# Maritime Safety and Highly Automated Systems

An Industrial Technology Roadmap

Output of the industrial workshop on safety of maritime systems "eMIR Industry Days" in Hamburg, April 2018 including contributions from members of NMMT Working Groups on Civil Maritime Safety at GMT and Autonomous Maritime Systems at DGON.

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# Content

# 1 Executive Summary

The worldwide competition in maritime industry is strong. Norway has defined autonomy and green shipping as part of their national strategy and funds numerous projects. A similar strong governmental support can be observed for the Netherlands and Finland. China has made huge investments in their maritime infrastructure and has setup four major testbeds that implement new traffic management and eNavigation services as part of a multi-year project just started in 2018. South Korea currently invests more than 100 Million EUR into the SMART Project to foster maritime safety, eNavigation and to implement broad band communication on sea. Strong efforts and investments are needed to maintain the position as a global player.

Digitalization is going to change the way in that we will operate, navigate, communicate and control future maritime systems and has the potential for enabling disruptive innovations. Success in digitalization will be a crucial factor to dominate global markets and strengthen an individual company's position.

This document sets up a roadmap with the focus on identifying four lead applications that significantly benefit from digitalization and have the potential of being a future game changer for the German and European maritime industry. To identify lead applications, we first analyze the current industrial situation and then present it together with the actual normative situation. We then take a closer look on current technological opportunities that enable four lead applications: (1) intelligent bridge systems, (2) remote control and surveillance, (3) autonomous vessels and underwater vehicles, and (4) traffic and transportation management.

With the help of our partners from the industry and the feedback collected in several workshops we propose a technology roadmap that demands application driven-research. It's important to point out that dependability and safety are essential for these future maritime technology applications. The new level of complexity introduced e.g. by interconnected systems of systems and algorithms that were trained by data require new engineering methods and verification and validation platforms as well as interconnected maritime testbeds.

The roadmap proposes technological topics to be investigated together with the corresponding research enablers for the upcoming years. We divided the technology roadmap therefore in three main sections reflecting: the relevant application-driven research topics and technologies, the relevant engineering methods and finally verification and validation platforms as well as national testbeds. All these are urgently needed to test and experiment with the next generation of interconnected maritime technology like e.g. highly automated systems implementing a complexity that needs to be managed to ensure operational safety and to prevent cyber-crime and terrorism. In the best case they are future game changers and create entire new ecosystems introducing new sets of technologies, like cars a century or smart phones did a decade ago.

Politics, governmental administrations, industry, research and education must work hand in hand to shape the future of the maritime industry.

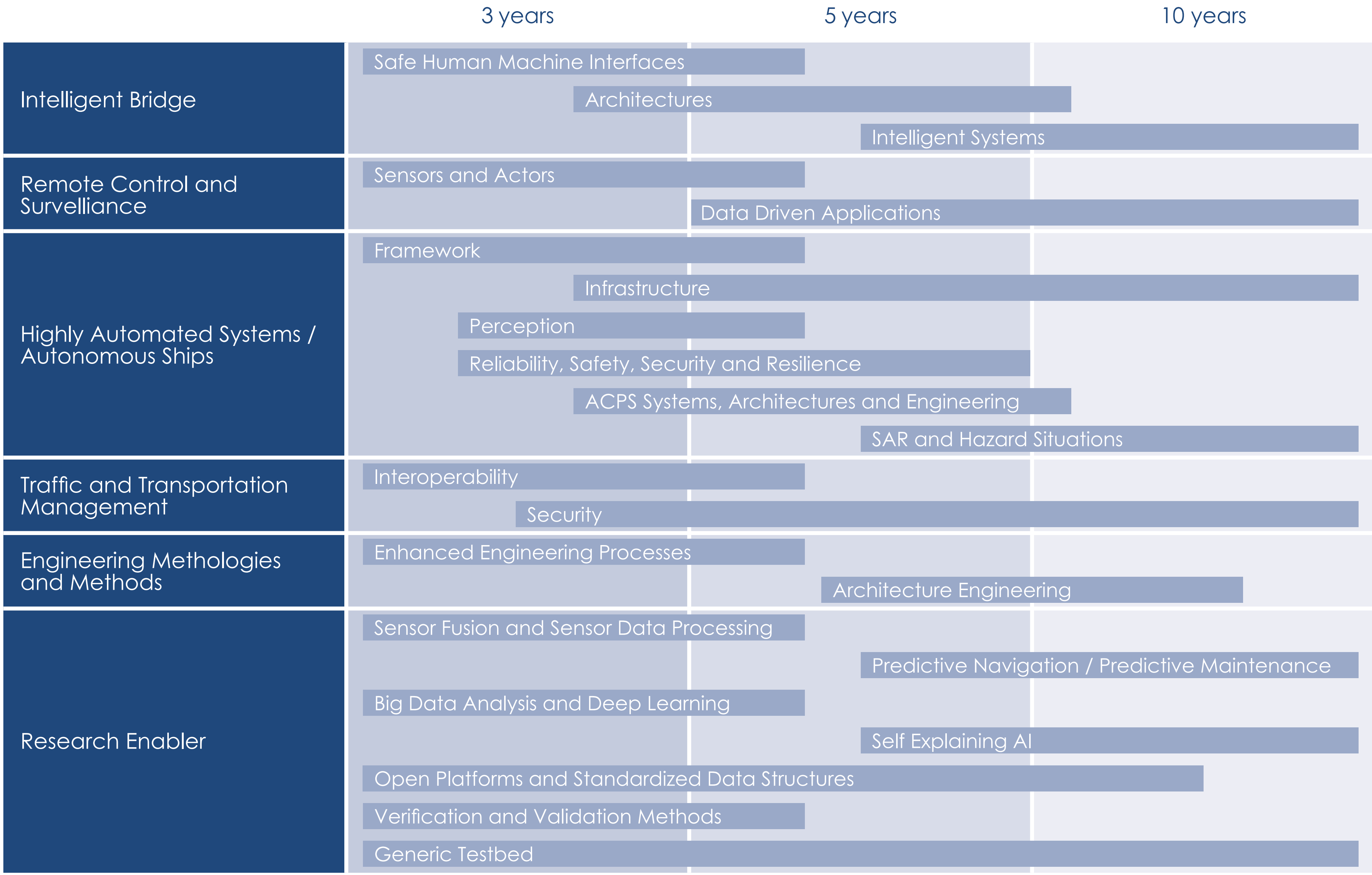


*Figure 1: Overview Roadmap Maritime Safety and Highly Automated Systems; Application-Driven Illustration (c.f. section 8.1)*

### *Recommendations*

Digitalization and upcoming technologies like Artificial Intelligence have the power to be a game changer in maritime safety and automation[1].

Highly automated vessels equipped with intelligent bridges in an interconnected traffic and transportation management environment will enable a greener, safer and efficient future.

These lead applications have the power to accelerate the development of required technologies, but also demand new engineering, verification and validation methods as well as national test-beds that are also interconnected on a European level.

This roadmap identifies technological topics to be investigated together with the corresponding research enablers for the upcoming years with respect to the lead applications, new engineering, and validation and verification methods.

Recommended actions:

- Foster / invest into lead applications to drive joint national/European-level initiative or projects.
- Develop new methods for system of systems engineering that ensure reliability, availability, maintainability and safety for complex, interconnected systems.
- Support test-beds for validation, verification of highly automated and connected systems.

# 2 Introduction

The roadmap aims to increase the presence, perception and competitiveness of German and European maritime technology on national and international markets. Securing and further creating high-quality jobs in the future markets of **maritime safety and highly automated systems** is of significant strategic importance, while at the same time, innovations in these areas need to be carefully match the regulatory and normative situation.

The identification of four lead applications: “Intelligent Bridge”, “Highly Automated Ships”, “Remote Control and Surveillance”, and “Traffic and Transport Management” is the outcome of a rigid analysis of the market needs and technological options and was performed in workshops with the industry and research organizations on a national and a European level in the last year. Most of these stakeholders are also currently collaborating to setup and run the eMIR eMaritime Reference Platform.

Further on, position and white papers of the NMMT working groups on Civil Maritime Safety at the GMT and the Autonomous Systems working group of the DGON [2] and several individual contributions from the industry have been considered to reflect the actual position of the maritime industry on a broader scope.

The authors explicitly aim at contributing a **technical** and **research-oriented roadmap,** elaborated on these four lead applications that we also use to identify specific requirements for future maritime testbeds, which are a mayor technology enabler.

# 3 Vision

Digitalization offers new opportunities for operation, navigation and usage of vessels or other maritime systems. Some innovations will be incremental changes, some will be disruptive and lead to new concepts, cooperation models, and tasks and to entire new business models:

**“Intelligent bridge** systems provide new technologies for operation, navigation and usage of vessels and other maritime systems to the seafarer. **Remote Control and Surveillance** will allow operators on land to support the vessel operation and traffic flow. Digitalization will provide more and more information about the vessel status, and its surroundings. Detailed information about the traffic situation of waterways, will be provided just-in-time and will be customized for the specific tasks of the crew on land or at sea. Advanced means of communication will improve distributed decision making and connect the systems on board and shore. This opens the road for **intelligent traffic and transportation management and control** and enables a deep integration into industrial supply chains. There will be the option for operators that dedicated tasks can always be taken over by the automation. With more and more tasks being automated the **autonomous vessel** will be developed and implemented for applicable use cases.”

For this vision to become reality, we first analyze the current industrial situation in the upcoming section. Then we review the actual normative background in section 5.

Thereafter, in section 6, we take a closer look at the technological opportunities as there are there right now. Section 7 describes the four lead applications that we use to explain the benefits of new technologies and to derive missing technologies that still need to be developed. The results of sections 4-7 then opens up the space to derive a technical and research-oriented roadmap in section 8. Finally section 9 conclude the document and the annex (section 10) details the current state of the eMir eMaritime Reference Platform and its roadmap for the next couple of years.

# 4 Industrial Situation

Germany and Europe have a strong position in maritime technology, but it requires joined forces of the industry, governmental organizations and research to hold and further strengthen this position. This section sums up the situation of the industry with respect to the economic situation, the continuously raising system complexity, the impact of digitalization and currently available technological platforms for testing future maritime systems.

## 4.1 Economy

Maritime transport is by far the most efficient mode of transportation of goods. The shipping sector is expected to grow by 160-250% over the next 30 years. European shipbuilders are the world market leader by turnover. In Europe currently 4.78 million people are employed in maritime related activities in ports and logistics that support the movement of goods. For instance, in Germany around 400.000 people are working mostly in one of the 2800 small and medium sized companies (SMEs) in the German maritime sector, which are often technology leader in their respective areas[3]. These SMEs contribute significantly – directly as well as indirectly – to the value creation in Germany and Europe with an annual estimate revenue of around 18 billion EUR. During the construction of a ship for instance, about 70 to 80 percent of the value added is generated by suppliers. Currently around 50% of the suppliers' products are exported outside Europe.

With a significant annual growth of freight traffic (around 2,5% per year) till 2030 in Germany[4], efficient and modern traffic control and safety as well as security management and supervision are indispensable. To prevent traffic hazards, incidents, and accidents and to organize an efficient maritime traffic flow in such vulnerable traffic areas such as the German Bay, modern, complex technical surveillance and monitoring systems are required. The maritime safety, security and surveillance sector in Germany has an annual revenue of around 400 Mio EUR [5] and an annual growth between 5%-10%. SME suppliers in this sector often remain invisible to a broader audience (i.e. hidden champions) and their performance depend on the availability of highly educated academics, such that the lack of skilled engineers on the German job market as well as the steady entry of Eurasian competitors specifically from Russia and China constitute increasing challenges.

Developing complex maritime systems requires engineering skills and knowledge on a high level of expertise. This is even more relevant the more automation, security and safety are being considered in engineering. In order to encounter the lack of skilled labor in Germany, massive investments in higher education (not only in the maritime domain) are necessary. Specifically, the underlying technologies such as systems of systems, cyber-physical systems engineering as well as security and safety technologies are very relevant areas the need to be addressed in higher education courses. Engineers need to be well prepared to design, implement and validate future autonomous systems, which will be complex system of systems composed of tightly coupled hardware and software.

This Eurasian market pressure requires Marine Technology SMEs to focus more on Research and Development (R&D) as of now (according to NMMT in 2011 only 22% of the companies involved in Maritime Traffic, Safety and Security performed R&D on a continuous basis [4]) in order to have a chance to gain market shares with innovative products and processes and to remain competitive on a global market level. Smart Ships and Systems Engineering are just two prominent examples along many others that come with the promise to disrupt current markets while at the same time open up completely new markets.

The German government also estimates that the degree of automation in the maritime transport will significantly increase [6]. In particular, through progressive developments in the field of new sensor technologies, new security systems with real-time capabilities and developments in the field of artificial intelligence and digitization. The results, such as highly automated, remote-controlled or fully autonomous ships and systems are expected to have far-reaching effects on the entire maritime sector. Germany as one of the technology and market leaders in the automotive industry has the chance to transfer the experiences and knowledge in the automation of land-based transport to the automation in the maritime sector.

Looking from the user perspective, the increasing level of automation also requires e.g. watch officers and members of the sea crew to undergo specialized education. While automation promises offloading of prior manual sea crews' routine tasks to the machine, education in system supervision and digital technologies becomes urgently needed. The more automation the less human participation in vessel control. This requires new on-board crew training concepts so that it is ensured that the crew remains capable of manual navigation for the case that an unexpected event occurs.

The industry has high premises in system automation that can be implemented on several levels reflecting **different degrees in autonomy** (see section 7.3). In general, autonomy is seen as a chance to further reduce crew workload, especially for error-prone routine tasks, while at the same time promises a safety gain without significant additional costs.

The area of autonomous shipping promises to strengthen the competitiveness of the German flag, as safety and reliability of the underlying technology becomes essential and autonomous ships are increasingly operated from shore (monitoring, diagnosis, maintenance, configuration, etc.). Therefore, an excellent IT-based training of skilled workers in Germany offers new opportunities on the job market.

Two types of assistant systems are frequently mentioned: First, intelligent systems to handle distress situations such as decision support systems offering an intelligent support in handling unexpected and rare events or offer support to combat piracy attacks. Second, automated berthing systems that provide support in controlling complex berthing maneuvers. These kind of systems are seen from the perspective of the industry as the upcoming development steps towards the ultimate vision of entirely autonomous vessels.

Remotely controlled or partially autonomously controlled vessel traffic along the coastlines and along the inland waterways is seen as a reasonable first step as soon as mobile network coverage provides sufficient bandwidth and low latency. A continuously connected vessel is expected to communicate performance data and all data relevant for maintenance automatically to raise the awareness about potential problems, which can be analyzed before they actually occur (predictive maintenance, e.g. driven by big data analysis).

Future vessels and maritime systems will increasingly interact with each other and also with the coastal transport infrastructure in order to implement an efficient and safe use of coastal waterways, traffic separation areas and shipping routes. Germany as a coastal state with one of the busiest sea areas has the opportunity to implement, test and early adopt relevant technologies along Germany's coast lines to become a market leader on the world market for other coastal regions.

But there are also several major challenges that need to be addressed.

**Security and Safety** are the top-most stated concerns with respect to raising the level of autonomy of maritime traffic. This is also reflected by the National Masterplan for Maritime Technologies (NMMT) [4], which demands significant more research efforts to be invested into maritime safety and security.

German shipyards massively changed their portfolio. 2006 nearly half of the production capabilities went into cargo ships. Nowadays over 95% go into the production of passenger vessels (in 2016) and also the export quota changed from 69% in 2006 to nearly 100% in 2016. Europe produces nearly all the high-value cruise ships in the world. But China is expected to become a relevant player in the cruise vessel market in the close future. With passenger transport being in focus of ship construction, safe and secure transportation is indispensable, since not only collateral damage of environments and transportation infrastructure needs to be considered, but also thousands of passenger and crew lives on board of a modern cruise liner.

Also new technologies for **traffic surveillance and monitoring** of close to port traffic are required to raise and ensure traffic safety. The Maritime Agenda 2025 [5] highlights the German leadership in the area of maritime safety. German sea port companies served for over 120.000 vessels a year and are responsible for handling 2/3 of the maritime foreign trade, encompassing over 300 million tons of freight and 20 millions of passengers per year. The Maritime Agenda 2025 [5] predicts an annual port growth of around 2.8% till 2030 and a growth in throughput of about 74% from 2010 till 2030.

Maritime infrastructure along coasts, ports, sea straits is system relevant for Germany.

Any major accident on the lower Elbe River for instance may end up with the port of Hamburg no longer being accessible for a long period. While the German government has set up two research programs covering “Maritime Safety and Real-time Services” [7] and “Civil Security” [8], the impact of a hacker’s attack to a vessel’s onboard systems or the vessel traffic service should not be underestimated.

Requirements and recommendations for components to consider security and safety at design time and during vessel operation are elaborated in a proper section (c.f. sec 3.2). There are also challenges when it comes to ship classification of autonomous ships. Entire new ways of classification, e.g. based on simulation, are required to be investigated in. And in fact, first promising approaches like the Open Simulation Platform have been recently proposed by a European joined industry initiative.

Pioneering countries like e.g. Norway and Finland and others already established **designated test areas for autonomous vessel testing**[1], and first use cases like fully automated docking have already been already implemented [9], while in Germany designated test areas still need to be identified, established and equipped with relevant infrastructure. Urban areas with a complex network of waterways such as Berlin, the Lower Elbe region and large ports are particularly attractive for autonomous shipping. First Technology Development Platforms, such as the eMaritime Integrated Reference (eMIR) platform for instance have been recently setup as joined initiatives between science and the industry and already include a reference waterway with enhanced infrastructure. Currently simulators are used for testing more complex scenarios like autonomous vessel navigation maneuvers since regulations for field tests in such a designated area are still missing. A detailed summary and roadmap of the eMIR platform is provided in the appendix (section 10).

In the Asian countries, huge investments have been performed or are being currently set to vastly improve **maritime infrastructure.** For example, in China the **digitalization** of the Yangtze River to optimize traffic management and reduce accidents is part of a multi-year project starting in 2018, focusing on communication between ships and with the shore side on the basis of an LTE communication infrastructure. The Yangtze River project is one of four traffic management and e-navigation testbeds currently being run independently from each other but soon being connected with each other. At the same time, the Republic of Korea is pushing ahead with the optimization of maritime traffic near the Korean coast, also aiming at accident prevention. The Korean national SMART Navigation project addresses the introduction of route planning services, maritime LTE, real-time transmission of electronic nautical charts and site images as well as the harmonization of meteorological, environmental and hydrographic information for environmentally friendly and safe navigation. In Singapore the Strait of Malacca was recently equipped with the latest communication technologies as part of the Sesame Strait project, explicitly pursuing the goal of reducing CO2 emissions by optimizing the shipping routes and speeds for the Strait of Malacca.

According to the European Community Ship-owners’ Association (ECSA), around 40% of the world merchant fleet is controlled by European companies, and approximately 25% are flying the European EEA flag [10]. Of the top 5 world ports three are European.

Algorithms to optimize shipping movements and port operations are of great benefit for those companies to reduce energy consumption, and to improve resource efficiency while lowering costs. Such algorithms require globally networked systems. But optimizing systems on a global level requires a formal description and engineering methods. While nowadays networks (such as energy networks for instance) have been hierarchically planned, they are costly to establish and difficult to change. Having a modern maritime infrastructure set, **standardized platforms** are the basis for the secure and network agnostic provision of **maritime services** (such as e-Navigation services and services to coordinate and optimize the logistic supply chain for instance). Their seamless integration into vessel navigation and control systems has already been initially highlighted by the NMMT in 2011. In the European Union the Sea Traffic Management Validation Project (STM) [11] and the EfficienSea2 (ES2) [12] project foster such a platform, the Maritime Connectivity Platform (MCP) [13]. The MCP provides efficient, secure and seamless electronic information exchange between all authorized maritime actors using the available heterogeneous communication systems. Major maritime stakeholders such as IALA, CIRM, BIMCO and commercial providers such as MAERSK and DFDS have already agreed to use parts of this platform for the provision of their future services. In Germany the digitalization and implementation of basic communication infrastructure is still in an early state. For instance, a recent study by HTC and ifak ("Institut für Automation und Kommunikation e.V.") commissioned by the Land of Saxony-Anhalt, the Free and Hanseatic City of Hamburg, and the Land Brandenburg, collected a long list of actions still to be performed for the basic digitalization of the Elbe river [14]. Currently, AIS or even basic mobile network access is still unavailable for most parts of the river Elbe. European and international efforts in standardized platforms should also be considered. There is the chance that such platforms could reveal themselves as a disruptive technology enabling the first time also startups and small companies to enter the maritime sector by developing innovative maritime services.

Impact on Technology Roadmap

- Investments in education for maritime system engineering
- Designated national waterway areas for testing of highly automated vessels
- Standardized Platforms for maritime service provision
- Improved IT-Security, Safety and Resilience
- Maritime Broad Band Technology

[1] *https://www.oneseaecosystem.net/test-area/*

## 4.2 Thinking in Systems

The overall system complexity is dramatically increasing. More and more sensors and actuators are used to provide data for different systems onboard a ship and ashore. Products in the maritime domain are typically not used in insolation but as part of a complex setup. Compared to system integration in aeronautics and automotive, the level of system integration in the maritime domain is still in its beginnings.

In aeronautics and automotive huge OEMs organize the main integration of all hardware and software components. Complex supply chains have been established and coupled with extensive data exchange, a comprehensive requirement tracking, and shared or interconnected methods, models, and tools along these chains.

But future bridge systems, for instance, will also be embedded deeply into the vessel infrastructure. Similar future automated underwater vehicles e.g. for wind farm inspection, will depend on numerous services to operate successfully.

The maritime industry is therefore facing these challenges with systemic approaches. The understanding of the product as a subsystem of a complex system is a factor for successful innovation. For this, the development and maintenance of maritime systems such as the aforementioned bridge systems needs to be considered in a broader scope that includes networks of interconnected systems, sensors and actuators onboard a ship and also ashore.

Engineering and lifecycle management of those systems will be based on Model Based Systems Engineering (MBSE). It provides formalized methods to model system architectures, related requirements, design, verification and validation in order to support development and maintenance in the different phases of a systems lifecycle as outlined in ISO 15288. In addition, the Maritime Architecture Framework (MAF) as one method for this, supports the specification of systems from an architecture viewpoint and enables the contextualization of multiple systems and their interdependencies with the maritime topology and hierarchy of management and control systems. Further methods for V+V must be applied in the respective phases.

In System of System Engineering, SysML (an extention to the Unified Modelling Language UML) for instance, enables the Systems Engineers to design and describe Cyber-Physical Systems of Systems (CPSoS), combining software and hardware in one architecture.

CPSoS consider the continuous change and the inherent emergent behavior of such complex systems in practice. This is to the fact that such complex systems are typically very long living and continuously evolving. Instead of a centralized optimization, CPSoS therefore demand for innovative approaches for distributed optimization, novel distributed management and control methodologies that can also deal with partially autonomous systems, are resilient to faults, and are not vulnerable to cyber-attacks. Additionally, in CPSoS engineering the earlier strict separation between the ^vengineering phases and operation gets blurred. Instead integrated approaches for design and operation are required to cover the full life-cycle of modelling, simulation, optimization, validation, and verification. Thinking in systems is crucial for successful product design, production and market entry.

Impact on Technology Roadmap

- Emergent behavior of complex systems
- Joint activities for maritime products
- Cyber security for cyber-physical System of Systems
- CPSoS engineering and Systems Lifecycle Management for integrated approaches for design and operation

## 4.3 Digitalization and Artificial Intelligence

One main technical driver of digitalization are intelligent sensors and actors interconnected by a pervasive network. Such interconnected sensors offer an entire new level of data availability.

From an operational point of view this new level of data availability can either be used online or intelligent decision making as offline for data analysis and processing and as training data to derive algorithms such as deep learning. This is in line with the concepts of “Industry 4.0” also “Maritime 4.0” promising a massive efficiency gain by digitalization such as by introducing flexible and intelligently interconnected production lines that can scale down production to manufacturing of individual products while remaining competitive in costs on the market. The Maritime Agenda 2025 [5] also highlights the potential of goal-oriented big data analysis specifically to improve merchant shipping and port supply chains and to introduce a digital life cycle management. With the recent mobile network provider initiatives for 5G (such as driven by the 5G Dialogforum) the Maritime Agenda proposes to also consider the specific requirements of the maritime sector along the entire logistics chain.

From a design perspective the data availably enables the digitalization of products. An example is the "digital twin" – a virtual representation of the entire vessel offering new management and maintenance concepts. The idea of a digital twin goes far beyond of the concept of exchanging standardized digital data documents. Instead, product digitalization promises seamless engineering processes with early component tests based on simulation. Most importantly, these tests can not only be performed on an individual component level but also on an integration level.

With all the advantages of product digitalization and new methods in artificial intelligence one needs to take in account that like in other transportation domains, learning systems also induce new ethical and methodical questions. Practically there will be a massive need for new verification and validation methods since existing traditional functional testing approaches are no longer directly applicable for trained algorithms.

Product digitalization and open platforms raise the chance and reduce the barrier for innovative small and medium sized enterprises to enter the supplier market with innovative products. First tests of a new component can be performed much faster and at lower costs as soon as there is a digital twin. Such simulations can also be performed to predict and to ensure seamless maintenance operations. Often, the areas of operation for a ship are well known and such information can be used to predict maintenance intervals and to consider e.g. the environmental impact of an LNG carrier on its typically route through the arctic region. Additionally, the impact of exchanging components and systems for maintenance to new ones or to those offered by another supplier could be tested on a simulation level before the actual maintenance is being performed to reduce the chance of unexpected problems.

On a European level, digitalization is also the key to maintain the competitiveness of the European industry and to ensure the quality of living of European citizens: The demand for the reduction of emissions and the efficient use of resources conflict with a global maritime market in that participants often compete by reducing costs. Further optimization in costs requires to consider a global perspective: A Systems of Systems one.

Impact on Technology Roadmap

- Big Data Analysis and Artificial Intelligence and Learning
- Product Digitalization "Digital Twin"
- Open Platforms and Standardized Data Structures
- Verification and Validation for Complex and Learning Systems

## 4.4 eMIR Technology Development Platform

Maritime systems engineering for highly automated maritime system of systems is a new system class which needs novel methods for its development. Therefore, actual tools and new methods and processes from different perspectives with maritime characteristics for, e.g. validation & verification methods, security, architectures or interconnectedness are necessary. The technology development and test platform eMIR is a step forward in this respect and enables the rapid development and safe and reliable testing of new maritime systems or services from the early design phase up to prototypes under real maritime environmental conditions [15].

### *Maritime Tests and Testbeds*

Maritime Testbeds are used for prototypes of e-Navigation technologies [16]. A lot of maritime projects developed testbeds to test specific technologies, e. g. the North Sea [17], Baltic Sea (EfficienSea [12] [13]), Baltic Sea and Mediterranean Sea (STM Validation project [11]), Adriatic [18], Ionian Sea [19], straits of Malacca [20] and Japan [21]. These testbeds are specialized by their individual use-cases. Most of them want to improve planning and coordination of ship movements and increase safety on sea. An important role is the exchange of information to be able to create new features and derive improved functionality for every testbed on sea. Validation of Flow Management utilises the European Maritime Simulator Network (EMSN) and the test beds for Voyage Management. MONALISA 2.0 has developed and created a network of interconnected simulator centres in a number of EU countries – the European Maritime Simulator Network (EMSN). This network enables testing of Sea Traffic Management in complex traffic situations, as well as other functions, like Search and Rescue, as a safer alternative to live testing. This EMSN will be used both to simulate varying traffic conditions and further test and validate other parts of STM that are not possible to test and validate in real life at this stage, such as area management.

### *German Testbed Initiative*

The aim of the initiative from the German Industry and research institutes for eMIR is the further development and sustainable maintenance of an open maritime research infrastructure consisting of basic technologies, simulation platforms and testbeds.

eMIR supports efforts to introduce e-navigation, such as the provision and development of MCP components (see section 5.2) and intelligent navigation technologies for organisations such as IALA and IMO through research, development, testing and demonstration services for both industry and science.

### *Supported Technology Readiness Levels*

The development along the Technology Readiness Level (TRL)-scale [22] is initial supported up to TRL-5, from the idea, basic research and system or rather test formulation and applied research. As a pre-phase of the development, system prototypes provide further on elemental system characteristics by verification and validation methods in the laboratory and real environment (debugging and system hardening) by eMIR. Further on, the idea of a national maritime demonstrator should support further technology readiness up to level 7. Whereas successfully tested and demonstrated sophisticated prototypes can be completed to a marketable product by the industry, ready for series production to launch the market for commercial applications.

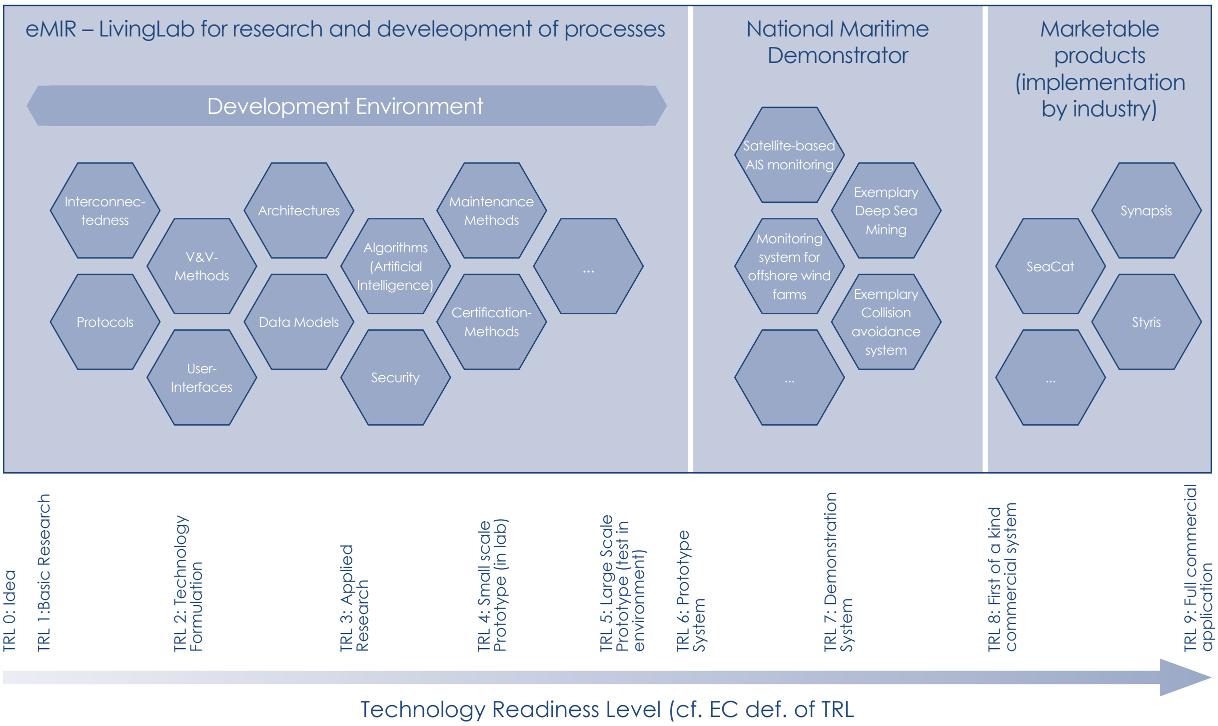


*Figure 2: Supported Technology Readiness Levels*

An open maritime testbed for new e-Navigation technologies will bring technologies of the maritime domain faster forward. Helping the development process with accessible and component based test environments that are obstruction free as possible is the aim of eMIR [23]. Open testbed means that eMIR is open for interested partners and stakeholders, the German maritime industry, research institutes, federal higher authority and research centres.

In the context of future applications, such as automation & autonomy and enabling technologies and services, eMIR also offers a basis and various possibilities to address important non-technical cross-cutting issues in a forward-looking manner in parallel with actual and future technological developments, e.g.:

Impact on Technology Roadmap

- Create trust in autonomy and systems for users and stakeholders
- Analysis of maritime Systems and Modelling
- Technical development, testing and demonstration
- Regulatory design and increasing acceptance by creating trust in autonomy and for new systems
- Operating reliability
- Training and education
- Testbed for new business models

# 5 Normative Background

## 5.1 e-Navigation

The intention of the e-Navigation initiative is the optimization of cooperation between current and future technical- and operational services. Such cooperation's address an interoperable information exchange between ships and between ship- and shore side and its human actors. According to IMO's strategy implementation plan (SIP) [24], this initiative refers to a set of five prioritized solutions to be followed for its integration in the maritime transportation sector. Those solutions are regularly supplemented and adjusted in line with the progressive evolution of maritime innovation and needs:

- S1: improved, harmonized and user-friendly bridge design
- S2: means for standardized and automated reporting
- S3: improved reliability, resilience and integrity of bridge equipment and navigation information
- S4: integration and presentation of available information in graphical displays received via communication equipment
- S5: improved communication of VTS Service Portfolio (not limited to VTS stations)

Solution S1 requires the development of human centered designs for ship bridges as basis for a harmonized Human Machine Interaction (HMI). The herein intended bridge designs shall consider existing technical bridge equipment, but also a changing number of bridge officers. Furthermore, it also reflects information (cognitive) overload in terms of usability of bridge equipment. This is especially crucial in critical situations or for tired personnel. Accordingly, the IMO has already published MSC.1 / Circ. 1512 [25] as approach to coordinate (future) bridge designs.

Furthermore, solution S2 requires the establishment of technical support in order to provide the mariner with the ship's own data and incoming information in accordance to the respective traffic situation as intelligently as possible. S2 also deals with automated reporting beyond navigation-relevant information. This makes it necessary to create technical possibilities for the electronic exchange of the IMO FAL Forms for standardization of freight documents and other administrative documents for trade at sea in conjunction with port and customs authorities on international and national level.

S3 addresses the integration of systems for ship-side e-Navigation such as an Integrated Navigation System (INS, see section 6.1). This includes also the verification of the integration of relevant information from sensors and actuators in such a system environment.

S4 postulates the development of graphical displays for received information such as MSI. It formulates the necessity for the provision of standardized technical interfaces for a common data exchange but also for a global wide standardized and holistic visualization of such information. Moreover, the usage of harmonized interfaces also requires the use of a Common Maritime Data Structure (CMDS). Such a common data structure enables the interoperable information exchange between heterogeneous technical systems. IMOs solution for this is the application of the S-100 standard modelling approach of the International Hydrographic Organization (IHO). S-100 is further outlined in section 6.5.

Finally, e-Navigation solution S5 focuses more on the shore-side of the maritime sector, especially on maritime traffic management. It highlights communication once again as an enabler for e-navigation and formulates the need to identify potential communication methods. One scenario could be the interconnection between different VTS areas in order to exchange and fuse traffic surveillance information. That information could be used to apply a continuous tracking of maritime entities and its movements across divergent sea regions. This requires consequently the consideration of safety and security issues for the respective communication means. S5 also refers to the provision of testbeds as a basis for demonstrating and evaluating current and future communication methods in coastal areas as well as at the high sea [26].

Additionally, the IALA concretizes aspects of the e-Navigation architecture from a more technical perspective. The IALA provides for instance guidelines for structuring shore-based system architectures. The corresponding IALA Guidelines 1113 and 1114 [27], [28] refer to the design and implementation principles as a basis for standardized system architectures of shore-based infrastructures. Those guidelines facilitate the service-oriented approach in the e-Navigation and encapsulate communication means such as AIS, VHF or Radar into technical services for data exchange. Those services are moreover classified into different groups according to their characterization.

Finally, the realization of e-Navigation requires the application of Systems Engineering methods for socio-technical Systems of Systems. In concrete, this means inter alia the identification of requirements and demands for the harmonization of existing systems and respective regulations, the standardization of technical components, potential adjustment given regulations (especially for highly automated shipping) and the provision of testbeds in designated test areas for further verification, validation and certifications of solutions.

Impact on Technology Roadmap

- HMI standardization & HM cooperation focused development (HCD)
- Reporting Systems
- Route assistance systems
- Cooperative situational awareness
- Tracking for maritime entities
- Common Data Structure / S-100
- Safe, secure and standardized communication
- Interconnected Radar Chains covering different areas
- Interoperable data processing
- Information fusion
- Generic / sustainable test platforms and validation infrastructures
- Test areas
- Maritime Architecture Framework (MAF)
- Standardization of subsystems / components
- Legislative Requirements
- Open SoS Architectures

## 5.2 Maritime Service Portfolio

The Maritime Service Portfolio (MSP) defines and describes the set of operational services in the context of e-Navigation and their level of service provided by a stakeholder in a given sea area, waterways or ports, as appropriate [29]. The intention is to structure relevant (navigational) operations in Maritime Services to ensure a safe voyage berth to berth. For this, the MSP addresses six topological areas inside the maritime sector, namely port areas and approaches, coastal waters and confined or restricted areas, open sea and open areas, areas with offshore and /or infrastructure developments, polar areas and other remote areas. They are currently refined in the IMO MSC as well as inside the IMO-IHO Harmonization Group on Data Modelling for further standardization of S-100 (see section 6.5). The implementation of the IMO's e-Navigation strategy requires the establishment of the Maritime Services in the form of operational and technical services by national stakeholders. Therefore, the IALA is currently developing a new guideline on Maritime Services to assist service providers with the integration of new digital services and to migrate from conventional to digital services. As one requirement, the establishment of an (global) common identity management is required in order to enable the authorization of maritime actors using or providing those services.


Moreover, for the establishment of highly automated shipping, the provision of the Maritime Services is also mandatory. Highly automated navigation is not explicitly considered in the MSP. The establishment of Maritime Services for highly automated navigation is particularly necessary with regard to design standardized safe navigation and traffic management operations in the expected mixed traffic between (semi-) autonomous and regular shipping. Taking into account the different levels of autonomy, a number of assumptions and requirements can be defined for the support of maritime safety by the MSP:

For instance, the support of e-Navigation solution S4 (integration and presentation of available information in graphical displays) in conjunction with the MSP for the safe navigation of highly automated ships may lead to the provision of the available information in shore-based surveillance- or remote-control stations. Such a facility enables human actors to monitor and remotely control vessels of different levels of autonomy taking the MSP into account. Additionally, the information based on the respective MSP service (for instance Ice Navigation Services) has to be provided also to the highly automated ship itself in a machine-readable format to be considered for its safe navigation. Consequently, the implementation of these Maritime Services such as in MSP #8 Vessel Shore reporting requires the establishment of an appropriate technical infrastructure onboard an highly automated vessel for the collection, processing and transmission of own ship information or about the environmental situation in a human independent form.

In addition, for instance Nautical Chart Services or Maritime Safety Information Services also require an automatic provision of information by the ship and environment. This includes the automatic processing of information received by the ship for consideration in the decision-making process for safe navigation onboard an highly automated ship. Overall, this results in the requirement for the MSP services to be implemented as technically and digitally as possible to guarantee automatic data transmission („Machine to Machine") between the ship- and shore side.

Impact on Technology Roadmap

- Maritime Services
- Identity Management
- HM cooperation focused development (Human Centered Design)
- Common Data Structure / S-100
- Reporting Systems
- Traffic infrastructure
- Remote Pilotage / Pilotage for Autonomous Vessels
- Design Rules for autonomous ship navigation and operation
- Cooperation strategies
- Sensor and sensor fusion

## 5.3 European Initiatives

Based on the overall e-Navigation strategy and corresponding regional and national initiatives such as the European e-Maritime initiative [30], a number of technical innovations are already established. Based on Directive 2010/65/EU of the European Commission, the vessel traffic monitoring and information system, SafeSeaNet [31], was developed by the European Maritime Safety Agency (EMSA) and is based on the European Maritime Single Window (EMSW) approach [32]. It includes inter alia aspects of the aforementioned e-Navigation solutions. SafeSeaNet is a technical infrastructure for the exchange of maritime information within Europe and between respective national regulatory bodies ashore. It supports a Europe-wide harmonization of maritime traffic data (in particular AIS data), automatic reporting as well as the provision of port information and ship movements.

The intention of SafeSeaNet is to support a reduction of administrative burden of the involved authorities and to optimize reporting for navigational aspects as well as to support the optimization of hinterland connections through digitalization. Based on this, the EU Commission launched the eManifest project in 2015 with the aim of exploring the possibilities for digital transmission and consolidation of freight information and other reporting formalities. eManifest is based on SafeSeaNet. It addresses the given structures of the FAL forms, defined by the IMO FAL Convention [33].

Impact on Technology Roadmap

- European Maritime Single Window
- SafeSeaNet
- Reporting Systems
- Information fusion
- Tracking for maritime entities
- Digitalization of supply chains
- E-Government

## 5.4 Autonomous Shipping (IMO)

The global trend of autonomous vehicles influences also the maritime sector. Plenty of countries such as Finland, Norway, the Netherlands or Singapore undertake own projects to investigate technical practices and approaches to establish autonomous shipping within established maritime (economic) procedures. There are high expectations in this innovation, although a worldwide or even regional deployment of autonomous vessels in operational service may not happen in the near future. More than 70% of maritime incidents are caused by humans [34]. With the introduction of autonomous shipping, the reduction of maritime incidents is a valid assumption. Moreover, once established, the construction could be technically optimized and become more price-competitive against current shipping. The expected high innovation costs can be reduced by the adoption of approaches from the automotive and aviation domain. Autonomous vessels may need to be equipped with reduced measures and systems for human safety onboard. Nevertheless, such a change of operational paradigms leads also to worldwide regulative implications as the conventions of the IMO are formulated from the perspective of human seafaring.

Therefore, the IMO endorsed with MSC 99 in May 2018 a framework to investigate to which extend "IMO instruments" (SOLAS, COLREG, Load Lines, STCW, STCW-F, SAR, Tonnage Convention, SPACE STP, STP) are adoptable for autonomous shipping. The different definitions such as from Lloyd's register are facilitated inside IMO's degrees. Whereby also different degrees of autonomy are further outlined in section 7.3. The initiated IMO task force will analyze in a first iteration specific parts of the SOLAS convention (III/17-1, V/19.2, II-1 / 3-4) following a specific methodology taking into account the human element, technology and operational aspects [35]. First results are discussed at MSC 100 in December 2018. This process was recommended inter alia from German initiatives such as from the Deutscher Verein für Internationales Seerecht (DVIS) but also from the International Working Group IWG.

Concluding the previous information, it can be assumed that existing regulations and conventions for the integration of autonomous navigation into the maritime sector should be adapted accordingly and already taken into account in the design and construction of autonomous ships: The integration of autonomous vessel requires, inter alia, possible adjustments to the collision prevention rules (COLREG) in order to enable its clear formalization and interpretation by technical devices. But also, standards for maintenance or equipment of autonomous ships with lifeboats and other rescue mechanisms for persons on board.

Market Impact on Technology Roadmap

- Legislative Requirements / Regulation changes
- Economic Effects
- Testbeds to create trust in autonomy
- Autonomous / Predictive maintenance
- Certification

# 6 Technological opportunities

## 6.1 Integrated Navigation Systems

In the current state an INS is regulative-wise no mandatory on board-equipment. However, it can be used to meet the equipment requirements. An INS is more than the sum of the individual devices it contains. Within e-Navigation the INS is seen as a core component for the navigation on board a vessel.

The purpose of an Integrated Navigation System (INS) is to enhance the safety of navigation by providing integrated and augmented functions to avoid geographic, traffic and environmental hazards. It comprises navigational tasks such as “Route planning”, “Route monitoring”, “Collision avoidance”, “Navigation control data”, “Navigation status and data display” and “Alert management”, including the respective sources, data and displays which are integrated into one navigation system. Also, alert management is a part of the INS.

By combining and integrating functions and information the INS provides “added value” for the operator to plan, monitor and/or control safety of navigation and system status of the ship. Integrity monitoring is an intrinsic function of the INS. The INS supports safety of navigation by evaluating inputs from several sources, combining them to provide information giving timely alerts of dangerous situations and system failures and degradation of integrity of this information. The INS presents correct, timely, and unambiguous information to the users and provides subsystems and subsequent functions within the INS and other connected equipment with this information. The INS aims to ensure that, by taking human factors into consideration; the workload is kept within the capacity of the operator in order to enhance safe and expeditious navigation and to complement the mariner's capabilities, while at the same time to compensate for their limitations.

Future developments are to be seen as the integration of information that is made available to the ship through various external maritime services via appropriate communication channels. Navigation-related data should be provided with integrity information by appropriate checks, which give the user a better overview of the reliability and applicability of the data. New sensors (e.g. Lidar, IR sensors), which support the increasing automation, will be added-value. The exchange of navigation relevant data (e.g. route data) between ships or with control stations ashore will increase. User interfaces of individual devices/sensors are integrated and combined.

Impact on Technology Roadmap

- Legislative Requirements
- Assistance systems
- Information fusion
- New human machine interaction
- HMI incl. Augmented Reality & Wearables
- Reporting Systems
- Secure communication
- Self-explaining bridge
- Smart Voyage planning

## 6.2 Ship, Machine and Propulsion

Even before autonomy becomes a reality onboard ships, the usage of assistance and support systems also for machinery operation will gradually increase. In early scenarios, humans will of course still interact with the systems and will stay responsible. But even in this case, the direct interaction of onboard systems including bridge, automation and propulsion systems, will lead to new challenges which will need to be considered in approval and certification of such systems of systems. Today, bridge console and assistance systems do not communicate directly with ship propulsion. Safety relevance of such direct interaction will need to be examined.

As software has a central role in integrated process control systems and even more so in its sub-(assistance)systems, like the power management system or the auxiliary machinery management, it will become necessary to utilize simulation-based methods to assure the integrity of systems of systems. Such simulations will include the embedded software either through Hardware in the Loop or Software in the Loop procedures.

Actual deployment of integrated assistance systems in ship operation will start in those areas where complexity is higher already today. This would most likely be navy, cruise, mobile offshore units and research vessels as it can be seen e.g. by the increasing use of dynamic positioning systems.

The next step towards autonomy will be taken through assistance systems realizing partial autonomy. These would support ship officers e.g. through navigating and operating in selected profiles. Consequently, integrated bridge systems would interact with control and monitoring components of the propulsion system, with power management, and with positioning and navigation systems.

Loss of propulsion might be caused on the one hand through e.g. engine failure, mishandling of the control lever, or failure in secondary / supply systems. These include engine control, control of secondary systems, higher level control systems coordinating the interaction of secondary systems, control of rudder and controllable pitch propellers, bridge systems with connection to the propulsion system or remote monitoring and alarm panels. Mechanisms for updating control system software will need special consideration as they might pose an additional risk. This affects both procedures for appropriate testing of a new software version to ensure safe operation (-> cyber safety) as well as procedures ensuring secure communication and a controlled update process itself (-> cyber security).

Other important functions for autonomy and remote machinery operations are:

- Overall supervision of machinery-related systems
- Machinery control and monitoring (including auxiliary functions like fuel, cooling, heating lube-oil, air, hydraulics, pneumatics etc. as needed)
- Electrical Power generation and distribution
- Fuel optimization
- Emission control and monitoring
- Fuel management
- Battery charging control and monitoring

For a ship where the operation is relying on these technologies as well as their interaction with a human operator, a set of additional risks to ship safety emerge. These risks are not adequately addressed by our existing class rules. Therefore, DNVGL has been launched the class guideline “Autonomous and remotely operated ships” [36] to support the industry and the regulatory bodies in documenting and assuring a safe implementation. The guideline covers four types of concepts:

- Decision supported navigational watch
- Remote navigational watch
- Remote engineering watch assisted by personnel on board
- Remote engineering watch

The above concepts may be linked to the degrees of autonomy used by IMO for their scoping exercise of maritime autonomous surface ships [35]:

1. ships with automated processes and decision support
2. remotely controlled ships with seafarers on board
3. remotely controlled ships without seafarers on board
4. fully autonomous ships.

In the DNV GL's approach the following main principles form the foundation for assessment of autonomous and remotely operated vessels:

- equivalent safety
- risk-based approach
- operational focus
- minimum risk conditions
- functional focus
- degrees of automation and human involvement per function
- system engineering and integration
- design principles
- software engineering and testing

New vessel operational concepts based on autonomous and remote control of vessel functions shall have a level of safety equivalent or better, compared to conventional operations of vessels with respect to safeguarding life, property and the environment. When considering safety measures for a vessel, the risks associated with the new operational concepts shall not focus only on consequences for the on-board crew, but also take into consideration consequences for the public, the assets and the environment. An equivalent or better level of safety shall be obtained in all these respects.

New business models such as performance- or availability-based contracts aim at selling outcome rather than products. They can be summarized as a trend towards servitization. The component or system maker has to ensure system integrity in operation. Without own crew members, they rely on automatic monitoring and analysis of data received onshore.

Based on this, a clear need for managing digital twins comes up. This is analogous to the trend in other industries. Condition data needs to be collected systematically to allow for timely decision making with respect required maintenance, control software updates, reconfiguration. The ability to simulate component and system behavior is crucial in this respect. Additionally, due to increasing system complexity, simulation will couple engineering disciplines. This calls for new design methodologies such as Model Based Systems Engineering (MBSE) – with its artefacts to be transferred into operation phase: e.g. control software updates will require systematic testing on the digital twin before installation over the air.

Market Impact on Technology Roadmap

- Human interactions with onboard systems
- Assistance Systems
- Secure communication
- Real Time maritime Data
- Interoperable Data processing
- Requirement Engineering
- Model Based Systems Engineering
- Common Information Systems
- Remote Pilotage
- SAR Support (by autonomous vessels)
- Highly reliable Communication
- Simulation Platform for Engineering
- Fusion of all ships sensors

## 6.3 Ship Safety and Security Systems

The increase in automation interconnections between systems and their respective coupling will significantly increase in the future. This will not only happen for the design phases that consider complex systems as a whole (Cyber-physical Systems of Systems engineering), but also in their very concrete physical realization in that all systems and machineries are technically required to be interconnected in order to support continuous monitoring, constant system supervision, and their respective automated control.

Actual approaches on cyber security need to be re-thought as they often end up demanding system isolation like e.g. keeping sub-systems (ideally physically) isolated and having them not being directly connected to the internet such that they can no longer be maintained. Current threads that target for instance at preventing or improve the line of defense for physical access as it is happening right now (e.g. removable media-based data exchange between systems, which might introduce malicious software). When compared to future on-board systems that depend on online updates and continuous network connections, more complex defense mechanisms are necessary.

While today cyber-attacks that may affect a vessel, ports or shore-centers, which are mostly assumed to be targeted attacks, for that a company or a ship's system and its data are the intended attack, future maritime systems being in constant network connection and information exchange can be just one of many, many other targets in the interconnected world of sensors and systems. Hostile untargeted attacks, as they are already a common practice in the World Wide Web, will become the most frequent way of cyber-attacks. Untargeted attacks are not directed to affect a specific company but benefit from a flaw or erroneous function of a commonly used sub-system or system component and can cause damage on a much wider scale (e.g. all vessels that share the same version of a sub-system).

Therefore, safety and security assessment methods as well as risk management are required in order to implement a systemic view on assessing system of systems, systems, their sub-systems and components. As of now, security is often understood by introducing (additional) building blocks to an existing system, such as firewalls, intruder and anomaly detection systems. Metrics and other quantification methods to analyze existing systems combined with innovative approaches for securing control functions (e.g. location-based security, resilient architectures and by applying AI-methods to learn from previous attacks) will drive future secure and safe automated ship operation.

Also new ways for training operators to manage cyber risks are required. While learning systems and anomaly detection might identify an attack (e.g. GPS and AIS data spoofing), mitigation procedures need to be identified and trained to ensure that a ship's crew (or a future remote supervisor) is able the cope with such complex attacks.

Impact on Technology Roadmap

- Safe and secure update mechanism
- Standardization of subsystems / components
- Safe and standardized communication
- Cyber threat handling for complex hostile untargeted attacks
- Safety and Security Architectures
- Machine Learning for automated response to cyber security attacks

## 6.4 Maritime Connectivity Platform

Based on the e-Navigation strategy, concrete solutions to solve the addressed issues are under development such as for instance the Maritime Connectivity Platform (MCP). The MCP is intended to enable harmonized communication between different **authenticated** maritime actors. It accordingly addresses the need for a uniform communication and information infrastructure as requested as underlying structure for the e-Navigation solutions S2, S4 and S5. The MCP addresses the service-oriented approach from the e-Navigation and enables the registration and discovering of technical services for further usage such as to optimize the navigation onboard a vessel. It is furthermore equipped with a global identity management for humans and machines. The target group of the MCP are mariners, ship owners as well as other maritime actors to search for relevant technical services to support route planning etc. and then display the functionality and information provided in existing systems such as an ECDIS with electronic charts. The authentication by the MCP of the involved actors provides a relationship of trust between service provider and service consumer [37].

As the operational benefit of MCP is based on the provision of e-navigation services in addition to global identity management for maritime stakeholders, IALA has published guidelines for the uniform specification of such technical services in Guideline 1128 [38]. This guideline is based on the interfaces offered by the MCP and is intended to support the desired interoperability between service consumer and service provider. While the registration of e-navigation services inside the MCP is not mandatory, the most valuable point of the MCP seems to be its global identity management. This is currently developed based upon a distributed approach for combining different identity registries using a Public Key Infrastructure (PKI). This enables identity provider to be connected inside this authentication network without sharing sensitive information among the actors.

The MCP is currently in the process of conception and prototypical implementation within various national and international projects. This is done under the umbrella of the Maritime Connectivity Platform Consortium, founded February 2019. Parts of the MCP and possible technical services are currently tested in the eMIR reference platform. The maturity of the MCP can currently be compared with TRL 6. The core components and other software components such as for instance for linking the MCP with ECDIS software as well as the provision of user interfaces for the administration of technical services, actors or for identity management are available as reference implementations under an open source license [13]. The future development and integration of the MCP into the maritime world requires the establishment of a superordinate body to coordinate standardization efforts and further development. It is also necessary to define globally uniform operational processes for the use of MCP in order to ensure harmonized use between individual MCP instances of different providers interoperable not only at the technical but also at the operational level.

The further elaboration of the functionalities as well as their integration into the existing system landscape and the promotion of perception and acceptance among the maritime partners are to be identified as current and upcoming challenges.

Market Impact on Technology Roadmap

- Maritime Services
- Common Data Structures / S-100
- Reporting Systems
- Generic / sustainable test platforms and validation infrastructures
- Maritime Architecture Framework (MAF)
- Cooperation Strategies
- Open SoS Architectures
- Management of information
- Legislative Requirements
- Distributed Identity Management
- Public Key Infrastructure

## 6.5 The Common Maritime Data Model: S100

The IMO e-Navigation Strategy Implementation Plan sees a Common Maritime Data Structure as a major building block for interoperability of interconnected systems in e-Navigation [29].

In the past, unified navigational data exchange was limited to electronic nautical charts (ENCs) in the context of maritime navigation. S-57, introduced by the International Hydrographic Organization (IHO) in 1990, became the standard for structuring and storing data. As digitalization proceeds, combined with improved system performance and communication infrastructures, new concepts for data services are also conceivable in the maritime domain. Today, strategies to increase safety through improved information availability or to optimize the economic efficiency of ship transport are being tested in various research projects [39].

The S-57 standard does not take this development into account, as it is not designed to include any kind of data. Furthermore, a standard requires durability to ensure planning reliability and compatibility for system actors. The S-100 Universal Hydrographic Data Model is being developed by IHO to take this problem into account. It is explicitly not considered a new version of the S-57. Rather a soft transition from one standard to the other is aimed for. S-100 introduces new concepts of data structuring and follows ISO/TC211 and ISO 19100 standards for geographical information in terminology and concepts.

S-100 defines rules and procedures for creation and harmonization of product specifications instead of specifying them itself, thus achieving openness and extensibility, since additions and changes, e.g. to data structures, encoding or portrayal, do not flow into the standard itself. In order to achieve standardization, product specifications developed according to S-100 are defined in outsourced standardization processes and named according to the S-1XX schema: E.g. the S-124 specification defines data structures for the exchange of maritime safety information.

One aspect of the ISO/TC211 and ISO 19100 alignment is the introduction of a registry with subordinate registers. Amongst others the S-100 Geospatial Information Registry includes a Feature Concept Dictionary (FCD), metadata registers and portrayal registers with the aim to store already S-100 compliant modeled data structures in these registers and to reuse them beyond product specifications. Thus, creating a syntactically and semantically uniform understanding between all actors. Mapping processes between different product-specific data structures can be simplified. At the same time, product-related elements can be defined via a separate feature catalogue in order to obtain the necessary flexibility for new data structures and thus for today's innovative systems.

In 2011, the IMO Correspondence Group on e-Navigation called for S-100 to be at the core of the IMO's e-Navigation concept, recommending to all industry players to design future data structures in line with the standard. In 2017 a task force named IMO/IHO Harmonization Group on Data Modelling (HGDM) was formed to further work on S-100 and directly involve the IMO in this process. Rules shall be defined how a Common Maritime Data Structure, based on S-100, may be designed. At the latest with this strategic decision of both organizations the role of this standard for future software developments in the maritime domain has manifested itself as significant.

With this perspective, it is important to evaluate for which systems product specifications should be standardized according to S-100 in the future. This applies in particular to new and existing Maritime Technical Services, which are provided, for example, by the MCP. Due to the various actors, the advantages of the FCDs come into play by harmonizing the data structures. This also applies in research and development, since the increasingly complex interaction of Systems of Systems requires an intuitive, uniform understanding of the data among all, usually differently focused, actors in research or development projects. Therefore, an S-100 compliant specification of data models is also aimed for testbeds.

Market Impact on Technology Roadmap

- Common Data Structures / S-100
- Legislative Requirements
- Information fusion
- Data Models and (Industrial) Standard

# 7 Driving Lead Applications

Driving force for innovative technologies are dedicated applications. In the best case they are game changers, come with their own ecosystems and have the potential to develop new business opportunities and products (Figure 3: Lead Applications generate additional Products.)

This roadmap follows the approach and makes use of four dedicated applications and technology clusters to make the applications, usage and of course benefits of new technologies easier to understand and of cause to derive necessary technologies to be developed. These Applications are identified by industrial and other stakeholders during the eMIR Industry Days 2018.

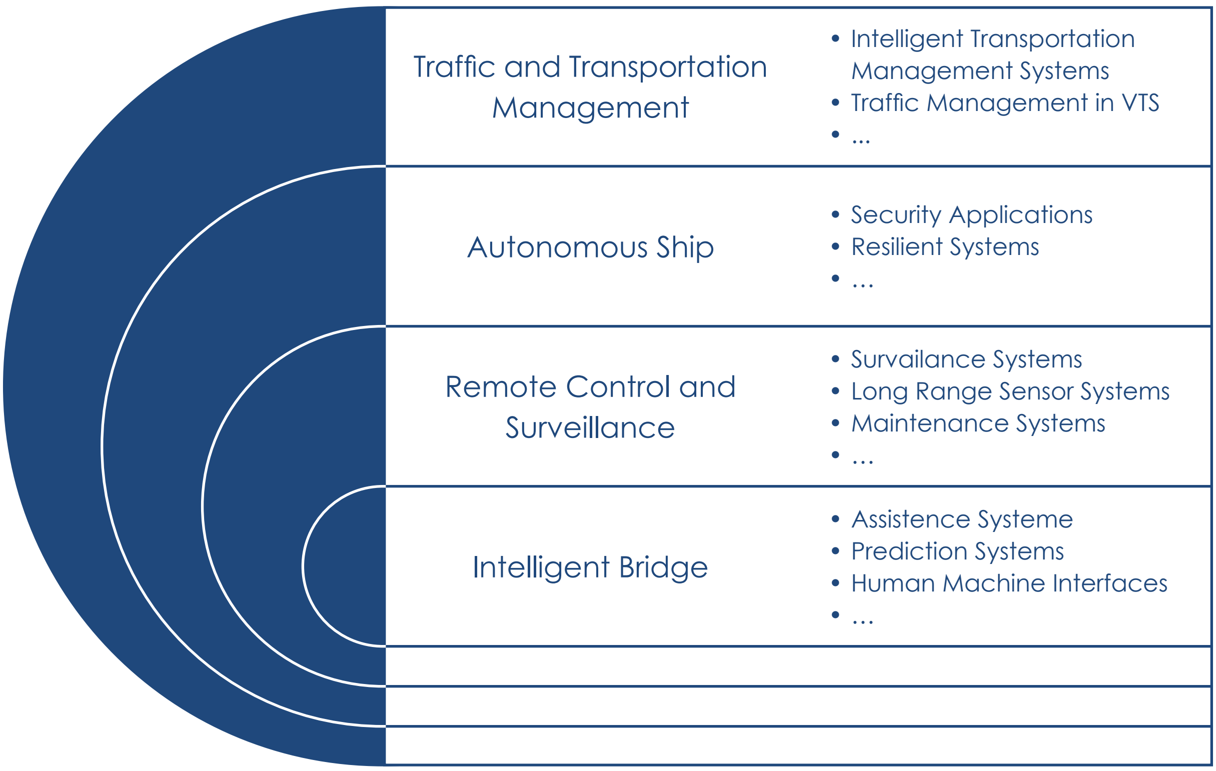


*Figure 3: Lead Applications generate additional Products*

## 7.1 Intelligent Bridge

In the advent of e-Navigation, integrated navigation systems are defined by the IMO as the bridge system of the future. This combines dedicated maritime bridge systems like ECDIS, Conning etc. into an integrated system. Intelligent Bridge systems incorporate highly automated assistance systems to reduce workload and to improve team cooperation and of cause maritime safety.

Intelligent Bridge Systems aim at improving the shared situation awareness of the crew and support their decision making. An example is the recent MTCAS project. A Maritime Traffic Collision Avoiding systems under development by several companies [40]. It improves alarm generation and supports safe negotiation of evasive maneuvers.

Linking of Bridge Systems to other systems at sea as well as on shore has the potential to increase safety and efficiency, to reduce crew workload and to improve the traffic flow in congested waters. Examples of such linkages will be between Intelligent Bridge Systems of different ships on the one hand side and with e.g. VTS systems, portable pilotage units, fleet assistance centers and terminal logistics on the other. Such thorough integration will lead to a fully new understanding of maritime traffic also as an open system of systems that needs to consider challenges like cyber security and to develop suitable emergency response measures in case of system failures.

Future intelligent assistance systems aiming at supporting the seafarers' work will make use of artificial intelligence and machine learning algorithms, e.g. to predict the future movements of the own ship as well as of traffic in the vicinity. Respective suitable validation and verification methods to guarantee dependability are presently missing, though. Such approaches also require an improved data basis which presently is not available on board. Thus, intelligent sensors are required which reliably provide e.g. environmental, time and position data at high resolutions and which are resilient against manipulation. Furthermore, such assistance systems will not just be limited to support in navigation tasks. The Intelligent Bridge will be self-explaining and be able to guide the user through complex problem-solving processes. It will also be accompanied by remote support capabilities.

Impact on Technology Roadmap

- New Intelligent Sensors
- Assistance Systems
- Intelligent Systems (Machine Learning and AI)
- Verification and Validation Methods
- Open Communication Platforms
- Cyber Security
- Fail-to-Safe Operations

## 7.2 Remote Control and Surveillance

Digitalization comes with three core elements: intelligent sensors, communication networks and Big Data / intelligent systems. Digitalization has the power to change the way we manage ships, fleets and whole sea areas. Fleet performance monitoring is an early adaptor of these technologies to allow remote management of the fleet status including for example efficiency control and predictive maintenance. Vessel Traffic Services and maritime surveillance centers already make use of intelligent multi-modal sensors and sensor data fusion.

These are only starting points for intelligent application of the future. Ship/fleet wise remote supervision leads to new ways for fleet management and remote supervision. For instance, a classification organization will be able to monitor the ship integrity 24h and 7 days a week. Maintenance can then be predicted and scheduled for the next stop and the required spare parts are ordered and delivered just in time.

Windfarm companies and governmental organizations implement new intelligent sensor technologies, new data fusion and analytic methods to further improve their operational picture of the actual situation and predict further developments, which enables preemptive interventions. This activity also include surface, underwater and aerial activities.

Impact on Technology Roadmap

- Intelligent Sensors
- Wide Range Sensors
- Network and communication technologies
- Big Data Analytics
- Anomaly Detection
- Prediction

## 7.3 Autonomous Ships

IEEE states in their lead journal [41]: "Forget autonomous cars, autonomous vessels are almost there!" and current maritime activities around the planet prove this statement. In Norway MV Yara Birkeland awaits water under its keel [42] and there are activities around the world as in Finland [43], China [44], South Korea.

In automotive development, a 6-stage model [45] has been established for the discussion of the automation of motion functions, whereby stage 0 corresponds to an absence of automation and stage 6 to full automation. This can be used to design a similar model for autonomous ships. Table 1 presents such an adapted layer model and describes possible contributions of intelligent methods. Artificial intelligence methods are particularly suitable for implementation because they are self-learning and flexible in use.

| Level | Automatisation | Description | Use of AI methods |
|---|---|---|---|
| 0 | None | The human being is responsible for controlling, monitoring the environment and collision avoidance. | None |
| 1 | Assistance Systems | The human is assisted for steering by the autopilot. Assistance systems help to perceive the environment and collision avoidance. | Control, object recognition, forecasting methods for the development of the traffic situation and hazard recognition |
| 2 | Partial Automation | Level 1 and additionally suggestions for manoeuvres to avoid collisions are output. In critical situations, maneuvers are initiated automatically. | Optimization Technique |
| 3 | Advanced Automation | The ship travels completely autonomously, but still needs to be monitored by humans. Docking and departing manoeuvres must be carried out manually. | Methods of decision finding |
| 4 | Full Automation | The ship travels fully autonomously, including docking and departing manoeuvres. No human has to be on board. | Methods of self-observation and autopoiesis. |

*Table 1: Levels for assistance systems and automated navigation functions in shipping and use of methods for artificial intelligence.*

As stated in 5.4 IMO and others discuss various levels of autonomy also, but the mentioned levels are more generic and adopted in other domains as well.

It is important to reflect the diversity of shipping when discussing autonomous ships. Of course, sending containers with multi billion worth on a container vessel around the globe is another application as a remote tugboat [46] or a postal service / delivery boat between Swedish Skerries, Friesian Islands or offshore wind farms.

In autonomous vessels there is no quick human backup, as the first line of defense is a remote-control center. This leads to dedicated challenges in autonomous situation detection, decision making and in dependability of all vital ship systems.

In addition to technologies of intelligent bridge systems, remote control and surveillance a set of technologies is required to ensure safety in severe situations or on systems failure.

Impact on Technology Roadmap

- System self-observation and degeneration
- Resilience Architectures
- Online updates

## 7.4 Traffic and Transportation Management

Gaining an integrated operational picture also makes it possible to establish a fully different management regime for fleets, sea areas, transportation, logistic- and supply chains. Combining an operational picture with predictive data analytics, enables intelligent traffic and transportation management systems to receive a new understanding of the actual situation and get an improved danger analysis and prediction. Using this information, coordinated and optimized traffic flow or transportation and supply chain management approaches can be developed and implemented. Intelligent distributed cooperation and planning tools have the power to make use of available optimization potentials and speed up efficient maritime transportation. This will save costs and time to make maritime transportation an established part of intermodal regional or global transportation.

Existing infrastructures can be used to a higher degree and the better efficiency can reduce the need for new transportation infrastructures. Instead new digital backbones are the foundation of an Intelligent Traffic and Transportation Management (Bits instead of Bricks). There is the need for a wide range of high bandwidth communication/ internet technology.

Today maritime systems are mostly seen from the ship or shore side. This traditional approach needs an update in order to understand maritime traffic and transportation as an integrated system. Ship to ship and ship to shore communication and coordination provide a new form of quality for these systems, including port operations and hinterland logistics.

Recent projects like EfficienSea or Mona Lisa / Sea Traffic Management Validation Project show the potential of the approach and present first prototypes for supportive technologies like the Maritime Connectivity Platform, Voyage Information Systems and Port Collaboration Management.

Impact on Technology Roadmap

- Reliable and save broadband communication
- Intelligent spatio-temporal planning and optimization
- Predictive analytics

# 8 Technology Roadmap

The following technology roadmap sets the lead applications in context with the required developments, technologies, research and enablers. It provides input to future research programs, the further elaboration of legal and normative frameworks, and also aims at providing input to evolving education programs for maritime safety and autonomous systems.

The following identification of required activities as part of the roadmap will contribute new ideas to foster new future European and national initiatives to strengthen the maritime industry. Joint undertakings like for instance the eMaritime Integrated Reference Platform, coupled with joined testbeds are elementary building blocks of a future common strategy of the maritime industry. Politics, industry and research have to prove their ability to act and show strength in implementing the technologies presented here.

The following technology roadmap is based on the current perspective of the maritime industry and the normative background (which have been detailed in the previous chapters). It systematically derives technological and scientific challenges and condenses them into the four potentially game-changing lead applications. It considers the feedback collected in several workshops with the industry and details them into three basic areas: application-driven research (c.f. section 8.1), engineering methods (c.f. section 8.2), and verification and validation platforms and testbeds (c.f. section 8.3).

## 8.1 Application Driven Research and Technologies

For the lead applications a set of required developments, needed prerequisites, technologies and enabling research is identified also from the DGON AMS working group [2].

*Intelligent Bridge*
The intelligent bridge as an intelligent system, the bridge system architecture and the user interface are the main future challenges that need to be addressed in the upcoming 10 years. Table 2 summarizes upcoming challenges for each area of action with their respective research enablers.

| | 3 years | 5 years | 10 years |
|---|---|---|---|
| Intelligent Systems | • Common Defines Data Structures / S100<br>• Smart Route Voyage Planning<br>• Safe and standardized communication<br>• Integrate more information (heatmaps)<br>• Alert Management<br>• Intention Prediction of Ship Behavior | • Integrated ship-shore systems<br>• Integrated risk and operational picture<br>• Adaptive Sensors and Actuators<br>• Standardization of subsystems / components<br>• Legislative Requirements<br>• Expert Systems with local pilot knowledge | • Convoy shipping<br>• Management of information<br>• Tactical decision making<br>• Swarm Organization<br>• Online Learning |
| Architectures | • Open SoS Architectures<br>• Safety and Security Architectures | • Multimedia Support | • Adaptive Architectures<br>• Design & Evolution of ACPS enforcing system integrity (online integration) |
| Human Centerd Design | • Central alert interface<br>• Harmonization easy Handling<br>• Ergonomics / Adaptive / Intelligent user interfaces<br>• Speech output | • HMI standardization<br>• Multimedia, VR, AR integration for remote control / pilotage<br>• Distributed Virtual Multifunctional Consoles | • Cognitive Human Machine Interfaces |
| Research enablers | • Better data (e.g. weather) quality and reliability<br>• Context sensitive data/information reduction<br>• Quality Awareness<br>• Big Data Analysis and Deep Learning | • Training Methods<br>• Self-explaining bridge<br>• Remote Support | • Predictive Navigation<br>• Predictive Maintenance |

*Table 2: Roadmap for Intelligent Bridge Assistance Systems*

### *Remote Control and Surveillance*

70% of our planet is covered by water and therefore a potential area of traffic control and area surveillance to ensure safety and security. With the traffic continuously increasing and automatically adapting based on future assistance systems new challenges arise in the area of remote control and surveillance. Table 3 summarizes the challenges to address in the upcoming years together with the relevant research enablers.

| | 3 years | 5 years | 10 years |
|---|---|---|---|
| Sensors and Actors | • Sensor platforms<br>• Extended AIS messaging | • Long Range Sensors | |
| Data Driven Applications | • Shared models and data structures<br>• Reporting Systems<br>• Identity Management | • Maritime Services<br>• Fusion of all ship sensors<br>• Remote Ship Health Monitoring<br>• Trust Center for Message and Information Exchange (e.g. AIS data) | • Land and air based ship monitoring (e.g. pollution)<br>• Ship sensors to monitor bilge pollution<br>• Verification of Co-operation Strategies<br>• SoCPS und ACPS |
| Research enablers | • Vessel Movement Prediction<br>• New Services from already existing Databases<br>• Machine Learning for Surveillance<br>• Big Data Analysis and Deep Learning<br>• Open Platforms and Standardized Data Structures | • Real Time Pollution Monitoring Platforms<br>• Maritime Connectivity Platform | • Improved Navigation Sensors / Radar Fusion<br>• Interconnected Radar Chains covering different areas<br>• Detailed Knowledge of Sensor Behavior |

*Table 3: Roadmap for Remote Control and Surveillance*

*Highly Automated Systems / Autonomous Ships*

Autonomy and autonomous systems like vessels are complex systems that need to integrate a wide variety of technologies in numerous components. Some, such as machine learning, are very new and it is not clear how to ensure operational safety.

| | 3 years | 5 years | 10 years |
|---|---|---|---|
| Framework | • Economic Effects<br>• Education<br>• Liability regulations & supporting Systems | • Stakeholder Integration<br>• Design Rules for highly automated ship navigation and operations<br>• Regulation changes to adopt highly automated Vessels | • Certification procedure |
| Infrastructure | • Highly reliable Communication<br>• Navigation in Harsh Weather<br>• Fall back strategies | • Traffic infrastructure | • Traffic Separation Areas for highly automated Vessels |
| Security and Resilience | • Security Architectures for Systems of CPS<br>• Protecting against piracy<br>• Anomaly detection<br>• Identity Management | • Integration Safety and Security<br>• Safe and secure update mechanisms<br>• Predictive Maintenance<br>• Self-monitoring fail (safe) operations | • Machine Learning for automated response to cyber security attacks<br>• enforcing system integrity (online integration) |
| ACPSystems, Architectures and Engineering | • Self-learning systems<br>• Adaptive Architectures | • V+V methods for self-learning systems<br>• Cooperation Strategies<br>• Reconfiguration, Self-Organisation<br>• Architecture evaluation<br>• Hardware Software Architectures | • ACPS for robust and cooperative distri-butes planning in SoCPS |
| Reliability & Safety | • Remote Pilotage | • Pilotage for Highly automated Vessels<br>• Dedicated PPU for Highly automated Vessels | • Safe self-degeneration<br>• Robot Crew Systems<br>• Highly automated maintenance |

| | 3 years | 5 years | 10 years |
|---|---|---|---|
| Perception/ Localization information | • Sensor-based perception<br>• Test environment for testing in the real world<br>• Verification and online correction of digital maps | • Reliable detection and evaluation of the uncertainty of environmental information<br>• Representation of uncertain information<br>• Deduction of reliable conclusions under information uncertainty<br>• Characterization of the accuracy and reliability of localization information | • Ext. Test environment for continuous testing in the real world |
| SAR and Hazard Situation | • SAR Operations | • SAR Support by highly automated vessel<br>• Dedicated Control Handover | • Mechanisms of Systems entering the Ship |
| Research enablers | • Sensor and sensor fusion<br>• Object detection for different scenarios<br>• Better numerical models for controllers | • Testbeds to create trust in autonomy | • Self-explaining AI for safety and certification |

*Table 4: Roadmap for Autonomy / Highly automated Systems*

### *Traffic and Transportation Management*

Nowadays trade is organized in world-spanning transportation chains and maritime transport is the elementary transportation mode for goods in such chains. An intelligent traffic management helps to improve the efficiency and safety of maritime transportation, specifically for Germany since its waterways belong to the world most dense traffic areas. Table 5 summarizes the roadmap for sensors and actors, interoperability, and security challenges for future traffic and transportation management for the upcoming years together with relevant research enablers.

| | 3 years | 5 years | 10 years |
|---|---|---|---|
| Sensors and Actors | • Extended AIS messaging | • Environmental monitoring<br>• Long Range Sensors | • Arial sensors |

| | 3 years | 5 years | 10 years |
|---|---|---|---|
| Data Driven Applications | • Marine Hydrographic information<br>• Ballast Water Assistance Systems based on voyage plans<br>• Route assistance systems<br>• Per unit container tracking | • Cooperative, situational awareness<br>• Weighting capabilities<br>• Tidal Window Information on PPU<br>• Digitalization of supply chains<br>• Cooperative strategies<br>• Conflict-resolution<br>• Maritime Services | • V+V Cooperation-strategies of SoCPS and ACPS<br>• Autonomous Operations in Transportation and Logistics |
| Interoperability | • E-Government<br>• Maritime Architecture Framework | • Standard worldwide single window | • Common Information Systems |
| Security | • Tracking for maritime entities<br>• Workflow for rerouting<br>• Identity Management | • Secure communication<br>• Scanning / Screening | • Trust Center |
| Research enablers | • Blockchain technology<br>• Information fusion<br>• Big Data Analysis and Deep Learning | • Real Time maritime Data<br>• Interoperable data processing<br>• HMI incl. Augmented Reality & Wearables<br>• Data-based System Operation<br>• Education | • Data Models and (Industrial) Standard<br>• AI pilots<br>• AI based vessel control |

*Table 5. Roadmap for Traffic and Transportation Management*

## 8.2 Engineering Methodologies and Methods

The technologies and innovations presented in this roadmap require the use of established methods from the field of Systems Engineering. The following Table 6 lists these methods in the context of the respective task, derived from the previous chapters.

| | 3 years | 5 years | 10 years |
|---|---|---|---|
| Driver for new enhanced engineering processes | • New human machine interaction<br>• Requirement Engineering adopted to the drivers<br>• Design requirements for highly automated systems<br>• Scenario based verification<br>• Information fusion<br>• Human-centered Design Methods<br>• Verifiable architectural properties<br>• Architectural description methods and languages<br>• Learn mechanism of safety-relevant systems that have not been taken into account | • Control mechanisms for traffic management<br>• System validation from different perspectives with maritime characteristics<br>• Virtual Integration Testing<br>• Rapid Prototyping<br>• Verification adopted to main drivers (AI, ...)<br>• Certification requirements guidelines<br>• Handling uncertainty in algorithms<br>• Safety critical updates upgrades, interoperability, dynamic reconfiguration<br>• Design process for learning systems | • Abstraction interface MBSE + complexity beyond<br>• Pattern language Engineering of resilient system architectures<br>• Autonomy, self evaluation systems, complex/heterogeneous SoS<br>• Increasing complexity due to AI<br>• Consistent Requirements for al design phases<br>• Performance requirements and safety-related desired functional aggregation |
| Architecture Engineering | • Maritime Architecture Framework (MAF) | • (Multi-)Critical architecture evaluation<br>• Suitable architecture frameworks and development tools for architectures "blueprints" | • Seamless integration / orchestration of cyber & physical models<br>• Automatic architecture synthesis |
| Lifecycle Support | • Maintenance with reliable, predictive data of self-evolving systems<br>• Ext. Test environment for continuous testing in the real world<br>• Big Data Analysis and Deep Learning<br>• Product Digitalization "Digital Twin" | • Metrics to measure / anomaly prediction of system status<br>• Certification procedures<br>• Self-verification – testing<br>• Efficient Re-Verification<br>• Liability Tracing | • Methods to handle increasing complexity<br>• Shadow Mode with shadow communication<br>• Incremental certification |

| | 3 years | 5 years | 10 years |
|---|---|---|---|
| Research enablers | • HM cooperation focused development (HCD)<br>• SoS Architecture patterns<br>• Modularity, composability, scalability, maintainability<br>• Cross System Border Thinking<br>• Systemic Thinking<br>• Situational awareness | • Better understanding of complex systems<br>• Dev Ops Approach<br>• Exceptions from regulation e.g. for testing<br>• Information transfer<br>• Architecture evaluation | • Traceability between artefacts & impact analysis in case of changes<br>• Fault diagnostics & prognostics<br>• Artificial intelligence |

*Table 6: Roadmap on Methods and Tools*

## 8.3 Verification and Validation Platform and Testbed

The engineering methods need support by development platforms and engineering environments. In systems engineering, seamless testing starts in the early design phase and ends in the physical world under realistic circumstances.

*Simulation Platform for Engineering*

Early conceptual and model testing is done in simulation environments supporting model, software and hardware in the loop testing.

| | 3 years | 5 years | 10 years |
|---|---|---|---|
| Maritime Simulation Scenario Database | • Recording of marine traffic<br>• Identification of "interesting" scenarios | • Simulation scenario database (location, ship types, weather, etc.) | • Scenario database with public and private parts |
| Development of maritime Scenarios | • Simulation scenario description language | • Guided simulation scenario generation | • Automatic scenario generation and parametrization |
| Development and Provision of Maritime Models | • Models (like Vessels, Buoys) with realistic parameters | • Identification of real vessels models. | • Open Model Database |
| Harmonization of maritime simulation components | • Support of international standards<br>• Description of simulation component capabilities | • Maritime Simulator Library | • Automatic simulation setup |

| | 3 years | 5 years | 10 years |
|---|---|---|---|
| Maritime Simulation Component Development | • Realistic Communication Simulation<br>• Environment Simulation<br>• Multibody Dynamics Simulation<br>• Sensor Simulation | • Human Interaction on Ship Bridges<br>• VHF Simulator (Reporting of sea signs, Mayday, etc.)<br>• Machine Room Simulation | |
| Maritime Simulation Analysis | • Offline Evaluation of observed vessel data and sensor environment | • Observation of vessel data and sensor environment | |
| Mixed maritime simulations | • Usage of Augmented-Reality to display additional information about vessels | • Transition between simulation and reality, augmented reality-based testing. | |
| Research enablers | • Scenario Database / Library<br>• Near collisions Database<br>• Maritime Scenario Generator<br>• Vignettes and/or Traffic Sequence Charts<br>• Maritime Model Database | • Maritime Simulator Library<br>• Online Scenario Database | • Open Scenario Database |

*Table 7: Roadmap for Simulation based V+V*

### *Physical Platform for Engineering*

A physical V+V platform to enable consistence of requirements over the entire design has to be seamless integrated in a virtual testing platform/simulator and should provide a testing environment with correlated interfaces and methods as the component or system is used later, combined with instrumentation to operate the V+V.

| | 3 years | 5 years | 10 years |
|---|---|---|---|
| Data Provision | • Bidirectional data exchange<br>• Metadata for reproducing tests<br>• Automatic translation between different protocols | • Real time data<br>• High secured data vs. open reliable data<br>• Data Access Management<br>• Raw data access layer<br>• Latency and frequency (bandwidth) Data quality knowledge / verification accuracy<br>• Model compatibility | • Behavior provision (interaction)<br>• Data transfer for new tech. e.g. 5G with high bandwidth |
| Testing | • Test areas, National<br>• Connection of simulation platforms<br>• Change / manipulate testbed components<br>• Catalog of possible methods<br>• Configuration of input values<br>• Physical component exchangeability | • Generic / sustainable test platforms and validation<br>• Navigation Control and Interfaces<br>• Registry of different services<br>• Different layers for different stakeholders<br>• Services oriented<br>• Different detailed scenario provision<br>• Simulation based scaling<br>• Data fusion, Sensor-based perception<br>• Follow official rules (SOLAS, COLREG...) | • Responsible / Central Agent<br>• Intelligent evaluation component<br>• System border definition / evaluation<br>• Reliable detection and evaluation of the uncertainty of environmental information |
| Research enablers | • Test areas, National<br>• Communication ship to ship and ship to shore<br>• New sensor / components integration into testbed<br>• Databased applications (V&V simulation) | • Inland waterway test areas (Elbe 4.0)<br>• User experience and assessment | • Domain knowledge integration / usability |

*Table 7: Roadmap for Simulation based V+V*

# 9 Conclusion, Recommendations and Road Ahead

This technology roadmap proposes technological topics to be investigated together with the corresponding research enablers for the upcoming decade. It focuses on identifying relevant application-driven research topics and technologies, relevant engineering methods and finally verification and validation platforms as well as national testbeds. All these are urgently needed to test and experiment with the next generation of interconnected maritime technology like e.g. highly automated systems implementing a complexity that needs to be managed to ensure operational safety and to prevent cyber-crime and terrorism.

Together with the industry four lead application have been identified: Highly automated Systems, Intelligent Bridge, Remote Control and Surveillance and Traffic and Transportation management. In the best case they are future game changers and create entire new ecosystems introducing new sets of technologies, like cars a century or smart phones did a decade ago.

The worldwide competition in maritime industry is strong, we therefore need a joint effort to hold and strengthen European and German position in the global market. We require sustainable innovation programs that complement current research programs focusing on TRL 1-4 to offer opportunities for extensive collaboration between research institutes and the industry to master the a TRL up to a market entry.

Supporting engineering environments like verification and validation testbeds is often beyond the possibilities of a single company (and especially for SME) and requires a cooperation and support of governmental, industry and research entities. This is also specifically important to design and adapt normative specifications and legal framework to support the development of highly automated systems and future autonomous vessels as part of an interconnected traffic and transportation management environment for a greener, safer and efficient future.

Specific recommendations are:

- Foster / invest into lead applications to drive joint national/European-level initiative or projects.
- Develop new methods for system of systems engineering that ensure reliability, availability, maintainability and safety for complex, interconnected systems.
- Support test-beds for validation, verification of highly automated and connected systems.

# 10 Appendix: The eMaritime Integrated Reference eMIR-Platform

## 10.1 Overview

The eMIR research platform offers the industry, companies, small and medium-sized businesses and research institutes a basis for researching, developing and testing new concepts of maritime safety and bringing these results, experience and competencies together to promote the integration of maritime safety systems and exploit synergies. For instance, by operating a communication and integration architecture, systems can be flexibly commissioned and shared on site at high sea, coastal areas, inland waterways and in the port. In this way, the diverse competencies of the German maritime industry can be bundled in a market-effective manner, synergy effects can be achieved, and thus global competitiveness can be strengthened.

Associations of the German maritime industry, research institutes, federal higher authority and research centres have identified a high demand for research, testing, demonstration platforms and real maritime test areas in Germany by various working groups, joint meeting workshops and demo projects over the last years, which illustrates the importance, the ongoing need and continuous support of reference platforms and testbeds such as eMIR. Those platforms can accelerate and improve the development of new maritime safety and autonomy technologies on the one hand and increase global competitiveness through integrated demonstration opportunities on the other.

eMIR provides a service-oriented research infrastructure and services for the development and research into new technical solutions, verification and validation, demonstration and environmental monitoring. For this purpose, a physical testbed for in-situ experiments and a co-simulation environment for e.g. risk and efficiency assessments, is made available. The open test bed design supports a system-technical approach based on model-driven design of new technologies, cooperation schemes and human-machine interfaces. In-situ experiments provide a technology demonstration environment for both technical experiments and a database for simulation systems, operational processes, HMI or nautical education. Open testbed means that eMIR is open to integrate new technologies, demonstrations or sub platforms. For interoperability and to implement shared services, eMIR provides a shared infrastructure and interoperability architecture.

The main areas of research within the framework of eMIR: (1) Development of maritime test beds, (2) observation systems for the recording of traffic and environmental data, (3) detection and persistence of critical traffic situations, (4) infrastructure for research into new human-machine interaction concepts, (5) intelligent signal- and information representation, (6) assistance systems for bridge crews and VTS personnel, (7) infrastructures for research into environmentally influenced, efficient route planning and optimisation of logistics processes, (8) construction of a virtual simulation-based test bed for early risk and efficiency assessment of new maritime concepts and systems, and (9) development of new simulation based and supportive V&V methods. In conclusion, all these topics address the basic idea of managing the increasing interoperability in the maritime domain.

The following table provides a summary of the possibilities for using and exploiting eMIR along the typical technological development steps.

| TRL-Level | Description | 10 Maritime systems of systems engineering and technical support by eMIR technology development platform |
|---|---|---|
| 0 | Idea | Exchange and development of ideas through existing technology/demonstrators/systems and interdiscipli-nary networking |
| 1 | Basic principles/research observed/reported | Examination of principles, use of non-native/-commercial systems/methods, domain atypical solution approaches |
| 2 | Technology concept and/or application formulated | Methods for flexible deployment/maintenance/V&V, engineering/product development support, design rules for highly automated ship and platforms and navigation and operations |
| 3 | Analytical and experi-mental critical function and/or characteristic proof-of-concept | Open simulation system for the virtual testing and evaluation of maritime services/assistance systems/products, modelling tools, architectures, metadata and also real time data for environment and traffic, data models and standard harmonized data struc-tures, model/hypothesis testing for e.g. safety and efficiency analysis |
| 4 | Component in laboratory environment | Open communication and integration platform for maritime products, basic services for communication between maritime systems on land and at sea, provi-sion of test data, sensors and sensor fusion, manage-ment of information, integrated bridge system |
| 5 | Component in relevant environment | Demonstration and Evaluation, reference routes and areas (port, reference waterway, shipping route), rese-arch vessel equipped with a mobile experimental brid-ge, flexible and mobile equipment, seamless integration of different areas and use cases, certification, regulation |
| | | Further development and implementation by industry |
| 6 | System/subsystem model or prototype demonstration in a relevant environment | Installation in the North Sea without affecting the operational operation of the existing monitoring systems, reference routes and areas (port, shipping route, offshore wind farm and open sea) equipped with sensor and communication technology |
| 7 | System prototype demon-stration in an environment | Behaviour over a longer period of time, elimination of errors from long-term investigations |
| 8 | Actual system completed and qualified through test and demonstration | Pre-commercial prototype of the system with all functions |
| 9 | Actual system proven through successful mission operations | Market launch of a commercial product |

*Table 9: eMIR technology development platform, support for maritime systems of systems engineering*

Since 2013, the eMIR initiative has been driven forward by an ecosystem of projects [11]. The research centre „Critical System Engineering for Socio-Technical Systems (CSE)“ [13], which was funded by the state of Lower Saxony, enabled the first components of eMIR to be developed. Such as a mobile platform for maritime sensor technology, which can be installed on ships, buoys and on the coast for application-specific research questions. The EFRE-funded project SOOP „Safe Offshore Operations“ contributed results for planning safety offshore operations in wind farms. In the project CASCADE and the Artemis project D3COS, concepts and systems for intelligent ship bridge design could be integrated into eMIR. The project COSINUS of the BMWi and the project management organisation Jülich contributed concepts for the integration of ECDIS and VTS systems for cooperative ship management. The MTCAS project integrates an intelligent maritime collision avoidance system. The ENABLE-S3 project demonstrates the first steps towards an efficient development of highly automated and autonomous systems (ACPS) with virtual and semi-virtual tests and verifications, test selection methods and standardization. Finally, the ACCTRESS project supports eMIR by mobile platforms, sensors and technologies such as an experimental ship bridge as an architecture and technology development platform for maritime system of system engineering, for real-time capable and safety systems.

For the long-term continuation of the initiative for eMIR, fundamental government support is desirable as a basis for new and further projects. These contributes to the future development of German driven e-navigation, autonomous systems and testbeds for maritime safety. Further project results should be integrated in eMIR and be used for the development and testing of new technologies by the German maritime industry. Furthermore, the future legal system is faced with the task of creating a set of rules [14], which keeps pace with the technical development without preventing it. In this respect, a „state of the art“ oriented legal regulation of the traffic with unmanned, highly automated vessels should be aimed for. Through eMIR, an infrastructure and appropriate methods will be accessible to all interested parties and it is explicitly designed for use by other research projects, by the industry, but also by public authorities. Concrete requests for use can be negotiated with the partners involved via OFFIS.

## 10.2 eMIR Roadmap

In summary the following roadmap for eMIR can be identified

| | 3 years | 5 years | 10 years |
|---|---|---|---|
| International collaboration | | • Joining platforms and projects | • Joining platforms and projects |
| Type of Use | • Mobile equipment expansion<br>• Flatrate for existing scenarios / payment for new scenarios<br>• Payment by public funding Public Private Partner Ships<br>• Container / Hard-ware Twins / Mirro-ring Software<br>• Finding and setting formalized test proce-dures and standards | • Connect equipment to [/by] standard[s]<br>• Use for validation trial an error for all business models<br>• Easy and simple accessibility Web Interface<br>• Transfer eMIR to a basic funded agency<br>• Fullcost call to bring eMIR into public projects<br>• Process regarding IPR / data security against competitors | • Remote operation |
| Desired Services | • Scenario Generation<br>• Open user community<br>• Provision of test data<br>• Time Slots for research Vessel<br>• Provision of standard sensor interfaces<br>• Provision of simulation and/or engineering as a service | • Support technology, product and service readiness level (system hardening)<br>• Database with scenarios / public private parts | • Support of internati-onal standardization |
| Research enablers | • Test areas, National<br>• Communication ship to ship and ship to shore<br>• New sensor / com-ponents integration into testbed<br>• Modularity, compo-sability, scalability, maintainability<br>• Cross System Border Thinking<br>• Systemic Thinking<br>• Situational awareness | • Inland waterway test areas (Elbe 4.0)<br>• Exceptions from regu-lation e.g. for testing<br>• Formalization regula-tion e.g. for testing<br>• Databased applica-tions (V&V simulation)<br>• Information transfer<br>• Architecture evaluation | • Domain knowledge integration / usability |

*Table 10: eMIR Roadmap*

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Digitalization is going to change our way to operate, navigate, communicate and control maritime systems. Digitalization fosters disruptive innovations, which lead to new thinking, products and finally business models. Opportunities for the maritime industry are countless. Global competition is fierce but full of chances.

Four lead applications are identified by systematically analyzing the current position of the industry and by reviewing the actual normative background in joined workshops with the industry. The applications are detailed and discussed with respect to other global activities, relevant technologies and research activities.

By a technology roadmap, relevant evolutions of technology and research enablers are structured for the upcoming years. Finally, requirements for the eMIR – eMaritime Integrated Reference Platform are identified to setup a testbed for future maritime system development. It requires a joined effort of politics, governmental administrations, industry, research and education to shape the future of the maritime industry.

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