If the scene is illuminated by a light source, preferably by a laser, optronic systems with many advantages can be built. Based on the measurement of the time of flight of light pulses precise range information and 3D information is obtained. With gated viewing, higher ranges also in case of dust, mist, fog, and rain can be achieved. With active sensors, the segmentation of objects from the background is generally no problem. Further, the resulting accurate 3D data can be used for very reliable object classification and identification.

Innovative microphone technology. The installation of a microphone array in harsh environments, typical of blue border surveillance, requires innovative concepts to meet the requirements regarding sensitivity, range, directional resolution, bandwidth, robustness, (wanted)-signal to (unwanted)-noise ratio.

Use of Satellite Data for IBM. Space applications can contribute significantly to detect and track non-cooperative vessels. Both optical (when suitable) and radar data can enhance the situational awareness and provide more comprehensive geospatial information. In the context of non-cooperative vessels, satellite data of low and medium spatial resolution as well as high resolution are important and can complement each other for the success of a task.

4.0 RADAR-BASED DETECTION AND TRACKING

4.1 Higher-Level Information from Precision Radar Tracks

The primary objective of tracking aims at exploring the underlying target kinematics, i.e. tracking applications gain “Level 1” information according to the terminology of the JDL model [5]. Kinematic data, however, are not the only information to be derived from tracks. In many cases relevant to detect, track, and classify non-cooperative vessels, higher level information according to the JDL terminology can be obtained [6].

Inferences based on Retrodicted Tracks. The first type of higher JDL level information to be inferred from tracking data is based on an analysis of the track histories provided by retrodiction. The statements derived typically refer to object characteristics that are either time invariant or change with time on a much larger scale than kinematic quantities usually tend to do. This is the main reason why the gain in accuracy achievable by retrodiction techniques can be exploited.

Inferences based on multiple target tracking. A second type of higher JDL level information is related to mutual object interrelations, which can be inferred from JDL level 1 data provided by multiple target tracking. More specialized aspects in this context are Common History, since multiple target tracking may identify whether a set of targets belongs to the same collectively moving group, Object Sources and Sinks, where the analysis of larger amounts of tracks enables the recognition of sources and sinks of moving targets, and, finally, Evaluating Split-off Events.

Inferences of specific object characteristics. A third type of conclusions from JDL level 1 information aims at specific object properties. Among other events, we here look at Identifying Vessel Stops, indicating anomalous behaviour, Off- and On-Lane Vessels, where digital sea lane maps are incorporated into the tracking algorithms, permitting to test the hypothesis “Off-lane vessel” versus “On-lane vessel” and vice versa, and, finally, Rare Event Detection, where an alert message is produced if a vessel is observed at an unusual time at an unusual sea region.

4.2 Tracking-Based Sequential Anomaly Detection

In complex sea surveillance applications, we can often take advantage of context information on the maritime environment insofar as it is the stationary or only slowly changing “stage” where a dynamic scenario evolves, e.g. digital sea-lane maps and related information [7]. A second category of context information is provided by visibility models and littoral or weather maps indicating regions, where a high clutter background is to be taken into account, e.g. A third category of context information is delivered by human observer reports [8]. In principle, it is even possible to extract information on sea-lanes not previously known from tracking results. See [9] for details.

In certain applications, sufficiently detailed planning information is available, which provides valuable context knowledge on the temporal evolution of the objects involved and can well be incorporated into the tracking formalism. Often planning information is given by space-time waypoints that have to be passed by the individual objects during the travel at sea, i.e. by a set of position vectors to be reached at given instants of time and via particular routes between the waypoints. In addition, we assume that the acceptable tolerances related to the arrival of the objects at the waypoints are characterized by known error covariance matrices, possibly individually chosen for each waypoint and object, and that the association between the waypoints and the objects is predefined. Let the information on an object state at an instant of time be given by a probability density. The impact of waypoints on the trajectory to be estimated from future sensor data (assuming the plan is actually kept) can simply be obtained by processing the waypoints as additional artificial “measurements” via the standard tracking paradigm, where the tolerance covariance matrices are taken into account as the corresponding “measurement error covariances”. If this is done, the processing of sensor measurements with a time stamp younger than that of the waypoints are to be treated as “out-of sequence” measurements with respect to the artificial waypoint measurements processed earlier [10]. According to these considerations, planning data, i.e. higher-level information can well improve both track accuracy and continuity as well as facilitate the sensor-data-to-track association problems involved, provided the plan is actually kept.

Regularity Pattern Violation. A practically important class of anomalies results from a violation of planning information. An anomaly detector thus has to decide between two alternatives: 1) The observed objects obey an underlying pattern. 2) The pattern is not obeyed (e.g. off-lane, unplanned). Statistical decisions of this type are characterized by decision errors of first and second kind that are described by the corresponding error probabilities. In most cases, it is desirable to make the decisions between both alternatives for given decision probabilities. A sequential likelihood ratio test fulfils this requirement and has enormous practical importance. As soon as the test decided on “plan kept”, the calculation of the likelihood ratio can be restarted since it is more or less a by-product of track maintenance. The output of subsequent sequential ratio tests can serve to re-confirm “regularity” or to detect a violation.

5.0 DETECTION AND TRACKING BASED ON OPTRONIC SYSTEMS

In this chapter, optronic systems for the automatic detection, tracking and classification of vessels and other objects on water are discussed. The sensors used can be passive (i.e. without emission of any radiation) or active (i.e. emitting light).

The wavelengths in question include visible light, but also infrared (IR), which is preferred to maintain good day and night performance. Each band in the IR region (short wave, mid wave, and long wave IR, see Figure 2 as an example) has some advantages over other bands under specific conditions (for details see [11]). The use of multiple cameras with different wavelengths or a multi-color camera can increase the performance under varying conditions, however at considerably higher costs.

Figure 2: Infrared images of a boat in different wavelength ranges. Left: short-wave IR 1.2-5 µm. Middle: mid-wave IR 3-5 µm. Right: long-wave IR 8-9 µm (from [11])

Other essential sensor parameters are the field of view, the spatial resolution, the frame rate, and the radiometric sensitivity. The selection of the adequate optronic sensor depends on the specific task for which the sensor shall be used. Secure navigation, situational awareness and threat recognition is a complex task, consisting of several sub-tasks, such as the detection, tracking and even classification and identification of the objects in the surrounding of the own vessel. For an optimized performance, more than one sensor is required. In the following sections, the use of passive and active optronic sensors is discussed, focusing on the sub-task for which each sensor should be applied.

5.1 Detection and Tracking based on Passive Sensors

Generally, there is a trade-off between the large field of regard that has to be observed, and the desire to achieve a high spatial resolution. To fulfill both antagonistic requirements, at least two different types of sensors are used:

- **panoramic sensors:**

  For the surveillance of the complete area of regard, sensors with a wide field of view are required. For situational awareness, the complete 360° panoramic view should be observed. For collision avoidance, the view can be limited to the directions in which the own vessel is approximately moving.

  The full field of regard can be realized by a rotating or scanning optronic sensor. The drawback of this solution is that it is not possible to achieve reasonably high spatial and temporal resolutions. Therefore, depending on the actual size of the field of regard, more than one identical optronic sensor shall be applied, such that the field of view of each sensor is slightly overlapping the adjacent field of view of another sensor. Using for instance sensors with a horizontal FOV of 30°, more than 12 sensors would be required. To keep price and maintenance effort at a lower level, uncooled IR cameras (bolometers) are mostly preferred.

  The image sequences of the panoramic sensors are automatically processed, trying to detect and track all potential objects of interest. The output is not considered as final result, but is used as an input for the application of the second type of sensors.

- **verification sensors:**

  As the limited spatial resolution of the panoramic sensors does not allow deriving much information, at least one sensor with a higher spatial resolution shall be applied. The sensor with higher spatial resolution is used for further evaluation. Fist, according to the angular position of the detected object, the sensor has to be oriented towards this direction. Then the object shall be detected and further tracked in the high resolution image sequence.

  If the inner and outer sensor parameters are known, the distance of an object on the water surface can be computed automatically. Then the true size of the object and the 3D-trajectory of the objects can be derived. These features can be used for classification and for threat evaluation.

  For the verification, cooled IR cameras with high sensitivity are mostly preferred.

The panoramic and the verification sensors work in parallel, but are sequentially applied for a certain object. In Figure 3 this procedure is illustrated. In Figure 3 left an image of a typical panoramic sensor suite is shown. The sensor is an uncooled long wave IR camera with a FOV of 19° x 25°. At the right side of the image a small boat is visible. This boat was successfully detected and tracked by the Fraunhofer IOSB algorithms. To derive more information, the high resolution verification sensor is turned into the direction of this object. Figure 3 right shows an image of this verification sensor (same time as the corresponding image of the panoramic sensor in Figure 3 left). This sensor is a cooled long wave IR camera with a FOV of 4.4° x 3.5°, mounted on a steerable pan/tilt head. The Fraunhofer IOSB algorithms are handing over the object from the one to the other sensor, the object is then automatically tracked in both sensors while the verification sensor is following the movement of this object. The passively derived distance (600 m) allows a coarse classification and motion analysis. More information on the used algorithms is given in [12].

Figure 3: The trade-off between the field of view (FOV) and the spatial resolution of optronic sensors. Left: Small boat in wide FOV IR image, used for detection. Right: Same boat in narrow FOV IR image, used for verification.

The Fraunhofer IOSB has conducted multiple measurement campaigns at various climatic regions, using different active and passive optronic sensors, cooled as well as uncooled, and operating at various spectral bands. The captured scenarios cover mainly asymmetric threats, e.g. small boats and swimmers. For both, panoramic sensors and verification sensors, image sequence algorithms have been developed. These algorithms consist of many modules, such as image pre-processing, image stabilization, temporal and spatial filtering, segmentation, multi-target tracking, and classification.

The results of the automatic analysis of passive image sequences are often impressively good. In many cases dim or small objects are detected which a human observer, looking at a monitor display, is not able to find (see examples in Figure 4). On the other side, there are still also weaknesses; the results of segmentation, classification and identification of objects in images are often not sufficient. Therefore, human observers shall finally be responsible for classification and identification. Further, the additional use of active sensors (LIDAR and Gated Viewing see following sections) is a good means for achieving good segmentation, classification and identification results.

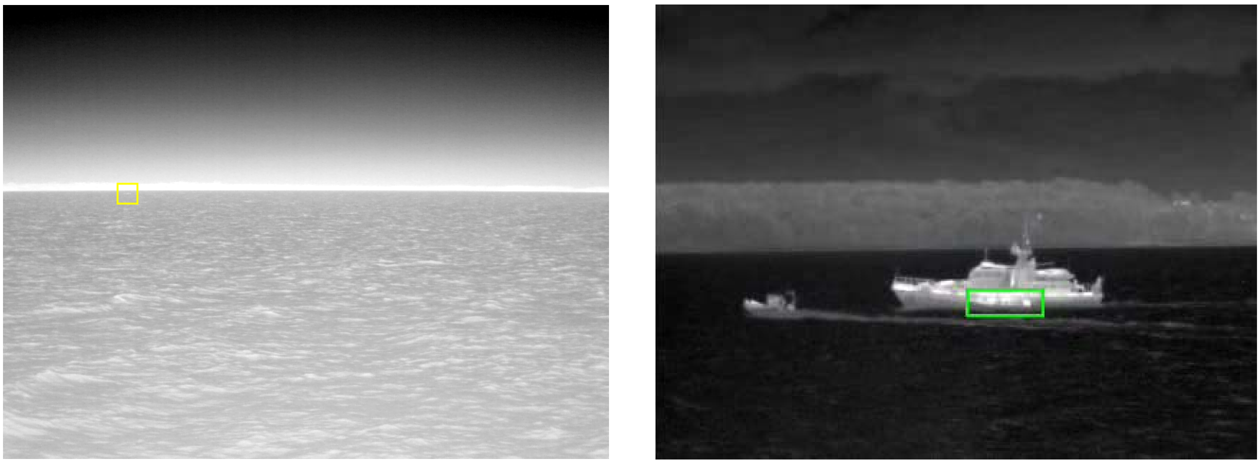

Figure 4: Examples for small boats, automatically detected by IR image sequence analysis which would probably not be detected by a human observer.

5.2 Segmentation, Tracking, Classification and Identification based on LIDAR

LIDAR (Light Detection And Ranging, also LADAR or Laser Radar) is an optronic remote sensing technology for measuring the distances to the surrounding scene (objects and background) by illuminating the scene with light from a laser. The range information is directly given by the time of flight of a laser pulse from the emitting laser source via the reflecting object in the scene to the optronic detector system. Thus, LIDAR systems can generally deliver two image sequences: an intensity image sequence (see example in Figure 5 left), and a range image sequence (see example in Figure 5 middle).

The main advantage of using range images instead of passive sensor data is that automatic object classification and identification can be performed very reliably, even in non-controlled outdoor environments with variable background, illumination, and clutter. In passive imagery, object/background segmentation is an extremely difficult task. If object and background have equal or similar intensity values, segmentation results are often very unreliable. In range data, on the other hand, discontinuities of the data correspond to true object boundaries.

If only passive or non-range sensor data is available (infrared, visual, etc.), the automatic recognition of objects in natural, outdoor scenes is far from being solved. However, if range imagery is available, fast, robust solutions can be obtained by the following steps (from [13]):

- **Step 1: Object/ground segmentation:** This step separates arbitrary objects from the terrain surface on which they are located. It requires no object models. In case of objects on a water surface, multiple reflections of the illuminating laser pulse can induce additional incorrect range measurements which have to be segmented as well.

- **Step 2: Object classification and pose estimation**: This step calculates the position, orientation and shape parameter vector of objects extracted in step 1.

- **Step 3: Object identification:** In the final step the extracted object is matched with all feasible models having similar shape parameters. Model matching compares the expected range image of the translated and rotated 3D model with the current image. The best match defines the object identity.

Fraunhofer IOSB has set up a **data base for the classification** of maritime vessels, consisting of more than 8000 range images of 146 different ships at various orientations and ranges [14]. This data was collected using the Portable 3D Flash LIDAR Camera from Advanced Scientific Concepts Inc., consisting of a 128 x 128 detector array together with an eye safe laser. Each detector element outputs a digitized pulse profile of the reflected signal. The range for each pixel is calculated by finding the maximum of a smoothed curve fitting the digitized signal, achieving a range accuracy of about 15 cm. The laser intensity image is defined by the height of the pulse maximum for each pixel.

The 3D-models of the model library are partially incomplete and inaccurate, each being generated from a single reconnaissance range image, using symmetry properties of naval vessels. Only 46 of the 146 ships were modelled, the others being potential false alarms. Nevertheless, a classification accuracy of 96% was attained for the entire data base. For 15 models the detection probability was 100% with a false alarm rate of 0. For the rest (except for 2 highly inaccurate models) the area under the ROC-curve was over 97%.

**Figure 5: Laser radar: sensor data and derived 3D point cloud of a small boat.
Left: Laser intensity image. Middle: Range image (both including reflections on water).
Right: 2D view of the 3D point cloud of the boat.**

5.3 Segmentation, Tracking and Classification based on Gated Viewing

Similar to LIDAR, Gated Viewing is also an active optronic sensor technology, both taking advantage of the limited speed of light. The principle of Gated Viewing is to send out a very short laser pulse with a pulse duration of only a few nanoseconds and to measure the incoming reflected light intensity within an exactly specified short time interval, down to some hundreds of nanoseconds. This requires a special optronic sensor that can rapidly be switched to be sensitive or insensitive to incoming light. By setting the start and end time of the measuring interval, a range gate is defined. Thus, only the light reflected from objects at a certain range interval is acquired. Therefore, gated viewing images allow generally very reliable object/background segmentation.

Fraunhofer IOSB has built up a Gated-Viewing system that provides range gated imagery up to several kilometers and operates in the eye-safe laser wavelength region at 1.57 µm [15]. At this laser wavelength, the system is well suited for maritime applications because the water surface reflects and absorbs a great deal of the emitted laser energy. For this reason, the water surface appears black at this laser wavelength and a nearly perfect segmentation of the object and the background is possible (see Figure 6). The maximal energy per laser pulse is 65 mJ. Fraunhofer IOSB has combined this laser source with the Intevac Gated-Viewing detector M506 that is typically operated in the binning mode, resulting in a spatial resolution of 640 x 480 pixels. By equipping the detector with suitable optics, very narrow field of views down to 4 mrad x 3 mrad can be realized. An appropriate beam shaper is mounted in front of the laser output, providing a homogeneous, rectangular illumination of the whole field of view of the camera. The actual range of the target is measured with a laser range finder that makes use of the illumination laser. Thus, the gate position is automatically updated according to the instantaneous target range, enabling a reliable 3D target tracking.

Figure 6: Gated viewing images of various types of vessels at distances from 500 m to 5000 m.

By acquiring a sequence of Gated Viewing images with slightly increased range gate positions – a so-called sliding gates sequence – it is possible to obtain 3-D information of the acquired object likely to a LIDAR system (see Figure 7). The smallest step size for sliding the gate is 75 cm. By applying a suitable regression curve, Fraunhofer IOSB has achieved a range resolution better than 9 cm at a distance of 2 km under low turbulence conditions (see [16]). The disadvantage of the sliding gates method is that the object has to be relatively static during the image acquisition. Nevertheless, due to a maximal frame rate of 20 Hz of the Gated Viewing system, small object movements are tolerable.

In comparison with passive optronic sensors and with LIDAR, by means of gated viewing much longer distances can be achieved also in the case of dust, fog, and rain. Further, presently available gated viewing systems have better spatial resolutions and higher frame rates than existing flash LIDAR systems.

Figure 7: Sliding gates sequence and resulting range image of a vehicle at a distance of 2.6 km.

6.0 COMBINED APPLICATION OF METHODS

As mentioned above, maritime data fusion systems can be well described by the JDL process model for data fusion [5]. The level 1 problem (Object Refinement) was in the focus for section 5, while the fact that higher-level information can be inferred from precision tracking was discussed in section 4. See [17] for discussions of theoretical and implementation points of view. The fusion of contributions provided by all the above-described sources is still under investigation. So far, decentralised or centralised data fusion architectures have been considered. The decentralised option originates from operational constraints and unavailability of raw data at central level. Theoretical advantages of centralised approaches, used in multi-sensor tracking, are still to be demonstrated for MSA applications. Hybrid data fusion architectures have been developed in [18], where the track-break-fuse solution exploits both measurements and track information in a multiple hypotheses frame. For any data fusion strategy, the key aspect is data association. The nature of sensor data is expected to hinder the association process in highly dense target areas, degraded sensor coverage areas, for low SNR or intermittent target sources, etc. Knowledge Base is expected to aid the association process, as discussed in [19].

Example: Fusion of Emitter Localization Sensors and Cameras

The practical use of sensor data fusion is exemplarily shown by considering the fusion of emitter localization sensors and the optical sensor devices previously discussed. Figure 8 illustrates a multi-sensor system of this type. In this set-up, an array antenna, possible carried by a UAS, collects measurements of an emitter’s azimuth and possibly even elevation angles. The obtained angular estimates are used to direct optical sensors towards the region, where the emitter is expected. Both sensors are mutually complementary: the emitter localization sensor typically provides a poor angular estimate, but gives a clear indication that an emitter and what type of emitter is present in the scene. The optical sensor, on the other hand, is not able to provide this information, but delivers much better angular measurements. After solving a data association problem, which results in correlating corresponding information related to the same object, the fusion of the data provided by each of the sensors is possible, and provides results that are typically (much) more accurate and reliable than the individual exploitation results of the sensors.

Figure 9 illustrates an experimental set up where this principle has been experimentally evaluated. As sensor platform we consider an unmanned UAS-demonstrator carrying an emitter localization sensor (polarization sensitive array antenna with 4 elements) and a commercial camera, serving as a substitute for the more complex sensor solutions considered above. In the scenario three stationary emitters and a car-borne emitter has to be localized. The fusion algorithm is based on calculating the so-called intensity function of a correlating non-homogeneous Poisson Point Process (PPP) [20]. This function has much in common with an ordinary probability function, but is a more general notion in that it provides not only position and kinematical estimates, but also estimates of this a priori unknown number of emitters present in the scenario. A comparison of Figures 10 and 11 makes exemplarily clear that a significant benefit can be obtained if measurements from emitter localization sensors are fused with data provided by optical sensors.

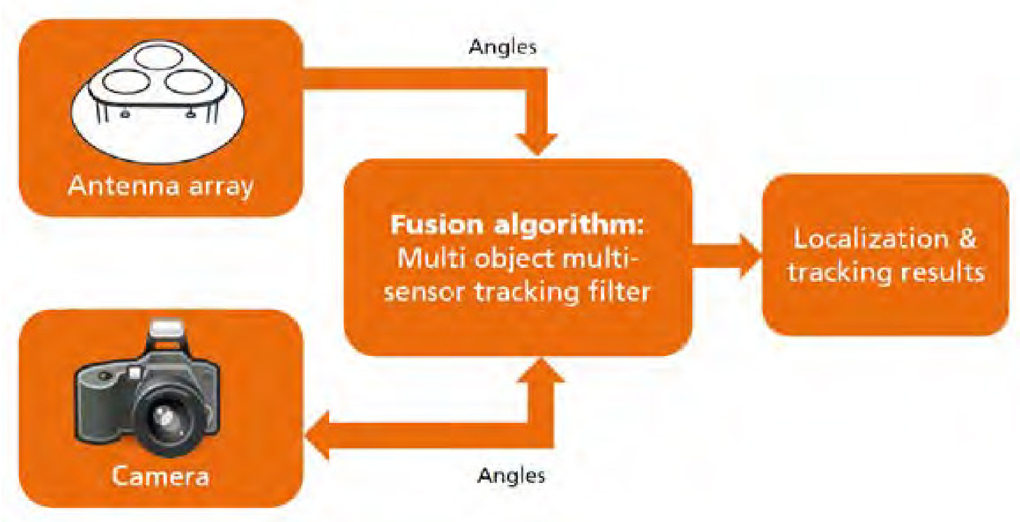

Figure 8: Schematic overview: fusion of emitter localization and optics-based sensors for providing emitter localization and tracking.

Figure 9: Experimental set-up for a measurement campaign involving emitter localization (DoA) and optical sensors: aerial platform (manned UAS demonstrator), 3 stationary, 1 moving object to be localized.

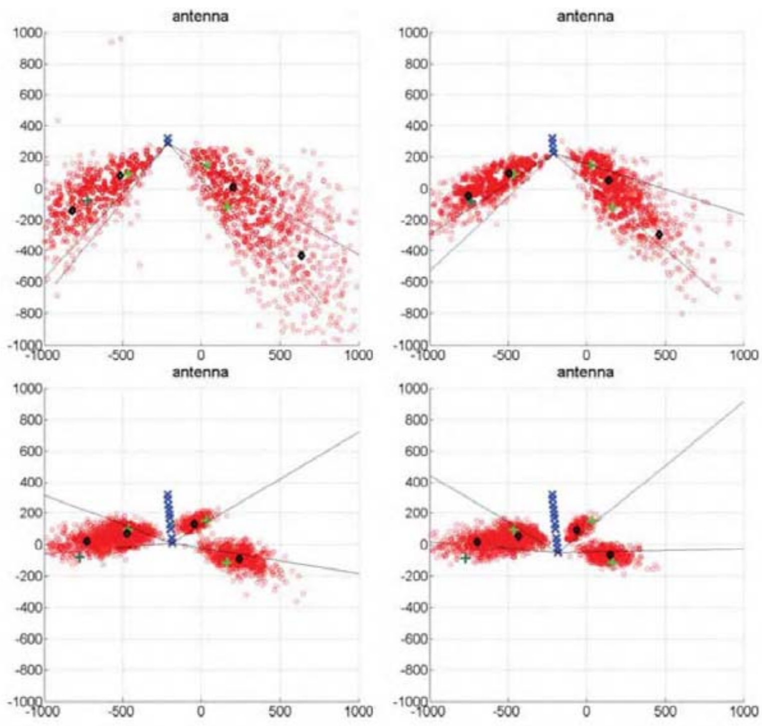

Figure 10: Particle representation of a PPP intensity function for calculating estimates on the number of emitters involved and their kinematic properties (DoA sensor only).

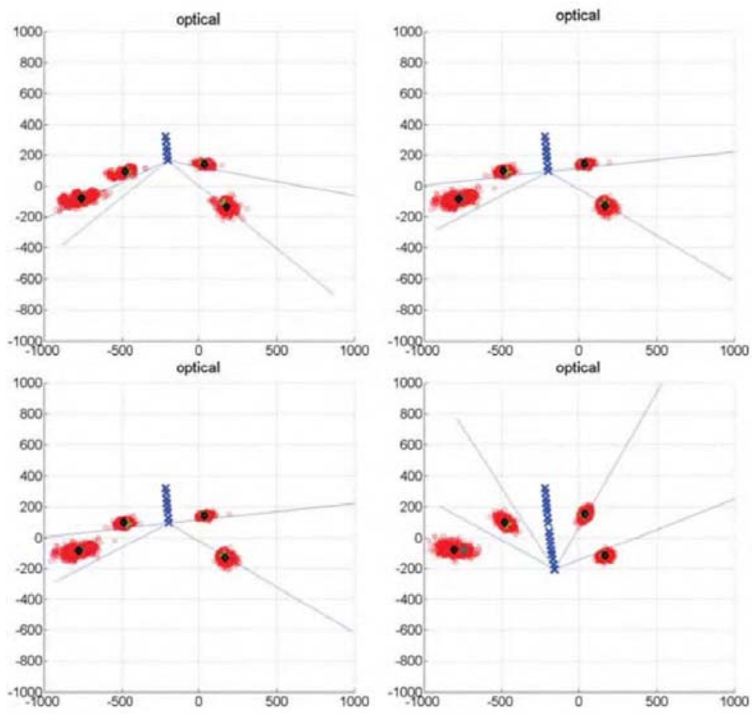

Figure 11: Particle representation of a PPP intensity function for calculating estimates on the number of emitters involved and their kinematic properties (DoA and optical sensor fused).

7.0 SUMMARY AND CONCLUSION

Ideally, all vessels should be equipped with AIS transponders and all AIS transmission and receiving systems should work perfectly, such that everybody on a ship or on land could have complete information about all moving and stationary vessels in all areas of interest. However, it cannot be expected that this will ever be the case. Moreover, AIS often does not work as reliable as required. Non-cooperative methods for vessel detection and tracking are thus inevitable. In this paper, we discussed several information sources for reaching this goal and showed its potential exemplarily. First, we discussed the relevance of precision tracking for inferring higher-level information. Second, we addressed issues from optical sensing. And finally, we showed the potential of fusion of heterogeneous information by an example.

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