Weather routing for ships in degraded condition

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Abstract

Aim of EC funded project is to develop decision support system for onboard use in case of a hazard. The crew of a vessel in degraded condition faces mostly the lack of time to take proper decisions. A system displaying most relevant information and remaining options accompanied by shore assistance helps to gain valuable time.

Presented here is the weather and sea state routing advice based on the momentary condition of the vessel, which is one module of the entire system. Principal considerations, the layout of the system as well as mathematical and numerical aspects are described. The article finishes providing some results for a particular vessel.

Keywords

Weather Routing, Degraded Condition, Crisis Management Advice, Shortest Path Optimization.

1. Introduction

Crew of a vessel in degraded condition is mostly suffering of time to take proper decisions. Assistance from ashore is usually provided, but additionally time consuming due to necessary exchange of information. A decision support system especially created for this situation aims at reduction of necessary communication from ship to shore (by offering access to the system from shore via internet) and by displaying condensed information from ship's systems tailored to the particular crisis. Additionally, recommendations and access to further detailed knowledge is offered: calculation of remaining vessel structure stability, floating stability and maneuverability. This information and results are also used to calculate route recommendations based on weather forecasts for the following 72 hours.

The weather routing module is presented in this article. The idea of numerically optimized weather routing is not new (Wit, 1968). In recent years services of meteorological institutions as well as of specific SMEs have improved and got established at the market. Spaans and Stoter (2000) give a brief but comprehensive overview on ship weather routing and the system SPOS they developed and presented first in 1994. Principles of weather routing are presented in the similar titled chapter 37 of Bowditch Maneuvering Manual (2002). The availabilty of reliable sea state forecasts and route recommendations led to a significant reduction of encountered wave heights (Sternsson and Björkenstamm, 2002), which is a remarkable success.

Optimal weather routing is basically what experienced seafarers do for centuries when talking of voyage planning (Motte, 1972). Adding numerical capabilities to obtain reliable forecasts of the environmental conditions to be expected during the voyage and to optimize on basis of comparison of several feasible voyage plans is what is meant when talking of optimal weather routing today. So, weather routing and voyage planning is a procedure where an optimum route is sought for a particular ship on a particular transit based on forecasts of weather and sea state and the ship performance characteristics. For intact merchant vessels "optimum" is a combination of several objectives:

1. minimum or specified (line service) passage time;
2. minimum fuel consumption within specified passage time;
3. minimum damage to ship and cargo;
4. maximum comfort of passengers;

Shipmasters show a natural tendency to go for 1 and in limits 3 in the first part of an ocean voyage, to ensure to be on time, and for 2 (and 3) for the second part, with the overall goal of their voyage planning to arrive just in time at minimum fuel consumption.

Obviously there are well defined constraints and variants defined by this procedure to have a multiobjective optimization scheme applied with the aim to find a route optimal in the sense above but based on one seek strategy for the overall passage and not changing strategies for several parts.

Numerical weather routing has proven to be cost reductive (for instance Lehmann et al. 1996) additionally to the reduction of encountered severe sea states mentioned above. The benefit of weather routing with the always improved accuracy of weather forecasts is evident and the day to day business of companies like "WeatherNews Int.", "AMI", "C-Map", "SMHI", "SPOS", "seaware", "Weather Routing Inc." in arbitrary order and choice.

Situation on board changes dramatically, and most often very suddenly, in case of a hazard. Be it damage or fall out of a technical device or component or an average like collision or grounding. The demands on weather routing and route recommendations change as well, obviously. A vessel heeling or with damage in the rudder engine behaves different in sea as the intact one and needs therefore adopted maneuvering and route advice. The destination usually alters, too.

Provision of optimum route advice for ships in degraded condition therefore has to consider additionally changing (i.e. decreasing) maneuvering and propulsion capability. In difference to the situation for optimum weather routing, this information is not static and not predefinable for all cases. Such a routing advice tool therefore depends strongly on situation assessment, in the presented system gathered and provided by dedicated neighbor modules.

2. Layout of the system, general considerations

2.1 Part of a DSS

A decision support system is developed to assist crew on board a vessel after an incident. The system does twice: First it filters and displays only relevant information to cope with the situation; second a status assessment of the vessel is performed. Besides, the system offers access to third parties ashore they can get a clearer view on the situation onboard without distracting the crew.

The system is designed as part of the bridge instrumentation and has interfaces to automation, safety management and navigation system. Signals gathered are processed as input to modules and to display to user.

Maneuvering and propulsion capability assessment is based on continuous correlation of predicted and actual behavior of the vessel. After sophisticated noise filtering the approach provides fast and flexible forecast of the actual vessel's responses on maneuvering devices and sea state. These continuously updated ship responses (Response Amplitude Operators, RAOs) are basis for optimum route advice for a ship at reduced maneuvering or propulsion capabilities.

Other data needed, like position, heading, speed… are gathered from the onboard navigation system (NMEA-interface).

2.2 Weather routing advice

The system is designed as part of the bridge instrumentation; use in non degraded situation is foreseen. On the one hand, crew may get additional information from the system on the other they could practice emergency scenarios and get familiar with the vessel and strategies.

Weather routing is of interest in day to day operation, too. The module provides recent weather forecasts (Figure 1) and a route recommendation. Route planning is assisted by displaying weather forecast for the position and date of each of the waypoints of the autopilot's GPS.

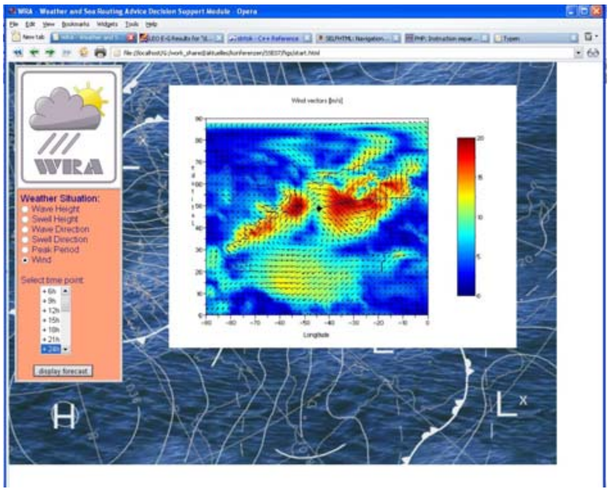

Figure 1: weather forecast presentation in cruising mode

System's overall concept follows experience done in a former project on ship and logistic chain specific weather routing (SEAROUTES, EU FP-5) and its approach is comparable to SPOS system (Spaans and Stoter, 2000). We affirm their conclusions in terms of localizing the system onboard and keeping user's interaction as clear and easy as possible. Avoidance of confusion is a must for ship's instruments.

The weather routing for the intact vessel considers ship behavior and characteristics, this makes route recommendation individually for a particular ship. The system requires ship responses to evaluate the "quality", or fitness when coming to evolutionary optimization, of a feasible route. The vessels characteristic behavior and reaction to the sea way is gained from strip theory calculations using SEAWAY by J.M. Journée (2000). Exemplary vessel is a 4500 TEU container carrier "Hannover Express" from Hapag Lloyd. The strip theory code SEAWAY provides Response Amplitude Operators (RAOs) for heave, pitch, roll and acceleration due to waves. 2D coefficients are gained from potential flow solution using conformal mapping with close fit. Ship speed is accounted by introduction of additional source terms. There are semi-empirical methods to properly model surge coefficients and roll damping. Typical ship responses of interest for weather routing are (bow, bridge) accelerations, slamming probability and additional resistance due to wind and waves.

Environmental data are provided by DWD, the German met office, with a resolution of 1° spacing at coarsest and three hours time steps. Weather is usually considered to change rather slowly. Forecast periods are between 72 to 156 hours. Data of interest for sea weather routing are:

- swell, direction, period, significant height

- wind waves, dir., per., sign. height
- waves, dir., per., sign. height
- wind, speed and direction

Actual ship speed and heading combined with position and date allow to determine in routing calculations encountered wave angles and period, acting on the ship.

To calculate ship responses, the sea state is modelled being in the form of a Bretschneider spectra:

$$S_\zeta(\omega) = \frac{172.8 \cdot H_{\frac{1}{3}}^{\ 2}}{T_1^{\ 4}} \cdot \omega^{-5} \cdot \exp\left\{\frac{-691.2}{T_1^{\ 4}} \cdot \omega^{-4}\right\}$$

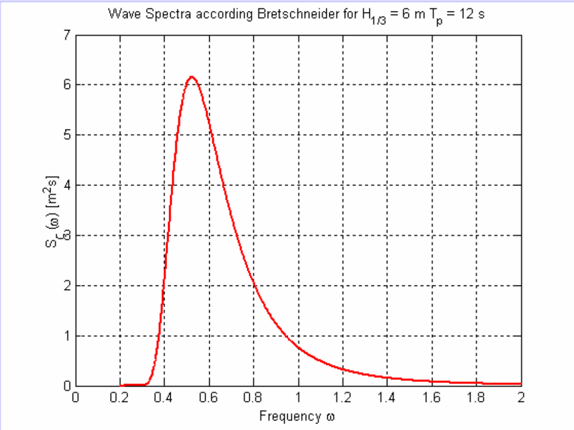

Figure 2: Wave spectra according to Bretschneider

Response amplitudes, for instance for relative motion of the bridge, are pre-calculated and stored in a databasis:

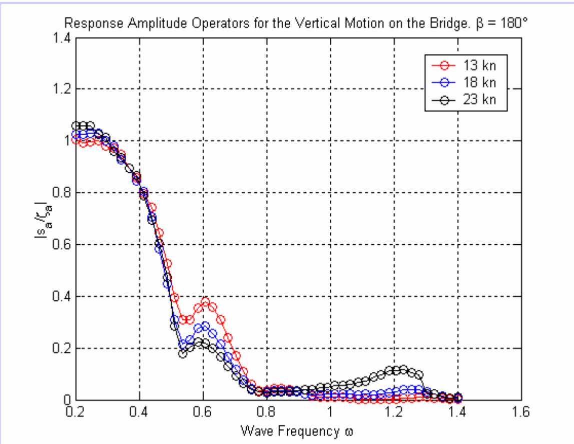

Figure 3: RAO for vertical motion of the bridge

Vertical acceleration on the bridge is than gathered from RAO for Bretschneider spectrum:

$$S_s(\omega) = \left|\frac{s_a}{\zeta_a}\right|^2 \cdot S_\zeta(\omega)$$

Used to calculate fourth moment:

$$m_{4s} = \int_0^\infty S_s(\omega) \cdot \omega_e^{\ 4}\, d\omega$$

Provides forecast for bridge acceleration:

$$\ddot{s}_{a\frac{1}{3}} = 2.0 \cdot \sqrt{m_{4s}}$$

Similar approach is applied to all the other movements.

Fuel consumption is gained from the following procedure. The added resistance due to waves is calculated from:

$$R_{AW} = \int_0^\infty RF \cdot S_\zeta(\omega)\, d\omega\,.$$

The determination of the calm water resistance is based on the approach of Holtrop Mennen (1984) a regression analysis of model tests and full-scale data. The operating point of the propeller was calculated according to the ITTC power prediction method (ITTC 1978), using the characteristic of a propeller with the same diameter, number of blades, similar pitch and blade area ratio as given by Samsung (1991). In a final step the fuel consumption and the compliance with the permitted operating condition was determined in agreement with the project guide available from the producer of the ship's main engine (MAN 2000).

In general, detailed information on the propulsion system and the ship lines are required to set up a vessel specific weather routing capable to consider ships movements in and responses to the sea state and environmental conditions.

Route recommendation is than gained from evolutionary multiobjective optimization and is than part of a Pareto optimal frontier. The method is based on probalistic methods for creating a population of feasible routes ("solutions"). Evaluation of the fitness of each of the population members is according to the gain variables, i.e. travel time, fuel consumption and others. Damage and comfort are taken into account by consideration of accelerations at specific positions on board the vessel (bow, bridge, cabin). In each operation the genetic optimum search modifies the route variables (position and speed along the initial track), routes with extended travel time or land contact are sorted out. The route is therefore prescribed as a B-Spline, along which the supporting points are varied. Further variable for variation is the ship speed from 15kn over service speed of 21kns to maximum speed of 24kns. Figure 4 illustrates the corridor for route population. The optimization calculation and the presentation of the result are shown in figure 6, 7 and 8.

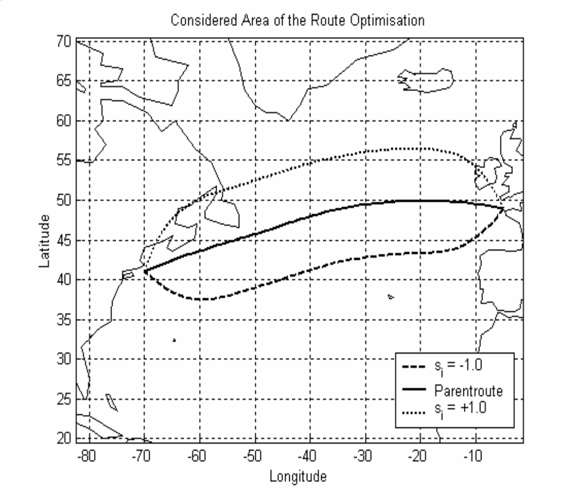

Figure 4: Parent (initial) route and area for variation

2.3 Situation adapted routing

After an incident, the system switches to degraded mode and changes display color to grey. Now, a set of opportunities is provided to be played through. The optimum routing consists in provision of an optimal route in terms of constraints and in displaying consequences of each of the opportunities left to the vessel. It is not up to the system to decide on one of the strategies or to discard one or more of them.

The aim is to provide decision support and not assistance by taking decisions.

In general there are only few opportunities to react on an incident in terms of routing decision, see Figure 2. However, the calculation of an optimum is different for each of them. Therefore a set of three numerical optimization schemes is included in the module:

- Genetic algorithm (or possibly Simplex) for multiobjective optimization for intact weather routing as well as for "go ahead" and weather out option.
- Fast graph theory based shortest path seek in multiparameter domain (Möhring 2004) to determine optimum routes under remaining maneuvering and propulsion capacity to reach safe harbor or at least a close refuge.
- Deterministic calculation, where situation is subject of the sea state, wind and momentary speed and heading of the vessel, only, as for the free drifting vessel, calculation of leeway. The drift speed and direction is gained from a balance of acting forces. The orientation of the vessel and the encountering angle of wind and waves, which is vital for the calculation of drag coefficient and active face, are obtained from vessels onboard instruments (GPS for heading) and assumed to be balanced for the actual moment. Further development is assumed to be the one of minimum equilibrium.

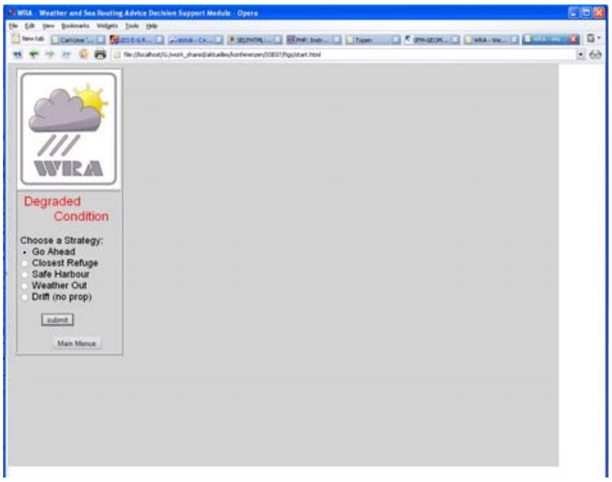

Figure 5: Browser-approached weather routing in degraded condition, accessible from vessel and ashore (background changed to clearly show the altered mode).

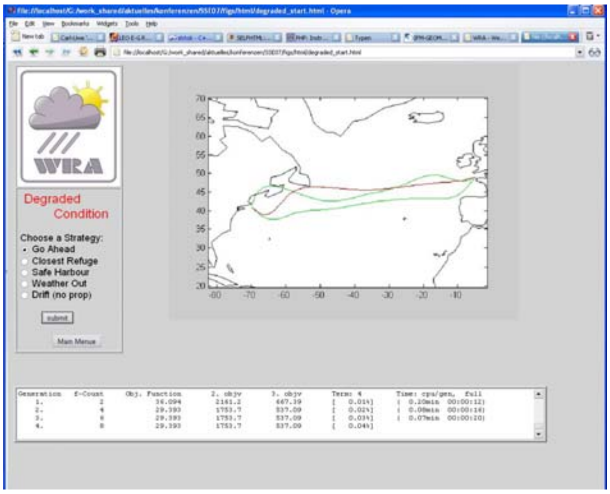

Figure 6: Calculation of "go ahead" route started

The module keeps user informed on its activity by the listing on the bottom. Figure 3 shows starting calculation using genetic algorithm optimization for a route cross the Atlantic, this is similar to the intact vessel mode, but with slightly altered vessel performance. Shortly before calculation is finished, a set of routes evaluated is displayed (Figure 4), then the module displays the "optimal" route recommended (Figure 5) and provides corresponding way points to the other modules of the system via UDP on request.

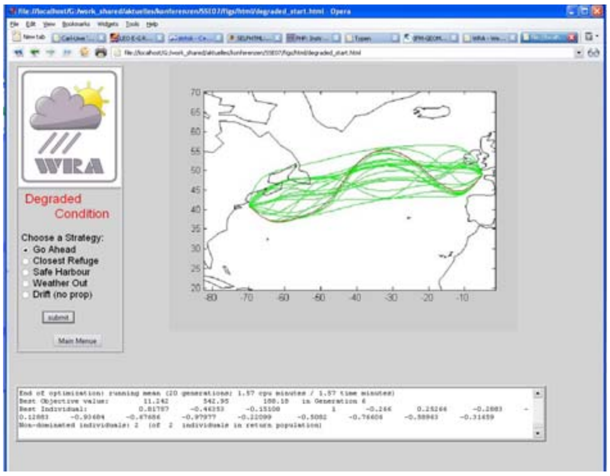

Figure 7: Calculation of “go ahead” finishing

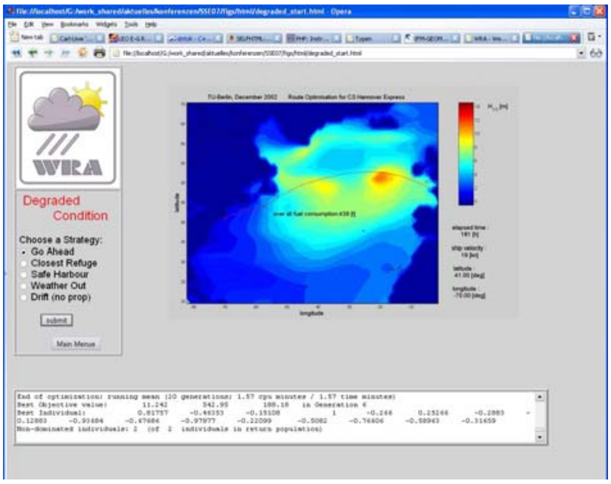

Figure 8: Calculation of “go ahead” finished

2.4 Optimization schemes

Seek for the optimum depends strongly on the mathematical characteristics of the field the search is done in. More precisely, effort and success of a seek strategy and numerical scheme to determine a local extreme value (minim or maximum) depend strongly on the condition of the search domain. Provided the domain is strictly monotonic decreasing, the absolute extreme can be found based on a deterministic approach, like the simplex algorithm where the local gradient is used to determine the way to the extreme’s position. More complex search domains typically have a number of different local extremes, the seek strategy has to avoid getting stuck in the next extreme in the vicinity and leaving out the higher or lower extreme a bit further. In this case either the domain has to be scanned completely or intelligent random sampling is applied. This is how genetic algorithms are successfully introduced for optimums seek.

For the shortest route recommendation if a close refuge or harbor is known and shall be reached in the shortest possible time period multiobjective Dijkstra algorithm is applied to a graph of feasible lines.

Graph theory as a basis for shortest path seek is advantageous if a fast and flexible seek in a changing field in space and time is requested. Each of the edges of a graph represented a way of the vessel in space and time, so the time domain is included in the optimization scheme directly. Edges and nodes are created automatically based on the momentary position of the vessel, electronic chart data and vessel’s remaining maneuvering and propulsion capability. Figure 6 and 7 illustrate automatically generated graph for a shore approach.

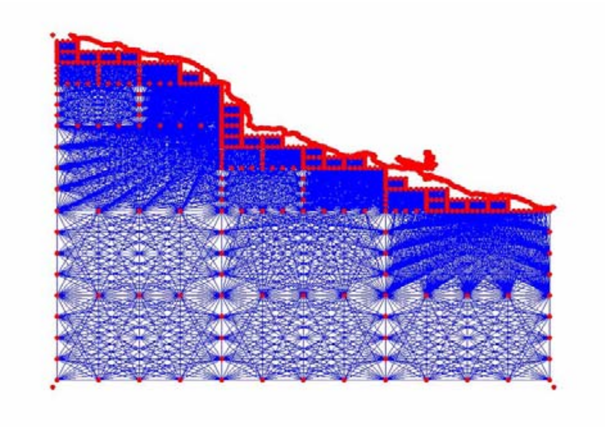

Figure 9: automatically generated edges for coastal approach

Each edge is a connection in space and time from one node to another, the seek area is therefore represented by a number of equal weighted edges. More detailed view is presented in Figure 7 to illustrate this aspect.

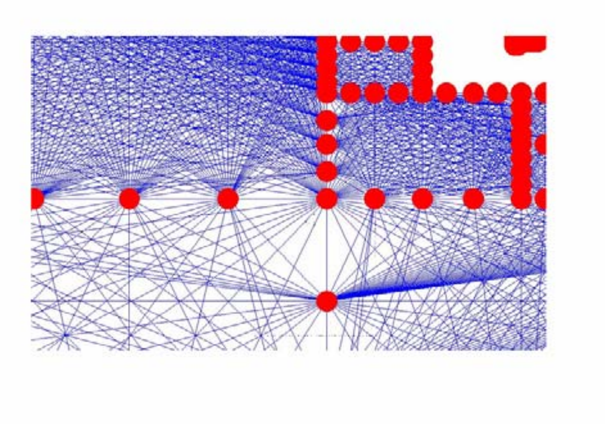

Figure 10: detail of the graph in Figure 6

The closer the vessel gets to the shore line, which is actually the 15m water depth line (depending on the vessel’s dimensions), the finer becomes the resolution of the edges. Optimization calculation starts with sorting out unfeasible (due to turning angle) edges. The remaining edges are weighted by a penalty function to finally reach the cheapest (shortest) path. To determine this optimum for a set of boundary values and cost functions, a generalization of Dijkstra's algorithm to the case of two objective functions by Aneja, Aggarwal, and Nair (1983) is applied. For a higher number of objectives (accelerations, fuel consumption, bending moments, rolling angles…) evolutionary optimization is used. On the other hand graph theory is quite fast and allows continuously adopted route recommendation in case of, even slowly, deteriorating condition of the vessel.

2.5 Route Variation

The evolutionary optimization and the Simplex algorithm both require variation of the routes. Therefore the path of the route and the velocity profile are represented by B-splines bridging departure and destination. Travel time is introduced as a boundary condition. The B-splines are spanned over a set of points along the route (Figure 4). Perturbations of these points in orthogonal direction to the route build the free variables for optimization. The method is described in detail by Harries and Hinnenthal (2004). The route is than evaluated based on the positions along the B-spline, a specific weighted cost function of the objectives decides on the degree of "fitness", which is elementary for genetic algorithms.

2.6 Simulation and optimization of degraded scenarios

Depending on the incident, remaining options are very likely either to reach a certain point or to "survive" the period of heavy weather for easier assistance from outside later. No matter whether the vessel needs a refuge or the strategy is to ground intentionally to avoid break of the vessel in two parts, in terms for routing advice the task is to provide the optimal path in space and time with lowest impact of sea and wind on the structure at a reasonable travel time to the shore, harbor, refuge, or beach for grounding. Until there is no dedicated list, the position of this refuge has to be entered manually to the system and optimal route is calculated similar to intact vessel routing based on graph theory approach. Ship responses database is adopted by the condition assessing modules of the entire system.

In case of complete loss of propulsion, the guessed positions for the following 72 h in steps of 3 hours are calculated based on the vessels hydrodynamic masses and the currant speed, wave period, height and direction as well as wind and vessel's speed and heading. For a fall out of rudder or rudder machine, a strategy to weather out the severe sea on help of remaining thrusters or other maneuvering aids and the main propulsion system is calculated, on basis of a Simplex optimization for the route in sea with the lowest impacts on structure (accelerations) and lowest rolling angle.

2.7 Performance comparison

Multiobjective optimization using free variables from B-Spline represented routes suffer from the provision of the B-Splines and the evaluation of route positions. A 7 day passage across the Atlantic, only the open water part of the journey was subject of optimization, pilot time and estuary traveling was deliberately left out for practical reasons. A multiobjective optimal route in terms of accelerations, rolling angle and fuel consumption (subject of the three parameters wave period, height and direction) calculated based on evolutionary optimization takes on a average PC about three minutes computing time, to evaluate 15 generations and 3 objective functions. Due to the approach, computing time and best route are varying in small borders, depending on the chromosomes and variations created. At least nine points along the speed profile B-spline and 7 along the path are required to obtain reasonable results. In this comparison 10 points along the path and 15 for the speed profile were applied. Optimization based on local derivation (gradient evaluation, similar to Simplex) for the same route representing set of parameters takes much longer (> 20 minutes computing time for 54 iteration cycles, 1288 iterations), but leads to a well defined optimum, depending only on the conditions at the departure. Figure 8 gives a comparison of the results of each of the approaches; the optimal route in terms of moderate sea state is similar for both techniques, the longer seek with gradient method lead to a route with lower fuel consumption overall. This is very specific for the particular weather situation on north Atlantic and can .not be generalized.

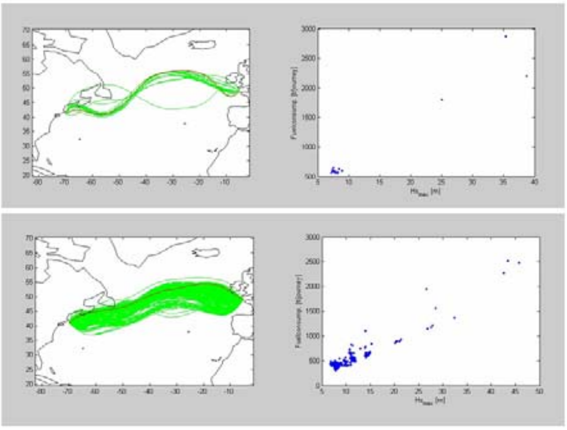

Figure 10: Comparison of route recommendations of mutliobjective genetic algorithm (top) and gradient based seek for multiobjective functions (bottom)

Graph theoretical approach is not used to optimize ocean passage. The optimization is divided in two parts: Set up of the graph takes about ten seconds computing time depending on the size and shape of the shore line, and bathymetric conditions. Determination of shortest path on the graph takes less than one second computing time, which makes this approach very useful for any "play through" functionality at different conditions. Additionally, this approach allowed to add other vessels or moving obstacles, but was not implemented in the presented work.

3. Conclusions

A weather routing system has been presented which is based on established approaches but designed for the specific requirements of a decision support system for ships in degraded conditions. In contrast to routing of intact vessels, such a system needs a wider functionality and different optimization approaches, suitable to each of the optimization tasks. Three implemented optimization schemes were presented with their characteristics.

Ship specific responses and consideration of remaining propulsion and maneuvering capability is essential for this approach. For day to day weather routing tasks of intact vessels, the inclusion of ship characteristics has turned out to be sufficient if rather roughly. The masters reserve the right to balance the route recommendation of the system. This was the reason to reduce ship specific models in SPOS system and to additionally display instead the raw weather forecast data, which were the base for route calculation.

The approach presented here combines both: pure information for intact vessels with a unobtrusive route guidance to the masters and a sophisticated calculation considering ship behavior in sea in detail in case of an hazard, where the vessel behaves not as used to the crew and responses become easily subject of misjudgment.

4. Acknowledgements

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