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TOWARDS IMPROVING OPTIMISED SHIP WEATHER ROUTING

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ABSTRACT

The aim of the paper is to outline a project focussing on the development of a new type of ship weather routing solution with improved uncertainty handling, through better estimation of ship performance and responses to sea conditions. Ensemble forecasting is considered to take into account the uncertainty levels that are typical of operations in a stochastic environment. Increased accuracy of weather prediction is achieved through the assimilation of real-time data, measured by an on-board monitoring system. The proposed system will allow smooth integration of short-term Decision Support Systems for ship handling in dangerous or peculiar situations with long-term Decision Support Systems for weather routing. An appropriate user interface is also a critical part of the project and it will be implemented in a commercial Electronic Nautical Chart environment. A prototype of the full system will be installed and tested on a commercial vessel in regular operations and under real environmental conditions.

Keywords: weather routing, Decision Support Systems, uncertainty handling, ensemble forecast

INTRODUCTION

Improving safety and navigation performance is a prime challenge in the current global economic scenario and this strongly relies on the ability of the shipping industry to efficiently move feedstocks and goods. Increased attention to seakeeping, since the early stages of design, has resulted in encouragingsafety reports and more competitive transportation [10, 13]. Moreover, the urgent need to reduce emissions has boosted research into advanced methods for improving a ship's operational efficiency.

Ocean-going vessels are required to operate all year round, often in weather conditions that are far from calm. Over the years, a strong research effort has been dedicated to the development of techniques for investigating the most favourable paths and speed profiles, depending on the expectedweather conditions, in order to efficiently accomplish this. These methods are generally referred to as weather routing (WR). The first approach to WR was the isochrone method [20], proposed for manual usage, based on geometrically determined and recursively defined time fronts (isochrones). Computer implementations of the method have been developed over the years (e.g. [14]). The isochrone method has a single-objective and, therefore, limited possibilities for handling dynamic constraints. The other approaches to WR include dynamic programming for a grid of points (which was proposed by [26, 56]) and in 3D (by [5, 38, 58). Graphic algorithms have also been successfully adopted, typically adopting the A* or Dijkstra algorithm, as presented in [23, 29], for motor-driven vessels, and in [61, 62], for sailing vessels.

The importance of accounting for multi-objective solutions to guarantee an adequate balance between safety and costs was raised at an early stage. The issue was initially overcome by aggregating the objectives to a single criterion (as in [49]) or maintaining the most promising solutions encountered during the search process (as proposed in [41]). In recent years however, the application of dynamic programming and evolutionary algorithms has become more popular, allowing the objectives to be kept separated and offering a set of favourable solutions, in the form of a Pareto-optimal set, from which the final route can be selected. A purely mathematical approach to such optimisation was proposed by [15, 24, 43, 53]. Efforts made by the industry to integrate more advanced route optimisation procedures in the daily operations of seafarers are also described in [6, 50]. More complete reviews of the weather routing methods proposed in the literature are provided by [7, 33, 40]. The results from the various types of weather routing systems showed that ship traffic has main routes for ocean crossings [51] and for coastal navigation [39] but bad weather is avoided whenever it is deemed appropriate [9] and ships deviate from these routes. Thus, the effects of the weather that ships experience in their lifetime must be incorporated into their design [54, 55].

Although remarkable progress has been made, shipping is still largely weather-dependent, especially with regards to schedule, reliability and control of fuel consumption and emissions [12]. One of the main reasons is the stochastic behaviour of oceanic and atmospheric processes, making the weather forecasts subject to significant uncertainty. Nowadays, this is in great part due to inaccurate or missing information regarding the initial conditions, rather than numerical limitations. The effect of this is a reduction in the accuracy of the estimation of effects that are affected by the predicted weather conditions [27], such as ship motion and added resistance.

The recent ROUTING project was initiated with the objective of overcoming the limitations of the currently available systems. The project aims to develop a prototype for a brand-new, on-board solution for ship weather routing which is able to handle the uncertainties from weather forecasting during ship voyages and to conduct continuous updates of local weather predictions, based on the measurements and modelling of sea-ship interactions. The goal is achieved by taking into account uncertainties in the prediction of the sea-states the ship will sail through and the adoption of ensemble forecasting, as described below. Moreover, a complete monitoring system (installed on-board) will allow the collection of information about ship behaviour and performance in navigation and estimation of the sea conditions encountered along the route by exploiting the ship-buoy analogy [16, 31]. The latter will eventually be assimilated in the forecast [17] for a real-time update. Details on the methodology adopted are described below, including an overview of the system design, the integration with commercial ENC-class software and a suitable user interface, to facilitate the officers' interaction with the software.

This new approach is expected to result in a reduction of long-range ship transportation costs (i.e. fuel consumption), improved schedule-keeping and improved safety and security of the crew, cargo and the ship itself. An in-service experience is planned for the last part of the project, in order to test the system under real operational conditions and analyse the technical requirements, as well as its capability of being smoothly integrated into on-board operations, in order to effectively predict the expected impact on shipping.

DEALING WITH UNCERTAINTIES

For all weather-routing methods, the main objectives are the optimisation of safety and cost. These factors are related to the ship motions that, besides compromising safety, may impose voluntary speed reductions and affect the efficiency of the propulsion system, in terms of fuel consumption and attainable ship speed. On the other hand, for a given ship, motion and efficiency are strictly related to the weather conditions in which it is navigating and, thus, to the uncertainties associated with their prediction. The direct consequence is that a reliable route optimisation primarily requires a trustworthy weather forecast as well as an accurate ship model, in order to be able to assess the behaviour in any given sea-state. While results from classical ship models are largely considered as being satisfactory for operational purposes (particularly with regards to ship motions), this may not be the case for weather forecasting. Even state-of-the-art mathematical models are affected by uncertainties in the initial conditions.

To cope with this issue, ensemble forecasts are often generated[2, 22]. These consist of several runs of the same model (or different models in the case of multi-ensemble), each with some deviation in the parameters defining the initial conditions, according to their probability distributions [57]. In this way, the output of the forecast can be given in a probabilistic manner, namely the probability distribution of the predicted parameters (e.g. the significant wave height) or, more commonly, the average values and the corresponding confidence intervals or standard deviation, the latter typically increasing with the time-lag of the forecast.

Uncertainties can also be estimated when ensemble forecasts are not available. A recent study conducted by ECMWF [4] provides a quantitative assessment of the uncertainties from different forecast centres. It can be seen that a scatter index (standard deviation of the error divided by the mean value) of below 0.3 is realistic up to five days ahead.

The ROUTING project aims at dealing with the uncertainties related to weather forecasts in two ways: by continuously updating the forecast and by assimilating the information relative to the uncertainties in the optimisation procedure, thus propagating such information until the evaluation of the objectives and the constraints driving the optimisation. For the latter, two different approaches are currently being researched, i.e. the "probabilistic approach" and the "ensemble approach".

PROBABILISTIC APPROACH

Probabilistic methods are typically adopted in the structural reliability analysis of ships [36, 45, 46]. These are used to define the safety factors to be used in the Rules of Classification

Societies for ship design [11, 19]. Applications to short-term periods, more compatible with the time interval of ocean passages, can be found in [45, 47]. With regards to the maritime industry, risk assessment analysis is often applied to accidents (for instance, through Bayesian networks [3, 25, 48, 59]) or Formal Safety Assessment (FSA) approaches [18]. Reliability analysis is also adopted for the assessment of the probability of on-board human error.

A peculiarity of route optimisation is that safety and efficiency depends on several factors (e.g. roll amplitude, local accelerations, slamming, propeller racing, etc.) and so the joint effects have to be estimated [8]. The aim is to develop a probabilistic risk assessment model for the ship's journey that allows for the definition of a reliability index, based on the probability of all potentially dangerous events occurring. Following the classical method for evaluating ship operability [8], a limit state can be defined as the line in the H_S–T_P graph, above which the ship cannot operate due to the exceedance of at least one seakeeping criteria (see Fig. 1). This concept can easily be extended to include different headings, in which case the limit state assumes the dimensions of a surface.

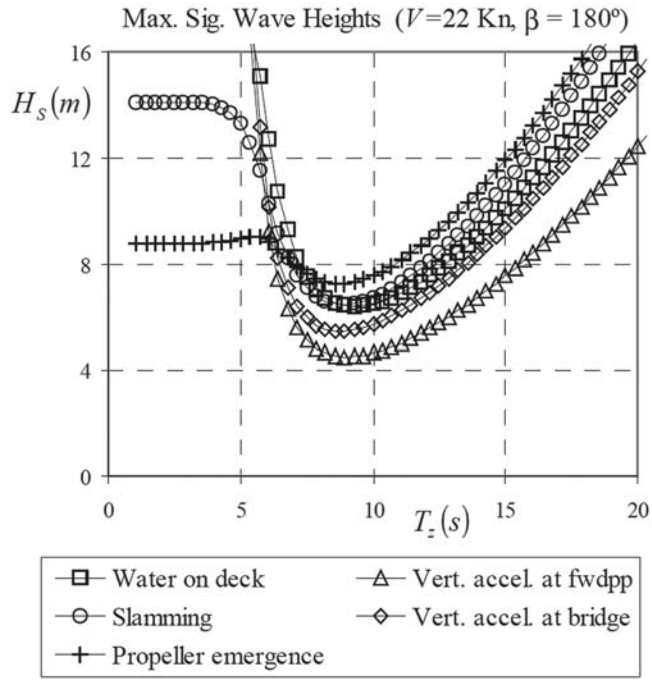

Fig. 1. Example of the maximum allowed wave height for different seakeeping criteria (from [8])

Contrary to traditional methods, and because weather conditions cannot be deterministically estimated, the sea-state (described by the H_S, T_P duplet in Fig. 1) that the ship will face will be represented by a point and contours of decreasing probabilities will be centred on the mean forecasted conditions. An example is given for a forecasted sea-state in Fig. 2, where H_S = 3 m and T_P = 6 s, with standard deviations of 0.4 m and 0.1 s, respectively.

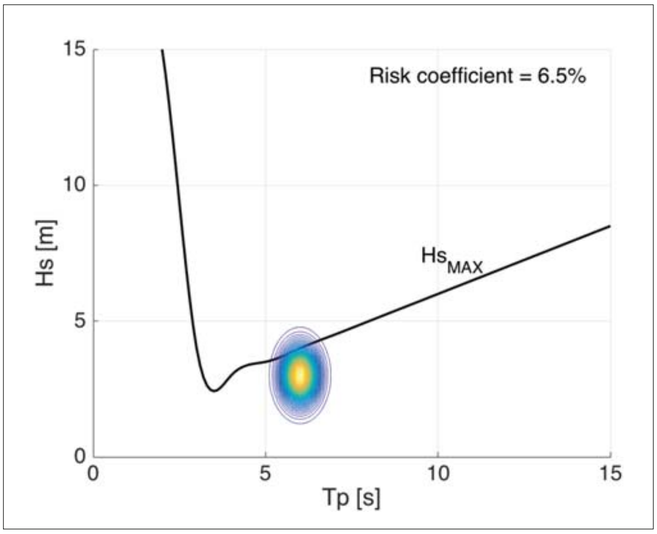

Fig. 2. Example of the application of the probabilistic operational risk assessment method. Black line refers to the maximum allowed H_s and the contour indicates the probability distribution of the forecasted sea-state

In Fig. 2, the black line indicates the maximum allowed wave height for the ship to be operable, meaning that all of the seakeeping criteria are respected, while the contour shows an estimation of the probability distribution of the predicted sea-state, assuming a Gaussian probability density function. The risk coefficient that reflects the probability of failure (when the ship will be operating above the maximum allowed significant wave height) is represented by the portion of the contour above the black line and can be calculated as:

$$r_i = \int_{T_P=0}^{\infty} \int_{H_S=H_{S\_max}}^{\infty} f(H_S, T_P)\,dT_P\,dH_S \quad (1)$$

where r_i is the risk coefficient in the specific navigation location and $f(H_S, T_P)$represents the standard bivariate normal distribution. In the examples above, H_S and T_P have been considered independently, for simplicity, however, a correlation coefficient can be estimated from weather databases.

The above considerations are valid for a specific navigation location or a short track, in which weather and sailing conditions can be considered to be stationary. To extend the results to the whole route, a long-term probability of failure can be calculated as:

$$R_r = \Sigma_i f(l_i) r_i \quad (2)$$

where R_r is the risk coefficient for the proposed route and $f(l_i)$ is the probability of the ship sailing on the specific track, which can be calculated as:

$$f(l_i) = \frac{d_i}{d_r} \quad (3)$$

where d_i is the time required to sail the ith track and d_r is the duration of the voyage.

Besides representing an innovative approach to a ship's operational risk assessment, this method allows the smooth integration of ensemble forecasts, thus taking into account uncertainties associated with weather predictions (which are most significant in weather routing). In addition, this methodology allows consideration of special threats which are difficult to include in traditional approaches (e.g. ice, traffic, human errors and piracy), as well as other factors affecting the efficacy of the mission from a wider perspective (such as fuel consumption and voyage duration) once the targets are defined.

The method described so far, deals with handling uncertainties within the constraints of the optimisation. The proposed probabilistic approach requires the definition of the objectives (g_i) by means of a response surface, calculated for a series of expected weather conditions. Expanding the response surface in its first order Taylor series, the First Order Second Moment (FOSM) method can be used to estimate the expected value (μg_i) of the objective of interest as well as its variance ($\sigma^2 g_i$)in a specific navigation location. Thus:

$$\mu g_i \approx g_i(\mu_{x_1}, \ldots, \mu_{x_n}) \tag{4}$$

$$\sigma_{g_i}^2 \approx \sum_{j=1}^{n}\left(\frac{\partial_{g_i}}{\partial_{x_j}}\right)^2 \sigma_{x_j}^2 + \sum_{j*1}^{n}\sum_{\substack{k=1 \\ j \neq j}}^{n}\left(\frac{\partial_{g_i}}{\partial_{x_j}}\right)\left(\frac{\partial_{g_i}}{\partial_{x_k}}\right)\rho_{jk}\sigma_{x_j}\sigma_{x_k} \tag{5}$$

where ρ_{ij} represent the correlation coefficients between the variables influencing the given objective, which must be estimated numerically.

The objectives of the optimisation procedure (and its associated uncertainties) can then be calculated by summing the expected values and variances for all the tracks that comprise the route.

ENSEMBLE APPROACH

An alternative to the 'probabilistic approach' is the 'ensemble approach'. In the probabilistic approach, the sea-state (described by the H_S, T_P duplet in Fig. 1) is represented by a contour of decreasing probabilities, centred on the mean forecasted conditions. In the ensemble approach, the predicted sea-state is given by 20 different but equally probable forecasts. The different variants in the forecast are called ensemble members and can be directly processed by the optimisation method. Theoretically, ensemble members can be handled in a number of ways but, as will be shown here, some of them are not satisfying, in terms of effectiveness or efficiency. Three possibilities are briefly discussed below.

First of all, the weather routing optimisation process could be run separately for each of 20 ensemble members and then the results would be aggregated. In this case the optimisation process would be run 20 times, including all three optimisation objectives in each run. Each ensemble member would produce a separate set of Pareto-optimal solutions, which could then be joined and filtered to select the best candidate routes. Unfortunately, a solution found for one ensemble member can perform poorly for another member and there is no certain way of obtaining a solution that would be acceptable (safe) for all ensemble members.

The second possibility is that each combination of ensemble forecast and basic objective could represent a separate, new optimisation objective. Unfortunately, this means that if there were, for example, 20 ensemble members and 3 basic optimisation objectives, this would produce 60 separate optimisation objectives, which is impossible to handle efficiently.

The third option is handling all ensemble members during a single run of the weather routing optimisation process, taking into account just three optimisation objectives. For each considered route, an objective's value can be computed separately for all ensemble forecast members and then aggregated, by means of a weighted average, which can be biased towards a pessimistic assessment of the objective values. As for weather-related safety constraints, they would also have to be checked separately for all combinations of considered routes and all weather forecast ensemble members. However, in terms of constraints, instead of a weighted average, the most pessimistic assessment obtained over all ensemble members should be taken into account. Owing to this, a route could only be considered acceptable if it is safe for all ensemble members.

The third ensemble approach, described above, is the one that combines acceptable computational time (due to a limited number of optimisation objectives) with satisfying safety checks (all weather forecast ensemble members are taken into account). Therefore, it is this solution that is considered in terms of the ensemble-based approach to uncertainty handling.

FORECAST UPDATE THROUGH REAL-TIME WAVE ESTIMATION

One of the key aspects of the project is the ad-hoc correction of weather predictions, tailored to the navigation area of interest. Monitoring of ship behaviour and on-board performance is more and more affordable, as well as communication and data exchange between ship and shore. This gathering of information does not always correspond to a capability of taking effective advantage of the new possibilities offered. Within the scope of this project, the ship-buoy analogy can be exploited to offer a continuous assessment of the actual sea-state along the followed route, due to a suitable on-board monitoring system.

The estimation of the directional wave spectrum, based on ship motions, is achieved through a parametric procedure [16, 31, 32]. The wave spectrum is a-priori assumed to be composed of one or more wave systems, each characterised by a parameterised spectral shape (e.g. the generalised JONSWAP spectrum). The parameters governing the spectral model are estimated by applying a genetic algorithm to fit the current sea-state conditions.

The sea-state estimation method has been tested on board a relatively small navy ship (28.4 m long) equipped with a full monitoring system including, among the others, redundant accelerometers and angular rate sensors, accurate GPS and a wave radar for real time measurements of the encountered sea-state. The monitoring system was integrated in ViewLab (see Fig. 3).

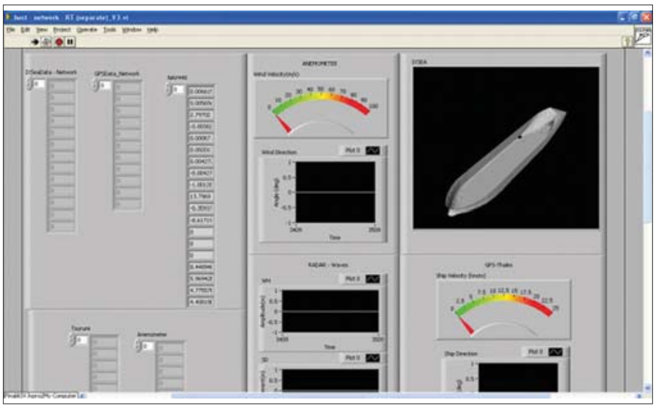

Fig. 3. ViewLab user interface (from 16)

A comparison of the estimated wave spectrum (1D to simplify the visualisation) and the measured one is shown in Fig. 4.

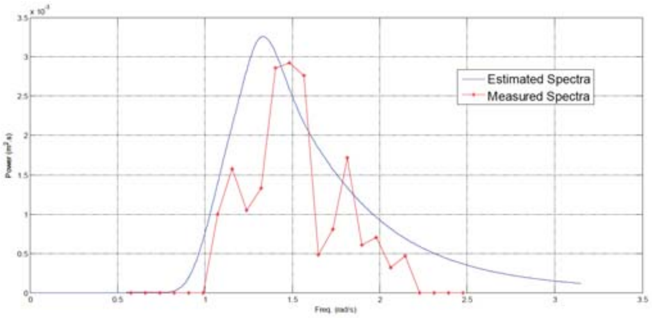

Fig. 4. Comparison of estimated and measured wave spectrum (from 16)

The actual sea-states computed through the above-mentioned procedure can then be compared with the predicted ones. The availability of the information regarding the gap between the two values in real-time and along the ship route, can be used to update the weather forecast through a data assimilation procedure [1, 17, 37].

The proposed procedure is promising, not only for providing more reliable inputs to the route optimisation system (achieving up to 25% of improvement in the forecast in the vicinity of the measurement spot, as shown in [17]) but, also, to fully exploit the widely-recognised value of in-situ ship measurements for the improvements of meteorological prediction and safety.

SYSTEM DESIGN

The proposed ROUTING system (Fig. 5) would consist of the following elements:

- ship handling decision support system (ship handling DSS),
- weather routing decision support system (weather routing DSS),
- ship-internet data transmission module.

The main objective of the weather routing DSS would be to provide a route recommendation for given departure and destination points, taking into account forecast weather conditions as well as a pre-defined set of optimisation criteria and constraints (both static and dynamic) for the ship having the system installed. Some parts of the data processed by the DSS would be uncertain and the uncertainty would propagate through the system (as described earlier) and, thus, an uncertainty level is associated with the objectives that are achievable, following the resulting recommendation. However, the system would be able to work just as well with entirely certain data sources (with no uncertainty level defined).

The optimisation part of the weather routing DSS would be implemented as multi-objective metaheuristics (MOMH), most probably based on the SPEA 2 method [60] but strongly customised to suit the special requirements of the weather routing problem. The optimisation criteria set would include two economy-related criteria (fuel consumption [35] and passage time [12] or delay) as well as a safety-related criterion (modelled as safety index, taking into account ship stability and other factors). The set of constraints would allow for the inclusion of land and shallow waters, as well as areas of excessive wave or wind conditions and areas with violations of IMO Circ. #1228 (which states that some combinations of wave length and wave height may lead to dangerous situations for ships, under certain operating conditions).

Proper modelling of the ship response parameters (made for the ship on which a prototype of the system would be installed and tested) would be one of the crucial elements required for successful deployment of the ROUTING system. Thus, a 'ship model' library or module would be separated inside of the weather routing DSS, providing information about the ship's optimal operational parameters (speed, fuel consumption, safety index, etc.) for given forecasted weather conditions. Separating the ship model from the route

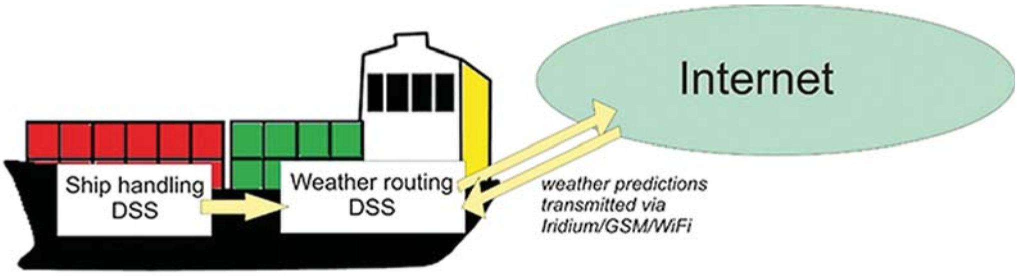

Fig. 5. A general overview of the proposed ROUTING system

optimiser is good design and programming practice, since it strongly facilitates the process of exchanging the ship model (in the case of changing the ship operating the system) but keeping the rest of the DSS intact.

The ROUTING system would utilise commercial ENC-class software [28] (NaviWeather, (NavSim, Poland) which would, above all, provide a means of uploading, analysing and displaying weather data, targeted at yachts and fishing vessels as well as commercial marine transportation. The tool will be utilised as a source of S-57 sea maps and provide an interface for GRIB files and weather forecast data. NaviWeather will provide a Graphical User Interface (GUI) for communication with users and present route recommendations. The weather routing DSS would be integrated with NaviWeather by NaviAPI as a separate software plugin.

The weather routing DSS would be located on a shore-based server to achieve high computational power and faster, cheaper access to standard weather forecasts. However, additional client-server communication would be required to achieve ship to shore data transmission. These data packets would include:

– origin and destination points (lon; lat),
– departure and ETA,
– ship performance statistics (to be uploaded to a data assimilation module).

In the opposite direction, 'shore to ship' packets of data would include the following:

– resulting routes,
– limited weather forecasts (compared to the server-side) to be displayed to the user to show the routes' performance.

The last data transmission module of the ROUTING system would handle all of the required ship-internet data transmissions. It would be associated with on-board equipment in order to allow interactive performance. Since transmission of vast weather forecast files via the satellite channel (Iridium) might be expensive, some kind of transmission cost optimisation would be required, as well as the application of proper system architecture for minimising the required data exchange. Therefore, in the ROUTING system, ship-shore-ship transmission would be realised via one of the Wi-Fi/GSM/Iridium satellite radio-modem communication channels.

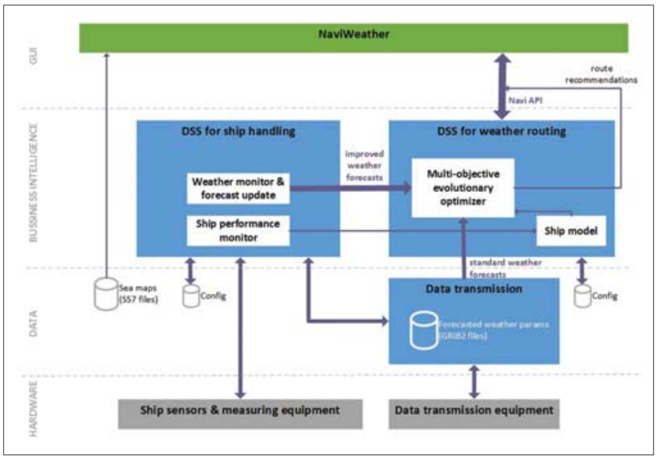

Fig. 6. Overview of the proposed ROUTING system architecture

During the project, a hardware and software tool would be constructed to optimise the transmission costs, where available. An overview of the architecture of the entire ROUTING system proposed is provided in Fig. 6.

IN SERVICE EXPERIENCE

With the aim of demonstrating the complete operability of the system, an agreement has been reached with the Portuguese shipping company Transinsular, making possible the realisation of a six-month long, full-scale test, under actual operational and weather scenarios. An on-board monitoring system will be installed on an 8,850 t, 126 m long container vessel sailing the North Atlantic waters around the Iberian Peninsula (connecting continental Portugal to Madeira and the Azores (Fig. 7)). The system is expected to measure or retrieve all the required information to be used for the estimation of the sea spectrum data assessment from the ship data acquisition tools. Post-processing of the data would be carried out in order to analyse the accuracy of the models adopted and the efficacy of the optimisation method implemented, by comparing the actual route with the proposed one. Furthermore, with the scope of providing an insight into the integration of the system into daily, on-board operations, a short and simple template

Fig. 7. Monte Brasil container-ship approaching the port of Lisbon (top) and typical route sailed

will be prepared for the seafarers in charge to record their experiences using the tools. This will eventually allow us to highlight any erroneous performance issues, as well as any difficulties in the utilisation of the DSS (for ship handling and weather routing) created during the course of the project.

The configuration of the on-board monitoring system will exploit the experiences encountered by previous projects [34]. The System Sensors are responsible for measurements of a ship's motions, the speed and location, the weather conditions (in terms of wind), waves and sea-surface currents, the engine operation point and fuel consumption and, possibly, the structural stresses of the hull girder. The sensors include a GPS, a midship inertial measurement unit (IMU), a bow accelerometer, a weather station, a wave sensor, long-base strain gauges and a flow meter. The integration of all data is carried out through a data acquisition system and sent to a computer located on the bridge, where the GUI and the NaviWeather software are installed to communicate with the user. The ship will also be equipped with a communication system designed to transmit information ashore, where the heaviest calculations are performed (e.g. the data assimilation and weather forecast update) and developers can control the correct functionality of the system.

CONCLUSIONS

The paper presents the first phase of research on the ROUTING project. The project aims at developing a novel solution for optimising ship routes, based on detailed models of ship behaviour, dynamic hydro-meteorological data and refined multi-objective meta heuristics (MOMH). The data sources will include weather forecasts, updated dynamically with real-time information, gathered by the ship sensors. The solution under development will take into account multiple problem-related uncertainties, including those associated with weather forecasts and those resulting from ship performance and responses to sea conditions. As for the former, they will be modelled here as ensemble forecasts and directly taken into account in the long-term optimisation process. The latter will be handled by a short-term Decision Support System. All of the available data will be processed by the main module of the system, utilising state-of-the-art, evolutionary, multi-objective optimisation (EMO) and incorporating decision maker (DM) preferences by means of configurable trade-offs between various optimisation objectives. The final results (routes recommended by the system) will be transmitted to the client application on board a ship and visualised in the ENC-class NaviWeather software. The proposed solution will be implemented as a prototype system and verified on board a container-ship navigating between continental Portugal and its archipelagos of Madeira and the Azores. The obtained results will be disseminated as well as used for further research on ship routing and ship behaviour in various weather conditions.

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