MARITIME TRAFFIC CO-SIMULATION FOR ANALYSES OF MARITIME SYSTEMS

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ABSTRACT
Analyses of maritime systems are necessary to improve the efficiency and safety of the worldwide shipping lanes. Distributed simulations provide a flexible and extensible testbed for these analyses. This paper describes a HLA-based maritime co-simulation to provide and analyze data about vessel traffic motions. The co-simulation focuses on a flexible configuration, high extensibility and reusability. It comprises of an analysis component as well as simulators for the environment, human behavior and the physics of vessels. The common semantic model enables the communication of these components with its consistent set of concepts and data types. The MTS is based on a physical model for vessel motions with four degrees of freedom. Three agent types are implemented on the base of the generic agent model to show its extensibility and practical use. The evaluation of the generated vessel traffic motion data is done by comparison with real AIS data.

Keywords: Flexible Analysis, Distributed Simulation, Maritime Traffic Co-Simulation, Extensibility, Semantic Model, DOF, HLA, RTI, MASON

1. INTRODUCTION

According to a 10 years survey there are significant challenges regarding a safe and efficient maritime traffic on the worldwide shipping lanes (Gale 2007). According to Gales survey 60 % of collisions and groundings are primary caused by human errors. The analysis of maritime systems like vessels can help to optimize their reliability and eNavigation equipment so that e.g. a single person's navigation error can be easier handled by such systems (IMO 2012). Consequently, the analysis of maritime systems can serve the improvement of the efficiency and safety of shipping lanes.

Distributed simulations are an appropriate way to run scenarios for the analysis of maritime systems (Läsche et al. 2013). Therefore this paper describes the architecture, components and semantic model for a flexible maritime traffic co-simulation. Moreover it describes the efficiency and safety on the same level above the micro models which include the full vessel dynamics and exact maneuvers. It supports a large selection of usage scenarios for the analysis of maritime systems like:

1) Testing of new algorithms for the planning and optimization (e.g. regarding the performance of maritime traffic routes)
2) The efficiency evaluation of shipping lanes with input parameters like the number of vessels and their goal ports
3) Testing of platooning to check its effect for the efficiency of shipping lanes
4) Evaluation of traffic management systems like VTS to evaluate and improve their reliability and usability
5) The evaluation of risks like grounding and collisions with different input parameters like the number of vessels and environment conditions
6) Testing of maritime traffic collision avoidance systems to check the precision of their algorithms

2. CO-SIMULATION INFRASTRUCTURES

Frydman et al. (2002) and Zini et al. (2004) presented a HLA-based approach for distributed environments. But Zini et al. (2004) focused mainly on the analyses in the military, maritime domains. Focusing on the same domain, the HLA-based approach of Bruzzone et al. (2008) takes human behavior into account. Longo et al. (2012) introduced an approach for traffic controllers and ships pilot training in marine ports environments. Massei et al. (2013) developed a HLA-based real time distributed simulation of a marine port for training purposes which considers also safety and efficiency aspects. IWRAP is a modelling tool for the evaluation of risks like groundings and collisions (IWRAP 2014). Beschnidt (2010) presented a simulation environment for traffic flows on inland shipping lanes which supports usage scenarios like the evaluation of navigation systems.

Our approach considers exclusively civilian usage scenarios like the risk and efficiency analysis of whole shipping lanes.

3. CO-SIMULATION ARCHITECTURE

The developed testbed is realized as a co-simulation allowing the components like simulation systems for vessel traffic, environment, human behavior and analytical proposes to work together in an appropriate way.
The simulation components exchange data in an inter-process communication. This is done by the open source runtime infrastructure (RTI) certiRTI. It implements the standard High Level Architecture (HLA) (s. Figure 1). Therefore it is able to enable the communication among all components and synchronizes them to ensure a common awareness of their shared environment (Noulard et al. 2009). The implementation requires a description of the communicated data in form of an Object Model Template (IEEE 2010).

3.1. Architecture Overview

The co-simulation-based testbed for the analysis of maritime systems comprises of the *Scenario Importer*, *Maritime Traffic Simulation (*MTS*), Environment Simulation* and the *Analysis Component* as well as the *Semantic Model* for the co-simulation. Furthermore *Controllers* role with commands like start, stop and *Observers* role are described.
The *Scenario Importer* is able to read Scenario Description files to set up co-simulation scenarios. The MTS provides vessel traffic data. The *Environment Simulation* provides the environment state for the MTS by HLA / RTI. The *Analysis Component* is able to generate key performance indicators (KPIs) that are intended to measure the efficiency and safety of shipping lanes.

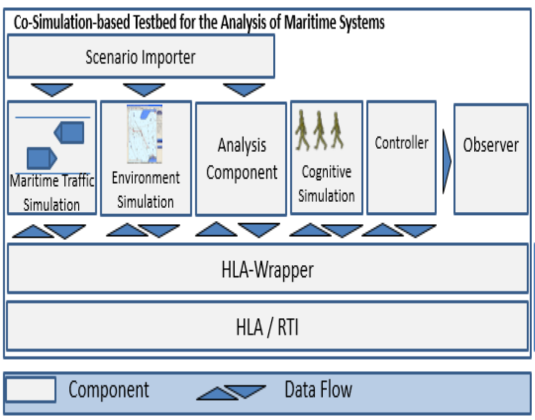

Figure 1: Co-Simulation-based Testbed for the Analysis of Maritime Systems

The *HLA-Wrapper* is used to simplify the usage of HLA as described in Puch et al. (2012) and Läsche et al. (2013).
The *Cognitive Simulation* provides simulation of human actors like nautical personnel. This component allows considering possible human errors in the co-simulation. Described detailed description can be found in Wortelen et al. (2006). In the following, the other components are explained in depth.

3.2. Scenario Importer

The *Scenario Importer* reads XML-based scenario configuration files. A scenario configuration file includes values to configure e.g. the MTS for the determination of properties like length, draught, MMSI, GPS start position etc. Moreover the *Scenario Importer* is able to import scenario configuration data for the *Analysis Component* which is explained in section 3.5.

3.3. MTS with its Physical Model

The MTS is based on the physical model from Fossen (2011) reduced to three degrees of freedom (DOF).
DOF are individual variables which define the position and orientations of a vessel (s. Figure 2 and Table 1).

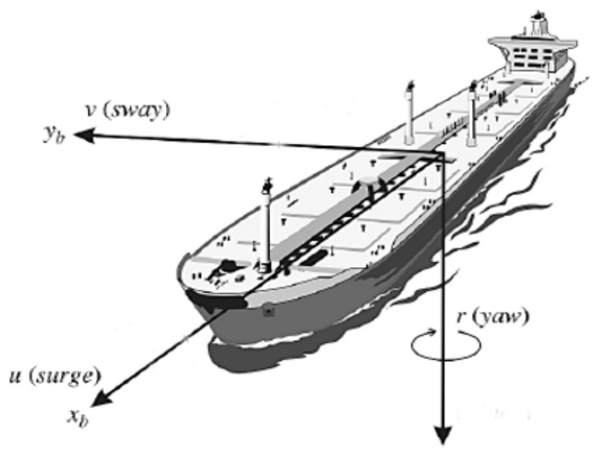

Figure 2: Movement in three DOF (Fossen 2011)

Table 1: Notations for marine vessels (SNAME 1950)

DOF		Forces and moments	Linear and angular velocities	Positions and Euler angles
1	Motions in the x direction (surge)	X	u	x
2	Motions in the y direction (sway)	Y	v	y
3	Rotation about the z axis (yaw)	N	r	ψ

The "horizontal plane model" with three DOF (surge, sway and yaw) is defined as follows:

- **Surge**: Describes the sum of all forces that have an impact on the forward and backward movement of the vessel. This comprises of all environmental parameter of the physical simulation as well as the propulsion of the vessels.
- **Sway:** Describes the sum of all forces that move the vessel to the right or left. All environment factors must be considered for the sway.

- **Yaw:** Describes the sum of all forces that have an impact on the rotation of the vessel. The environment parameters are considered together with the rudder.

The forces acting on a ship (level and torque) can be defined by the model from Abkowitz (1964); Fossen (2011); Gronarz (1997). Furthermore the physical simulation considers the moment of inertia for each of the three DOF.
In the realized physical simulation, the current draught of a vessel depends only on its loading condition. This means that movements influenced by environment factors like waves of a vessel are not considered.

3.3.1. Architecture of the MTS

The implementation of the MTS is based on MASON. It is a framework for multi-agent simulations which is based on the Java platform (Luke 2013). MASON implements an event-oriented simulation (discrete event simulation). This means that the simulation activities are implemented through a sequence of incoming events.

The *Visualization Component* is able to display simulated vessel traffic motions from the connected *Physics Engine*. The *Visualisation Component* and *Physics Engine* are split into two-layers and are part of the MTS (s. Figure 3, 4). Their split allows to exchange the *Physics Engine* as well as the *Visualization Component* in a simplified way (Luke 2013).

GeoMason allows the loading of geospatial data from various formats and provides corresponding data spaces for MASON (Sullivan et al. 2010). GeoMason is used to provide map data like the depth and buoys of waterways.

3.3.2. Agent Logic and Types

The *MTS* is an agent based simulation. The agent logic describes the behavior of each agent. The MTS allows a simple extension and changing of the agent logic. Furthermore the generic approach enables to specify all agent types based on one agent model. Any changes of this generic model are then automatically inherited by all derived agents.
By now, three agent types are realized with the generic agent model of the MTS: the non-interactive agent, interactive agent and automated agent. Each agent type has a different logic and is able to control vessels.
The scenario configuration file defines which agent type relates to which vessel.
The *non-interactive agent* can receive a list of steering commands (s. Figure 3). This agent moves according to the received steering commands and the physical characteristics of the vessel(s). The steering commands come from the MTS and external components over the HLA / RTI. Moreover the non-interactive agent sends information about its state (e.g. position data, velocity data etc.) in a parameterized interval over the HLA / RTI to external components like a collision avoidance system. At the beginning of the simulation, the *interactive agent* receives a start point over the HLA / RTI.

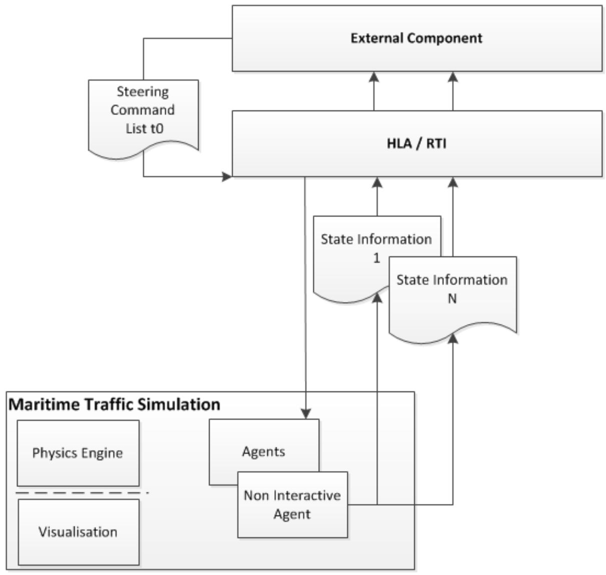

Figure 3: Steering Command List for the Non-Interactive Agent

During the simulation, the *interactive agent* receives new steering commands step by step from an *external component* like a keyboard, joystick, ship console or other components which are connected by the HLA / RTI (s. Figure 4). This enables the *interactive agent* to change the trajectories of the related vessel during the simulation depending on its physical characteristics. These characteristics depend e.g. on the defined velocity for the movement of the rudder.

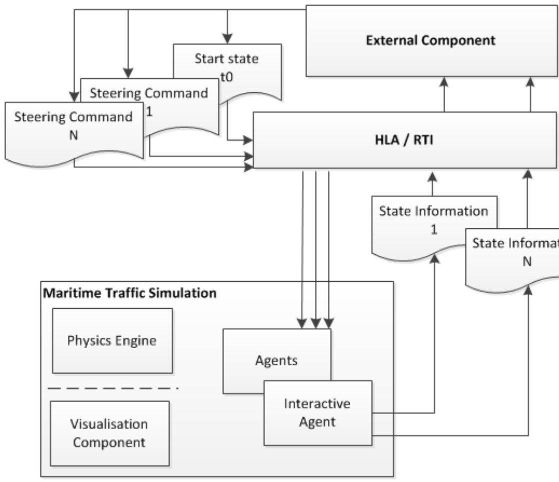

Figure 4: Steering Commands for the Interactive Agent

The *interactive agent* is also able to send information about its state in a parameterized interval over the HLA / RTI on *external components*.
A practical scenario for this agent type is e.g. the test of collision avoidance systems:
Users with a keyboard or ship console are able to change the course of vessels so that a collision with other vessel(s) is possible.

A correct collision avoidance system of the other vessel(s) will try to change their course in a direction were the probability for a collision is as low as possible (Hornauer & Hahn 2013).
The *automated agent* receives a traffic route by HLA with at least two GPS points (start and goal). It is able to automatically calculate steering commands under the consideration of the physically possibilities. This enables the generation of realistic traffic situations. The *automated agent* can be realized with different artificial intelligence, regarding the wayfinding and driving behavior. The currently realized *automated agent* uses the A* algorithm (Nosrati 2012) and the Taxicab geometry (Janssen 2007) to reach its destination.
This geometry is used to evaluate the costs under the consideration of the way. The route between the start and destination point is rasterized in squares. The standard grid-size is 2500 m². Thereby each square requires the following conditions:

1. the water depth [m] of each square has to be deeper than the required depth [m] of the vessel.
2. the square is in areas were vessels are allowed to drive.

Each square includes a value which increases proportionally to the distance of the start point. The way is described as a spatial sequence of squares. The optimal way is the one where the target square contains the lowest value. The surrounding squares are sampled in the case of barriers. The square which is nearer to the target square is selected as the optimal square in an incremental sequence. A vessel route over all squares is set after the identification of all optimal squares. The vessel route calculation has the sense to smooth the found way of individual squares so that the vessel is able to move adequate. This includes in particular the avoidance of many closely spaced course changes. Furthermore the planning of routes considers the vessel dynamics to ensure that the calculated routes can be followed by the individual vessel.

3.4. Environment Simulation

The *Environment Simulation* provides the environment state for the MTS by HLA / RTI. Beschnidt (2010) considered for his environment simulation the factors wind and stream. Our *Environment Simulator* provides the current, wind, sea level and wave data to have more realistic conditions. The maps used in this component are based on the S-57 standard. This is a transfer standard for hydrographical data which includes e.g. the GPS positions of buoys and draught information. The environment can be set up by two scenarios: the static scenario or the dynamic scenario.

The static scenario defines a fixed environment state for the whole map or a selected area. This scenario can be configured in the GUI in Figure 5. The configuration comprises of the following factors:

- the current speed (= *Current speed [m/s]*)
- the current direction (= *Current direction [degrees]*)
- the wind speed (*Wind speed [m/s]*)
- the wind direction (*Wind direction [degrees]*)
- the sea level (*Sea level [m]*)

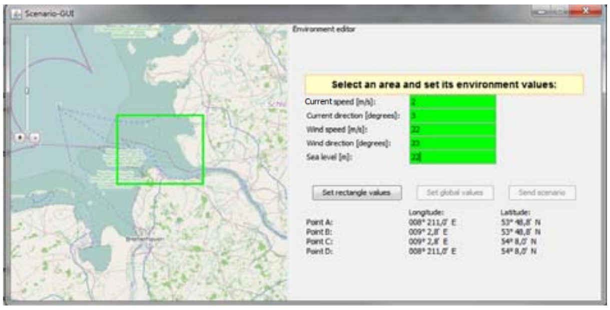

Figure 5: GUI for the Static Environment Scenario

The definition of a fixed environment state is sensible to examine waters regarding the possible risks during user defined environmental conditions. This can be e.g. a storm and a strong current.

The dynamic scenario provides a dynamically interpolated environmental state. The calculation is based on a linear interpolation function which takes the factors defined in the configuration file or GUI as a first start point. Furthermore it gets historical data to make an approximation to the real environment conditions. The historical data of the stream is read from GRIdded Binary (GRIB) files.

3.5. Analysis Component

The analysis component allows to set up scenarios on shipping lanes to analyze the effect of different input parameters like strong wind. They are passed to the simulation component which executes the scenario, while it returns all relevant data back to the analysis component. The analysis component analyzes the data and creates an assessment of e.g. the efficiency of vessel traffic in the form of key performance indicators (KPIs).
The co-simulation can answer the following two exemplary questions:

- Can the traffic efficiency be improved by platooning maneuvers?
- Can a dredged shipping lane with a deeper water level be used for a denser traffic and thus contribute to increasing transport efficiency in estuaries?

Input Parameters
The user has the possibility to define input parameters describing the initial situation of the scenario. The input parameters are passed to the simulation component at the start of the scenario. The parameters to be considered are listed below:

- The number of vessels

- The start point of each vessel [GPS]
- The orientation of each vessel [°]
- The type of vessel (length, width, depth, [m], etc.)
- The agent type of each vessel
- The waterway section which is relevant for the efficiency or safety review
- The characteristics of the waterway
- The environmental situation (e.g. strong wind, high current, low sea level)

Output Parameters

During the execution of the simulation scenario, the simulation component sends all relevant data to the analysis component. These are:

- MMSI of each vessel
- Position [GPS]
- Orientation [°]
- Speed over ground (SOG) [m/s]

The analysis component creates KPIs based on this information. Exemplary KPI are:

- The number of vessels that can pass through the stretch per unit of time
- The transport tonnage of these vessels
- The type and number of violations of navigation rules as provided by the simulation

The definition of KPIs is done through queries. Moreover the necessary evaluation of KPIs depends on the particular analytical question(s). It follows, that it is the responsibility of the user to carry out the assessment and apply an appropriate evaluation function. For this purpose external programs such as Excel can be used.

The KPIs are provided after a simulation run. KPI data can be exported to text files or to a relational database.

Comparison with real AIS data

Another objective of the analysis component is to provide a basis for the validation of the simulated vessel traffic motions e.g. by comparison to AIS data. Nevertheless it has to be considered that the AIS signals do not contain information about the environmental influences like current during a period. Therefore recorded environment data has to be taken from exactly the same period. In this case, the *Environment Simulation* would be able to provide realistic environment conditions. Furthermore the situation around the vessel during that period has to be considered.

A first evaluation concept considers a part of the route from Hamburg to Bremen. The input parameters describe a typical cargo vessel with a length of 270 meters and a gross tonnage of 61870 m^3. The simulated vessel is visualized in yellow triangle in the bottom right corner of the map in Figure 6.

Currently, the authors implement a surveillance platform at the Elbe to get sufficient data to calibrate the system.

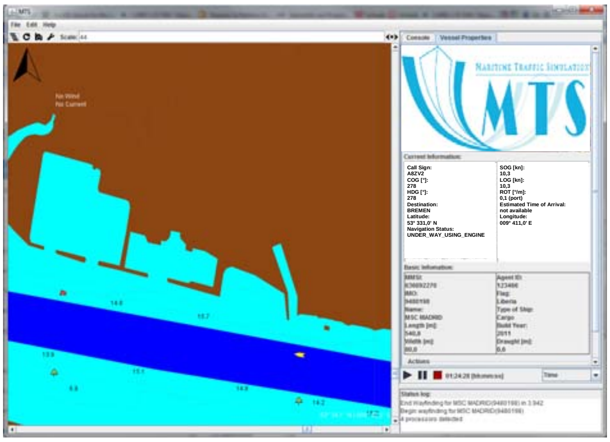

Figure 6: Visualization of the Simulated Vessel

3.6. Observer

The *Observer* is a passive component which does not influence the simulation during its processing but can observe each aspect of the simulation. Therefore it is able to recognize predefined events like hazards and failures. A hazard is defined as: "A potential source of harm. Harm is a physical injury or damage to the health of people" (Esposito 2010). A failure can be defined as: "The termination of the ability of an element or an item to perform a function as required." (Esposito 2010). In the case of maritime systems, an example of a failure is the grounding of a vessel in a curve caused by the vessels engine damage (a hazard).

3.7. Controller

The simulation can be started and stopped by commands from the *Controller* before and during runtime over the HLA / RTI. Furthermore the controller can execute a save and resume command (Läsche et al. 2013). Then the maritime co-simulation states can be persisted and resumed at a specific point in time (e.g. near a collision of vessels or during a high density on shipping lanes).

Moreover environmental conditions can be influenced from the *Controller* over the HLA / RTI (Läsche et al. 2013). This means in the case of the *Environment Simulation* the possibility to change the factors wind, current and sea level during runtime. This enables the dynamic evaluation of shipping lanes regarding their safety and efficiency under different weather conditions and traffic density.

3.8. Semantic Model

The common *Semantic Model* is necessary to provide the concepts and data types for a formally described semantic and to enable the communication between the components of the presented testbed. This enables among others the common awareness of these components. The semantic model is structured in five layers (s. Table 2).

Table 2: Five Semantic Model Layers

Content	Name
Ecore, OWL, …	0: Languages
Unit, Graph, Math, 3DGeometry, …	1: Universal
Physics, Geography, …	2: Engineering
TrafficSystem, Vehicles, Sense, HMI, Environment, …	3: Application
Maritime, …	4: Domain

The basic layer covers all languages which are necessary to describe the *Semantic Model*. The concepts and data types are described using the metamodel Ecore which is based on the Meta Object Facility standard for metamodeling (Steinberg et al. 2008). This allows the usage of the EMF tool chain for further development based on the *Semantic Model*. Moreover the data types, which are defined in Ecore can be transformed into the Object Model Template (OMT). OMT files are necessary to configure the certiRTI regarding the data types which are the base for the communication between the co-simulation components. The transformation into OMT is done by an automatic model transformation as explained in Dibbern et al. (2014). The Web Ontology Language (OWL) will be used to describe the concepts of the model to improve knowledge management (W3C 2014b).

The layers one to four comprise of model packages. Each model package encapsulates topic specific concepts and data types and follows the design rationale high coherence. In addition, loose coupling is realized to other model packages. This simplifies the exchangeability and maintainability of model packages if e.g. a new standard has to be considered.

The *Universal* layer comprises of concepts and data types which have a general meaning for all layers below with model packages like Unit (common definition of Time, Engineering Unit), Graph, Math and 3DGeometry. The *3DGeometry* model package contains concepts and data types from the ISO19125 and the S100 Simple Geometry (ISO 2004; IHO 2010). It is used to describe geometrical data. Therefore it comprises of data types like 'GeoPoint', 'Curve', 'Surface' and 'Polygon' that could be both two- or three-dimensional.

The *Engineering* layer includes model packages for physics and geography. The model package *Physics* contains concepts and data types from the Bullet Physics library like RigidBody and EnvironmentFactor (Real-Time Physics Simulation 2014). The package *Geography* comprises of concepts and data types from the S100 Feature Catalog to describe e.g. buoys on a shipping lane like the Weser. Examples for buoys are shown in Figure 6 on the left and right side of the fairway.

The *Application* layer includes all concepts and data types to integrate different applications like Sensor Simulation and Cognitive Simulation. It comprises of the model packages TrafficSystem, Vehicles, Sense, Human Machine Interaction and Environment. The *TrafficSystem* model package includes data types like 'WayPoint' and 'Trajcetory'. The *Vehicles* model package is necessary to define concepts and data types like MMSI and the dynamics of a vessel.

The model package *Sense* is necessary to integrate sensor simulators. In case of maritime systems, it is e.g. required that this package includes concepts and data types like GPS so that the MTS is able to communicate the vessel positions to a radar simulation. Because of that the *Sense* model package contains concepts and data types from the *SensorML* (Open Geospatial Consortium Inc. 2007) and *Semantic Sensor Network Ontology* (W3C 2014a). The Sensor Modelling Language is a XML based standard which is used to describe sensors as well as their measurement process. It also includes models to describe observations of these devices. The *Human Machine Interaction* model package includes concepts and data types like Display and InformationObject to be able to integrate *Cognitive Simulations* as shown in Figure 1. The current concepts and data types of the model package *Environment* are shown in Figure 7. It is necessary to integrate *Environment Simulations* like explained in section 3.4.

Figure 7: Model Package for the Environment Simulation

The *Domain* layer comprises of model packages of different domains like maritime, aviation and automotive. The model package *Maritime* is realized to provide additional concepts and data types like specific vessel types such as HighSeaVessel and InlandVessel.

4. CONCLUSION

This paper describes a HLA-based co-simulation for the analysis of maritime traffic systems. The co-simulation integrates the following simulators and components: The mathematical model is the base for the MTS and considers four degrees of freedom to provide a realistic physical behavior for analysis purpose. Its agent model supports the flexible configuration, extensibility and reusability of the co-simulation by its generic construction. The environment simulator provides a static and dynamic behavior so that wind, waves, current and sea level can be generated based on the historical data with an interpolation function. The analysis component is connectable by HLA / RTI and is able to get the required data for efficiency and safety analyses from the environment, maritime traffic and cognitive simulation. It supports the definition of individual queries to allow flexible analysis of maritime systems. The MTS and Environment Simulation can be influenced by the Controller so that the co-simulation states can be saved and set up again. Furthermore errors can be inducted and environment parameters like the wind can be changed to analyze the effect of rare events. The MTS is able to communicate broken traffic rules by HLA / RTI so that observers can recognize such rare events. The common semantic model enables the communication between the co-simulation components with its set of consistent data types. The evaluation of the MTS will be realized with a comparison of recorded AIS data from the Elbe. The challenges to use AIS for evaluation purposes of the MTS were explained.

Furthermore it is planned to extend the simulation logic regarding traffic rules with more rules of "The International Regulations for Preventing Collisions at Sea" (Lloyd's Register 2005). By now, the agents are able to follow the rule to move on the right side of the fairway, to hold an adequate distance to other vessels and to make overtaking maneuvers.

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