Integrated Test Bed for Save and Efficient Maritime Systems

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"Safe voyage from berth to berth": This is the goal of all e-navigation strains, driven by new technologies, new infrastructures and new organizational structures on bridge, on shore as well as in the cloud. To facilitate these efforts suitable engineering and safety/risk assessment methods have to be applied. Understanding maritime transportation as a sociotechnical system allows system engineering methods to be applied. Formal and simulation based verification and validation of e-navigation technologies are important methods to obtain system safety and reliability. The modelling and simulation toolset HAGGIS provides methods for system specification and formal risk analysis. It provides a modelling framework for processes, fault trees and generic hazard specification and a physical world and maritime traffic simulation system. HAGGIS is accompanied by the physical test bed LABSKAUS which implements a reference port and waterway. Additionally, it contains an experimental Vessel Traffic Services (VTS) implementation and a mobile integrated bridge enabling in situ experiments for technology evaluation, testing, ground research and demonstration. This paper describes an integrated seamless approach for developing new e-navigation technologies starting with virtual simulation based assessment and ending in physical real world demonstrations.

Keywords: eNavigation, eMaritime, testbed, safety assessment, simulation

1. Introduction

Seafaring is and was always a joint undertaking between humans and their technology. Taking into account the impact of nature, such as wind, waves, etc. the reliability of technical equipment and its correct usage ensure safe voyaging. This holds true also for the implementation of e-navigation technology.

The e-navigation implementation process is accompanied by International Maritime Organization's (IMO) NAV and COMSAR sub-committees which merged into the NCSR Committee 2014, as well as the International Hydrographic Organization (IHO) and the International Association of Lighthouse Authorities (IALA). The NAV subcommittee IMO (IMO 2012) did a comprehensive gap analysis as a part of their development of a joint implementation plan for e-navigation which is leading to an updated strategic implementation plan to be presented at MSC94. Regulatory safety rules like SOLAS with the International Safety Management-Code (ISM) for safety management on board or the IMO resolution MSC.252(83) for integrated navigation systems define a set of features to be implemented to guaranty safe voyage under the actual state of the art derived from formal safety assessments (see IMO MSC 85/17/1).

The new guideline focuses on software quality and human centered design. To ensure safety of e-navigation technologies a holistic approach is required taking the whole sociotechnical system (man and machine) in its environment into account.
This paper introduces a system oriented approach for the development of new e-navigation technologies focusing especially on safety and risk assessment. This approach is already adopted in as similar way for accident analysis (IMO decision A.849(20) and A.884(20)) and consequently it should be applied in system analysis for new e-navigation technologies also. Model driven technologies support the safety analysis during the design phase by using formal analysis methods and simulation based on a simulation framework named HAGGIS. For scientific grounding and in situ experiments HAGGIS is accompanied by the physical test bed LABSKAUS with experimental Vessel Traffic Services (VTS) Systems, Bridge Systems, reference waterways and port areas.

2. Systemic Design and Safety Assessment

Engineering new systems requires a broad understanding of technologies to be selected and applied to the design and methodologies to handle complexity of the undertaking. Therefore, engineering applies methodologies (to define engineering activities and their order), methods and tools (to support the engineering activities) in addition to technological knowledge [1]. Engineering itself is an iterative process of synthesis and analysis activities. During synthesis, concepts and technologies are selected, applied and the design is elaborated: The system is under design. Then engineers validate (is the system fulfilling the right requirements?) and verify (are the requirements implemented correctly?) their design. Thus engineers can validate and verify their design developments as early and iteratively as possible to reduce costs and safe time. In electrical engineering Bell Laboratories introduced the concept of system engineering in the 1940s [2]. To understand the product under development as a system with dedicated sub elements, a system border and defined relationships can help to manage complexity. With the advent of technologies to describe elements and relationship in a reusable way by using computer models, this approach became popular also in other engineering domains.

Reusable computer models of the system under design (the system model) allow continuous flow of information between the different tasks and simple implementation of the mentioned synthesis/analysis loop [3]. Paying attention to the early phases of system design (to identify and validate/verify the concepts of the product) reduce the risk of later costly design changes. The concept of frontloading aims at improving design efficiency by reusing models from the early phases in the subsequent design, validation and verification. The propagation and transformation of models along the phases of the design process is called model driven design.
The process of developing new e-navigation technologies starts with the analysis of processes for using existing systems to identify existing hazards. A functional model is the first result which describes the system under development. For early testing and safety assessment, the functional implementation of the new control or e-navigation systems can run as a simulated software subsystem which is embedded in a simulation (software in the loop). Input from sensor systems and from communication to other systems is generated by the simulator. For user tests the functional implementation has to be connected to the virtual representation of the user interface in the virtual bridge to communicate with the user agents (see Figure 1). The models in the first step are executed by a process execution engine (MasCAS) or by cognitive model simulation (CasCAS) to simulate human and machine actions. The example in Figure 1 shows how the user interface is tested. The functional system model is executed in the simulation environment. User input is generated by user agents acting on a virtual bridge with a virtualized user interface. The virtualization is required to simulate the human interaction by software user agents. The user agents use the virtual user interface in the same way a human would use the real physical user interface. For testing a bridge system in traffic simulation a maritime traffic simulator generates the required test cases and data to be used.

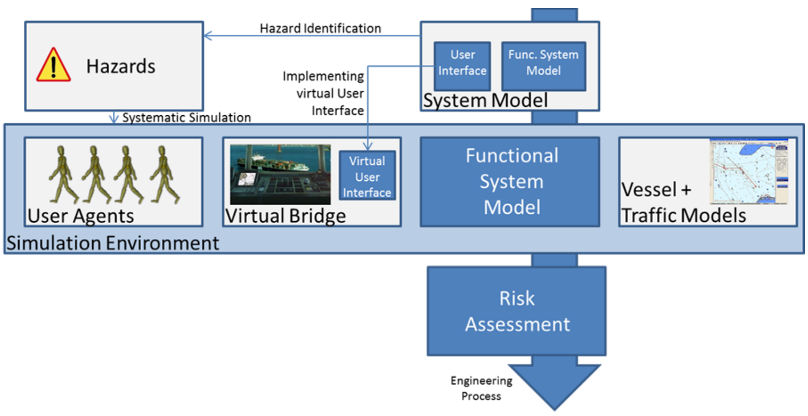

Figure 1: Simulation based Risk Assessment

The focus while testing the new systems in the virtual environment is on safety assessment and hazard detection. The identified hazards are used by the simulation environment to systematically seek risky/hazardous situations using rare event simulation techniques[4]. The behavior of the system is protocolled for further consideration in the engineering process.

After successful assessment in the virtual environment and subsequent analysis and synthesis iterations for improvement, the assistance system then can be assessed in a physical test bed. Our architecture described in Section 3 allows for direct deployment of the software systems on physical test platforms without adaptation to the new platform. This transparency of platforms is known from other platforms like Player[5], ROS[6] or DOMINION[7] in the robotics and automotive domain. Changing the test environment to the physical platform is done by deploying the software on an experimental VTS or a mobile bridge for example. The virtual user interface will be substituted by the real user interface and test persons will perform the actions that have been simulated by the user agents.

3. A platform for seamless development of e-navigation technologies

One of the main challenges in the design and development of new e-navigation technologies is the test environment. Ship-based e-navigation technologies are used in a rough environment (on sea), in which real world testing is not always possible. Therefore, simulation-based testing of new concepts is necessary and for this a very detailed and realistic simulation platform has to be used. However, still a gap between simulation and real world will remain. To reduce this gap we developed a model based approach for design and development of new e-navigation technologies based on a seamless architecture covering simulation and real world assessment that is shown in Figure 2.

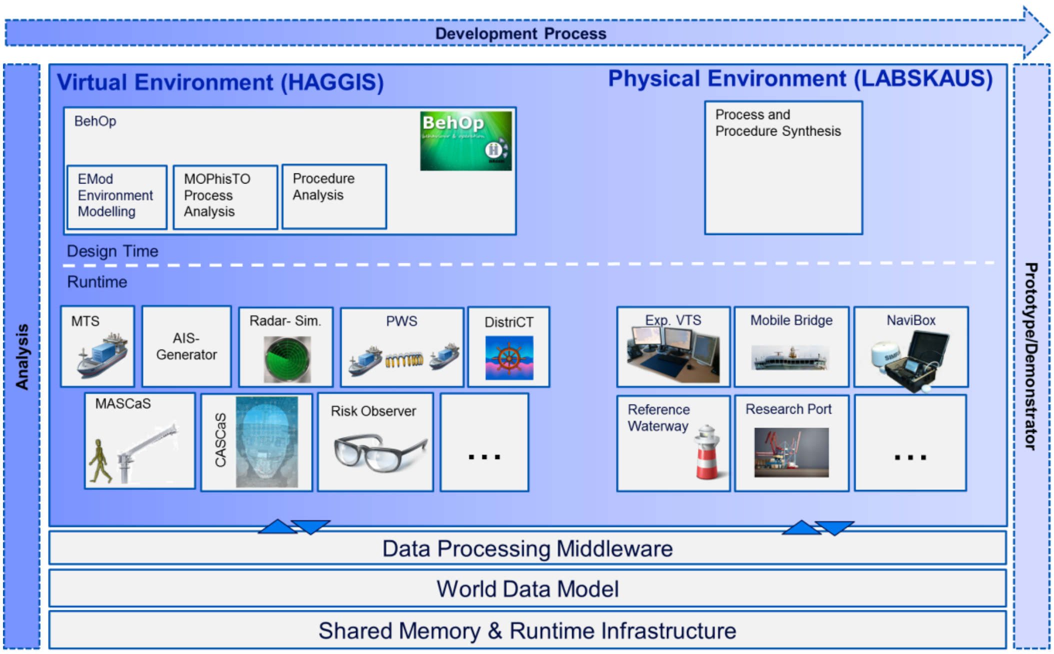

Figure 2: Architecture for seamless testing of new e-navigation technologies

This architecture allows the early testing of new e-navigation technologies in a complex simulation environment and the seamless transfer of these technologies into a physical testbed. The basis of the architecture is a shared memory and runtime infrastructure, a common world data model and data processing middleware. The shared memory & runtime infrastructure currently is a modified high level architecture implementation. This infrastructure allows the communication between different simulation components in a co-simulation environment but also the communication with developed software and physical testbed systems.

The world data model is the common semantic basis for all intelligence implemented in the simulation and new developed e-navigation technologies. It takes into account IHO S-100 aspects and is the virtual representation of the physical world. All simulation components as well as physical components like the mobile bridge work with this data model to generate high value semantically enriched information. The data processing middleware transforms data from different formats like NMEA 0183 and 2000, Asterix, IVEF etc. into the world data model. It furthermore, is an easy to extend sensor fusion middleware for generating high value information depending on what is necessary for the e-navigation technology under development.

This architecture supports the development of completely new e-navigation technologies like assistance systems for vessel guidance. Support is given from the analysis phase until the development of prototypes and demonstrators. The improvement to product quality level is done later phases of the development process.

4. Simulation Environment

System engineering shows that models are well suited to support the engineering process and to provide a valuable basis for validation and verification of the system under development e.g. for safety assessment.
This can be done formally by analyzing the model of the system and informally by using simulation tools. That requires that the models are sufficiently formal and executable. In addition, the test environment has to be defined (modelled) as well. Therefore, we split the simulation environment HAGGIS in a modelling and formal analysis toolset and a co-simulation environment.

4.1. Modelling and Formal Analysis

Figure 3 shows the general approach for modelling and formal analysis. For the safety analysis of new e-navigation systems (e.g. like a new integrated navigation system on bridges) a ground research is done by analyzing guidelines, accidents reports, nautical maneuvers etc. We use a generic hazard list to identify potential harming issues in the system. Process models are used to describe the activities (e.g. operations) and they are enriched by defining information availability, requirements and generic hazards. Formal model checking technology can applied to analyze whether bridge systems allow the required situation awareness of the crew. Further, automatically generated fault trees serve as a tool to identify and quantify the potential risks.

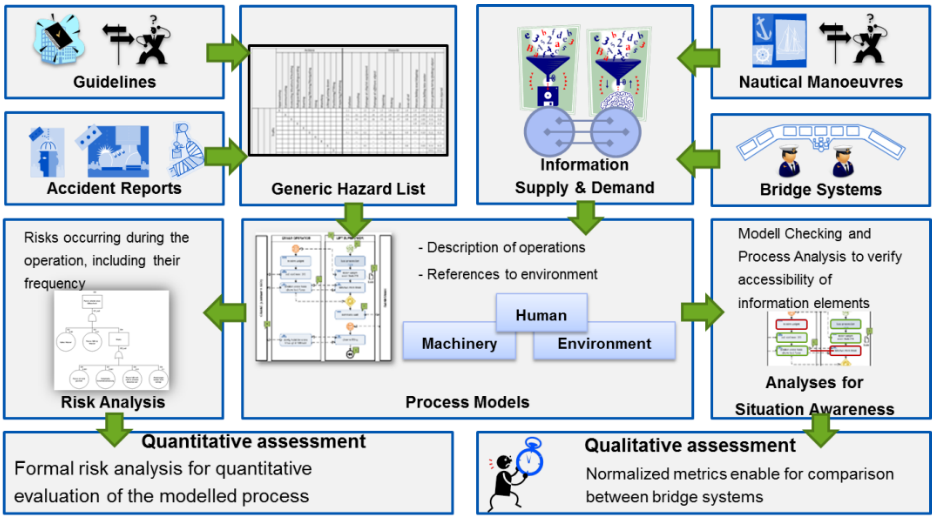

Figure 3: Modelling and Analysis Process

The analysis results in quantitative or qualitative risks / safety assessments. To support the assessments a number of tools are available: MOPhisTO – Maritime Operation Planning TOol, ShiATSU - Analysis of Situation Awareness on Ship Bridges and FTA – Fault Tree Analysis. This toolset is accompanied by EMod – Environment MODelling tool for defining the system environment for analysis by simulations. An overview about the modelling and assessment tools is given in Figure 4.

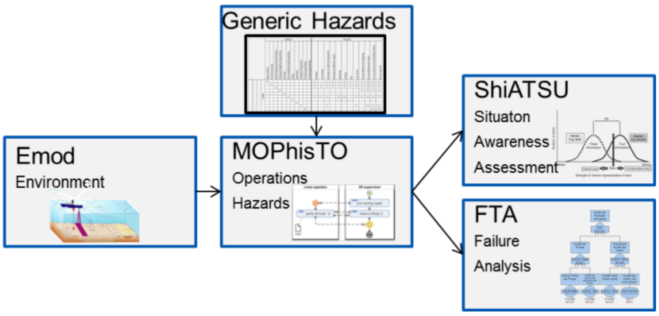

Figure 4: Modelling and Formal Assessment Tools

EMOD – Environment MODelling

EMod is an editor based on the Eclipse framework. EMod provides a system model that allows setting up a static scene according to a predefined scenario. This system model contains the fundamental components/entities of all used resources, actors and environmental factors. The user is able to load 3D geometric models of e.g. ships. The properties of these objects can be set according to the user´s need.

MOPhisTO – Maritime Operation Planning TOol

MOPhisTo enables maritime domain experts to graphically model processes of the operations defined for their field of expertise [8]. The process models are enriched by linking them to required information supply and demand as well as hazards from the generic hazard list. This information is used for information gap and automatic risk analysis. Additional benefit of the models is the option to use them for training and documentation purposes. MOPhisTo can make references to the data modelled with EMOD. MOPhisTo supports the description of normative behaviour for maritime personnel (e.g. individual tasks of an officer) and maritime machinery (e.g. behaviour of an adaptive display). The process modelling language is based on BPEL [9]. BPEL is extended to express the required references to EMOD entities failures etc.

ShiATSU – Situation Awareness Tool SUite for Ship Bridges

ShiATSU is a tool suite for analysis of situation awareness [10] on ship bridges during design time. It allows for analysis of socio-technical ship bridge system setups consisting of a ship bridge, operators and organizational aspects. Operators' interactions with information elements are extracted from MOPhisTO's normative processes and considered as information flows between human operators and the ship bridge. An automatic analysis is used to assess the information flows by facilitating multi-dimensional models of the ship bridge. The analysis comprises a verification of information accessibility, measurements of the spatio-temporal information access and supports engineers by identifying causes for situation awareness errors by consideration of distributed situation awareness. The measurement results in normalized metrics, which allow for system optimization and comparison.

FTA – Fault Tree Analysis

MOPhisTO is used for formal description of normative processes and the annotation of hazards and failures. The integrated FTA tool performs an automatic fault tree construction by using the modelled hazards and failures [11]. Resulting fault trees are the basis for a formal quantitative and qualitative risk assessment.

The tool enables a graphical presentation of generated fault trees to the user as well as manual construction of fault trees. Additionally, they are used for automatic generation of textual risk assessment results e.g. to construct Health Safety and Environment (HSE) plans [12].

Since identification of hazards and failures is important in early project phases, the tool supports users by suggesting hazards and failures modelled in the past. Therefore, it comes with a formal approach to learn data from performed analyses for later reusability of modelled hazard/failure combinations.

4.2. Co-simulation Environment

The sociotechnical model is analyzed in a simulation environment. The process models and the environment models are used to describe the system under analysis. The Generic Hazard List and the process models are used to define the normative behavior and provide a basis to identify critical situations during simulation. For human behavior a cognitive simulation is used. The approach is shown in Figure 5 and the general architecture of the co-simulation is sketched in Figure 6. Inputs are normative behavior and environment models. A maritime traffic simulator and a n-body simulator provide the required environment of the e-navigation experiments.

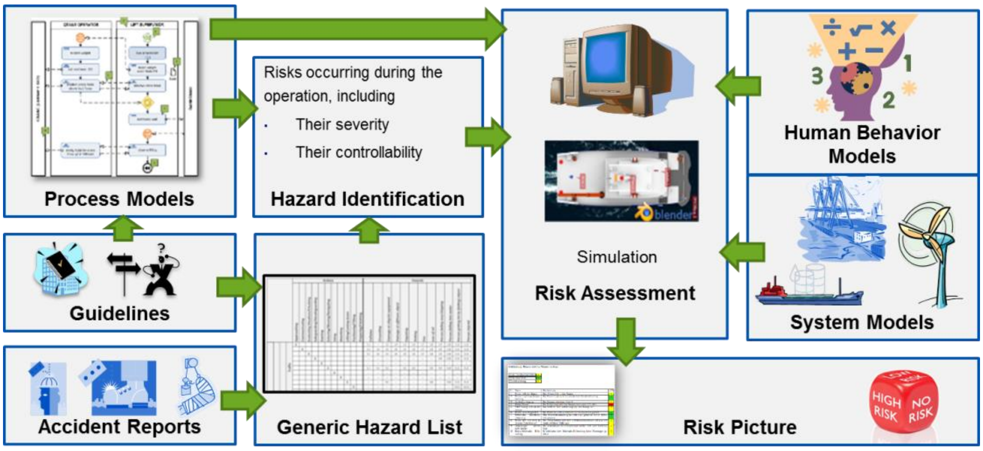

Figure 5: Simulation Based Risk Assessment

Agents are brought to live by MASCAS. MASCAS is executing the defined behavior. CASCAS is a cognitive simulation that implements the real human behavior by performing designated tasks [13]. The implementation currently uses High Level Architecture (HLA) as a co-simulation architecture with data specification of the world data model in HLA specific object model template (OMT) files. HLA is defined under IEEE Standard 1516. OMT provides a common framework for the communication between HLA simulations. Standardized wrappers are used to speed up the simulator integration. All data exchanged by the simulators is defined by the semantic world data model. A simulation control tool runs simulations automatically and supports the detection and provocation of rare events in combination with observer components for observing the simulation. The observer components are automatically generated by using the models defined with MOPhisTo.

Maritime Traffic Simulator

The MTS is a flexible usable maritime traffic simulation for implementing, executing and observing the behaviour of multiple vessels in a realistic context. Each of these vessels has a dynamic model that describes its behavior regarding environmental influences, like waves, current and wind. In addition each vessel is steered by an intelligent agent to follow a predefined path or find its own path according the maritime law regulations. The MTS is used to provide all necessary data about the traffic situation that is required by a statistical analysis or other simulators.

N-Body Simulator

The N-Body simulator simulates the physical interactions of rigid bodys inside the simulated environment [14]. That could be: The displacement of the cargo due to a collision with another object or the rapid (heave/sway/surge) movement. It contains a collision detection capability that allows for checking constraints like man under the cargo or man overboard.

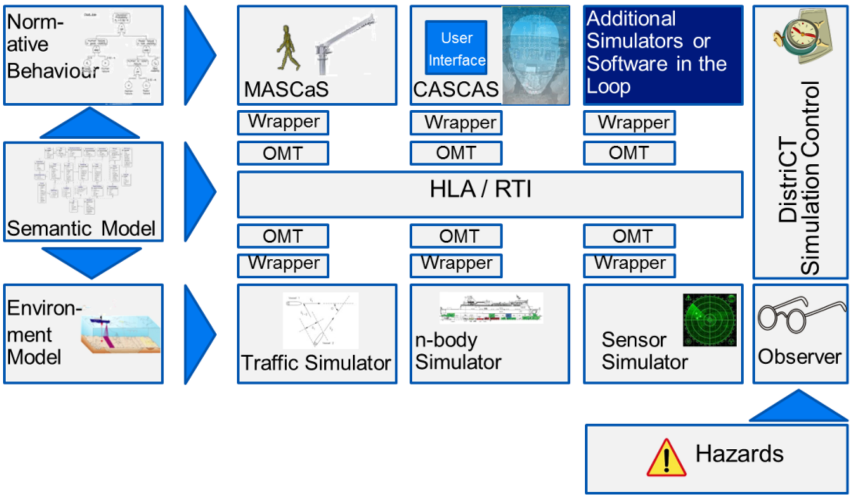

Figure 6: HAGGIS Co-simulation Environment

Sensor Simulation
The sensor simulation is used to generate realistic sensor measurements from a simulated context, e.g. the context of the maritime traffic simulation. The generated measurements can be extended by statistical, systematic or context-sensitive error models. In combination with a traffic simulation the Sensor Simulation generates AIS or Radar data for example.

MASCaS
In order to simulate simplified agents models by MOPhistTO, a simple model interpreter (MASCaS) has been implemented in Java. Changes of agent states are communicated via HLA to their related avatars in the N-Body simulation or Maritime Traffic Simulation. For example, MASCaS can give the avatar a motion command that is implemented by a description of the behavior of the avatar or the movement is directly controlled by the agent.

CASCAS
The cognitive architecture CASCaS (Cognitive Architecture for Safety Critical Task Simulation) is used to model human behaviour. CASCaS models generic domain independent cognitive processes in a modular way taking into account human perception, memory, knowledge processing and motor skills [13]. A key concept underlying CASaS is the theory of behavior levels which distinguishes tasks with regard to their demands on attentional control dependent on the prior experience: autonomous behavior (acting without thinking in daily operations), associative behavior (selecting stored plans in familiar situations), cognitive behavior (coming up with new plans in unfamiliar situations).

DistriCT (Distributed Controlling Toolkit)
DistriCT can be used to set up and control simulation components on different distributed systems. This involves starting and stopping of simulation components as well as receiving and sending objects/attributes to them. This can be used to inject failures or perform a systematical parameter exploration. Additional observers are used to evaluate the system state and the logical or physical distance to hazardous situations. They identify minima in these distances and guide the simulation in the direction of critical situations to find rare events and to reduce the required number of simulation runs.

5. Physical Testbed

The virtual environment is accompanied by the physical environment and testbed LABSKAUS (laboratory for safety critical experiments at sea). LABSKAUS is a living lab for experiments and traffic surveillance and provides a grounding for the HAGGIS simulation experiments and itself is based on the same world data model and the same architecture as HAGGIS. LABSKAUS offers services for e-navigation experiments. Services are a reference waterway, a research port, a mobile bridge system and a Vessel Traffic Services (VTS) System. One generic element for its implementation is the Navibox for mobile sensor systems.

5.1. Reference Waterway

The Reference Waterway covers the Elbe and Kiel Canal Approach near Brunsbüttel, Germany. It covers a basic maritime surveillance infrastructure with three Naviboxes (including AIS, Radar, cameras) and broad band communication via satellite and LTE. The system is used as an experimental platform and for demonstration of new technologies as well for setting up a database with travel patterns and near collisions.

5.2. Research Port

The research port addresses experiments for sensor data fusion in port areas. The small port Gestemündung in Bremerhaven, Germany has a ferry terminal, berths and an entry to a popular double lock. The research port is equipped with a mobile sensor network of Naviboxes especially to experiment with optical systems (visual light, IR and UV) in cameras and laser systems. The Naviboxes set up an ad hoc sensor network with broadband communication.

5.3. Mobile Bridge

For bridge experiments in lab and on ship a mobile bridge system allows set up of an experimental bridge on board without interfering with the vessels navigation systems. It provides a Raytheon Integrated Bridge in its standard configuration (other software is optional) and is linked to a Navibox which provides required navigational data such as compass, GPS, AIS, log, lot, radar, as well as a broad band communication system. This mobile bridge is used for experiments with assistance systems and for human centered design analysis.

Its mobile design consists of a controlling unit, modularly mounted with a PC station. The controlling unit enables ship steering e.g. put the rudder (in areas where permissions are given for this). The PC works as Electronic Chart and Data Information Systems (ECDIS) and radar display as common on ship bridge systems. The overall mobile bridge system is transportable within a box including display components, and ready-to-use for experimental applications with or without external power supply.

From the software perspective it is possible to connect simulation environments to the mobile bridge e.g. to send simulated sensor data. Intelligence from new developed e-navigation assistance systems is based on the world data model. E. g. collision detections uses the already mentioned world data model for analyses of the current traffic situation and for generating adequate alarms.

5.4. VTS System

An experimental VTS system was implemented by the company Signalis at the maritime research center in Elsfleth. It can be linked to the Reference Waterway and the Research Port as well as to the virtual environment HAGGIS. It consists of a PC system and multi-touch display components, which are used for HMI research applications in order to improve designs of current state of the art.

5.5. Navibox

The Navibox is a mobile, connectable sensor data hub which provides navigational data on board as well data for maritime surveillance systems. Sensors can be configured ad libitum. The Navibox provides WLAN and Broadband WAN communication facilities. The box is an aluminium case and comes with a radar pole.

6. eMaritime Reference Platform

LABSKAUS and HAGGIS are part of the open eMaritime Reference Platform a lead project and demonstration system of the German working group for civil maritime safety to implement the strategic national master plan in maritime technologies. In addition to the presented simulation system and physical test bed, eMIR covers also the Research Port at Rostock for experiments with satellite technologies and resilient Position Navigation and Timing (PNT).

7. Conclusions

Safety and dependability in combination with efficiency are the design goals of e-navigation systems. Model driven technologies support the efficiency of the development process and enable early design assessments, especially safety requirement verification and validation. To support a system engineering approach for e-navigation systems the paper introduced the eMaritime Reference Platform eMIR with a virtual simulation based environment (HAGGIS) and physical environment and test bed (LABSKAUS). HAGGIS supports modelling and formal analysis of e-navigation systems and a co-simulation environment with traffic and n-body simulation systems as well as human agent models for human centered design engineering. LABSKAUS provides an experimental VTS System, a mobile ship bridge and a reference port and a reference waterway for e-navigation experiments and systems demonstration. Both are based on a common architecture and data model to allow for a seamless development of new e-navigation technologies.

The approach is also directly linked to training and education of seafarers. Simulation environments are already an established elements on seafarer training. Training is possible with key user while the system is under development. An agent based approach is also able to improve bridge simulation systems by providing realistic behavior other vessels.

Of course the mentioned approach is limited to a encapsulated and restricted artificial test environment and final tests in real world environments cannot be avoided.

8. Acknowledgements

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