Next-Gen Intelligent Situational Awareness Systems for Maritime Surveillance and Autonomous Navigation

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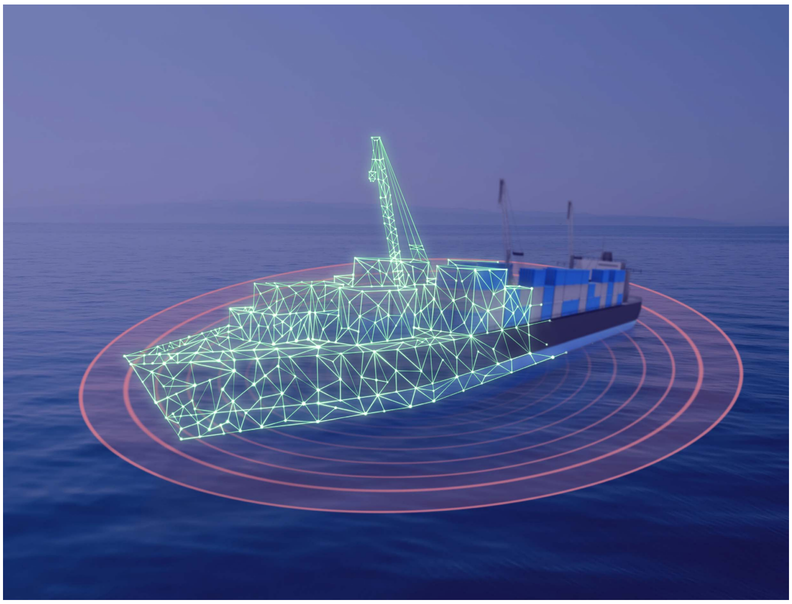

Today, the maritime domain is at the cusp of a new era, driven by technological advances in automation, robotics, multisensor perception, and artificial intelligence (AI), together with digitalization and connectivity. Smart ship infrastructure and technology, remotely controlled and autonomous ship operation to improve safety, security, cost efficiency, and sustainability are the future of maritime transportation [1], representing now the engine of 90% of global trade [2]. Ships will soon benefit from recent developments in sensors, telecommunications, and computing technologies to turn the smart shipping revolution into reality [3] and [4], as it has already happened for autonomous vehicles such as driverless cars, aerial drones, unmanned (or remotely piloted) aircraft, and underwater vehicles.

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I. FUTURE OF INTELLIGENT MARITIME SYSTEMS

Next-gen intelligent maritime systems across ships and ports will enable maritime operations to achieve the highest levels of critical safety, security, and efficiency. As technology evolves for maritime operations, more data can be captured, analyzed, and acted upon to better optimize systems. The availability of global networks for data transfer combined with the Internet of Things paradigm will help deliver smart vessels with shore-based control. As time goes on, ships and ports will become increasingly intelligent and capable of more advanced autonomous operation.

Several projects have been recently launched to explore the technical, economic, and legal feasibility of autonomous ships, for example, the EU-funded Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) project [5], the Advanced Autonomous Waterborne Applications (AAWA) project [3], the Sensor fusion and collision avoidance for autonomous surface vehicles (AUTOSEA) project [6], and the YARA Birkeland demonstrator [7]. The International Maritime Organization (IMO) has recently identified four levels of autonomy [8] for Maritime Autonomous Surface Ships (MASS) ranging from ships with automated processes and decision support, remotely controlled ships with and without a crew, and fully autonomous systems. It is estimated that 75%–96% of shipping accidents involve human error [2]. Such accidents could be prevented, or their impact minimized, through better use of data and analytics. Ships are becoming sophisticated sensor hubs and data generators. The next-generation ship-to-shore connectivity and the introduction of "big data" in maritime operations will improve real-time data processing and operational efficiency, allowing remote operators to make data-driven decisions.

Vital to the development of remotely controlled and autonomous operations of smart ships will be their ability to sense the surroundings through multiple data sources and communicate information in real-time, in order to navigate safely to a preset destination, perform complex maneuvers, and avoid collisions or other incidents along the way [3]. The sensor data processing should then be integrated seamlessly with intelligent navigation and situational-awareness systems to maintain, through data fusion, a detailed and constantly updated situational picture of the ship's immediate or predicted environment, a perspective that can also be augmented with contextual information, such as historical data, weather forecasts, and electronic nautical charts. In addition, research on ship motion prediction will offer advanced capabilities to project the kinematic state of vessels into the future with a prediction horizon of the order of hours [9].

The onboard command and control systems, as well as the authorities' surveillance systems, will need to integrate multiple sources of information, including traditional surveillance data from coastal radars, Long Range Identification and Tracking, Vessel Traffic Management Systems, and Vessel Traffic Monitoring and Information Systems. This data will be increasingly combined with the widely available Automatic Identification System (AIS) reports, and satellite-based images providing additional wide-area surveillance through synthetic aperture radar and optical data. Such multisensor perception systems will provide better means to monitor and analyze activities, events, and threats, enabling the development of enhanced maritime situational awareness with increased accuracy, timeliness, and a wider spectrum of automated functions.

Surveillance operators usually have to monitor the situation at sea and predict emerging distress situations from a large number of vessels within wide maritime areas. This can become a very demanding task due to the complexity, volume, and heterogeneous nature of maritime data. Next-gen situational-awareness systems will apply AI to surveillance data by merging sensing technology and historical patterns to gain real-time insights through predictive analytics and improve on-the-spot and overtime strategic decisions. Big data and AI-powered data fusion can improve anomaly detection [10] by helping to detect and evaluate all unexpected events posing potential threats, such as vessels entering forbidden areas, drifting and deviating from usual routes, or involved in illegal activities, for example, drug smuggling, piracy, human trafficking, and illegal fishing.

II. POTENTIAL RISKS AND CHALLENGES

While the emergence of the aforementioned technologies opens up huge opportunities in the maritime sector, it also poses different challenges and potential blockers that need to be considered. First, new technologies need to be robust in diverse operational situations against safety and security concerns, with the goal of further reducing the number of marine casualties and incidents. To this end, it is important to ensure that the regulatory framework for MASS keeps pace with technological developments that are rapidly evolving [4]. This may be one of the biggest obstacles to rolling out fully autonomous operations. Regulations related to shipping are still based on the principle of a manned vessel with a crew onboard, which means that several of these need to be updated for remote and unmanned operations [11].

Considering the increasing level of autonomy, variety of data sources, and systems involved, automated situation awareness systems will need to seamlessly combine the available information from multisensor perception systems to generate one coherent understanding of the vessel surroundings. To ensure the success of this technology, it is necessary to resolve conflicts between sensors and to interpret and support decisions in situations of ambiguity. Detection and classification capabilities must be reliable even for small objects and provide better coverage of the close-range sector by including, for example, optical and infrared cameras, and LIDAR. One of the difficulties in this area is that, while some conventional sensors such as Global Navigation Satellite System (GNSS) and AIS have well-established data standards, for other sensor types, such as LIDAR and cameras, data standards are not as established. It is also worth pointing out that most of the available current sensors are not built to support autonomy, as their data frequency is not high enough for the real-time decision-making needed by an autonomous system. In addition, an increased degree of autonomy on vessels will also need to comply with maritime anti-collision regulations [Convention on the International Regulations for Preventing Collisions at Sea (COLREGs)] [12].

In light of the recent advances in AI as a key technology in automated decision-making systems, these technologies are still developing and will need to develop further to ensure that fully autonomous operations are both realistic and safe. A major challenge comes from the various vulnerabilities in terms of reliability, to avoid failures or malfunction and interpretability that affect AI techniques [13]. These vulnerabilities could strongly impact the robustness of current systems, leading them into uncontrolled behavior and allowing potential adversaries to deceive algorithms to their own advantages. The robustness of AI-powered systems follows from the generalization capability of AI methods, which can usually be improved by using large-scale training data. However, in maritime scenarios, this might be problematic since the type and scale of data can largely vary, requiring the maritime research community to develop an improved fusion of multimodal data or to use various AI methods for different types of data [4]. Another challenge for AI systems is to better understand what tasks can be practically performed using the capability of online learning where sensor data is processed on the fly, typically for learning dynamics and prediction models or for refining a previously learned model. Offline learning, on the other hand, requires predefined training data and is especially applicable to identification and classification tasks. An additional issue of standard AI methods is that they cannot provide predictive uncertainty estimates, hence no quantification of the confidence with which the prediction outputs can be trusted is usually available. Given the safety-critical nature of maritime surveillance applications, future situational awareness systems will need to reliably quantify the prediction uncertainty together with the predictions to enable improved decision-making.

Furthermore, due to the increasing connectivity of future smart ships, cybersecurity is an important issue. Cyber attackers can exploit the increasing vulnerabilities in the communication links, human–machine interfaces, and several software-supported functions to directly launch attacks on the integrity or availability of the data and control systems [14]. Moreover, self-reporting sensor data such as AIS reports can be subject to intentional reporting of false information, or *spoofing*, and vessels can *go dark* by simply turning off their AIS transmitters [15]. The GNSS can provide positioning, navigation, and timing (PNT) services for autonomous or remotely controlled ships. Ensuring not only the accuracy, but also the integrity and operational continuity of PNT data is becoming increasingly pivotal for maritime safety. GNSS plays a key role in the time stamping of maritime sensor data from multiple sources and critical time synchronization in telecommunications and computer networks. However, GNSS is vulnerable to jamming and spoofing attacks that could induce a victim ship to synchronize to the attacker's signals instead of the legitimate satellite, negatively impacting or even disabling the ship's monitoring and control functions.

Autonomous ships will include complex automated systems with advanced onboard sensors. However, if a problem occurs in open waters, it might be useful—and necessary—to have a possibility for remotely operating the vessel from a land-based control center. This requires specific human–machine interfaces and interaction for data and status visualization, situation awareness, teleoperation, and remote guidance, which become crucial to maintain safe operation. The innovations toward autonomous operations are likely to follow an incremental approach. A first step might focus on new kinds of decision support systems based on situational awareness systems with suitable multisensor integration. Such systems will offer a basic level of autonomous capabilities for enhanced observation and self-guidance in different operational scenarios. The next step is about looking for development opportunities to scale up or expand toward more autonomous functionalities. Some existing technologies are expected to be extended and developed to unlock more functionalities, while other capabilities, for example, satellite data processing, will not necessarily raise new challenges, but rather be applied or combined together.

III. CASE STUDY: ADVANCES IN AUTOMATIC ANOMALY DETECTION

According to the European Maritime Safety Agency (EMSA), over the period 2014–2019 there were, within European Union member states, 19 418 reported marine incidents involving a total number of 21 392 ships and causing 496 fatalities, these last mainly occurring during collisions, floodings/founderings, and groundings [16]. Recent examples of major real-world accidents include fatal crashes involving commercial and navy ships such as the USS Fitzgerald, the USS John S. McCain, the collision between the container ship Delphis Gdansk and the cargo ship BBC Neptune in

Fig. 1. ***Overview of the automatic anomaly detection tool applied to the real-world scenario of the Suez Canal blockage [19]. The Ever Given trajectory reported by AIS from 23-03-21 to 29-03-21 is displayed on the left. In the middle panel, the nominal trajectory and the AIS observations are depicted right after the entrance of the canal and before the grounding. On the right panels, the anomaly score is reported as well as the nominal and the real speed of the ship. The alarm is triggered (red dots) when the score is above the threshold (white dotted line), while the nominal condition is declared (blue dots) when the score is below the threshold. Credit: Satellite image © 2021 Maxar Technologies.***

the Great Belt Strait; and of course the Ever Given grounding in the Suez Canal. The main reasons for such accidents typically remain poor visibility, untimely action of bridge teams, and no warning of the risk of collision/grounding from ashore. With next-gen anomaly detection systems providing an improved maritime situational picture in real-time, these situations could be automatically detected and suitable countermeasures activated.

Recent advances in automatic maritime anomaly detection [15], [17], [18] based on an innovative statistical representation of vessel kinematic data available from surveillance systems open up the possibility to reveal anomalous vessel behaviors and unexpected patterns. In this context, automatic anomaly detection tools have been successfully applied to the real-world major event in 2021 of the container vessel Ever Given [19], which was grounded in the Suez Canal on 23 March (see Fig. 1). The blockage was estimated to have affected $9.6bn of goods each day, or around 12% of total world trade [2]. The anomaly detector is designed to process the available sequence of reports such as AIS data, information from ground-based or satellite radar systems if available, and contextual information defining the expected nominal behavior of navigation to decide whether or not a deviation from the nominal behavior happened within a specific time period, for instance, two consecutive data points. Results based on the recorded AIS data from the Ever Given revealed that the proposed automatic anomaly detector could have been triggered and alerted to anomalous behavior a full 19 min before the grounding. This clearly could have helped avoid the accident that caused such a negative impact on maritime traffic and global trade.

Despite the recent emergence of disruptive technologies, developing a clear maritime situational picture requires sophisticated and automatic information processing. Advances in self-driving cars and other autonomous systems have shown that with advanced sensor technology and well-designed algorithms, it is possible to enhance situation awareness and autonomy. These innovative technologies, combined with a certain level of human–machine/human–system interaction and AI-enabled collaboration, may be key to reducing incidents due to human error in the maritime. The major event of the Ever Given sheds light on the critical role of next-generation automatic anomaly detection systems to augment crew perception and offers a new route to advanced situational awareness for future remote support and autonomous control of ships. ■

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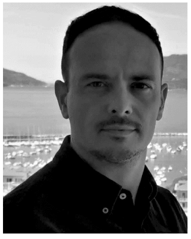

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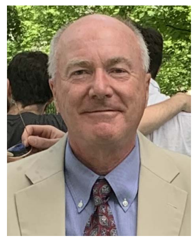

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