MANOEUVRING PREDICTION DISPLAY FOR EFFECTIVE SHIP OPERATION ON-BOARD SHIPS AND FOR TRAINING IN SHIP HANDLING SIMULATORS

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Abstract. A new prediction tool was developed to simulate the ships motion with complex dynamic models in fast time and to display the ships track immediately on ECDIS for the intended or actual rudder or engine manoeuvre. These simulations are based on input from the ships actual sensors via the Voyage Data Recorder and furthermore from diagnosis tools analysing the status of the manoeuvring facilities and providing information in case of failures, e.g. reduced engine power or larger rudder response time due to malfunctions of the equipment.

Within this paper investigations into the feasibility and user acceptance of the new layout of navigation display will be introduced and selected results of simulation studies testing the influence on manoeuvre performance dependent on different kind of prediction functions will be discussed. This Dynamic Prediction Display is intended be used on board of real ships but is also an effective tool for training in ship handling simulators because the trainee can immediately see the result of the actual rudder, engine or thruster commands, even before the ship has changed her motion. Examples will be given for results from test trials in the full mission ship handling simulator of the Maritime Simulation Centre Warnemuende.

1. INTRODUCTION – STATE OF THE ART AND NEW APPROACH

The role of computer based simulation is increasing on the ships bridge, especially for manoeuvre planning and for collision avoidance. Prediction tools are very helpful and already in use on ships for a long time. Well known is the so called Trial Manoeuvre mode in ARPA radars to be used in order to analyse future encounter situation for selected relevant course and speed alternatives to deck potential collision avoidance strategies.

With the emerging Electronics Chart and Information Systems ECDIS new tools were introduced for supporting voyage planning by means of manoeuvring characteristics as in

Fig. 1. For controlling the ship on her route the future track of the ship was shown as a so called "curved headline" overlay in ECDIS.

However, theses prediction are very simple only based either on new constant course and speed values as in the ARPA trial function or on estimated future courses & tracks based on the simple integration of the current ship motion parameters as rate of turn and speed components to be considered as constant.

The simplification of these predictions allows restricted use only. Therefore new concepts for on board displays and simulation tools were developed including the immediate response on changes of rudder and engine commands as drafted in Fig. 2.

This approach was investigated in research projects, dedicated on the one hand to the further development of user interfaces on ships navigational bridges and to investigations into potential improvements for manoeuvring assistance on the other hand. A prediction tool was developed to simulate the ships motion with complex dynamic models in fast time and to display the ships track immediately for the intended or actual rudder or engine manoeuvre (Benedict [5]).

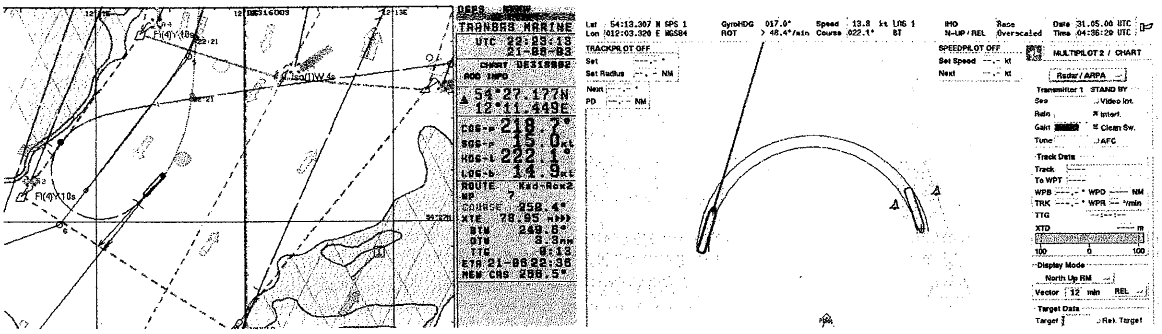

Fig. 1. "Path Prediction" for turning manoeuvres based on simplified motion models (TRANSAS-ECDIS, left) and "Curved headline" prediction calculating the ships track on the basis of integration taking the current motion parameters as constant (SAM-NACOS, right)

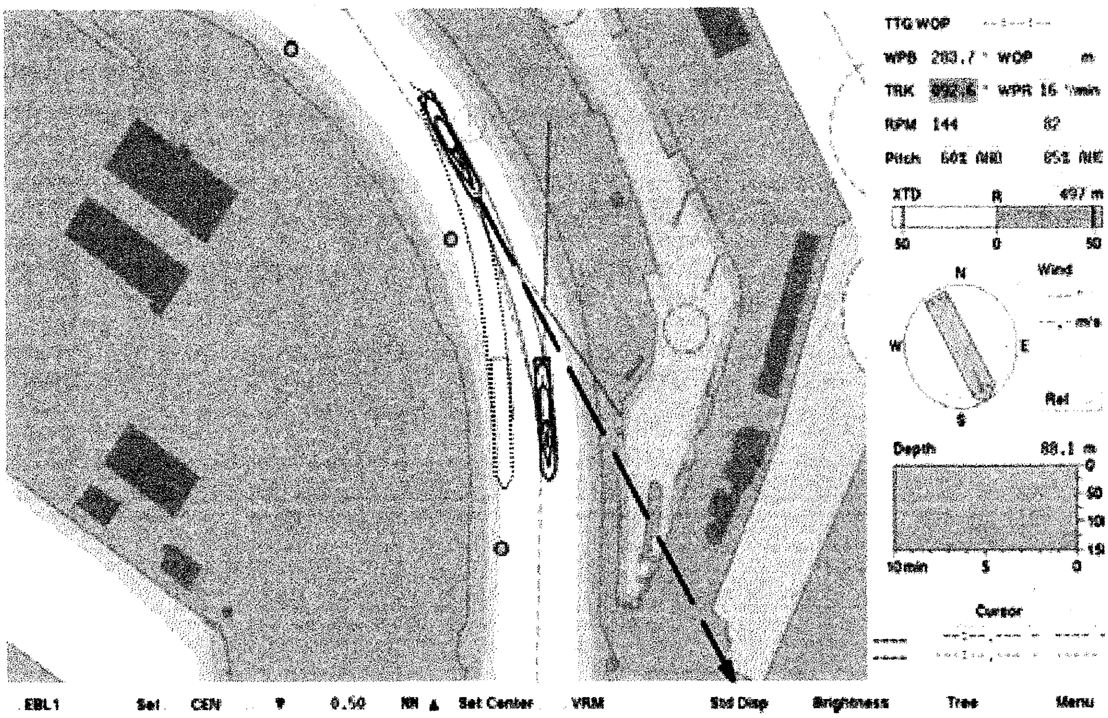

Fig. 2. New concept of an "On-line- Manoeuvring- Assistant: Simulated track predictions (red contour / broken lines to STB) of steering characteristics according to the current steering handle position /rudder angle as ECDIS overlay compared to conventional prediction (black contour / solid lines close to ahead vector)

Generally there are two areas of application of such a prediction tool. It can be seen both as training tool for ship manoeuvres and to be used as assistance tool on board vessels:

<u>Training Tool:</u> The prediction of ships motion as an immediate response could be an excellent method to demonstrate the results of changes or alternatives of using manoeuvring control devices as for instance propellers, rudders or thrusters. This is of increasing importance specifically for the growing complexity of manoeuvring control systems starting from simple one-propeller and middle rudder, via twin propellers with double rudder up to new azimuth propellers which can be turned by 360° (there are ships with even four of these sophisticated thrusters).

Assistance Tools: Predictions as elements of on board displays can be used as in the loop control elements to steer the ship manually but supported by the future track or speed indication in the ECDIS interface.

One crucial problem for the prediction is the accuracy of the simulation. In the mentioned projects a very sophisticated approach was used to represent the ships' dynamic by very extensive equations very similar to those used in Full Mission ship handling simulators. The parameters of the equation of motion will be estimated by an extra fast time simulation program and a data analyser already used for tuning of the hydrodynamic models in the ship handling simulator.

These methods will be described in the following chapters and examples will be given for results from test trials in the full mission ship handling simulator of the Maritime Simulation Centre Warnemuende (http://www.sf.hs-wismar.de) upgraded in 2007/2008.

The Maritime Simulation Centre Warnemuende at Wismar University, Department of Maritime Studies in Rostock-Warnemuende accommodates six simulators embracing a common network and comprised of four ship-handling bridge systems with differing levels of equipment, a ship's engine system and a VTS simulation facility. The interaction of many of the single simulators is one of the unique features of the MSCW: they can be interfaced to form a big scenario comprising all simulators and connecting e.g. the big bridge 1 with the full mission engine simulator. The Ship handling Simulator (SHS) is located on the first and second floors of the centre. It comprises four bridges: Bridge 1 consists of a fully integrated replica bridge assembly projector-based 360° visual display, Bridge 2 has a similar 257° visual display system which can be specifically used for manoeuvring a ship from bridge wing, the remaining two bridges 3 and 4 are used mainly as radar cabins, each being additionally equipped with 120° visual display screens. A lab with eight stations for computer-based Instructorless Training (ILT) completes the setup for effective ship handling training. They can be also interfaced into the complex scenario as own ships.

2. APPROACH FOR PREDICTION TOOL WITH FULL SIMULATION MODELS

2.1. Ship dynamic model and Technological setup for simulation

The following equation of motion was used as math model for the ships dynamic:

$$\begin{aligned} X &= m\left(\dot{u} - rv - x_G r^2\right), \\ Y &= m\left(\dot{v} + ru + x_G \dot{r}\right), \\ N &= I_z \dot{r} + m x_G\left(\dot{v} + ru\right). \end{aligned} \quad (1)$$

On the right side are the effects of inertia where u and v represent the speed components in longitudinal and transverse direction x and y, r is the rate of turn of the ship. The ships mass is m and x_G is the distance of centre of gravity from the origin of the co-ordinate system, I_z is the moment of inertia around the z-axis.

The ships hull forces X and Y as well as the yawing moment N around the z-axis are on the left side. Their dimensionless coefficients are normally represented by polynomials based on dimensionless parameters, for instance in the equation for transverse force Y and yaw moment N given as the sum of terms with linear components N_r, N_v, Y_r and Y_v and additional non-linear terms depending on speed components u, v, rate of turn r, revolution n and rudder angle δ. Other forces as for instance rudder forces and wind forces are expressed as look up tables. There are additional equations for the engine model, additionally with look-up tables to represent automation systems characteristics.

The solution of this set of differential equations is calculated every second; some internal calculations are even done with higher frequency.

This equation of motion (1) can be written in the form:

$$x'(t) = f(x, u_c, t). \quad (2)$$

Where:

– State spaces with track co-ordinates ζ-η, heading ψ:

$$x = [u, v, r, \xi, \eta, \psi, \delta, n_{ME}, n_{TH}, ...];$$

– Controls with commanded values *Cmd* for main engine ME and thrusters TH:

$$u_c = [\delta_{Cmd}, n_{ME\_Cmd}, n_{TH\_Cmd}, \cdots];$$

– With initial conditions at: $t = t_0$: $x(t_0) = x_0$, $u(t_0) = u_{c0}$:

$$x_0 = [u_0, v_0, r_0, \xi_0, \eta_0, \psi_0, \delta_0, n_{ME0}, n_{TH0} \cdots],$$
$$u_{c0} = [\delta_{Cmd0}, n_{ME\_Cmd0}, n_{TH\_Cmd0}, \cdots].$$

This equation of motion (2) can be solved by numerical integration for the prediction time period t_0 to t_1 in the form of the general solution:

$$x(t) = x(t_0) + \int_{t_0}^{t_1} x'(t)\, dt ,$$

i.e. for the full set of states and controls:

$$x(t) = x_0 + \int_{t_0}^{t_1} f(x, u_c, t)\, dt . \qquad (3)$$

A simplified solution for a simplified predictor is used by integration of track and heading assuming constant speed u0, v0 and rate of turn r0, which results always in a circular motion with constant speed:

$$x(t) = x_0 + \int_{t_0}^{t_1} f(u_0, v_0, r_0)\, dt . \qquad (4)$$

The Input output relations are shown in Fig. 3. The inputs consist of controls, the states and the data for the environmental conditions in the three blocks on the left side. The core module Simulation/Prediction is in the centre of the figure. Additionally there is an input of the Ships condition parameters. They are normally fixed but in case of malfunctions they might change, e.g. reducing the rudder turning rate or maximum angle. The results from the Simulation block are transferred to be displayed in ECDIS or Radar.

In that figure also the more technological setup of the structure of modules is described. A commercial IMO-proven Voyage Data Recorder (VDR) plays the role of data collector for the controls, states and environmental parameters measured by the ship sensors. After pre-processing these data they will be stored in Shared Memory 1, together with the condition parameters which will be provided by a diagnosis system. This system continuously checks the ships and engine conditions.

From this memory the data are available for other modules:

The Simulation Prediction Module uses the data from Shared Memory 1 to predict the ships track and speed for a certain time period, e.g. 10 minutes. The results are sent to Shared Memory 2. The Presentation Module uses the data both to display the actual position and from Shared Memory 2 to display the future track. The Prediction parameters are controlled by a user interface integrated in the Presentation module with regard to predicting cycle and length of track. Additionally a new simulation component was added for simulating predefined or full flexible manoeuvres.

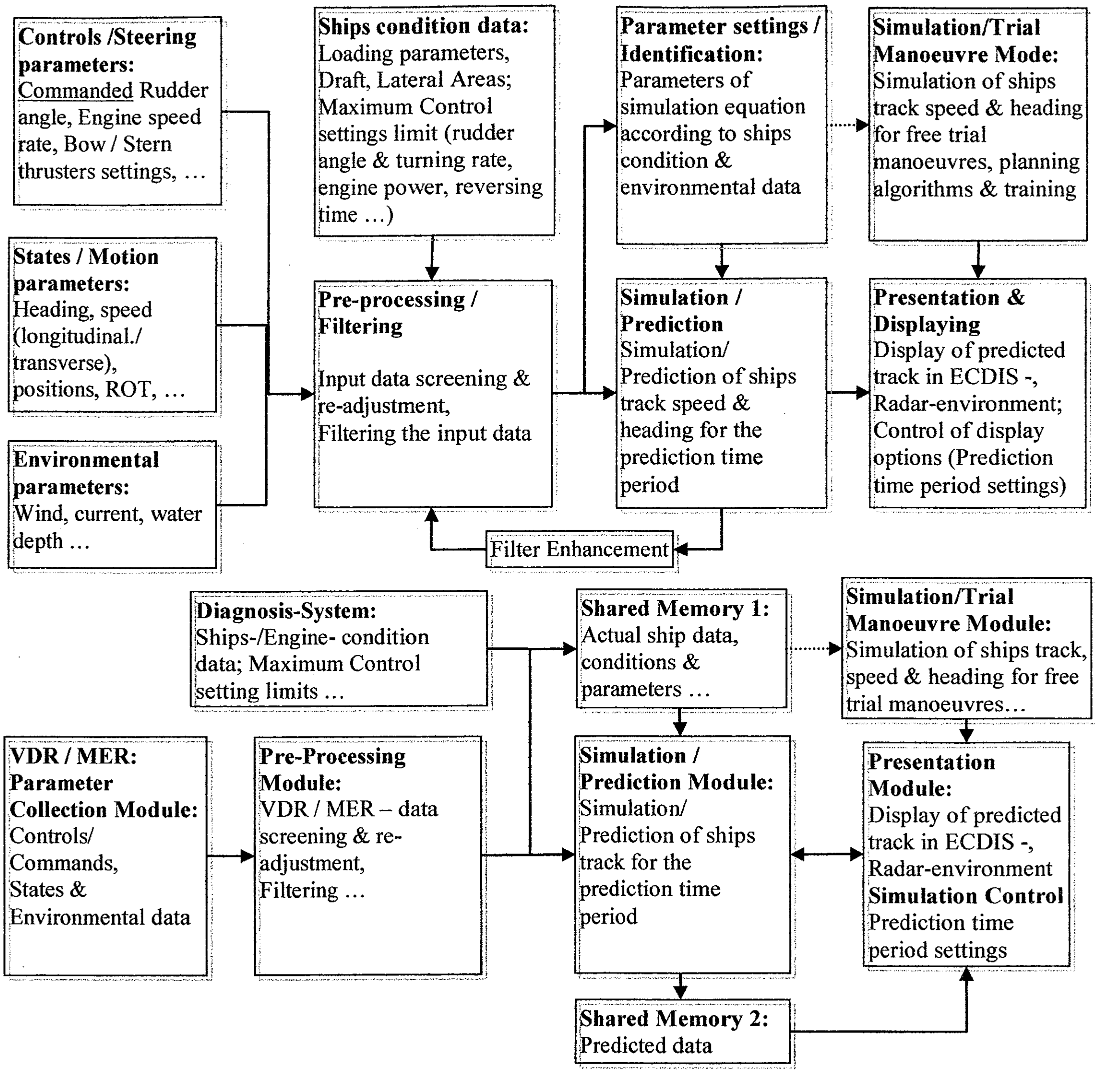

Fig. 3. Input / Output Concept for prediction processes and data flow (top) and Modules & data sources and sinks (bottom)

2.2. Presentation of dynamic Predictions in ECDIS environment

For a compact presentation of information to the captain, pilot and responsible navigating officer respectively a new layout of a conning display was designed and implemented into the equipment installed on an integrated navigation system. In Fig. 4 the layout of the prediction display in an ECDIS is shown. The display layout contains an overlay of ECDIS and CONNING information together with the prediction.

In the centre the ECDIS information in Head up Mode together with motion parameter for longitudinal speed (10.1kn and transverse speed (0.1 kn) as well as a circle segment with the rate of turn to STB (4.0 °/min) is shown. The ships position is displayed in the centre of the ECDIS as ships contour where the track prediction can be indicated as curved track or as chain of contours for the selected prediction time. The prediction parameters as range or interval of presentation can be set in the control window at the right side.

The predicted track for the simplified prediction is shown as red curve: According to the actual/present rate of turn to starboard the conventionally predicted track is presented as a circle segment to the right side as track for the time range of 5 min with a speed of 10.1 kn.

The dynamic prediction with the full simulation model is shown as blue curve. This dynamic prediction reflects the setting of rudder and propeller parameters shown in the left bottom window: The two rudders of the ferry used in this example are set to 14° Port and the Engine Order Telegraph for the two controllable pitch propellers are set to 100 % representing 159.8 rpm of the propeller. The actual pitch status is 53 and 54 respectively. This interface allows for a presentation of dynamic predictions of steering and stopping characteristics as an immediate response according to the current steering handle or engine order telegraph position.

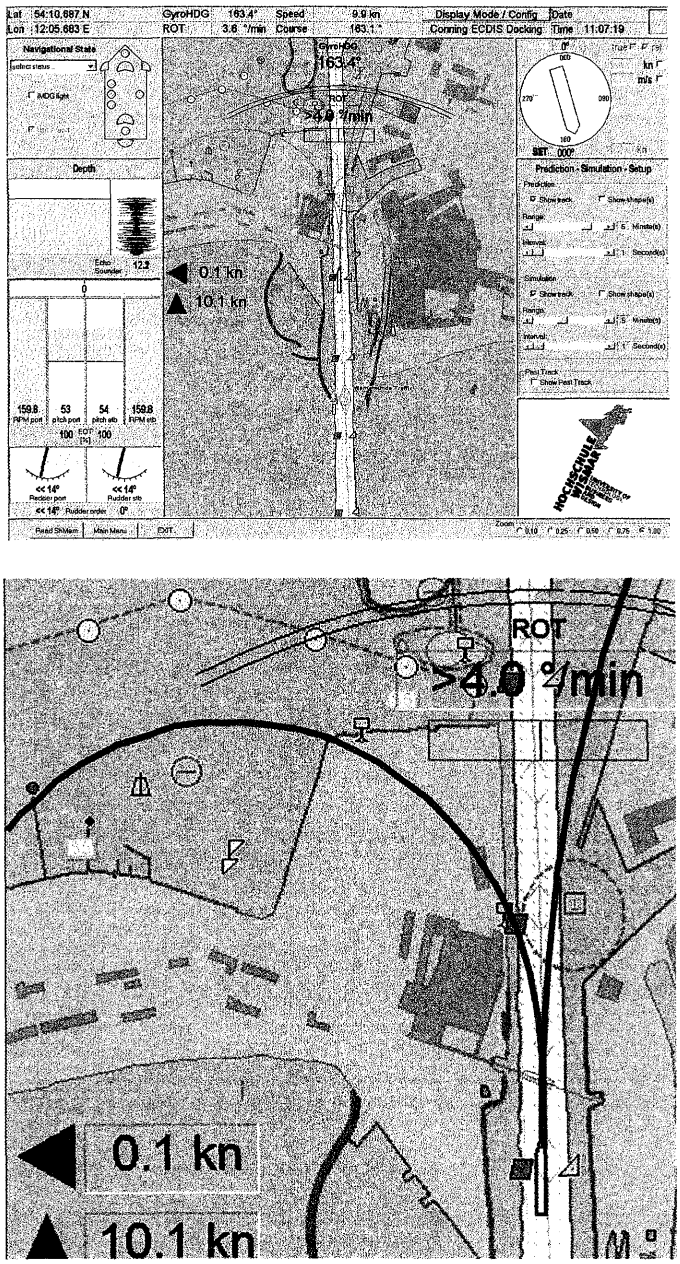

Fig. 4. Layout concept for Manoeuvring Prediction in ECDIS (left); Presentation of different track predictions (right) for rudder manoeuvres: a) Simplified prediction from integration Eq. (4) of current constant motion parameters (magenta track with small turning to STB) and b) Sophisticated dynamic prediction based on full math model Eq. (3) considering the change of rudder angle (too large!) to PT (blue track with turning to PT)

3. APPLICATION OF THE NEW DISPLAY FUNCTION IN SHIPHANDLING SIMULATOR AND SELECTED RESULTS OF TEST TRIALS

3.1. Test set up and scenario

For the purpose of testing the technical feasibility and user acceptance the new conning display with integrated prediction functions was implemented in the INS equipment of the large full mission simulator bridge of the Shiphandling simulator of MSCW. In Fig. 6 the bridge layout is shown for the experimental setup with the manoeuvring controls on the console in the foreground and the ECDIS / CONNING display on a separate display in the background.

The sample ship is the RO-PAX Ferry "Mecklenburg-Vorpommern" with Loa = 200m, Boa = 28,95 m, Draft = 6.2 m, Displacement = 22720 t and Speed = 22 kn. She has two pitch propellers and two rudders located behind the propellers and additionally one bow thruster.

Several test scenarios were developed and used for trials with ship officers and masters during test trials. One sample scenario is given in Fig. 6: the test area is the port entrance to Rostock Sea Port. A Ro-Pax-ferry is entering the port to be steered through the fairway and to be berthed in the dedicated basin. Before berthing the officer on watch has to turn the ferry in the turning area and to go astern to the berth.

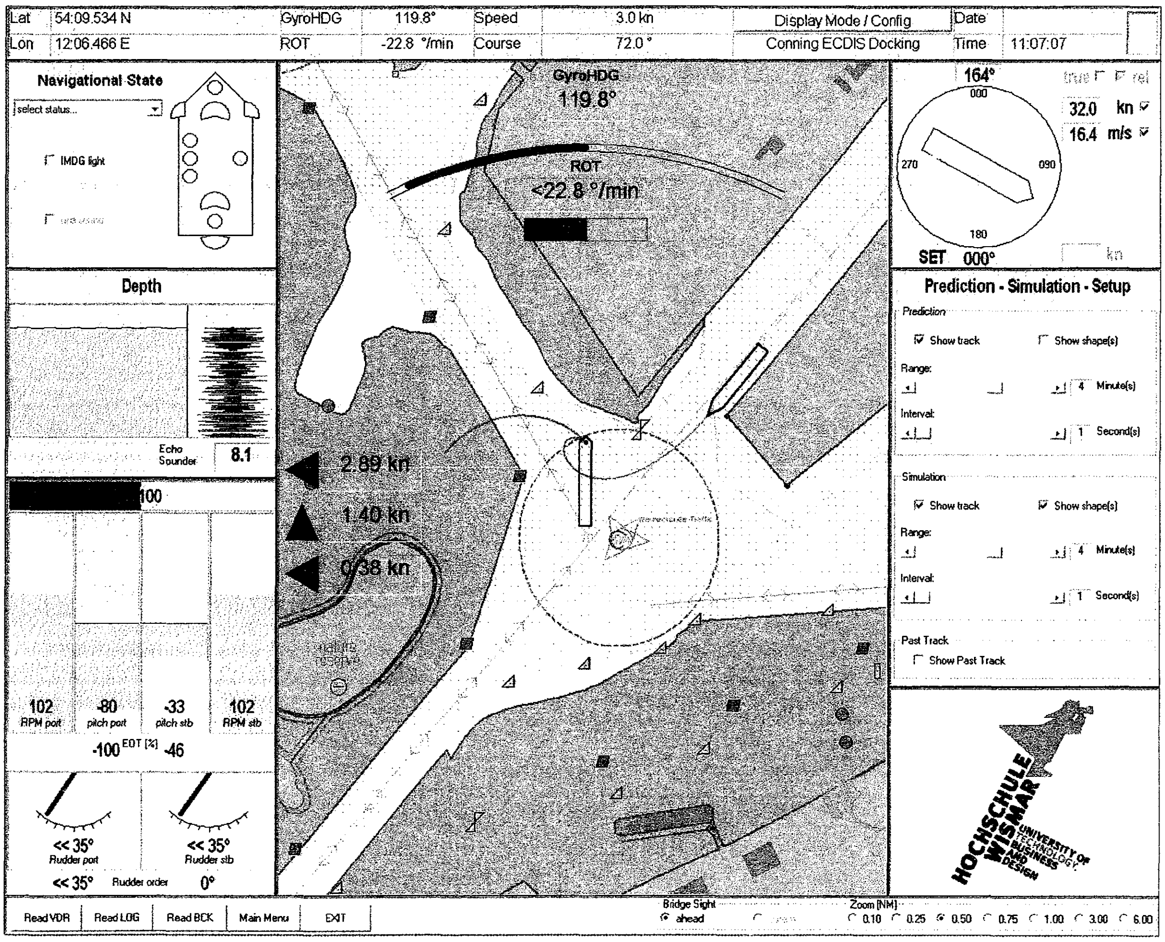

Fig. 5. Comparison of methods based on Different track predictions considering full rudder angle to PT and full astern: Simplified prediction from integration Eq. (4) of current constant motion parameters (left track, result from current PT turning of bow) and Sophisticated dynamic prediction Eq. (3) based on full math model (right track going astern and turning into harbour basin)

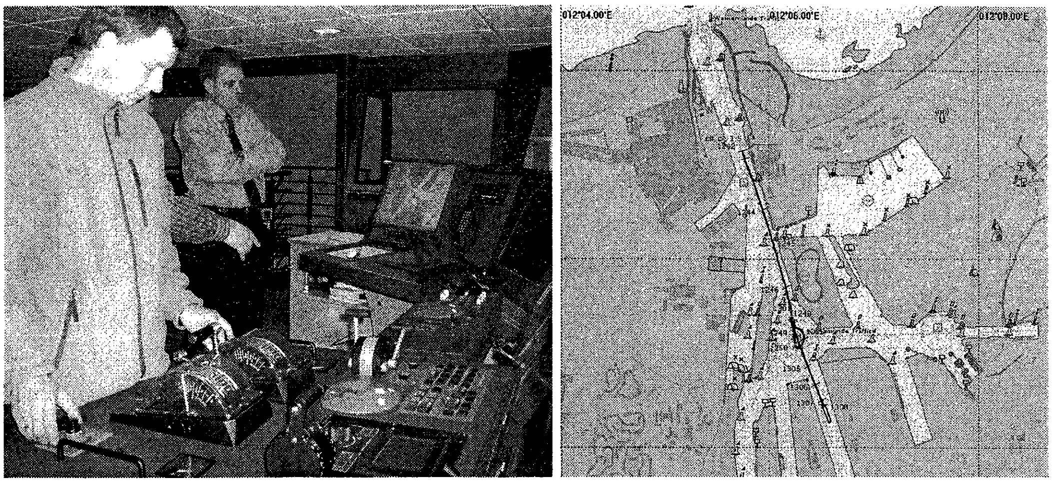

Fig. 6. Test setup for new Conning / ECDIS Display on Bridge 1 in Shiphandling Simulator during Test trials for new Prediction Display: Test area is sea port of Rostock in ECDIS presentation with scenario track of approach, turning manoeuvre and astern motion into ferry basin

3.2. Result of tests and discussion

The following series of figures will indicate the effect of the dynamic predictor and its advantage compared to the simplified look-ahead predictor. Whereas Fig. 4 showed the start of the scenario run in the fairway entrance Fig. 7 presents the predicted contours during the stopping manoeuvre at the turning area: It is clearly to be seen that the dynamic predictor allows the estimation of the stopping distance and even the consequence of going astern if the engine will be kept in reversed operation too long. In contrary the simplified predictor indicate a nearly straight motion with the constant speed at the beginning of the manoeuvre. After turning the ship by means of the bow thrusters the ship will be moved in astern direction into the harbour basin for berthing the vessel as can be seen from Fig. 8.

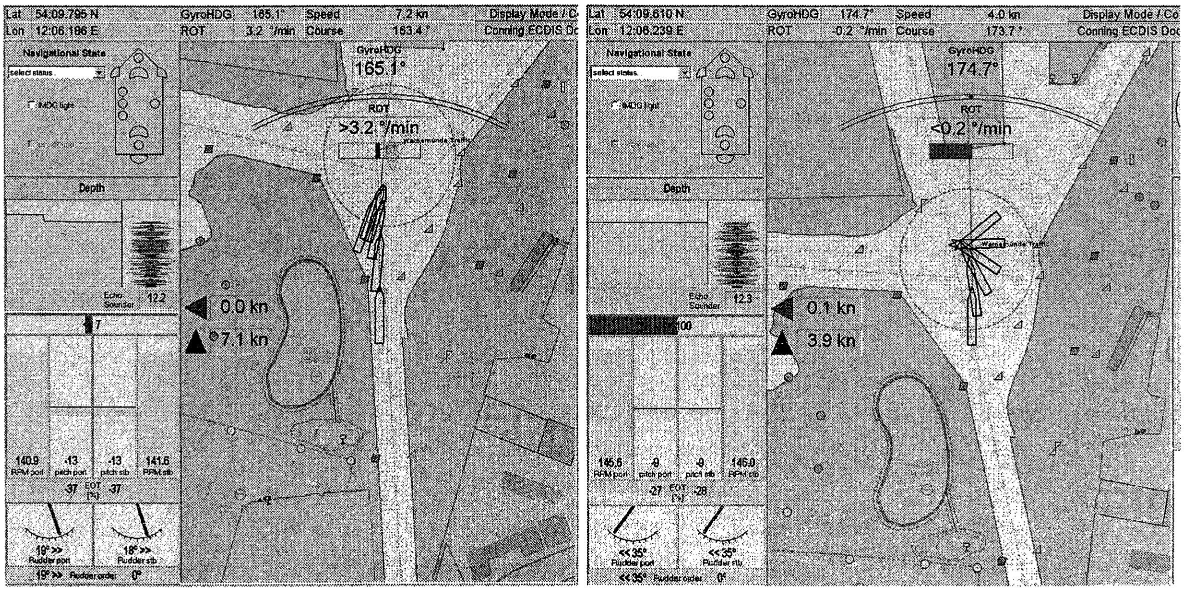

Fig. 7. Stopping manoeuvre at the turning area:

- predicted contours show the stopping distance and even the consequence of going astern if the engine will kept reversed operation too long (left), and
- Turning manoeuvre at the turning area: the ship is using rudders and bow thruster (right)

The user acceptance was assessed by using guided interviews and structured questionnaires. The first series of simulation trials were performed by eight experienced navigating officers and captains. The range of time at sea was between 5 years minimum and 25 years. Each participant started with an entry questioning and acted as captain after briefing. The bridge team was completed by a helmsman familiar with the manoeuvring facilities of the simulated ferry.

The most important result was that each participating navigator has reached the final goal without a crash already during his first trial. This is of special importance, because only one of the participants has practical experience with the ship used for the simulation study.

Although there are only results available from the series of the pilot trials some tendencies can be recognised: The overall assessment of the new Conning Display layout was ranked by the participants between minimum 6 and maximum 9 on a scale from 0 (worse, no enhancement) to 10 (excellent, practical and real assistance for my work). All participants summarised, that the fusion of conning information in combination with ECIDS is a new quality compared to conventional display layouts. The dynamic prediction was assessed as significant valuable element especially when only few or no experience is available in handling and manoeuvres the relevant ship or in harsh environmental conditions (Benedict [1], Baldauf [2]).

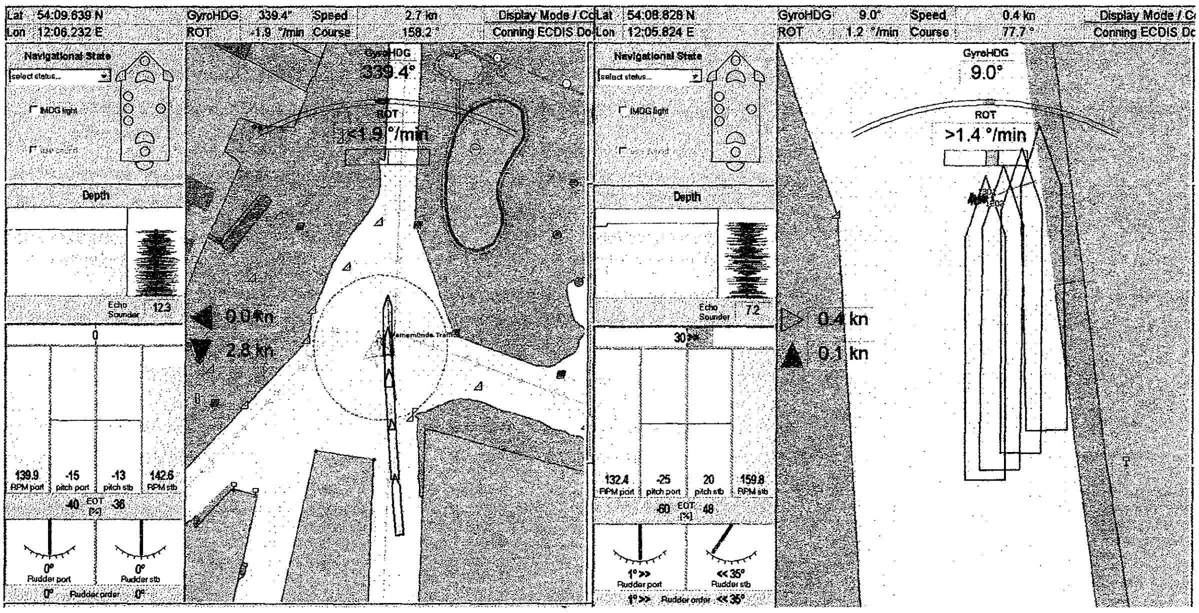

Fig. 8. Final phase of scenario: the ship is entering the basin for berthing (left) and is crabbing alongside the jetty (right)

4. PROVISION OF SHIP MODEL DATA FOR THE DYNAMIC PREDICTOR AND PARAMETER TUNING

4.1. Modelling of ships dynamic by means of fast time simulation tools

The quality of the math model for the simulation and the parameters in the equations are of high importance for the effectiveness of the dynamic prediction. There is a great need for fast and effective modelling / tuning processes not only for the predictor but also in Ship handling simulators where clients from shipping companies need to be trained on their ship types. This is the same procedure as we need for tuning the ship model parameters in the predictor.

If this modelling process is done manually by conventional tuning methods in the real Ship Handling Simulator (SHS) then there is high time consumption for this processes, up to one month or longer, because manoeuvre simulation is done in real time; even by using the simulator in "fast mode" – which is up to ten times faster – it is still to slow. Commonly there are no effective tools for supporting the modelling process, e.g. graphical comparison with analysis options. Moreover using the simulator for tuning of models generally means expensive occupation of simulator resources.

In order to avoid these problems PC-based simulation software was developed at MSCW with the same ships dynamic capabilities as the Ship Handling Simulator SHS (Benedict [5]) now to be used for the prediction tool. The Advantage and Capabilities of this software is: The Math Model reveals same simulation results as SHS, it is remarkably faster than real time simulation, the ratio is up to 1/100, the steering of simulator vessels is done by specific manoeuvre-control settings / commands for standard procedures and individual manoeuvres dedicated for tuning purposes.

4.2. SIMOPT & SIMDAT - tools for ship simulation model tuning

Fig. 9 show some details of the SIMOPT interface: The ships main data are displayed in the left part. The hull coefficients are displayed in the centre. Manoeuvres can be selected from the right top menu.

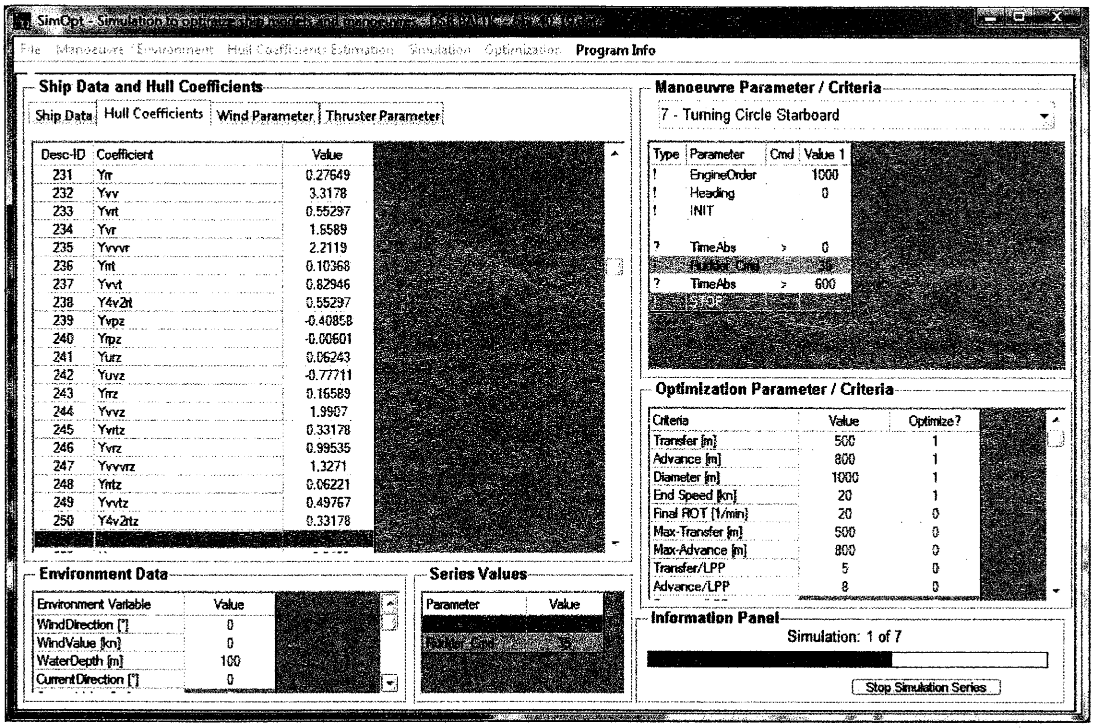

Fig. 9. SIMOPT Interface Elements – Overview: Ship Data (left) / Hull Coefficients, Manoeuvre Commands (top right) as well as Manoeuvre Optimisation criteria and Parameter series values

Several options can be chosen from the top menu in order to calculate the hull data and other parameters e.g. based on methods published in e.g. Oltmann [3], Clarke [6].

Manoeuvres can be selected from the right top menu. Simulations can be done either as single run or as simulation series for selection of up to 3 Parameter series to be simulated in parallel or sequential for:

- Simulation parameters, e.g. Manoeuvre series;
- Ship Parameters (L, B, T, or others);
- Hull / force parameters coefficient and
- Environmental data, e.g. wind force.

A specific new "Offline assessment tool" SIMDAT was originally designed at the MSCW to supply the instructor with semiautomatic assessment of the recorded exercise data in ship handling simulator (Benedict [4]). For the purpose of ships model parameter tuning and optimisation of manoeuvres this

SIMDAT tool was extended: The Data for the manoeuvring characteristics can now be automatically retrieved for all manoeuvres used for simulator ships tuning; enhanced Graphic tools are available for displaying various types of results.

The results of a particular evaluation are shown in Fig. 10. Additionally to the different graphical presentations specific overviews on the results are provided when series of manoeuvres have been simulated. This figure shows e.g. a comparison of simulation series results for turning circle with respect to Transfer, Advance, and Diameter. It can be presented in tables or in diagrams or used for optimization algorithms.

4.3. Sample of a Parameter – Optimisation series for a Ship model

The objective of the parameter optimisation or tuning process is to find suitable ship model parameter files which can be used in the simulator or in the predictor on-board to represent the real ships dynamic.

Starting from the ships main data a basic ship data file will be generated using simple methods e.g. Clarke estimation to have a first estimation of the dynamic behaviour. By means of the SIMOPT program the fast time simulation produces various results of manoeuvring characteristics which are retrieved by SIMDAT and compared with the manoeuvring characteristics of the real vessel. By adjusting the Model-Parameters the manoeuvring performance of Simulator Ship Model is improved. The final goal is to achieve an Optimised Ship Model-Parameter file which has to be applicable as ship model file for the dynamic predictor on the bridge of a ship. The biggest problem is that there are up to 200 parameters and the effect of the changes are not very clear; some changes may even have effects which counteracts the results of the others. Therefore it is very important to know about those parameters which have a clear impact on the manoeuvring characteristics.

One example is given to indicate the effect of tuning of one hull parameter; here the variation of ships moment of inertia I_z is given in Fig. 10.

For the demonstration a Parameter-Series of turning circles with Hard Rudder to Starboard was simulated varying the value of the factor kzz^2 which was initially 0.16 between 0.1 and 0.2 in steps of 0.01. During the simulation process the status of the execution is shown by means of coloured bars in the relevant data windows.

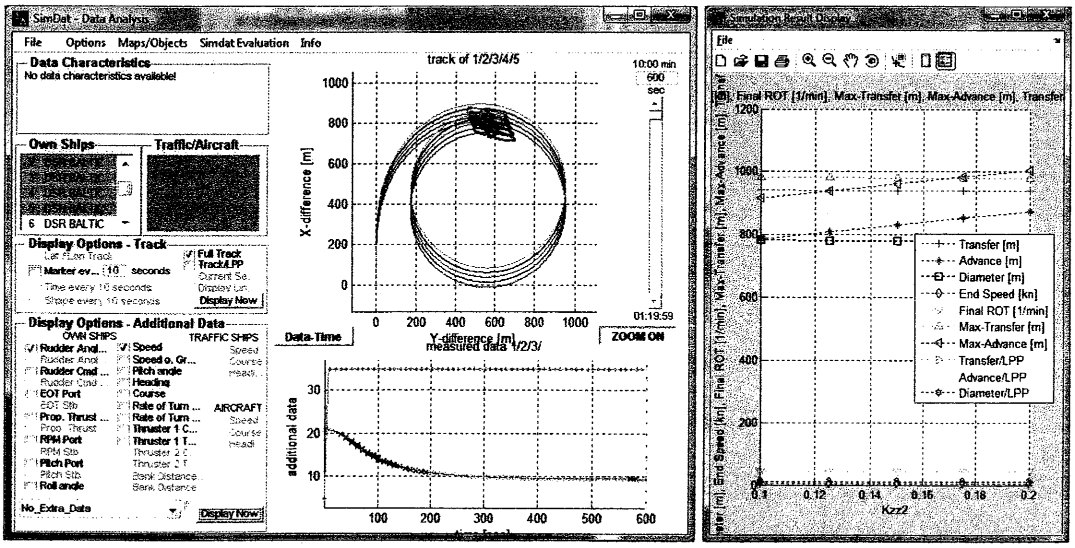

Fig. 10. Model tuning – Parameter series for changing Moment of Inertia for Turning circle tracks and speed plots (left); extract of characteristic manoeuvring data for turning circle in table format (right)

The result in Fig. 10 shows a clear effect on the advance of the turning circle whereas the diameter and the speed loss did not change. The optimization window shows parameters which can be set as target values for the optimization process.

5. CURRENT STATUS & OUTLOOK

5.1. Estimation the ship model parameters

The tuning of the ship parameter files from integrated data as Transfer, Advance, and Diameter used above will be supported by optimization methods in future.

In parallel there is an ongoing project to use Parameter estimation technologies for ship dynamic models from time history data sets (Project MULTIMAR).

For these purposes also test trials in real environment are intended. This will be an opportunity to make use of the new infrastructure given in the "Research Port Rostock" fully in operation since end of 2008. The installation of the infrastructure will serve as a GALILEO Satellite test bed and will provide e.g. pseudo-signals as a unique potential for maritime applications in the real port area of Rostock (Fig. 11).

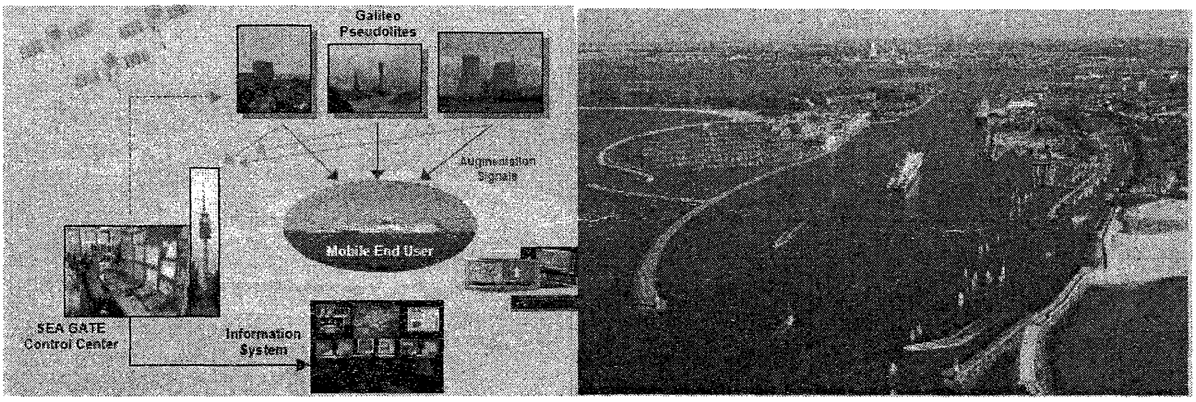

Fig. 11. GALILEO Infrastructure in research port Rostock: Setup of GALILEO pseudolites for simulation satellite communication as augmented test environment for users in maritime transport and cargo handling (based on research project SEAGATE by EADS / RST and DLR)

5.2. Extending the area of application for the prediction / simulation technology

The application of the predictor is currently extended in the ship handling simulator SHS of MSCW: It has proven some benefits for education and training because it enables the simulator instructor to immediately demonstrate complex manoeuvres in training sessions which needs less time in comparison to real time simulation.

Investigations for improving manoeuvres in ferry operation in the port of Rostock were made to analyse the performance specifically in the turning area. Analysing the VDR recordings from ferry approaches it was found that there is some space for improvements. Applying the predictor new strategies were found to save some minutes in this area which is very important in tight time schedules (Fehling [7]).

A new approach is under development trying a series of simulated manoeuvres to reach the final destination Fig. 13. Based on fast time simulation search methods are used to bring the ship into a harbour basin D by generating and evaluating sequences of elementary manoeuvres to find the optimal rudder and engine manoeuvres (Fischer [8]).

The simulation technology is also used to enhance Collision-Avoidance-Display in radar presentation Fig. 13 assisting for collision support by means of calculation of Risk based coloured areas (Baldauf [1]). This approach is using manoeuvring data of the ship which can be adjusted by simulation to actual manoeuvring capabilities of the Own Ship.

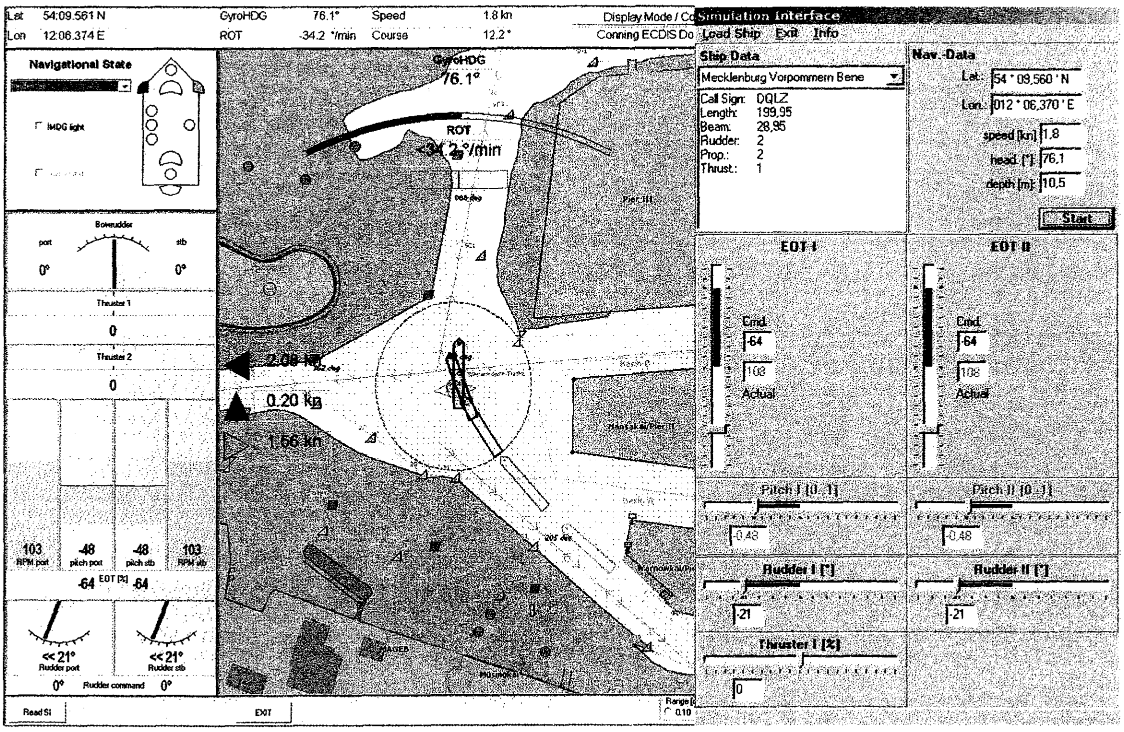

Fig. 12. Interface for Simulation / Trial mode based on manual input for simulated manoeuvres via the steering control panel on right sight of display for Manoeuvring Planning and training

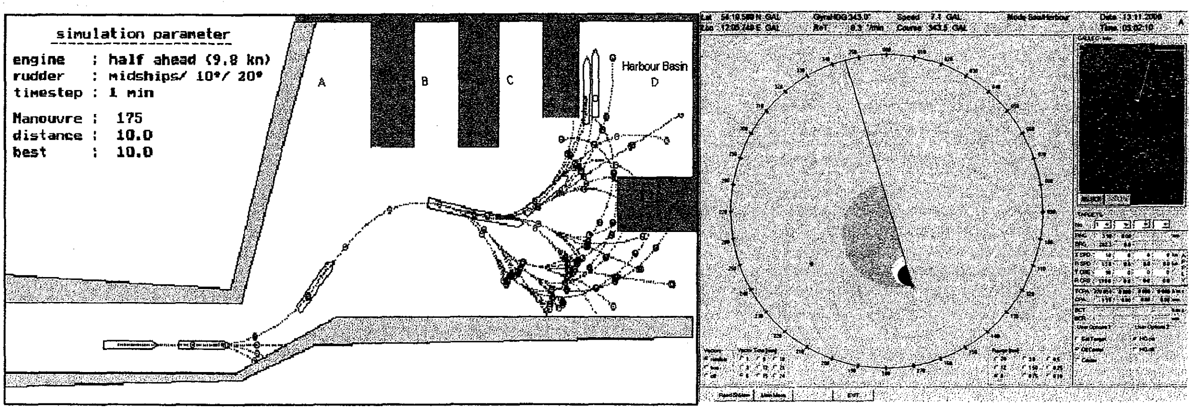

Fig. 13. Manoeuvring Planning methods based on search methods using simulated manoeuvring sequences (left) and Collision-Avoidance-Display in radar presentation (right) assisting for collision support with new approach for Risk based coloured areas using Manoeuvring Data Related to actual manoeuvring capabilities of the Own Ship

6. CONCLUSIONS & ACKNOWLEDGEMENTS

A concept for a prediction tool was designed and a prototype software module for an On-line Manoeuvring Assistance was developed based on a dynamic prediction tool using advanced simulation technology on board of ships. The results of rudder and engine control changes will be immediately displayed in an Electronic chart environment to be used for manual correcting steering actions. It was tested using the Maritime Simulation Centre Warnemuende. During the test trials several manoeuvring situations were managed with an increased performance when using the prediction tool.

The parameters for the ship model equations can be found using fast simulation techniques in the same way as for the tuning of ship models for the ship handling simulator. For the future it is planned to use optimization technology and parameter estimation technologies for ship dynamic model parameters.

The research results presented in this paper were partly achieved in research projects "Condition-based navigational displays" (ZUMANZ), "Safe passing distances of ships" (SIPAS) and "Identification of multi variable parameter models for ship motion and control" (MULTIMAR) funded by the German Federal Ministry of Economics and Technology (BMWi) and the Ministry of Education and Research of Mecklenburg-Pomerania, surveyed by Research Centre Juelich PTJ.

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