“PREParE SHIPS” for Automated Ship Passages by Modern Decision Support Tools by Exchanging Future Positions

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Abstract. Misunderstanding the intentions of other vessels is one of the most common causes of ship collisions today. Such misunderstandings are particularly dangerous during navigation in restricted areas, such as fairways, port areas, and inland water ways, and may be exacerbated with the introduction of unmanned vessels. To ensure safe operations, the understanding of the intentions and future positions of manned and unmanned vessels, the PREParE SHIPS project is creating a system capable of determining a ship’s position with high accuracy, predicting its future positions, and communicating the current and future positions. The positioning sub-system combines the signals of Galileo and EGNOS, EGNSS and SBAS respectively, with land based RTK corrections, providing a positioning accuracy of centimetres. Furthermore, by taking advantage of Galileo’s authentication features, the positioning system provides enhanced security measures against spoofing attacks. The prediction sub-system will use a ship dynamic model and machine learning to predict the future positions of the ship and improve said predictions with time, while the communication sub-system will broadcast the prediction through VDES ship2ship and ship2shore. PREParE SHIPS will improve the navigation and handling of ships, through high accuracy positioning and dynamic predictions, as well as reduce the risk of ship collisions, through the communication of present and predicted future positions. PREParE SHIPS is expected to increase safety and efficiency significantly and will be the base of future autonomous operations and standardisations.

1. Background

One of the main topics in research regarding autonomous shipping and navigation is collision avoidance and the challenges related especially to the navigational parts of COLREG (collision avoidance regulation), including Rule 2, 8 and 17. Most of the research topics here are focused on sensing and interpretation of sensor information, partly even perception, but little is done to ensure that ship2ship and ship2shore communication is enhanced to solve many of the challenges [1]. One of the exceptions is possibly the H2H project, which looks mainly at communication of relative position. By getting to know the intentions of manned or unmanned ships in the upcoming minutes and seconds,
allows for better decision making on all vessels and will solve one of the main challenges of today’s seafarers when it comes to ship collisions, a common situational awareness [2]. Accident statistics by a.o. EMSA are describing that collisions and loss of control are the dominating event types reported to European authorities. [3] The specific international rules on Prevention of Collision expressly or implicitly refer to the importance of situation awareness. Rule 5 (Look out) and Rule 6 (Safe Speed) are very good examples emphasizing on “Prevailing Circumstances and making a full appraisal of the situation” or rule 7 (Risk of Collision) requires the OOW “not making assumptions based on scanty information” and also paying attention to “Prevailing Circumstances” or Rule 19 (Conduct of Vessels in Restricted Visibility) which requires “Every vessel to proceed at a safe speed adapted to the prevailing circumstances and conditions”. [4]

Figure 1: Levels of autonomy in shipping with examples as derived by the PREParE SHIPS project (partly adapted from OICA’s Levels of Automated Navigation, based on SAE J3016)
domain; (3) analyzing and visualizing Technology Readiness Level (TRL) of analyzed systems. Bibliometric methods are utilized to depict the domain of onboard DSSs for operations focused on safety assurance and accident prevention. The results indicate that there are relatively many developments in selected DSS categories, such as collision avoidance and ship routing. However, even in these categories some issues and gaps still remain, so further improvements are needed. The analysis indicates a relatively low level of technology readiness of tools and concepts presented in academic literature. This signifies a need to move beyond the conceptual stages toward demonstration and validation in realistic, operating environments.

There are various approaches to describe the development towards more autonomy in navigation, where decision support tools will make higher automation feasible in the short and long term, one example derived in the PREParE SHIPS project context is shown in Figure 1. Dynamic Predictors have been around for some time. Basic predictors would only use dead-reckoning, i.e. ship position, speed, COG (Course over Ground) and heading as sources of information, while more advanced can be based on environmental as well as ship-internal factors such as wind, rudder set and is values, bow-thrusters, etc. While most of the big suppliers provide basic predictors, there is a need of considering more sources of data to give more accurate predictions.

Machine learning is an application of artificial intelligence (AI) that provides systems the ability to automatically learn and improve from experience without being explicitly programmed. Although machine learning has already been used in numerous branches of the digital world, it is adaptation to maritime industry has remained limited so far. This could be partly explained to the low level of integration of ship system and connectivity of ships. Standardisation of data collection techniques is another barrier. As the maritime transportation requires smart tools, application of the machine learning provide utmost benefits for sustainable transportation. [8]

Black models have been challenging in certain applications in the maritime domain for applications such as fuel savings. Simulations models have been used for a long time but have limits in capturing all operating conditions. Grey models seem to be a good trade off combining the advantages of both sides.

2. Making use of current industry developments
There are game changing developments ongoing within the shipping industry and the positioning industry. Examples are EGNSS services for positioning with high accuracy and integrity, VDES as the next generation AIS, and the S100 suit of standards for the accurate information of water depth, currents and Under Keel Clearance (UKC). The project builds its navigation decision support system within shipping on this development which contains the following:

1) EGNSS resilience positioning:
The possibility to dynamically predict future positions of other vessels requires of precise positioning solutions by Galileo receiver/transmitter PPP and HAS enhanced with RTK correction.

2) Real-time dynamic predictor:
Use data learning in order to obtain information of earlier ship behavior to exchange near-future positions with vessels in the vicinity and VTS centers (Vessel Traffic Services) to increase safety and improve decision making.

3) Ship-to-ship / ship-to-shore interaction:
In order to define the correct requirements for PREParE SHIPS combined positioning solution, a collaborative automated vessel application is defined and developed. The vessel application will rely on the high availability positioning solution and use it to couple its various navigational systems with ship2ship/ ship2shore and aggregate information received from other connected vessels by using the next generation AIS - VDES.

4) Geo-fencing:
Implement and demonstrate a fairway geo-fencing with high precision positioning, utilizing various data sources (e.g. wind and current) as well as a traffic monitoring and predicted positions
so it can allow for safe decisions based on robust data. This means that ‘PREParE SHIPS’ also will implement perception layer sensor fusion that uses information collected historically in similar conditions based on machine learning-hybrid models.

The picture below shows the flow of information that will be the enabler for PrePARE Ship’s Decision Support System.

![Flow Diagram](image)

**Figure 2**: The PREParE SHIPS scope, modules and total integration into ship system

The objective of the project ‘PREParE SHIPS’ is the development and demonstration of a collaborative resilience navigation solution. It aims to develop and enhance existing software solutions by exploiting the distinguished features of the Galileo signals as well as combining it with other nautical information on internal as well as external parameters and sensor technologies.

### 2.1. EGNSS development

There are several techniques for augmented GNSS that can be used in order to achieve a higher precision positioning like e.g. DGPS, PPP and RTK. In the PREParE SHIPS project we will develop methods in order to use N-RTK for positioning of ships. As this technology requires land-based reference stations it will focus on positioning in fairways and ports. The reference stations are used to calculate Virtual Reference Stations (VRS) that are placed at suitable locations in the fairway and port. Lantmäteriet, the Swedish mapping, cadastral and land registration authority, is responsible for the N-RTK infrastructure in Sweden called SWEPOS. Based on the physical reference stations (PRS), SWEPOS provides reference data for the locations of the VRS and distributes the reference data to GNSS receivers typically via an Internet connection. In PREParE SHIPS, the N-RTK reference data will be transmitted to ships in fairways via VDES base stations. RTK service area is limited to the locations of PRS:es, therefore PEPaRE SHIPS will use PPP when N-RTK is not available. The N-RTK corrections shall have an accuracy (in positioning domain) of at least 2 cm in at least 95 % of the time if the ship located inside the coverage area for N-RTK, and the PPP corrections (which in the future will be available through the Galileo HAS service) shall have an accuracy of at least 20 cm in at least 95 % of the time. In the Prepare Ship project, PPP (Precise Point Positioning) are developed and tested increasing the understanding of how one can fuse/ integrate RTK services with it. Also, the utilization of correction integrity data in the project is beneficial for increased automation of shipping.

ANavS will provide the Multi-Sensor, Multi-Frequency and Multi-Constellation GNSS receiver system for PREParE SHIPS. The system will differ in three aspects from a standard Multi-Frequency and Multi-Constellation GNSS receiver: First, it will implement an innovative VRS RTK algorithm,
that processes Virtual Reference Station (VRS) RTK corrections from a grid of VRSs concurrently instead of using RTK corrections from a single VRS. Second, the ANavS positioning system will determine also a PPP solution being initialized by the RTK solution and will perform an automatic handover between the RTK and PPP solution. The third contribution of ANavS will be the integrity analysis of the RTK/PPP solution. The main objective of these contributions is to enhance the accuracy, robustness and integrity of the positioning system, which is the basis for the predictor.

2.2. VDES development
The dynamic ship predictor requires substantial communication bandwidth in order to sustain accurate and timely predictions ship to ship. AIS cannot deliver this bandwidth so the research will be performed using VDES as communication channel. VDES is the next generation AIS with up to 32 times the bandwidth compared to AIS. The VDES terrestrial link denoted VDE-TER link ID 19 can deliver 702 bytes per slot after FEC (Forward Error Correction) and the project has selected this link as the primary link for the dynamic ship predictor research. An alternative, but discarded solution, could be VDE-ASM with link ID 5 that can deliver 36 bytes after FEC per slot. There are 2250 slots/minute in the AIS/VDES communication system with 37.5 slots per second.

With VDE-TER link ID 19 the dynamic ship predictors “payload” limit has been set to 650 bytes/slot as an initial assumption and the rest of the bytes (52) have been reserved for link management.

VDE-TER link ID 19 is the link in VDES with the highest bandwidth using 16 QAM modulation scheme. Since VDE-TER link ID 19 will be used at comparably short ranges ship to ship, a few nautical miles, the physical communication link will be very reliable since it also includes FEC.

If the dynamic ship predictor is broadcast every second as an example this will utilize \( \frac{1}{37.5} = 2.67\% \) of the total VDES bandwidth in that cell. The work with the VDES predictor exchange follows the standard development at IALA level \([5]\).

2.3. Integration and display of S-100 Products
The ECDIS kernel i.e. the platform on which ECDIS functionality is built upon will be able to support the following new data products according to the S-100 product standard.

2.3.1. S-101. The ECDIS kernel and ECDIS GUI will support the use and presentation of nautical charts following the IHO data product specification S-101 Electronic Navigational Chart (ENC).

S-101 is the new product specification for Electronic Navigational Charts following the S-100 product standard that will replace the current ENC specification S-57. S-101 follows the same general structure and principles as S-57 but makes use of the expanded opportunities of the S-100 product standard to add new capabilities to the specification.
The major new capabilities include Machine readable catalogues (allowing dynamic changes to chart features and portrayal over time), Complex attributes (allowing feature attributes to be composed of a structure of sub-attributes), Update features (allowing chart producers to clearly indicate important updates to the chart), Cartographic features (allowing chart producers better control over chart text placement) and Production system attributes (allowing chart producers to provide ECDIS systems with precalculated conditional symbology procedure information, speeding up the chart portrayal).

The S-101 data product will be used for chart portrayal in the PrePARE Ships project as shown in Figure 2.

2.3.2. S-102 Bathymetric Surface product. The ECDIS kernel and ECDIS GUI will support the use and presentation of nautical charts following the IHO data product specification S-101 Electronic Navigational Chart (ENC). The primary purpose of the bathymetric surface product is to provide high resolution bathymetry with special resolution down to meter level, in gridded form, as a supplementary layer to an S-101 ENC within an ECDIS. Portrayal of S-102 bathymetry with other S-100 compliant products is intended to support safe passage, precise berthing and mooring, as well as route planning of marine vessels. The secondary purpose of a bathymetric surface product is to provide high resolution bathymetric data for other maritime applications.

The S-102 bathymetric surface product is a digital elevation model which represents the seafloor in a regular grid structure. It will be used as an additional overlay in the ECDIS. The product specification is based on the IHO S-100 framework specification and the ISO 19100 series of standards. It comprises the content model (spatial structure and metadata), encoding structure, portrayal and exchange file format for a bathymetric surface product.

S-102 data product will be used for two main purposes in the PrePARE Ships project:
1. To determine GO and NO-GO areas with better accuracy than currently possible with current ENCs.
2. To improve the output of the Predictor System by providing more detailed information of underkeel-clearance, i.e. the distance between the hull and the seafloor, and thus improving the estimation of bank, squat, and channel effects.

2.3.3. S-129 Under Keel Clearance Management (UKCM). The primary purpose of the S-129 UKCM Product Specification is to provide a standard for encoding of information a ship needs to determine the time periods when there are suitable tidal conditions for it to transit a UKCM operational area. The UKCM data will be offered by service providers as a UKCM service. Based on the maturity of the standard, the data that can be derived from the S129 could be used in the system for more precise Underkeel Clearance Management based on the dynamic predictor.

3. The PREParE SHIPS Predictor

The Predictor System predicts the future positions and attitudes of the vessel in at least 1 second timesteps and with an indication of prediction accuracy at a minimum frequency of 1Hz. The predictions are based on the current position and attitude, accelerations, ship propulsion settings and environmental conditions. Figure below illustrates the content of the prediction. The predictions and accuracy indicators are used by the ECDIS to:

- Create a visual representation of the predictions and display them in the GUI.
- Create a message to be sent through VDES.

The contents of the datastore are initially defined during the setup up of the predictor system. The setup requires the vessel parameters and the initial settings for the prediction system. Once both are defined, the initial coefficients for the Dynamic Predictor are generated by Dynamic Predictor and the Coefficient Tuner and saved in the datastore.
The Dynamic Predictor module takes the sensor data and voyage data as inputs and returns a prediction of the future position and attitudes of the vessel as defined by the system settings. The predictions are calculated using the coefficients in the data store.

The Prediction Monitor module takes the predictions as input and returns them with a measure of quality unless they are below an absolute minimum safety value, if so, the Prediction Monitor outputs an error. The measures of quality are the result of:

- a learned assessment of the accuracy of the Dynamic Predictor module under the current and future conditions (e.g. deep or shallow waters) and,
- a continuous comparison of the recent predictions against the corresponding sensor data.

**Figure 4:** Real and predicted position of a ship.

**Figure 5:** The PREParE SHIPS system topology with the Prediction System in the center
The learned assessment of the accuracy of the Dynamic Predictor is the result of training a machine learning algorithm to predict the accuracy based on previous performance. The Coefficient Tuner, as mentioned, generates the initial coefficients for the Dynamic Predictor during the setup of the system. After the setup, the Coefficient Tuner continuously tunes the coefficients to improve the predictions of the Dynamic Predictor. The tuning of the coefficients is done through a machine learning algorithm. Class approval of self learning, improving or automated systems are a matter of current research and have a direct impact on the functional safety requirements. As the predictor system and its continuously improvements are limited by physical limits of the grey model, these barriers are still able to be overcome.

Further detailed descriptions of some of the essential elements of the Predictor System are given in the following subsections.

3.1. Adaptive Learning

The Adaptive Learning Module improves the prediction over time by tuning the Dynamic Predictor parameters. It compares previous ship positions with its predictions and then minimizes the deviation. This is done by performing tests using new parameters. If new predictions are closer to the actual positions, the new parameters will be used.

The new set of parameters are created by add/remove a change factor to each parameter element. Assuming linear independence of the elements, each set needs only to change one element at a time. Thus, the total number of “interesting” permutations is only two times the number of elements.

To assure that the new parameters gives better predictions, the position/prediction subset on which the test is performed, needs to represent all possible environmental conditions. To assure stability, the new predictions shall not differ too much from previous. The adaptive learning is based on suitable machine learning algorithms.

The figure on the next page is the use case diagram for the Prepare System. The diagram shows five types of actors:

- Officer On Watch onboard own ship (OOW): The target user of the Prepare System.
- Prepared target ship: A ship with a fully functional Prepare System that is within the VDES range of the own ship.
- STM target ship: A ship with an ECDIS capable of sending and receiving monitored routes through an AIS or ASM message according to the STM’s S2SREX specification.
- Multi-GNSS: Multiple constellations of Global Navigation System Satellites (GNSS) sending signals for position fixing.
- Lantmäteriet RTK/PPP: Lantmäteriet’s service of RTK and PPP corrections for GNSS signals.

As a list, the use cases in the PREParE Ships project, ensuring safe hybrid navigation, are:

- Determine own ship’s present position.
- Display own ship’s present position.
- Predict own ship’s future positions.
- Display own ship’s predicted positions.
- Broadcast own ship’s monitored route.
- Receive target ships’ monitored routes.
- Display target ship’s monitored routes.
- Broadcast own ship’s predicted positions.
- Receive target ships’ predicted positions.
- Display target ships’ predicted positions.
- Display warnings of possible conflicts between own ships and target ships.
- Receive target ship’s monitored routes.
3.2. Based on Functional Safety Analysis

The project has made use of established methods to define suitable SIL levels for the PREParE SHIPS concept as a basis for the design of all components and software. Functional safety as such, is a concept applicable across all industry sectors and applied more and more in the shipping domain. The trend towards more complex technology used for safety-related systems is enabled by the functional safety approach ensuring that the safety-related systems will provide the necessary risk reduction measures which are required to achieve safety for the equipment. The dynamic predictor module and all other related systems required to make the PREParE SHIPS system working, are computer based and are performing safety functions (hardware / software / other measures).

To enable the design-, development-, verification- and validation of the system, the functional safety was performed by support of the use cases and application scenarios.

The first step was to conduct a Hazard Analysis and Risk Assessment (HARA) for the PREParE SHIPS concept deriving high level safety requirements. Different scenarios (regarding travelling ships) were identified and the dimensioning (worst-case) scenario was selected as input for the risk assessment. Two safety functions - as described below - were also identified based on the Prepare Ship system architecture and assigned with the safety requirements derived from the HARA. The standard

**Figure 6:** Use Case diagram for the Prepare System including present/ current position and future positions. Officer on watch placed on «own» ship.
used as reference for this analysis was IEC 61508:2010. The result of the analysis showed that the two identified safety functions became assigned with strict safety requirements (SIL 3). A safety related electric/electronic or programmable electronic system that shall implement safety functions which must fulfil SIL 3 implies that each module included in the system, which plays part in implementing the safety functions, must fulfil SIL 3 themselves. It should be noted that IEC 61508 is an extensive standard in seven parts. However, IEC 61508 provides some flexibility for the developer on how to achieve SIL 3 by selection of different design patterns, but some summarized examples of common measures for SIL 3 are:

- **Management and development processes.** Usage of semi-formal notation and methods for system design specification. Strict following of the safety life cycle, including verification/validation and functional safety assessment with a high degree of independence.
- **Hardware.** Usage of highly reliable electric/electronic components only; Usage of two-channeled architectures (hardware redundancy) for all sensors, logic resolvers and final elements; No usage of commercial off the shelf products unless developed in accordance with IEC 61508.
- **Software.** All software is developed and tested by strictly following the V-model applying all applicable methods listed for SIL 3 in IEC 61508-3. No use of pre-existing software elements unless developed in accordance with IEC 61508 or supported by extensive statistical background data from use in an identical application (such as commercially available operating systems, communication stacks, etc.).

This activity can only be performed by the developers of the different modules composing the PREParE SHIPS system and who have knowledge of the modules detailed design.

The security analysis identified 10 threats, where two of those were of a criticality such that they should be further analysed for their safety impact:

1. Spoofing of trajectory data. If an attacker sends a fabricated trajectory data and lie about a ship’s intended route, this may lead to a collision as the OOW may take wrong decisions based on this.
2. Replay of trajectory data. If an attacker re-sends previous trajectory data, the data displayed on the display does not reflect the current position and intended route, thus, may lead to a collision as the OOW take wrong decisions based on this.

### 3.3. Providing an advanced decision support system

The decision support system will be built on a Type Approved ECDIS that combines precise positioning from the Galileo based Global Navigation Satellite System including Real Time Correction Data with a Dynamic Ship prediction model supported with high fidelity S-100 Chart Data products. The system will allow interaction with other ships through the VDES communication module allowing sharing of Ships routes and ship predictions.

The ship prediction model will use available sensor and chart data to predict the future movement of the vessel, and machine learning will be used to adapt the prediction model to the characteristics of the vessel. The decision support system will portray predicted future movement of both own ship and received predictions from other ships.

Effective navigation, ship handling, and conflict resolution require the prediction of the future events to come, as well the possible results of different courses of action. Predicting the future movements of a ship can be challenging. A navigation officer may find it difficult to consider the effects of wind, currents, shallow water, trim, and several other factors on its mental model of the ship’s response. If so, the control of the ship is reactive instead of predictive, leading to less precise movements. Clearly then, a prediction of the ship’s future movements that included transient factors would be of great help. The system developed by the PREParE SHIPS project will include a sub-system capable of predicting the future positions of the vessel through a dynamic vessel motions model (see Figure 6). Because all ships respond differently, the dynamic predictor will leverage
machine learning models to tune and improve itself continuously. With time, the dynamic predictor
will provide accurate predictions of the ship movements in the most challenging conditions.
Furthermore, for conflict resolution, the predictions of future movements will be broadcasted through
VDES and displayed on the ECDIS of compatible vessels. Doing so will provide a clear picture of the
conflict situation and how its development continues if no action is taken, supporting the selection of
actions that will avoid a collision. Overall, the dynamic predictor and the communication module will
provide an advanced decision support system.

![Figure 7: The Dynamic Ship Predictor](image)

### 4. Discussions and Conclusions

The Ship Decision Support System combines standard information in ECDIS such as Electronic
Navigation Charts (ENC), sensor data, AIS and ARPA overlay with state-of-the-art technology
developed in the framework of PrePARE Ship project. Position and attitude data determined through
the Galileo Global Navigation Satellite Service, Ships next route leg and predicted path both for own
ship as well as close ships where route and prediction is transferred via VDES, Bathymetric Surface
data and up to date Under Keel Clearance data to give the officer of the watch a better understanding
of where she or he can navigate. This all together will provide a situation display and decision support
system allowing officer of the watch to look ahead and understand how the navigation situation will
develop in the nearest future.

Besides a decreased risk for collisions, this also means additional benefits in the form of a more
energy effective maneuvering of the vessels, something which can also reduce the environmental
impact of shipping in line with IMO’s targets. The project will present and validate a positioning
solution. This will be done through development of existing software using Galileo-signals and
combining it with nautical information regarding internal and external parameters and sensor
technology.

The project has finalized the technical requirement specification and is currently in the state of
technical development which will be followed by component testing and integration testing during
early 2021 as well as demonstration on commercial ships by the end of 2021. The project aims
therefore to reach TRL levels corresponding to prototype level, while components will reach market
maturity. Challenges the project tries to solve relate to the project market implementation are related to
the standardization and rulemaking in the maritime industry.
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