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A generic testbed for simulation and physical-based testing of maritime cyber-physical system of systems

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Abstract. e-Navigation Systems are CPSoS, which are regarded as systems based on systems with physical and information technology-based components. SoS are usually open systems which can have emerging behaviour and are not fully defined during design time. Future maritime bridge systems, for instance, will be embedded into the vessel infrastructure and its navigation and safety subsystems receive continuous updates and additional functionalities for the ship's command and navigation. Suitable testbeds are required to support the technological and regulatory development and certification processes. To support the development and integration of CPS, this paper introduces the testbed eMIR as an open and modular research, development and test environment. The test environment is suitable for early testing, validation and verification or demonstration of new maritime technologies in a complex simulation environment (traffic, environment and sensors) and supports a seamless transfer of these technologies from a virtual into a physical testbed. eMIR comprised various interconnected virtual and physical components via a standardised co-simulation environment based on HLA, combined with a message passing middleware as a backbone for the physical testbed elements. The testbed was effectively applied in various maritime projects for the evaluation of maritime technologies in navigation, management and surveillance or maritime (transportation) systems.

Keywords: cyber-physical system of systems, maritime testbed, interoperable architecture

1. Introduction

By the increasing establishment of information and communications technology, ICT-based components such as maritime bridge elements and automation technology, a disruptive change similar to aeronautics and automotive industry can be observed. There is evidence of a trend towards highly automated vessel assistance systems with an outlook for the future describing autonomous seafaring, which are described in maritime technology roadmaps and strategy implementation plans [1]. Technological changes introduced to maritime shipping led to a large number of heterogeneous systems. In aeronautics and automotive, huge OEMs organise the system development and integration process of all hard- and software in an overall system architecture to cover the full lifecycle of modelling, simulation, optimisation and validation and verification. Complex supply chains have been established and coupled with data exchange, requirement tracking, and shared or interconnected methods and models. Compared to this system development and integration process, the level of system integration in the maritime domain is still in its beginnings. But in consideration of the global

nature of shipping and the resulting safety and security risks, there is a high demand for a common approach across the maritime domain. Tomorrow's vessel traffic services, integrated ship bridges and port coordination systems must all become part of an all-embracing maritime System of Systems (SoS). Today's technology with integrated sensors, actuators for interaction of the physical and the virtual world lead to a specific class of systems: Cyber Physical Systems (CPS) integrate computer and software components with mechanical and electronic components to control or monitor physical processes. Usually there are feedback loops where physical processes affect computation and vice versa. Furthermore, there are specific characteristics of CPS such as continuous passage of time and high concurrency.

With the e-Navigation initiative of the International Maritime Organization (IMO), the maritime world has long embarked on the voyage for safer shipping and better protection of the environment through an improved usage of data on ships and ashore as well as improved exchange and communication between ships and shore-based systems. A new global maritime connectivity therefore requires an in-depth review of all current maritime practices: legal and commercial regimes; responsibilities, liabilities and insurances; and, foremost of it all, it requires a complete rethinking of the engineering processes for the design, integration and testing of maritime systems. In this context, systems are characterized by a dedicated system boundary and comprises of connected components, which interact with each other as well as with elements beyond the system boundary. In the world of an interconnected e-Navigation however, system boundaries become permeable and time variable, subject to actively participating stakeholders and processes. Cyber-Physical System of Systems (CPSoS) consider the continuous change and the inherent emergent behaviour of such complex systems in practice. In a dynamic CPSoS there is potentially no central operations center, executing SoS-wide monitoring and control. Functional boundaries of operating software are no longer identical with hardware boundaries. Engineers are therefore no longer in control of all functional components in such a CPSoS. Failures and deficiencies occurring in a local sub system may cause huge consequential damages at any other places of the CPSoS. The maritime industry is therefore facing these challenges of complex, highly automated and autonomous systems with systemic approaches and harmonised strategies for e-Navigation system design, e. g. the **e-Navigation Strategy Implementation Plan by the IMO** [6]. E-Navigation Systems are CPSoS with physical and ICT-based components that have emerging behaviour and are not fully defined during design time. At this point it becomes apparent that conventional unit tests are no longer **sufficient to fully cover and validate the functional limits of Cyber-Physical System of Systems** [7]. Therefore, suitable integrated simulation-based and physical testbeds are required which supports the technological and regulatory development and acceptance process.

International organisations like the IALA and the IMO as well as national bodies that foster e-Navigation regard testbeds as an important method to invent and develop new e-Navigation concepts and technologies as well as their public dissemination and exploitation. Several testbeds for new e-Navigation and maritime surveillance technologies are under **design and implementation around the globe** [8]. These testbeds have numerous objectives: Understanding challenges and requirements for e-Navigation, the development and test (validation and verification) of platforms or the demonstration of the technology-readiness of new prototypes. In the following, we would like to examine an IALA registered maritime testbed constellation with interoperable and open virtual and physical test environments, namely HAGGIS and LABKAUS, which together define the eMaritime Integrated Reference Platform - eMIR [9]. eMIR is driven by the industry and operated by OFFIS in Germany.

The approach of the paper is divided as follows. First, we depict the basics of SoS engineering and the need and requirements for verification and validation of CPSoS. The next chapter introduces existing maritime initiatives and testbeds for prototypes of e-Navigation technologies, but also including a brief overview of testbeds of the automotive domain. Section 4 will present the eMIR testbed architecture through a detailed description of the setup of the virtual and physical experimental testbed and a traffic scenario database. The following section introduces conventions to the data model, the polymorphic interface, physical and virtual middleware and a simulation adapter to

integrate the systems under test. Section 6 presents the testbed experimental findings based on an illustrative project for the development of an integrated maritime collision avoidance system and methods of CPSoS scenario-based testing. Finally, we conclude this work by including a short summary and outlook of ongoing and future applications.

2. Systems Engineering and Verification and Validation of Cyber-Physical Systems of Systems

Systems in the maritime domain (like products for navigation assistance, communication equipment etc.) are typically not used in isolation but as part of a complex setup. The overall system complexity is dramatically increasing. More and more sensors and actuators are being used to provide data for various systems or information services on board a ship and ashore. Since such systems are typically continuously evolving during their service lifetime, the development and maintenance of maritime systems (e.g. bridge systems) need to be considered in its usage context that includes interconnected systems and external services, sensors and actuators. CPSoS demand innovative approaches for distributed optimisation, novel distributed management and control methodologies that can also deal with partially autonomous systems, and must be resilient to faults or cyber-attacks. Additionally, in CPSoS engineering the earlier strict separation between the engineering phases and operation gets blurred. Instead, integrated approaches for the design- and operation- phase are required to cover the full lifecycle by modelling, simulation, validation, and verification (V&V). Thus, prospectively, it will be necessary to monitor the system formation and to conduct a final assessment of the system by means of a suitable application of test cases in a controlled and comprehensible manner.

In order to meet the current and future engineering challenges, further methods for the verification and validation must be applied in the respective development, deployment and operation phases. Suitable concepts are also needed for architectural modelling to cover an even broader scope of the maritime domain, which were discussed for example within the framework of the EfficienSea2 [10] and the STM Validation [11] projects. The understanding of a system as a subsystem of a more complex system is a factor for successful innovation in engineering, design, validation and verification and lifecycle management to face additional challenges like extreme inert systems, limited communication, and legacy systems, low IT security or cooperative decision and information support. Whereas system theory is designed to manage complexity by assuming that a system is a properly defined aggregation of elements and optimally under full control of the engineer, this ideal assumption is not fully applicable for Cyber-Physical Systems of Systems, as they may have a permeable system boundary. Sub systems or components are operating on different spatial and temporal scales and interacting in changing context during operation of the CPSoS. While traditional systems are static in their operational environment, future maritime systems will be connected to other systems and by this will build up a maritime CPSoS. This makes it necessary to handle a multitude of different or even unknown system configurations within a SoS environment. System of Systems Engineering constitutes a major challenge for the 21st century and research into this topic has become an imperative.

Systems engineering encourages the use of modelling and simulation to validate assumptions or theories on systems and the interactions within them. Engineers can address the design challenges of each system in the hierarchy in a clearly demarcated way. Besides the architectural concepts, which cover the design time of a CPSoS, the verification and validation methods focus on the assurance that the design follows its specification and behaves correctly with respect to its later operational environment. Today, engineering and lifecycle management of those systems will be based e. g. on Model Based Systems Engineering (MBSE) [12]. It provides formalised 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 [13]. The systems engineering standard defines a set of processes that are divided into four categories: engineering, project, agreement and enterprise; comprising exemplary lifecycle phases of concept, development, production, utilisation, support, and retirement. In addition, the Maritime Architecture Framework [14] as one method for this, supports the specification of systems from an architecture viewpoint and enables the contextualisation of multiple systems and their interdependencies with the

maritime topology and hierarchy of management and control systems. In system of system engineering, SysML (an extension to the Unified Modelling Language UML [15]) for instance enables the systems engineers to design and describe Cyber-Physical System of Systems, combining software and hardware in one architecture.

The underlying infrastructure of the CPSoS systems must meet stringent reliability and security requirements – both in operational security and IT security and integrity [16]. Therefore, a testbed framework has to take dynamic V&V procedures into account to test components, systems or services along the progressive development process in a control loop (model/software/hardware/physics in the loop). For this purpose, the system or component under test is integrated into a simulated or physical testbed via its inherent interfaces to test the possibility of an attack, the potential of damage and technology dependency of human or rare events like safety relevant situations. Further on architectural concepts for e. g. real-time capabilities have to be tested to identify systematically safe and secure fallback level as well safe and secure system recovery. The design of real-time systems must satisfy specific requirements including functional requirements, temporal requirements and dependability requirements [17]. In the maritime domain, taking the example of an integrated navigation system, the weak points of today's nautical IT systems has to identify resilience to secure the navigation system throughout its lifetime against cyber-attacks (close entry points for attacks). Also human machine interfaces and assistance or shared system functions are crucial be investigated for user-oriented acceptance test of new CPSoS, like in the automotive assistance systems or a self-driving car [18] [19].

Testbeds for prototypes of e-Navigation technologies support therefore SoS engineering for verification and validation of actual and future maritime CPSoS with enhanced virtual and physical approaches, new methods and databases in several development steps by simulations and in-situ tests. Simulators can be used for simulating real life conditions for users like maritime bridge simulators found around the world or big scaled environment planning/control algorithms like the Maritime Traffic Simulator [20]. In this context, the eMIR maritime testbed can also be applied for a seamless V&V of complex highly automated CPSoS and for the development of new development methods by integrated simulation and physical based technologies.

3. Existing Initiatives and Testbeds

A couple of maritime projects developed testbeds to test specific technologies, e. g. in the **North Sea [21], Baltic Sea [22] or Japan [23]**. These testbeds are specialised by their individual use-cases or characterized by a single test pass. 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. For instance the **European Maritime Simulator Network (EMSN) [20] utilises a testbed network of interconnected simulator centres in a number of EU countries** for the validation of traffic flow management through virtual testing of various complex sea traffic situations. In the automotive industry also generic reusable and configurable testbed platforms are deployed and continuously evolved to test new CPSoS services and technologies, like the **Application platform for Intelligent Mobility (AIM) [24] AIM is an open component-based testbed for land traffic with mobile components like a car fleet or structural components like a research crossway, research railway crossing or an inner city and motorway reference way**. The research in this domain also focuses on Car2X, for the integration of vehicles into a comprehensive data infrastructure that enables direct communication between vehicles (V2V: Vehicle to Vehicle) on the one hand and infrastructure (V2I: Vehicle to Infrastructure) on the other. The AIM testbed also offers driving or virtual reality simulators. The virtual reality laboratory is built around a modular mock-up car which allows integration of new driving assistant systems, which then can be evaluated in a static environment. These components are test carrier for new technologies and services, moreover the gathered data will be used for simulations, developing scenario-based test methods for the verification and validation [25] or other research in design science [18].

4. Architecture and Components of the eMIR testbed

To support the whole development process of highly automated and autonomous systems and in order to be able to meet future CPS requirements as well, a maritime testbed should be open and sustainable. **Open testbed means that eMIR is open to integrate new technologies, services or sub platforms.** For comprehensive interoperability for SoS under test and to implement shared services to facilitate CPSoS testing, the following described testbed provides a shared infrastructure and interoperability architecture (cf. section 5).

To provide a test environment for the entire system development process, and meet time and cost reduction requirements, the testbed provides the ability of a seamless transition from virtual to physical test runs. To support this seamless integration, the eMIR testbed consists of a virtual and a physical test environment. In order to meet the requirements for a novel testbed for highly automated systems, the presented testbed enables the ability to check the predefined use cases of the System under Test (SuT) using concrete test scenarios (e.g. with the Traffic Scenario Database) and thereby validate the correct functionality of the system under test. In order to reflect the concept of interoperability, eMIR is based on the uniform data exchange format S-100 as connection between all existing elements and components. Figure 1 shows the implementation and connection of the eMIR testbed components in relation to the SuT. In the following the interconnected physical and virtual testbed components will be discussed in detail.

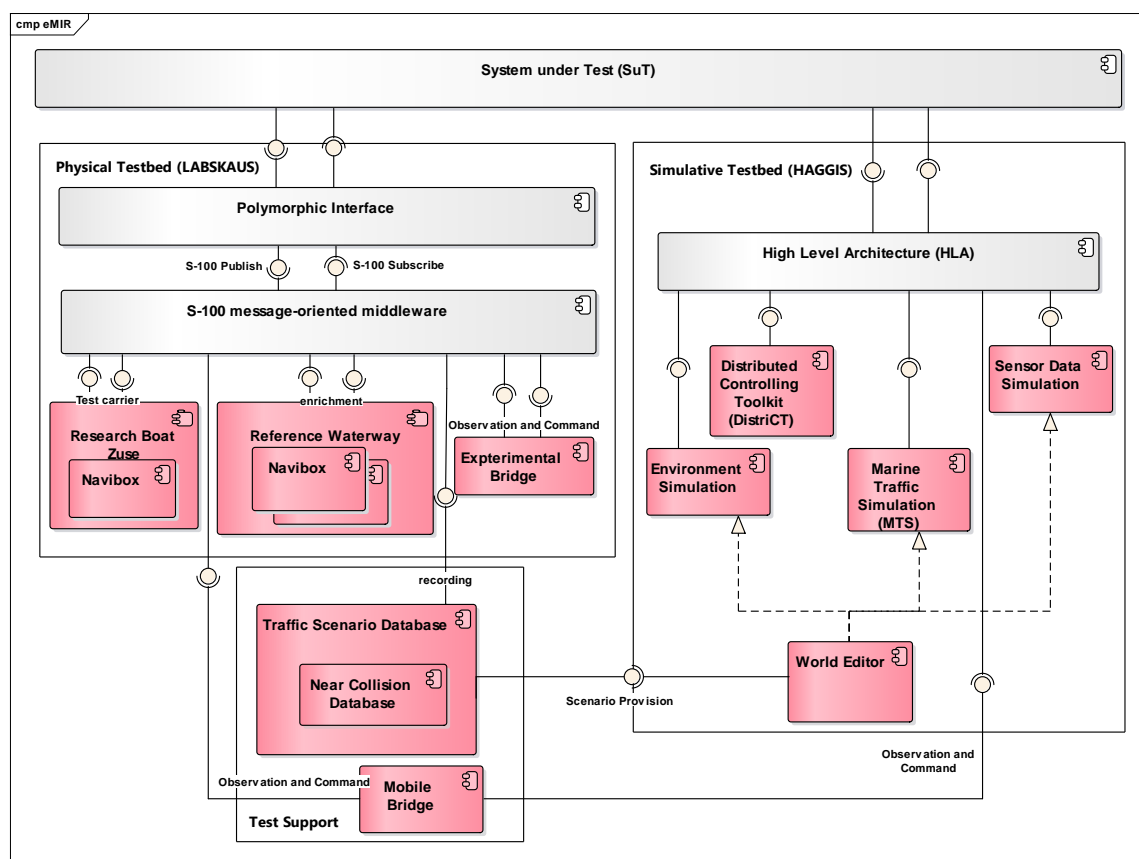


Figure 1. Overview of interconnected eMIR components for supporting the highly automated CPSoS development process

4.1. HAGGIS

Hybrid Architecture for Granularly, Generic and Interoperable Simulations (HAGGIS) is a modelling and open co-simulation environment to build virtual e-Navigation testbeds and is part of the virtual

eMIR testbed. It enables rapid testing of new e-Navigation technologies in a simulation environment. HAGGIS consists of a number of modules that can be orchestrated for different applications. These allow simulating sensors, traffic or environment. HAGGIS consists of the **Maritime Traffic Simulation (MTS)**, the Environment Simulation Component, **the Sensor Data Simulation Component**, several behaviour simulations for artificial generated vessels and the World Editor. To perform safety analysis on the simulated scenarios, it is possible to initiate a risk monitor which can determine predefined risk situations during simulation. This component is called the *Distributed Controlling Toolkit (DistriCT)*. To ensure the technical interoperability of the HAGGIS components, the High Level Architecture (HLA) as the communication middleware is used. As an international standard for co-simulation systems approved by the IEEE allows HLA the extension of the virtual testbed with external simulations, supporting the same standard. HLA takes over important tasks for the co-simulations such as the synchronisation of different simulations as well as the management of the simulation time as an implementation of the runtime infrastructure. *The World Editor* provides a system model to allow the setting up of an initial scene according to a predefined scenario and is implemented through the Eclipse integrated development environment. This system model contains the fundamental components/entities of all used resources, actors and environmental factors.

4.1.1. The Maritime Traffic Simulator (MTS) is therefore the basis of the HAGGIS simulation configuration. The MTS is a flexible maritime traffic simulator for implementing, executing and observing the behaviour of multiple vessels. The vessels of the MTS are initialized with a behaviour and a dynamic layer, to generate a lot of individual and different kind of transport users. Further, it is possible to define routes or to use NMEA-Messages from real world data e.g. Automatic Identification System (AIS).

4.1.2. The Environment Simulator can influence the simulated vessels with factors like wind, current or tide. The Environment Configurator allows an environmental scenario generation where several environment layers defined by polygons that can change over time. The loose coupling between environments allows to use one of the components together with real information e.g. in mixed reality test runs.

4.1.3. The Sensor Data Simulator uses the simulation information and provide them in a sensor specific format, like radar or lidar. Therefore, the generated measurements can be extended by statistical, systematic or context-sensitive fault and accuracy models.

4.2. LABSKAUS

The physical parts of the eMIR testbed LABSKAUS (German: LABor für SicherheitsKritische Analysen aUf See / English: laboratory for safety critical analysis on sea) is placed in the German Bight (the southeastern bight of the North Sea). Even though most components are transportable and can be located elsewhere. In the following paragraphs existing components will be described.

4.2.1. Reference Waterway. One essential component of the eMIR testbed is the Reference Waterway with communication and surveillance technology along the Elbe River sea lane estuary between Cuxhaven and Brunsbüttel; Germany. The Reference Waterway is equipped with both common and state-of-the-art maritime sensors, by expandable Naviboxes, to observe the maritime traffic on one of the busiest waterways with one of the highest accident rates in Germany and in Europe as well [27]. With the equipped sensors the testbed can provide a real-time situational picture from the prevailing traffic situation. Due to the loose coupling of the components, the data can be accessed from anywhere and used in any form [9]. The mentioned Naviboxes are compact sensor data hubs, which provide navigational data on board a ship as well as data for maritime surveillance systems on shore. The boxes provide a standardised communication infrastructure via LAN, WLAN and Broadband WAN communication facilities and interfaces for sensors which are sending data with COM, NMEA 0183,

NMEA 2000 or Ethernet. The minimal sensor setup consists of Radar, AIS antenna and wind sensor. An internal industrial PC handles the sensor stream management, processing and represents a broker for the information distribution.

4.2.2. Experimental Bridges. The eMIR testbed also includes two experimental ship-bridges for different use cases or user requirements. An Experimental Bridge can be used i. a. as a maritime control station to imitate situational awareness and V&V management tasks during a test run. These Experimental Bridges are installed in a 10-foot respectively 20-foot CSC-certified, insulated, air-conditioned and heatable Container (ISO 668) as a harmonised and transportable solution. The Experimental Bridge is equipped with common ship-bridge elements and several displays as workstations, to supervise the relevant information of the test run from shore. Further, it is possible to install both Experimental Bridges on different kind of vessels and connect them to the existing bridge infrastructure and communication bus to have a fully equipped Bridge, to manage navigational tasks at the provided workstations. For this purpose, a preinstalled satellite dome ensures high bandwidth communication on open sea. Experimental Bridges can be also connected directly to existing sensors or other testbed infrastructure to receive and provide several data within the testbed as well. Onshore the Experimental Bridges can cope VTS tasks

4.2.3. The Research Boat Zuse serves as a test carrier for highly automated software solutions and to enable the development of autonomous vessel technologies. The core of the research boat is an extended Navibox, which communicates with the testbed infrastructure and receives surrounded/environmental data. This allows e. g. in-situ testing of new sensors, assistance and automation systems, Electronic Chart Display and Information System (ECDIS) or Integrated Navigation System. The Zuse's Navibox adds a Differential GPS (DGPS) System that provide position, Course over Ground, Speed over Ground, True Heading and Rate of Turn. Moreover, access to engine (RPM, temperatures, pressure) and rudder angle indicator are attached by a helm control to the NaviBox. A triducer for speed through water, distance log, water depth and water temperature and an Inertial Measurement Unit (IMU) for acceleration, gyroscope and magnetic field measurements are installed as well. Furthermore, a sensor pole is attached to the vessel to gather sensor data independent from the ship navigation electronics. The integrated Navibox can accept remote steering commands by a switchable access between the throttle and the helm control unit. At last, the Zuse is equipped with cameras for situational awareness during remote control and object detection.

4.3. Test Support

In addition to the explicit components that can be assigned to the virtual and physical testbed, The Mobile Bridge and the Traffic Scenario Database can be used for both parts of the testbed equally.

4.3.1. The Mobile Bridge is a modular solution for e. g. bridge component tests. It is designed as a versatile mobile bridge for controlling a Research Boat from shore or on board of a vessel. It also serves as a human-centred designed information display and control mock-up for interactions with a modelled "Own Ship" in the HAGGIS simulation. Usually three boxes with integrated PCs and two multi-touch displays (each) are connected to act as an integrated ship bridge system. In its standard configuration a Raytheon Integrated Bridge and an open source bridge system is integrated. These are connected or linked to eMIR components which provide the required navigational data such as compass, GPS, AIS, log, radar, as well as a broad band communication system. On board, it can be used with a mentioned Navibox (cf. section 4.2.3) for a full integrated development and communication to shore-based infrastructures or services. As an experimental bridge on board of a vessel, the mobile bridge system does not interfere with vessels navigation systems but can permit ship steering control.

4.3.2. *The Near-Collision-Database* is a part of a Traffic Scenario Database and one of the test sources for several test scenario runs (virtual and physical). Here, AIS and radar tracks are collected online from the physical reference waterway and stored in a database and subsequently fused and automatically analysed to observe encounter situations [26]. Risk and criticality analysis evaluate the hazard potential of each encounter situation and provide therefore a catalogue of potential, high-risk scenarios. A further advantage of the database is that simulated performed test runs can be repeated to guarantee the correct functionality of highly automated systems after changes. But simulative scenarios can also be stored in the Traffic Scenario Database as well.

5. Integration of Systems under Test

Due to the increasing complexity of today's systems and their functionality and to support the overall development process, from the use-case definition through acceptance tests up to certification, both virtual and real tests must be coupled together. This approach of a testbed for maritime Cyber-Physical Systems supports model driven system engineering, safety analysis and simulation-based V&V of maritime safety systems in a Cyber-Physical System context. The CPS testbed interoperability architecture of eMIR as illustrated in figure 2 is centred on sensor and communication infrastructure with human-machine interaction components and enables the testing of models, implementation and physical prototypes in the loop. Closed-loop methods are particularly suitable for several reactive components which, as an overall system, must meet complex and safety-critical requirements and test within different scenarios [20]. In order to follow the vision of a sustainable and open testbed, following three conventions for a common Data Model, Polymorphic Interface and Simulation Adapter contributes significantly in the eMIR architecture for the interoperability and practical implementation of a CPS testbed [28].

5.1. *Convention to the Data Model.* A common maritime data structure is a major building block for interoperability of interconnected systems in e-Navigation. Consequently, the design decision to use S-100 for the canonical data model of the testbed infrastructure is recommended. S-100 shall be used as the new standard for the usage of various data related to the marine environment and safety. S-100 defines rules for creating product specifications instead of specifying them itself, thus achieving greater flexibility, since additions and changes, e. g. to data structures, encoding or portrayal, are not considered in the standard itself. The S-100 Geospatial Information Registry includes a Feature Concept Dictionary (FCD), metadata registers and portrayal registers with the aim to store S-100 compliant data structures in these registers and to reuse them beyond product specifications [29]. Thus, creating a syntactically and semantically uniform understanding between all actors. The backbone of the eMIR testbed infrastructure uses the evolving S-100 standard implemented by the uniform (canonical) data model. With S-100, the eMIR testbed can provide a sustainable connectivity and interoperability to novel systems and all compliant (prototype) systems is ensured. However, systems with common interfaces such as NMEA 0183 can also be connected to the testbed via a Polymorphic Interface [28] if mainly the geographic features of the testbed has to be taken into account, since NMEA 0183 sentences cannot generally be translated to the S-100 based reference data model.

5.2. *Polymorphic Interface.* A basic idea for a generic maritime testbed is an open and adaptable design for various kinds of prototypes. Therefore, the polymorphic interface provides a compatible interface for the system under test. The interface offers the ability to integrate prototypes of various technological implementation into the infrastructure of the testbed and is highly flexible and adaptable by supporting various maritime standards, formats and regulations, such as the inter VTS exchange format (IVEF) for a vessel traffic service (VTS) system, NMEA or S-100. For example, sensor data of AIS or radar will be deserialized, transformed from NMEA to S-100 (or other) and transmitted by a message passing bus. It is designed under the paradigm of loose coupling and uses a multi-broker communication network which communicates through lanes and knots and is realised through the

open source message broker software RabbitMQ [30]. The polymorphism mechanism which uses S-100 as a reference data model reduces therefore the complexity to handle various standards in the testbed infrastructure. It offers the ability to adapt and integrate actual and future non-proprietary and domain independent physical links, functional links and operational services as established in e-Navigation. Based on this, a prototype data model specified for example in XML can be interpreted. By the help of XSL Transformation (XSLT), transformation rules are semi-automatically defined that describe semantic interoperability of a prototype and the testbed. Based on the transformation rules that exist in XML, a platform- and programming-language dependent adapter is generated.

5.3. Physical and virtual Middleware. In order to ensure the extensibility, interoperability and flexibility of the testbed, both the virtual and the physical testbed use a middleware, which enables a standardised data exchange and where the existing components can connect and disconnect during a test run without affecting it. By considering synchronous and asynchronous communication, different test setups can be realised. Furthermore, the middleware of the physical and virtual world can be combined to perform mixed reality tests.

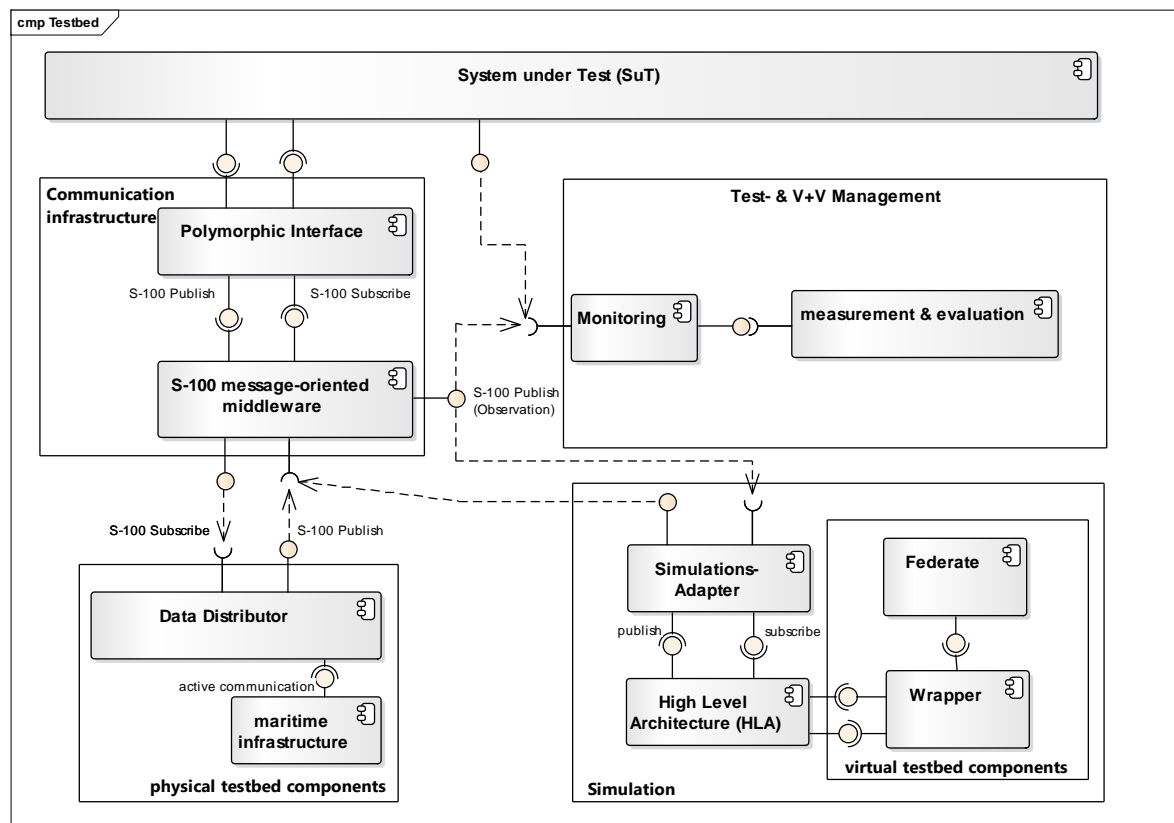


Figure 2. Testbed architecture for a cyber-physical system under test and V&V management with physical (left) and virtual testbed components (right), connected via a communication infrastructure (top left) with polymorphic interface and S-100 oriented middleware

5.4. Simulation Adapter. To integrate simulative components to the physical world and vice versa, the testbed architecture proposes a simulation adapter. The simulation adapter translates the different communication protocols of the virtual and the physical testbed. The modular and extensible design of the adapter makes it possible to create an interoperable data exchange between the virtual and physical testbed (cf. fig. 2). The architecture includes a static data stream processing chain consisting of the communication handler, syntax handler and semantic handler to realise the communication between

virtual and physical level. The tasks of the semantic handler differ from those of the static adapter, which is used to integrate the testbed components. All information of the data object relevant for the physical test scenario according to S-100 must be filtered as a partial section of the entire simulation model and sent to the message-oriented middleware, such as AIS and radar. For this purpose, the semantic handler of the simulation adapter offer users the ability to select the relevant data and send only this data to the central message-oriented middleware through an appropriate publisher. This process is also possible in the opposite data flow direction, so that the scenario of the real world is also mapped in the simulated environment. This enables tests to be carried out in closed-loop mode for systems to be tested according to a defined specification of a test scenario.

6. Experimental Experience

The evaluation of the testbed and its architecture has been proven in several experiments within research and industrial projects [31]. Also projects for a cumulative demonstration to increase maritime safety in the German Bight by the maritime utilisation concepts for the European Satellite Navigation System Galileo have been initiated [32]. Therefore DGNSS (Differential Global Navigation Satellite System) experiments on spoofing and disturbing of navigation system data to test the resilience of Position Navigation and Time technology by the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt; DLR) were conducted. Furthermore, the maritime testbed has been deployed within the Project MTCAS [33], wherein partners from industry and academia contribute to maritime accident reduction by developing an e-Navigation assistance system for pro-active, predictive and cooperative collision avoidance. This new maritime traffic alert and collision avoidance system implies the basic idea of learning from the Airborne Collision Avoidance System implementation TCAS. However, MTCAS' operational principal aims at detecting and solving conflicts with other ships taking into consideration the prevailing circumstances of the environment and traffic but also include relevant rules and regulations, bathymetry, and support by VTS. For this, the current traffic situation and ship dynamics are used that are delivered by the maritime testbed. The MTCAS units were integrated on bridge integrated navigation systems and on shore-based VTS Systems. With the support of HAGGIS and LABKAUS, critical and noncritical traffic situations are provided to evaluate the system behaviour. The polymorph interface also provides test configurations mocking up different communication methods for negotiating evasive manoeuvres. During system design, HAGGIS and its MTS generated test cases used for weekly integration test. For final system test and demonstration two vessels equipped with Naviboxes and the Reference Waterway providing VTS and communication services. eMIR provided navigational data, communication backbone and mobile bridge systems to explore the systems capabilities. Based on the four core-concepts improved situational awareness, context-sensitive prediction, n-Trajectory optimisation and decentralised automatic negotiation of evasive manoeuvres, finally MTCAS can be integrated as an additional assistance system into today's operations on-board of a ship.

7. Conclusions and Outlook

In this paper, the status of concepts and implementations of a seamless integrated maritime testbed for the validation and verification of CPSoS has been shown to facilitate the development of e. g. autonomous and automated seafaring. For this, the concepts of model driven development related to the testbed and interoperability concepts to integrate prototypes by a polymorphic interface are presented, as well as testbed components such as the data collecting and processing component Navibox or the research boat ZUSE. These testbed components address a wide field of sensor/data sources, sinks and an infrastructure to form the testbed for V&V. The open technology development platform uses a High-Level Architecture with polymorphic, i. e. adaptable interfaces for interactions between virtual and physical platform components and a system-wide S-100 data model. In order to meet future enhancements such as data stream transmissions and thus the path towards to enhance connected maritime System of Systems functionalities, the eMIR platform supports various levels of abstraction model-driven development by a system-technical approach. In-situ experiments at sea offer

data for new models or for the improvement of software and interfaces as shown by the referred projects, e. g. MTCAS. The wide scope of possible tests for e-Navigation technologies offers an open as well as extendable platform for research and the industry to support the development processes and assist steps with a seamless testbed that reduces the barrier of prototype evaluation and makes the development of an own testbed unnecessarily.

The eMIR testbed will be still expanded for the development and research of technology from the early design phase to prototypes under real maritime environmental conditions. The research focus of the maritime development platform also comprises assistance systems for bridge crews and VTS personnel, connected observation systems for the acquisition of traffic and environmental data including their analysis as well as ongoing modelling of critical or rare events in traffic situations for the research of safe, environmentally relevant, efficient route planning and optimisation [34]. Furthermore virtual, simulation-based test benches for early risk and management procedures up to the development of simulation-based V&V methods including their standardisation. Therefore the identification of new scenarios and expansions to enhance the testbed for continuous change and evolution is an ongoing process in research 0. All these topics address the rationale basic ideas of e-Navigation to improve the interoperability of systems in the maritime sector.

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