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# Optimal Maneuvering and Control of Cooperative Vessels within Harbors

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**Abstract.** The publication on hand presents the ongoing developments of a networked control system for maritime application within the joint project GALILEOnautic 2. It is based on the joint project GALILEOnautic, where a system was developed which enables cooperative maneuvering of networked vessels in a harbor environment. The present paper focuses on the planned automation of the research ship DENEB of the German Federal Maritime and Hydrographic Agency (BSH), and discusses the planned evaluation szenario. Therefore, it introduces the required extensions of predecessor system concepts to act on a level close to industrial application. The algorithms will be extended, such that they are capable to a higher number of participating networked ships, are more reliable and can handle error situations. Furthermore, the original cooperative network depended concept will be transferred to a single ship, such that autonomous ships can be integrated in conventional harbor traffic. The design of real-world experiments with an autonomous operating DENEB in the harbor of Rostock are discussed.

## 1. Introduction

The ongoing globalization results in a continuous growing global shipping. The international maritime organization (IMO) estimates that 90 % of all traded goods are transported via sea routes; with a growing rate of 2-3 % per year, referring to the total transport capacity. Therefore, the maritime sector is facing substantial technological changes. It results in a higher traffic volume in harbors and narrow waterways, which has to be coordinated in an effective and safe manner. Automation and networking of vessels enables cooperative autonomous navigation and optimal maneuvering, which can improve safety, optimize energy consumption, and therefore, reduces operating costs. For evaluation and validation of such system, proper evaluation szenarios should be defined, which are performed with real regular size ship in real harbor.

The subjects of recent research projects focus on unmanned and autonomous ships to demonstrate the feasibility of autonomous functions applying common technologies [3]. First of all, the transiting-motion mode is investigated. In that mode, almost no space limitations are restricting ship's motion and the established methods of automatic control are sufficient to

control vessels at that mode. In [7], a decision making system is developed, which can avoid collisions with other vessels. This approach is not cooperative and focuses only on a single vessel. In [5], a method is introduced, which applies Model Predictive Control (MPC) to realize collision avoidance between vessels. In this case, the behaviour of moving obstacles is not predicted and optimal controls for vessels are not considered. Furthermore, this referred work assumes a given reference path and considers only one target vessel.

Since the mentioned publications are dealing with simulations, the handling of real-world system disturbances, communication delays, etc. are not discussed. Furthermore, autonomous maneuvering in limited and safety-critical areas is excluded. Latest industry demonstrators, like Kongsberg YARA Birkeland [6] or DNV GL ReVolt [4] already handle real world challenges, but are single solutions without an overall concept, and cooperative approaches of a networked control system.

The publication on hand presents the developments within the joint project GALILEOnautic 2, where modules for guidance, navigation, and control (GNC) systems are developed for fully automated and cooperative vessels in areas with high safety and efficiency requirements, such as ports or shallow waterways. The modules are based on the developments of the predecessor project GALILEOnautic [8].Therefore, each networked vehicle participates a VPN (virtual private network) secured long term evolution (LTE)-based communication network with a central server. The vehicles estimate their own PNT solution, send them to the central server and in return receive trajectories, calculated by a central model-based optimization module. These trajectories are calculated after data synchronization with respect to all participating vehicles, vehicles which are not part of the network, but sending AIS messages and obstacles, detected by ships proximity recognition system, such that collision avoidance and optimal maneuvering is achieved.

GALILEOnautic 2 aims for extending this concept in order to make it feasible for industrial near future application. Localization is extended by new algorithms to enhance accuracy and preciseness and methods for enhancing reliability and integrity will be added. Fault-tolerant control approaches enable safe navigation of real ships. New approaches for trajectory generation enable handling of any number of ships in a network. In order to face the challenge of integrating automated maneuvering in today's harbor conditions, an ergonomic Maneuver Assistance System (MAS) will be developed for control and monitoring during maneuvering and single automatic maneuvers, initialized by the watch keeping officer. Furthermore, the system concept will be developed as scalable system, i.e. on the one hand it is able to process higher number of traffic participants, on the other hand it is even capable for being transferred to a single ship, such that autonomous operation of a single vessel can be performed independently from a Central Server.

All approaches will be validated in real-world experiments with different demonstrators. The present publication focuses on the demonstration planned with the research ship DENEB of the German Federal Maritime and Hydrographic Agency (BSH). A szenario is designed where DENEB passes the harbor of Rostock and encounters unmanned surface vehicles (USVs) as cooperative partners. GALILEOnautic 2 project partners are RWTH Aachen University, University of Bremen, University of Rostock, University of Applied Sciences Wismar, SCISYS Deutschland GmbH, Raytheon Anschütz GmbH and TRENZ GmbH.

This paper is structured as follows: In Section 2, the required extensions to the GALILEOnautic modular system concept for realizing automated navigation with DENEB will be described. Explanation of different system components, such as communication module, trajectory module, and control concept is provided. In Section 3, a validation szenario for the DENEB demonstrator is introduced and discussed. The last section contains a conclusion and an outlook for future work.
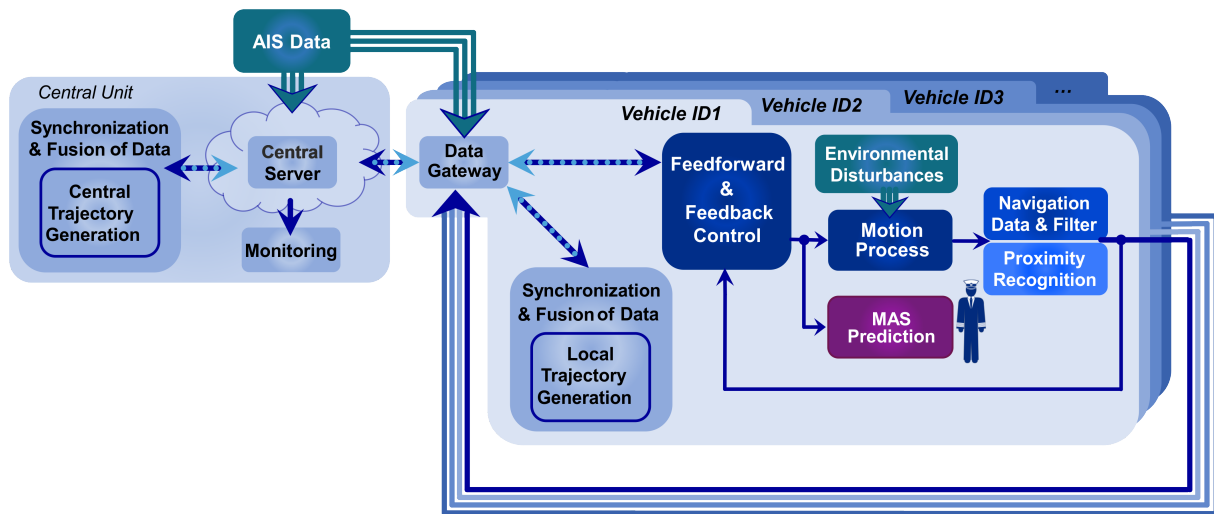
**Figure 1.** Modular concept of GALILEOnautic 2: Vessels can receive trajectories from the Central Server, or can calculate them by themselves.
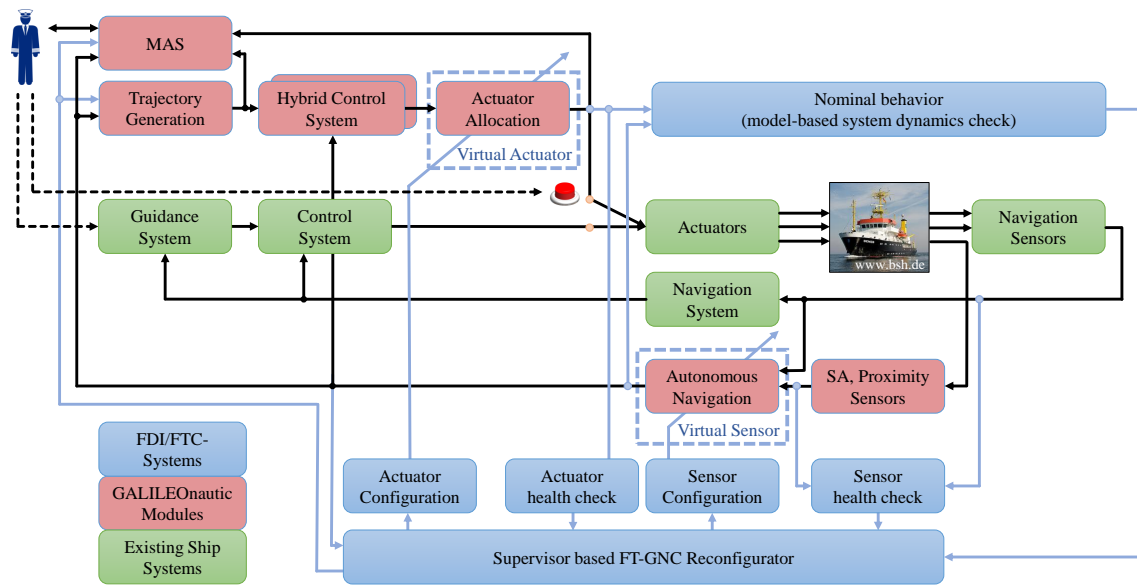
## 2. Methodology

### 2.1. Control System Concept

In [8] a hierarchical system consisting of a central computation unit (Central Server) and on-board applied control loops at each networked vessel has been introduced. This concept utilizes the Central Server for network-data processing, receiving it from the networked vessels and non-networked, but AIS equipped vessels. Network-delays are accounted, by synchronizing the hierarchical network on each layer via GNSS. The data is used to calculate optimal trajectories at the Central Server. These trajectories are provided to each networked vessel, and used as set-points for the on-board trajectory-control loops. This concept enables cooperative optimal maneuvering for the networked vessels, but requires a super ordinate omniscient unit like the Central Server.

For industrial near future application a system is required, which can operate autonomously even without this super ordinate unit, such that it can be integrated in a traffic, characterized by mostly manually controlled vessels. Therefore, to the original concept on the single ship level, an additional module for trajectory calculation is added. Figure 1 visualizes this concept. Here, parallel to the central data synchronization and trajectory generation, a local version on the ship level is shown. The difference to the central version is, that in the local case only the states of one ship, respectively the own ship exist, and other ships can only be recognized via AIS or the proximity recognition system. Finally a ship is able to act as part of a network while being independent from the network, if necessary.

On the single ship level, for automated reliable navigation, a framework of different autonomously running modules is necessary with guidance (see section 2.5), navigation (see section 2.3) and control (GNC) being the main components. GNC systems work like a closed control loop, where navigation provides optimal solution for vehicle position, velocities, and attitude calculated from equipped sensors; guidance generates the command values for the motion control system as well as serves as human-machine interface; and, control summarizes the modules for automatic motion control, with the aim to calculate the necessary control forces and torques generated by the propulsion and steering gears of the specific vehicle. A general overview about GNC functions gives [9]. Based on the commercially used modules for GNC of ships (green blocks in figure 2), additional functionalities have been developed within project GALILEOnautic (red blocks in figure 2) as described in [8]. Furthermore, the validation was

**Figure 2.** On board FT-GNC architecture towards autonomous ship operations applied to RV DENEB

carried out using two USVs, which had to manage an encounter szenario with an additional interfering manual controlled vehicle autonomously, as shown in [10].

On the bases of these developments, further investigations will focus on reliability and safety of automated ship operations as the final step towards autonomy, by adding fault tolerant guidance, navigation and control (FT-GNC) modules. The purpose of the FT-GNC system to be developed is to guide the ship automatically under all circumstances, even in cases of faults. Certain rules must be followed, restrictions must be respected, and the safety of the ship must be guaranteed. To achieve this, specific requirements must be met. To this end, work is being carried out to ensure consistent error handling in the ship handling process. The modules to be developed are part of the Fault Detection and Isolation (FDI) / Fault Tolerant Control (FTC) system (blue blocks in figure 2). These include determining the health status of the individual sensors and actuators, and comparing the behavior of components with expected nominal behavior based on simulations, and evaluate the deviations. A supervisor-based FT-GNC reconfigurator evaluates the information, adapts the sensor and actuator configuration if necessary and reports to the trajectory optimization and the nautical staff via the MAS Human Machine Interface (HMI).

The key technologies to put in practice autonomous ship operations focus on integration of the GALILEOnautic modules and the FDI/FTC parts shown in figure 2. Finally the integration into the RV DENEB will be done as explained in section 3, where parts are combined to the on board FT-GNC system.

*2.2. Communication Concept*

The communication concept of GALILEOnautic 2 is built upon the principles of its predecessor project, presented in [8]. Generally, all vessels are connected to a Central Server, which serves as main monitoring and control facility and distributes all data to their designated receivers. Since the project is meant to act in a harbor environment, mobile LTE network is used. This way 5G can be easily adopted as soon as it is established.

The main task for GALILEOnautic 2 communication concept is to improve the latency of data

transmission. The formerly used SOAP protocol (see [8]) wraps messages with XML, which leads to a non-feasible overhead in size per message. Therefore, the transmission protocol is replaced by a state-of-the-art M2M(machine-to-machine) lightweight messaging protocol, being Message Queuing Telemetry Transport (MQTT). MQTT is a publish/subscribe-messaging protocol, with a minimal overhead in message size. Clients connect to a broker, which is in charge of message delivery. Messages are sent and received via topics. Therefore, the client-broker is chosen for the vessel-Central Server concept of this application. Other protocols, like DDS could establish real Ship-2-Ship communication without a broker acting as a middleware facility, but every vessel then would need to send its data to every other participant in the network. With the broker, a vessel sends data once and the broker takes care of further operations. Clustering enables distribution of the workload to multiple brokers. Depending on the current data traffic,The cluster can be horizontally scaled. The Gateways on the vessels can now focus on monitoring and processing data, while the distributed broker-cluster delivers messages where they belong.

Using a broker, sender and receiver are not directly connected. For the project it is necessary to know if a vessel disconnects; and, even more important if such a disconnect was intentional or not. An intentional disconnect can be communicated by the vessels with a regular disconnect message. But for unintended disconnects we use MQTT's Last-Will-Testament feature. Once a vessel connects to the broker, it publishes a message, which is stored by the broker. This message is only distributed, if the connection between the broker and the vessel is interrupted unintentionally. All interested recipients will then get the message of the lost vessel.

### 2.3. Navigation Filter

For operation of real autonomous ships in a harbor environment robust, smooth, high accuracy and precise navigation information with high reliability is required. For this purpose in [18] a navigation filter providing 3D position, velocity and orientation, based on inertial navigation and aided by tightly coupled multiconstellation GNSS and Doppler-Velocity-Log (DVL) is introduced. It bases on Kalman Filter methodology. In order to increase accuracy of the states for the real vessel application, especially for automatic docking operations, the filter is extended by carrier phase processing. The filter will be able to process 40 satellites in parallel and therefore, in comparison to the 18 states from [18], the filter consists of up to 58 states in total, which are:

$$\mathbf{x} = \begin{bmatrix} \mathbf{p}^T & \mathbf{v}^T & \mathbf{q}^T & \mathbf{b}_a^T & \mathbf{b}_g^T & \mathbf{c}_b & \mathbf{c}_d & \Delta\Delta\mathbf{n} \end{bmatrix}^T \ , \tag{1}$$

where $\mathbf{p}$ is the 3D position in earth-centered-earth-fixed geodetic coordinates, $\mathbf{v}$ is the 3D velocity in the north-east-down navigation frame, $\mathbf{q}$ is the rotation quaternion, representing the rotation of the IMU bodyframe relative to the navigation frame, $\mathbf{b}_a$ and $\mathbf{b}_g$ are the bias estimates for the IMU accelerometer and gyroscope measurements respectively. Due to the processing of GNSS observable, and the unknown difference between GNSS system time and receiver time, the receiver clock bias $\mathbf{c}_b$ and the receiver clock drift $\mathbf{c}_d$ are estimated as well. $\Delta\Delta\mathbf{n}$ are the double difference ambiguities, required to describe the reference station aided double difference of the low-noise carrier-phase.

With the help of the new RTCM V3.3 format, this method allows a robust ambiguity estimation for Galileo and GPS multiconstellation, and therefore provides a high accuracy navigation solution. The tightly coupled architecture enables satellite selective algorithms to increase the integrity of the navigation solution. Based on Receiver Autonomous Integrity Monitoring (RAIM) Reliable Fault Detection and Identification (FDE) is introduced [19]. Furthermore, fallback layers are identified, to guarantee a navigation solution in each case, even though it is of a lower quality.

### 2.4. Vehicle Model and Model Adaption

The equations of motion for a rigid body moving in the horizontal plane with three degrees of freedom (namely surge, sway and yaw) can be written in component form as follows:

$$(\dot{u} - vr - r^2 x_G)m = X \tag{2}$$

$$(\dot{v} + ur + \dot{r} x_G)m = Y \tag{3}$$

$$\dot{r} I_{zz} + (\dot{v} + ur) x_G m = N, \tag{4}$$

where $m$ represents the mass of the ship, $x_G$ the longitudinal position of its center of gravity forward of the midships point and $I_{zz}$, its moment of inertia about the $z$-axis. The velocities in surge sway and yaw are respectively denoted by $u$, $v$ and $r$. The right-hand sides of these equations correspond respectively to the longitudinal and lateral forces as well as the torque about the $z$-axis. The forces and the torque are expressed as analytical parametric expressions following [16] and [17]. In the project GALILEOnautic, the parameters were identified for the few vehicles considered thereby using the nonlinear optimization library WORHP ([11], [12]). To this end some data were acquired during field surveys. The parameter identification was done only once at the beginning of the project. In GALILEOnautic 2, for the DENEB application, it is planned to perform online model adaptation in order to improve the accuracy of the ship models. In order to do so, data shall be constantly acquired on-board, compared to the corresponding model output and the model parameters adjusted consequently.

### 2.5. Trajectory Generation

In the context of optimal maneuvering, a trajectory is understood to be a time series of ship's states (position, heading, linear velocity, and rotational velocity, provided by the navigation filter) as well as the values of the ship's actuators (e.g., propeller revolutions per minute, rudder angle, etc.) accompanied by a timestamp marking its beginning. Within the project GALILEOnautic, such trajectories were computed at once for a group of networked vehicles as to minimize the overall energy consumption and the overall traveling time. The optimization approach was based on optimal control theory, and the solver used for the computation of such optimal trajectories was WORHP. For further details on this, see [10]. WORHP was already successfully used for optimal maneuvering in other applications such as AOCar ([15]), EnEx-CAUSE ([13]) and KaNaRiA ([14]). A few aspects distinguish the approach adopted in GALILEOnautic from that in GALILEOnautic 2 which is discussed here. In the former project, a single optimal control problem was created for the whole group of networked vehicles, and considered static (land, shallow water areas, buoys, etc.) and moving obstacles corresponding to other non-networked vehicles. Collision avoidance was achieved by modeling all objects by polygons, and considering their distances from each other and intersection areas. This led to successful results, but had the disadvantage of being computationally slow when many vehicles or obstacles were involved. In order to carry the basic approach closer to a near-future industrial application and to bring it on the DENEB research ship, this drawback shall be handled in two different ways. On the one hand, it is planned to group ships in clusters, each of them corresponding to a group of interacting ships. Therefore, optimal trajectories will not be computed at once for all vehicles within a single optimal control problem, but rather in parallel for each cluster. On the other hand, an entirely new approach is to be implemented where each ship is to be equipped with its own computational ability, making the ships independent of any central station. These two strategies are not to be implemented simultaneously, but rather as two independent options. For instance, a typical szenario would be a ship approaching a harbor, and computing its trajectory independently of a central station. Once it enters the harbor, it starts receiving trajectories from the central station and then switches from autarkic to cooperative mode.

In general, some other features are to be implemented. Firstly, a subset of the collision avoidance regulations (COLREGs) shall be abided by. These correspond to the regulations regarding ship encounters (e.g. overtaking, crossing, and head-on situations). Secondly, priorities shall be assigned to vehicles in order to better resolve encounter situations. Finally, the AIS history of ships with repetitive schedules (such as ferry ships) shall be used to generate reference trajectories in order to speed up the optimal trajectory computations.

### 2.6. Maneuver Assistance System

Today in safety-critical areas, the state of the technology is manual maneuvering by a nautical officer with appropriate training and often long-term experience. For the reliable application of automatic functionalities complementary to this manual control, the responsible officers must get the opportunity to accept the automation methods as a support of their own mental expert knowledge in daily routine to apply them later in critical situations. For the automatic project applications on real vessels, a Maneuver Assistance System (MAS) shall be introduced as a human machine interface between the human operator and automatic functionalities. The application of this MAS already starts with maneuver assistance to concentrate for easy handling, the most important information during the maneuvering process on one monitor. The essential function of MAS during maneuver assistance constitutes in overlaying the digital maneuver plan and the prediction of future ship motion originating from actual applied actuator settings. Thereby, the MAS supports the watch keeping officer in more precise and effective maneuvering, also in exceptional situations.

On the next level of maneuver automation, single automatic maneuvers shall be initialized by the human operator, such as automatic docking or collision avoidance. Similar to the activating of autopilot at open sea, the relevant requirements for the specified automatic maneuver have to be clarified, and complied in the moment of initializing. IMO regulations, captain's order and guidelines of shipping company are part of these requirements. In case of automatic docking, i.e. berthing for loading and unloading at the provided structure, the specific ship in size and dynamic motion behavior, the defined berth with tolerances, the characteristic of fender systems, and the resulting maximum final speed have to be known. In the presented approach, a recommended maneuver plan and geographical areas with different initializing requirements according to nautical algorithms will be determined. These algorithms include the motion states of the vessel in relation to the target states in berth position, such as heading angle, rate of turn or speed over ground. Figure 3 shows schematically the requirements for automatic docking maneuver. For initializing of an automatic docking, the MAS presents this scheme in the ENC and signals to the responsible officer whether the requirements are fulfilled. By initialization, the high-level trajectory optimization will calculate the berthing trajectory based on recommended maneuver plan and the current motion states of the vessel. By the predicted future ship motion in MAS, the officer assesses the automated maneuver strategy, and in an emergency, he could interrupt the automated control by manual maneuvering.

### 2.7. Proximity Recognition System

For a safe passage through the port or other safety-critical areas, the test ship shall be equipped with an environment observation system. Due to the size of the ship, several sensors have to be installed around the ship hull at exposed positions. The bow and stern of the ship are particularly important. According to current knowledge, 4 sensor systems will be installed on the research vessel DENEB. Each of these systems consists of a combination of LiDAR and RADAR sensor and will have a detection angle of 120 degree. With a range of up to 50 meters, possible obstacles can be removed sufficiently quickly. The individual sensor systems will communicate via WLAN with a central environment observation computer.The complete sensor data are synchronized and subsequently model-based fused. In harbor environment, the proximity recognition data

**Figure 3.** Schematic parameter overview for automatic docking

should be highly weighted in sensor data fusion because of its higher precision and reliability to determine the current motion states.

## 3. Experimental Validation Concept

### 3.1. Measurement Setup

In order to validate the developments discussed in chapter 2 of this paper in realistic environments they must be liaised with a state-of-the-art Integrated Navigation System (INS) and transferred onto an experimental ship. For those purposes the research ship DENEB (figure 4) of the German Federal Maritime and Hydrographic Agency (BSH) is planned. Due to its moderate size of about 51.9 m in length and 11.4 m in width at a draft of 3.45 m as well as due to its good maneuvering equipment with pump-jet and thrusters, the ship qualifies well for the aspired use cases to be tested. Due to its designated purpose as a research ship it is also well-equipped with above average navigation sensors and data management infrastructure compared to conventional merchant ships.Furthermore, it allows for installation of additional equipment such as camera and low-range radar equipment.

The ship also provides ample deck space to position a 10' standard container. In such a container, Raytheon Anschütz' integrated navigation system SYNAPSIS is installed on the research ship, and interfaced with the on-board sensors and actuators. SYNAPSIS consists of three INS workstations for ECDIS, Radar and Conning respectively; and, acts as the primary resource for data distribution. It also represents the user interface for the human navigator. As its standard features, SYNAPSIS already provides consistent sensor and data management throughout the entire system as well as a centralized status and alert management for the connected equipment. Due to its flexible system architecture, it is able to facilitate additional software and hardware components. In the context of the experimental validation setup for the GALILEOnautic 2 developments, SYNAPSIS thus constitutes the platform for the integration of the individual solutions described in this paper's second chapter. As a result, a holistic ship-board system is created that enables advanced functionalities for (semi-)automated navigation and maneuvering to be tested under real environmental conditions.

In addition to DENEB, the USVs MESSIN and SMIS of University of Rostock are used for evaluation. Figure 5 shows the two USVs and an inflatable. MESSIN is an agile catamaran with a length of 3.5 $m$, a breadth of 1.7 $m$. The navigation sensors include an IMU based on optical gyros, a DGPS and a DVL. The maximum vehicle speed is 4 kn. The podded drives are used for steering. The MESSIN will be equipped with proximity recognition and high accuracy navigation filter as introduced in the section 2.3

SMIS is a semi-submerged vehicle, whose hull is mainly under water. In addition, the main sections of the vehicle are flooded. It has a length of 4 $m$ and a width of 0.7 $m$. The navigation

**Figure 4.** Designated test vehicle DENEB of the German Federal Maritime and Hydrographic Agency (BSH).



**Figure 5.** USV vehicles and inflatable boat; Foreground: SMIS, Background: MESSIN [10]

sensors include a DVL, a MEMS-based IMU and a DGNSS. Since no proximity recognition will be mounted, it is the less intelligent participant of the network.

The inflatable boat is equipped with an AIS class B transmitter and therefore can imitate a non network participating, manually steered vessel; disturbing the autonomous cooperative traffic, and is recognized only by its AIS message and the proximity system of DENEB and MESSIN.

More technical details of the USVs can be found in [10].

*3.2. Use Case: Automated Navigation in Harbor*
In order to demonstrate the capability of GALILEOnautic concept to act in a network of vehicles providing their states to a super ordinate Central Server, telling the network participants where to drive, by submitting optimal trajectories as well as enabling a single vessel (DENEB) to drive autonomously through a harbor, a unique szenario is designed.
The requirements of the cooperative szenario are as follows:

- Demonstrate the capability of cooperative maneuvering with networked vessels by causing a collision avoidance szenario with at least three participants.
- Super ordinate trajectory planning taking care of fairway and infrastructure.
- It is visible that optimal trajectory planning reduces the amount of energy for the whole network, e.g. giving priority to the more heavy and less maneuverable vessel.

The requirements of the non networked DENEB szenario are slightly different:

- Demonstrate the capability of independently acting DENEB to do collision avoidance without receiving optimal trajectories from the super ordinate Central Server
- Show that potential collision partners are recognized with the proximity recognition system and AIS.

In order to visualize the differences of networked and independently acting DENEB, a unique szenario should be driven one time with DENEB as part of the network and another time with DENEB acting independently. A less optimal maneuvering of DENEB in the second case should be visible, e.g. more steering is executed.

Figure 6 shows the bird eyes view of the designed challenging szenario, fulfilling the mentioned requirements. Here, DENEB (red) drives down the Warnow on the fairway in the harbor of Rostock to its regular berth. At the same time one USV (yellow) leaves its berth to cross the regular path of DENEB. In addition a second USV (blue), coming from north crosses both paths.

## 4. Conclusion
This work presented the concept of a networked control system for maritime autonomous maneuvering. It explained the need of modular system which can be applied on the network level as well as on a single ship level, such that near future application in maritime mixed traffic, consisting of manual controlled, assisted, and autonomous vessels is enabled. The paper provided an overview of the required modules: Reliable high precision navigation, a fault tolerant controller on the ship level, and a reliable trajectory planning, which is tolerant against model errors.

The paper discussed a reasonable design for a szenario, which can demonstrate the capability of the whole system to control a real ship in collision avoidance szenarios. The szenario design takes care of presenting capability of the ship: acting cooperatively with other ships, by communicating with a Central Server, planning the harbor vessel traffic; and on the other hand, acting independently, without contact to this Central Server.
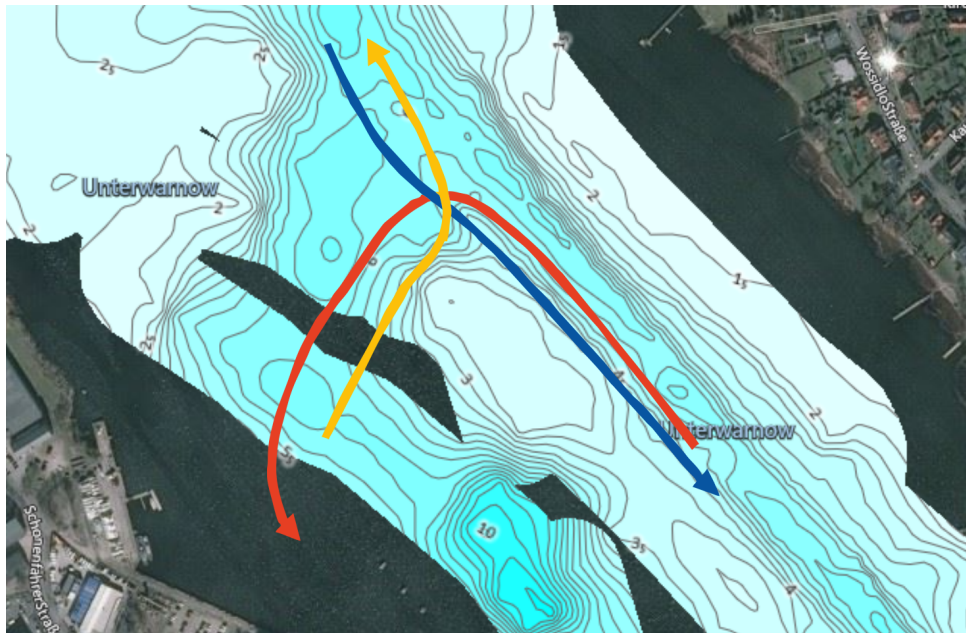
## 5. Acknowledgment

**Figure 6.** Red: DENEB, Yellow: USV 1, Yellow: USV 2. Szenario which will be performed with DENEB in autonomous, cooperative and in autonomous, independently operating mode, without contact to the Central Server. Map Data: ©2019 C-MAP

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