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MANOEUVRING PREDICTION TECHNOLOGIES IN SHIP HANDLING FOR TRAINING AND USE ON-BOARD - OVERVIEW & NEW DEVELOPMENTS -

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The company "Innovative Ship Simulation and Maritime Systems GmbH" (ISSIMS GmbH; www.issims-gmbh.com) is developing and maintaining the professional version of the SAMMON software tool used in this paper.

Keywords

Ship-handling, Manoeuvring Prediction, Simulator Training, Fast-time simulation, energy efficient operation

Abstract

In ship handling practice several manoeuvring prediction technologies are used to have a better insight into the development of ships motion. There is a historic development from very simple methods based only on the measurement of current ship motions up to high-tech innovative technologies where complex models of ship manoeuvring dynamics are used to forecast the response on commanded ruder, engine or thruster application or even external effects as wind and shallow water immediately for a suitable time period of the future motion.

In the paper the already known technologies will be compared with potential new methods from single up to multiple prediction and step ahead prediction with unrivalled extension of the decision horizon.

The SAMMON software system for "Simulation Augmented Manoeuvring Design, Monitoring & Conning" will be used to analyse the different prediction methods This system has been developed and matured over years, and promising experiences were made at the Maritime Simulation Centre Warnemuende MSCW.

The software is based on the innovative "Rapid Advanced Prediction & Interface Technology" (RAPIT) to simulate the ships motion with complex dynamic math models and to display the ships track immediately based on Fast Time Simulation in an Electronic Sea Chart.

Using this technology provides insights into the potential benefits in safe and efficient ship operation of the prediction methods discussed both for simulator training and future on-board application.

The benefits for increasing the effectiveness of lecturing and simulator training using these methods are obvious specifically for complex manoeuvring systems and will be made visible in this paper by using ships both with twin screw and azimuth propulsion for discussion of manoeuvring effects.

1 INTRODUCTION

1.1 OVERVIEW ON PREDICTION METHODS

In ship handling practice several manoeuvring prediction technologies are used to have a better insight into the development of ships motion.

There is a historic development from very simple methods based only on the measurement of current ship motions up to high-tech innovative technologies where complex models of ship manoeuvring dynamics are used to forecast the response on commanded ruder, engine or thruster application or even external effects as wind and shallow water immediately for a suitable time period of the future motion.

In the paper the already know technologies will be compared with potential new methods from single up to multiple prediction and step ahead prediction with unrivalled extension of the decision horizon:

- The simplest prediction is the speed vector giving only information about the momentary speed and the direction of motion.
- The path prediction reflects the momentary speed but also the turning motion of the vessel - therefore it can be seen as a speed vector with a curvature according to the amount of rate of turn
- The dynamic prediction shows the real path according to the steering commands provided by a simulation model
- The new step ahead prediction allows not only for on but at least for two or more manoeuvring segments
- Parallel prediction can be used to display and compare some of the previous prediction methods in parallel to give a better understanding of the motion and the precision of the prediction.
- Multiple Prediction is used for simulation of numerous manoeuvres to form a bunch of manoeuvring tracks of characteristic manoeuvres to allow an overview on the ship's domain.

The SAMMON software system for "Simulation Augmented Manoeuvring Design, Monitoring & Conning" will be used to demonstrate and analyse the different prediction methods. This system has been developed and matured over years, and promising experiences were made at the Maritime Simulation Centre Warnemuende MSCW.

1.2 SHORT INTRODUCTION OF THE SAMMON SOFTWARE

The software is based on the innovative "Rapid Advanced Prediction & Interface Technology" (RAPIT) to simulate the ships motion with complex dynamic math models and to display the ships track immediately based on Fast Time Simulation in an Electronic Sea Chart. Using this technology provides insights into the potential benefits of the prediction methods discussed both for simulator training and future on-board application.

The SAMMON system represents the full information from Ships' manoeuvring documentation and additional trial measurements, which have been condensed in a complex ship dynamic simulation model, capable of simulating environmental effects. Even with standard computers it simulates 1000 times faster than real time: in 1 second computing time it simulates a manoeuvre taking up to 20 minutes. This technology was initiated in research activities of the "Institute for Innovative Ship Simulation and Maritime Systems" ISSIMS at the Maritime Simulation Centre Warnemuende MSCW, which is a part of Hochschule Wismar, University of Applied Sciences - Technology, Business & Design in Germany, specifically in its Department of Maritime Studies, Systems Engineering and Logistics. The technology has been further developed and is maintained by the company ISSIMS GmbH [2].

There are several modules of the fast time simulation system (FTS):

- The centre element SAMMON is the innovative system for "Simulation Augmented Manoeuvring – Design, Monitoring & Conning". It comprises several software modules, the two most important are (a) the Manoeuvring Design & Planning Module and (b) the Manoeuvring Monitoring & Conning Module with Multiple Dynamic Manoeuvring Prediction. These modules are made for both for lecturing and simulator training for ship handling and also to assist manoeuvring of real ships on-board, e.g. to pre-pare manoeuvring plans for challenging harbour approaches / departures.
- Important tools are made to support SAMMON, e.g. the SIMOPT software for modifying ship math model parameters both for simulator ships in Ship Handling Simulators (SHS) and for on board application of the SAMMON System and the SIMDAT software module for analysing / displaying simulation results both from simulations in SHS or SIMOPT /SAMMON and from real ship trials [2].

The interface of the SAMMON Manoeuvring Design & Planning tool combines the following windows (see Fig. 1)

- The right window represents the steering / control panel: this is for adjusting the controls for the selected actual Manoeuvring Point MP (actual position in red) or entering the environment conditions e.g. wind, current and water depths (bottom right),
- The centre window displays the electronic navigational chart (ENC) where the simulated ship's motion is visualised: the ships positions are shown as black contours indicating in time intervals for the display range. The reference position can be shifted by means of the time slider at the bottom to any position of the already predicted track. There a new MP can be set and controls may be changed there,
- The left and top window display the ship status at the reference ship position on the track, indicated as ship shape in blue colour in the ENC – this status is defined by e.g. the current navigation data and actual ship manoeuvring control data.

The benefits for increasing the effectiveness of lecturing and simulator training using these methods are obvious specifically for complex manoeuvring systems and will be made visible in this paper by using ships both with twin screw and azimuth propulsion for discussion of the manoeuvring effects.

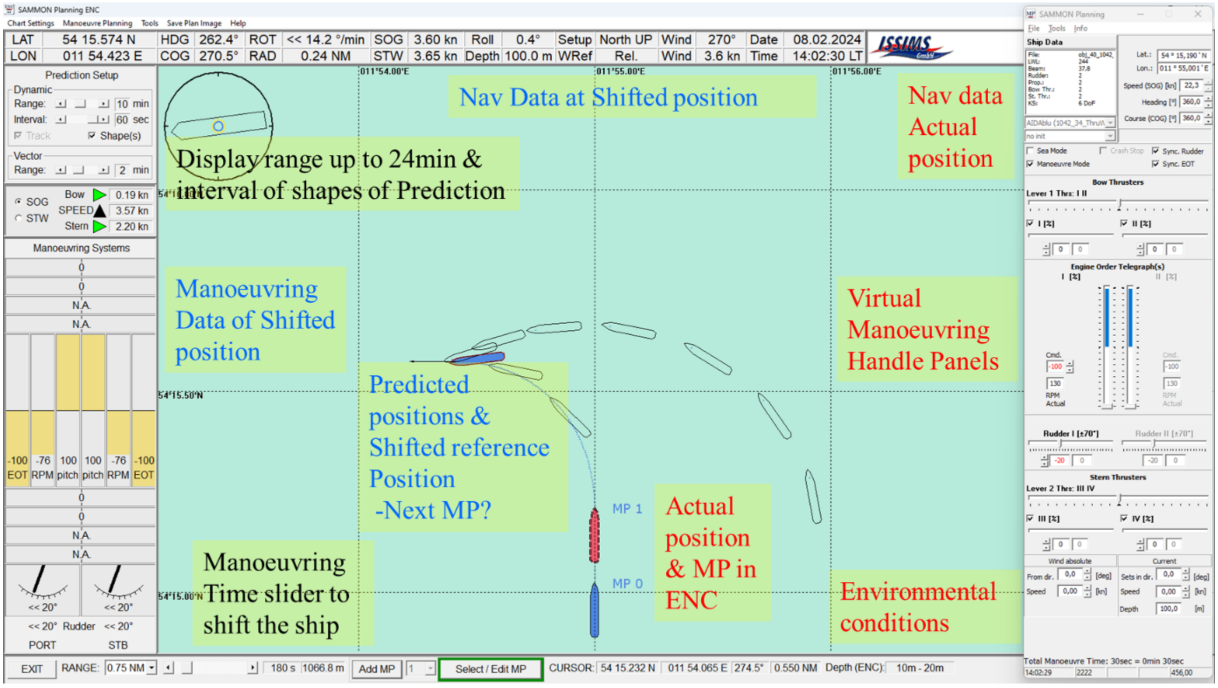


Fig. 1 Interface elements of SAMMON Manoeuvring Design & Planning tool with additional comments (more information under YouTube [3].

2 SPEED VECTOR AS SIMPLE PREDICTION AND USE FOR STOPPING DISTANCE INDICATION

The speed vector is an indication for the momentary speed of the vessel and also for the direction of motion.

- The vector is pointing into the momentary direction of motion of the vessel. That means when moving in a turning circle the speed vector is a tangent to the circular track.
- Normally the length of the vector can be adjusted in its length e.g. from 1 to 6 min. This means, the vector shows the distance along the ship is moving in this time period.

The length of this vector can be used as a reference length for manoeuvring characteristics which are depending on the speed of the vessel, e.g. for comparison with the stopping distance from a certain initial speed, specifically when the ship is moving on a straight track.

One of the elements during the lectures in simulator training courses is the familiarisation with the ship manoeuvring characteristics and its effective application – and SAMMON is a very smart tool to do this in a short time and with high success. The following example addresses the ships stopping capability. Specifically, for the samples in this paper a mathematical model of the cruise ship "AIDAblu" is used. This ship has the following dimensions: length LPP= 244.6m, beam B=32.2m, mean draft Tm= 7.00 m. The ship is equipped with two pitch propellers, two rudders and two thrusters each at the bow and at the stern.

To get an overview on the ships stopping distances from several speeds and with various astern power, some test trails could be done either with the Design & Planning tool (Fig. 2) or with the SIMOPT and SIMDAT program (Fig. 3).

By means of the Planning tool (Fig. 1) the ship can be set in the chart window on an initial position MP0 (Fig. 2, bottom) where the initial speed can be adjusted using the handles in the right window. Then the ship is moved by the time slider at the bottom of the chart window, e.g. to a position after 1 min and there the MP 1 is set pressing "Add MP". Then the handles at this MP1 are used to reverse the engine to EOT=-100% and immediately the stopping position can be seen on the chart window.

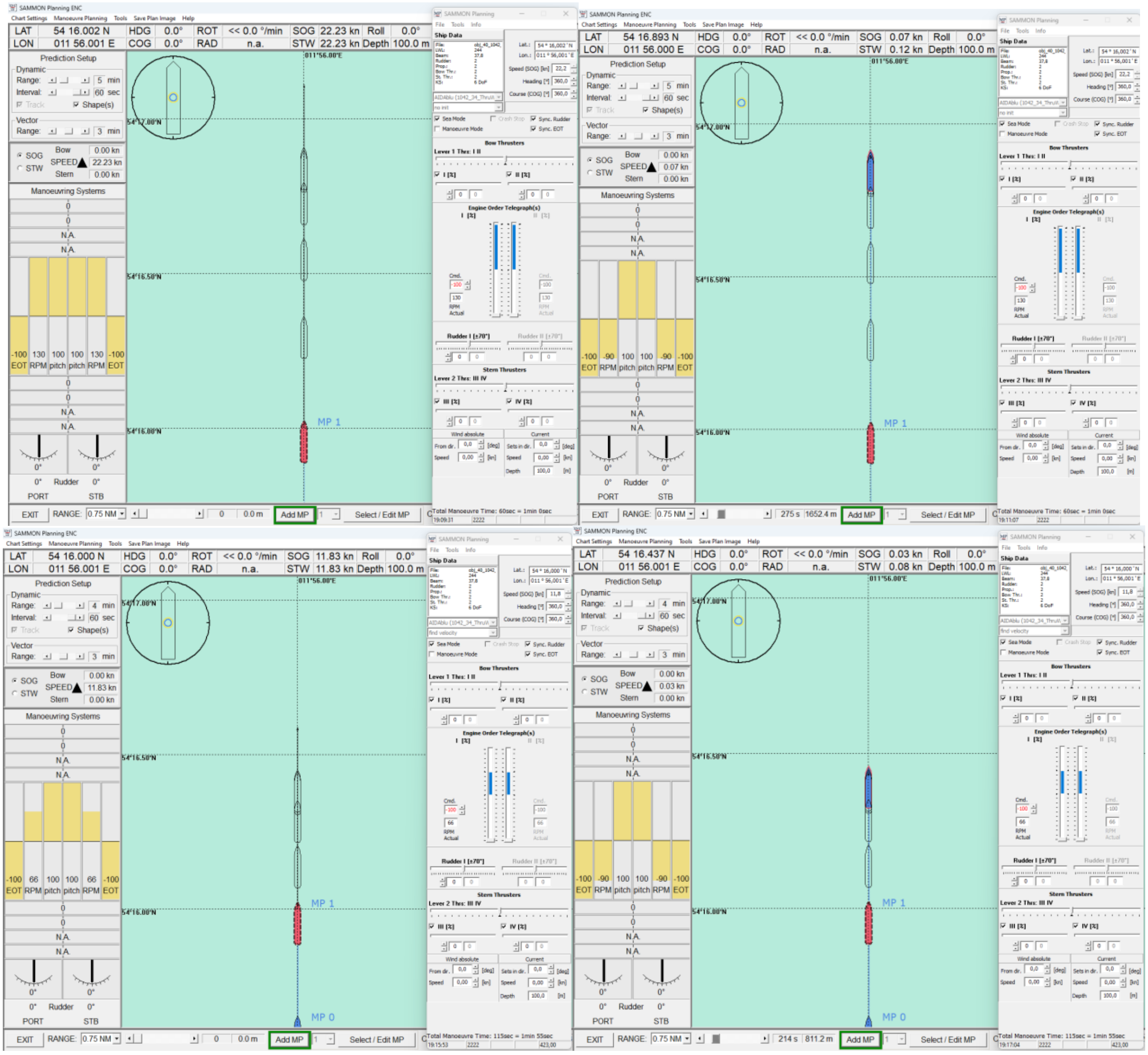


Fig. 2 Display of the Manoeuvring Design & Planning Module: Two stopping manoeuvres for Cruise ship from different speed rates to Full Astern (EOT=-100%):

- Top: Crash stop from Full Ahead (EOT=+100% for 22, 2 kn) at MP1
- Bottom: Stopping manoeuvre from Half Ahead (EOT=+50% for 11.8 kt) at MP1

As long as such a sophisticated dynamic prediction tool is not available on the bridge or in the simulator yet, it is helpful to use the speed vector as alternative, because it shows the distance the ship runs in the vector time set. The basic idea is to adjust the speed vectors' length to the stopping distance: The required speed vector length can be easily calculated from the well-known relation speed = distance /time, which can be changed to time = distance / speed. From this equation, we can calculate the Vector time and this is

$$t_{vector} = \text{Stop way / Starting speed} \qquad (1)$$

e.g. the Crash Stop Stopping Distance 1600m from starting speed 22 kn (12 m/s) gives:

$$t_{vector} = 1600 \text{ m} / 12\text{m/s} = 138 \text{ s} = 2{:}18 \text{ min.} \qquad (2)$$

With the SIMOPT tool, series of pre-scripted manoeuvring procedures can be simulated in very short time. In Fig. 3 the results from several stopping manoeuvres are shown for several engine orders, specifically for the stop-way from the starting speed and the vector time, the diagram shows the graphic presentation. These calculations were done for all stopping distances of the solid lines in Fig. 3 (bottom) in order to get the broken line graphs for the respective vector times. The result is, that for all stopping manoeuvres with Full Astern (EOT=-100%; red line) the vector time is lower than 2.5 minutes (red broken line); and for stopping manoeuvres with Slow Astern (EOT=-30%, blue line) the vector time is lower than 3 minutes (blue broken line).

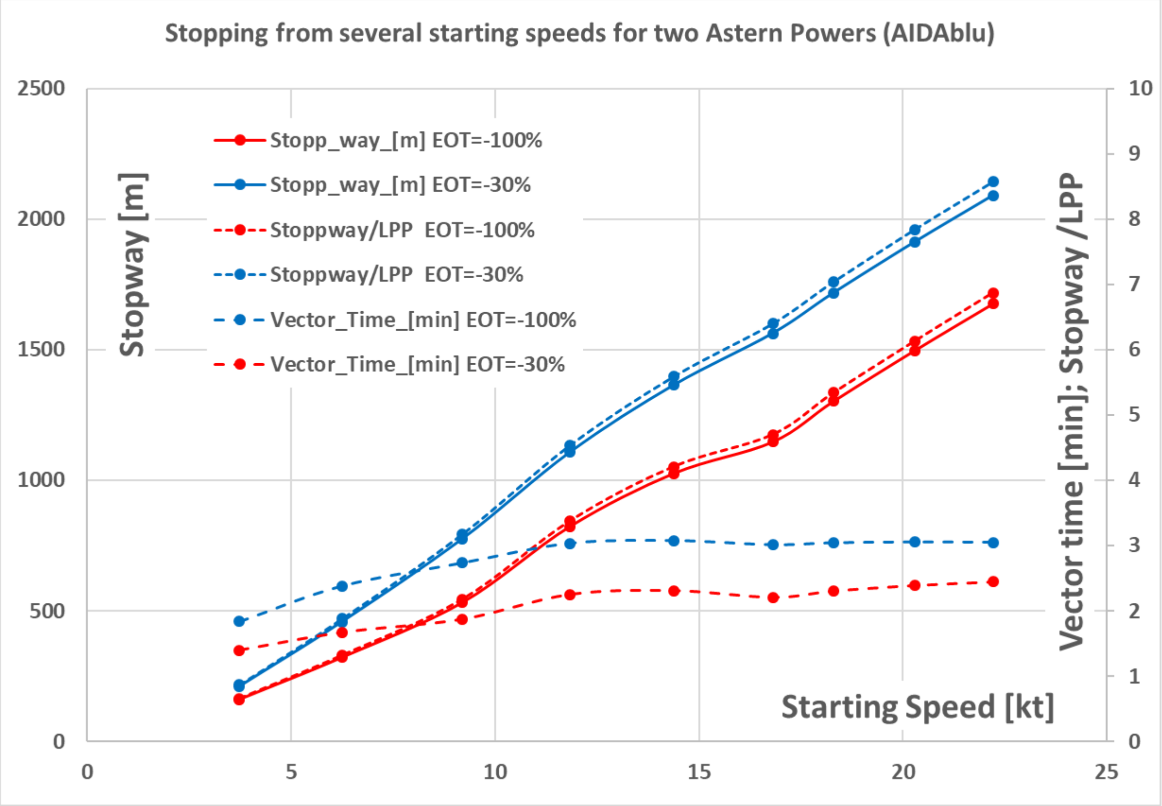


Fig. 3 Stopping diagram for distances (solid lines in [m], dotted lines divided by LPP) and respective times for speed vector length (broken lines) from series of stopping manoeuvres for several Ahead speed rates from EOT =20 to 100 % and for two Astern power variants with EOT= – 100% and -30% for model of cruise ship AIDAblu (SIMOPT program: Computing time 17 sec, visualised in SIMDAT program)

This knowledge can be applied in practice as can be seen in Fig. 4 where the ship stops from 6.2 kt when entering the turning area of Rostock Port: With Full Astern EOT = -100% the black dotted ship shapes show that the ship comes to a hold sufficiently before the end of the 3 min speed vector; and even with the lower Astern Power she stops earlier than the 3 min vector.

Therefore, the conclusion might be: Setting the speed vector for t_{vector} = 3 min would give some extra safety distance reserve and would even allow to stop the ship with lower Astern power of EOT= -30% only!

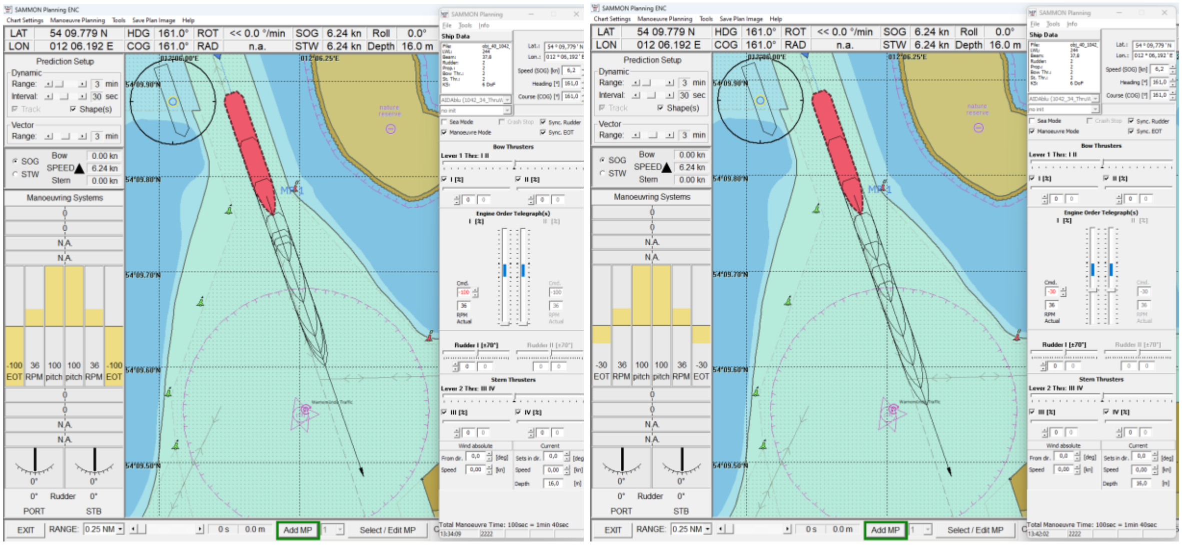
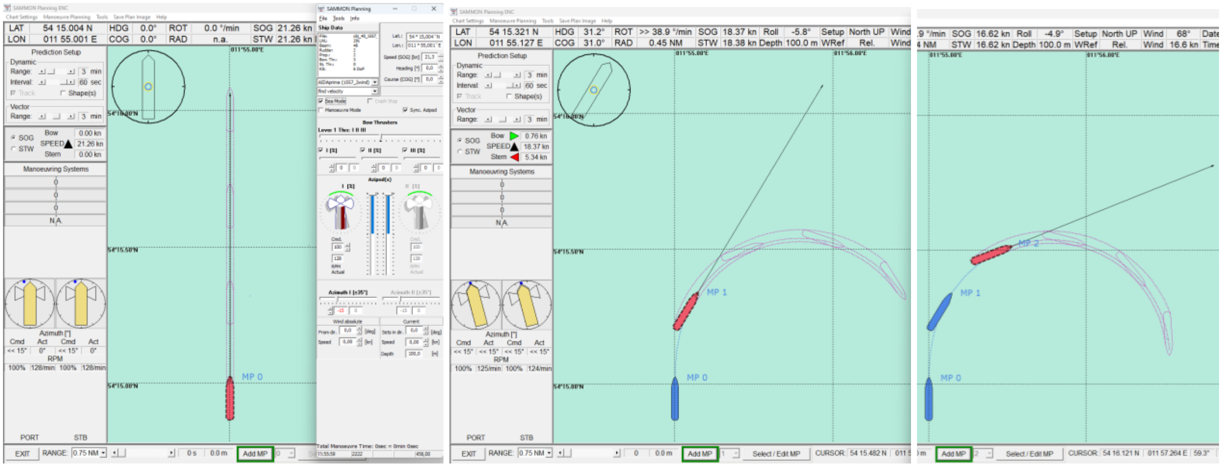


Fig. 4 Display of the SAMMON Planning Module with stopping manoeuvres for AIDAblu from Dead Slow Ahead (EOT 30%, 6.24 kn) to Full Astern EOT=-100% (left) and Dead Slow Astern EOT -20% (right) for Comparison of dynamic prediction (black dotted shapes, starting from red contour) with the speed vector (black arrow) set to 3 min.

3 STATIC PATH PREDICTION AS INDICATION OF CURRENT MOTION STATUS

Path Prediction is a well-known feature in various bridge navigation or pilotage systems to be used in ENC or Radar image environment. It is based on a simple method to use the momentary ship speed and rate of turn as constant and integrate these values over time. The result is a track in form of a circle segment with constant curvature and the positions of the ship are shown as equidistant ship shapes on that circle. This means for a turning manoeuvre as for the podded ship in Fig. 5 in the first moment after rudder action when the ship is not turning yet then the predicted path, presented by the magenta shapes, which are lined up in a straight line (top) – same as the speed vector. When the ship starts turning then the predicted track is bending according to the momentary rate of turn. This means the information of the future track is not very informative in the first phase of a turning manoeuvre. The prediction is always changing, allowing only for information on the tendency of the turning direction and the change in rate of turning. Only when the rate of turn and the ship speed has reached its constant, steady state motion status then the predicted track is equal to the future ships motion.


LAT 54 15.004 N HDG 0.0° ROT 0.0 °/min SOG 21.26 kn
LON 011 55.001 E COG 0.0° RAD n.a. STW 21.26 kn

LAT 54 15.321 N HDG 31.2° ROT >> 38.9 °/min SOG 18.37 kn Roll -5.8° Setup North UP Wind
LON 011 55.127 E COG 31.0° RAD 0.45 NM STW 18.38 kn Depth 100.0 m WRef Rel. Wind

.9 °/min SOG 16.62 kn Roll -4.9° Setup North UP Wind 68° Date
4 NM STW 16.62 kn Depth 100.0 m WRef Rel. Wind 16.6 kn Time

Fig. 5 Samples for Static Path Prediction (magenta ship shapes) in SAMMON Planning for a turning manoeuvre of a ship with Azimuth Propellers 15° PT

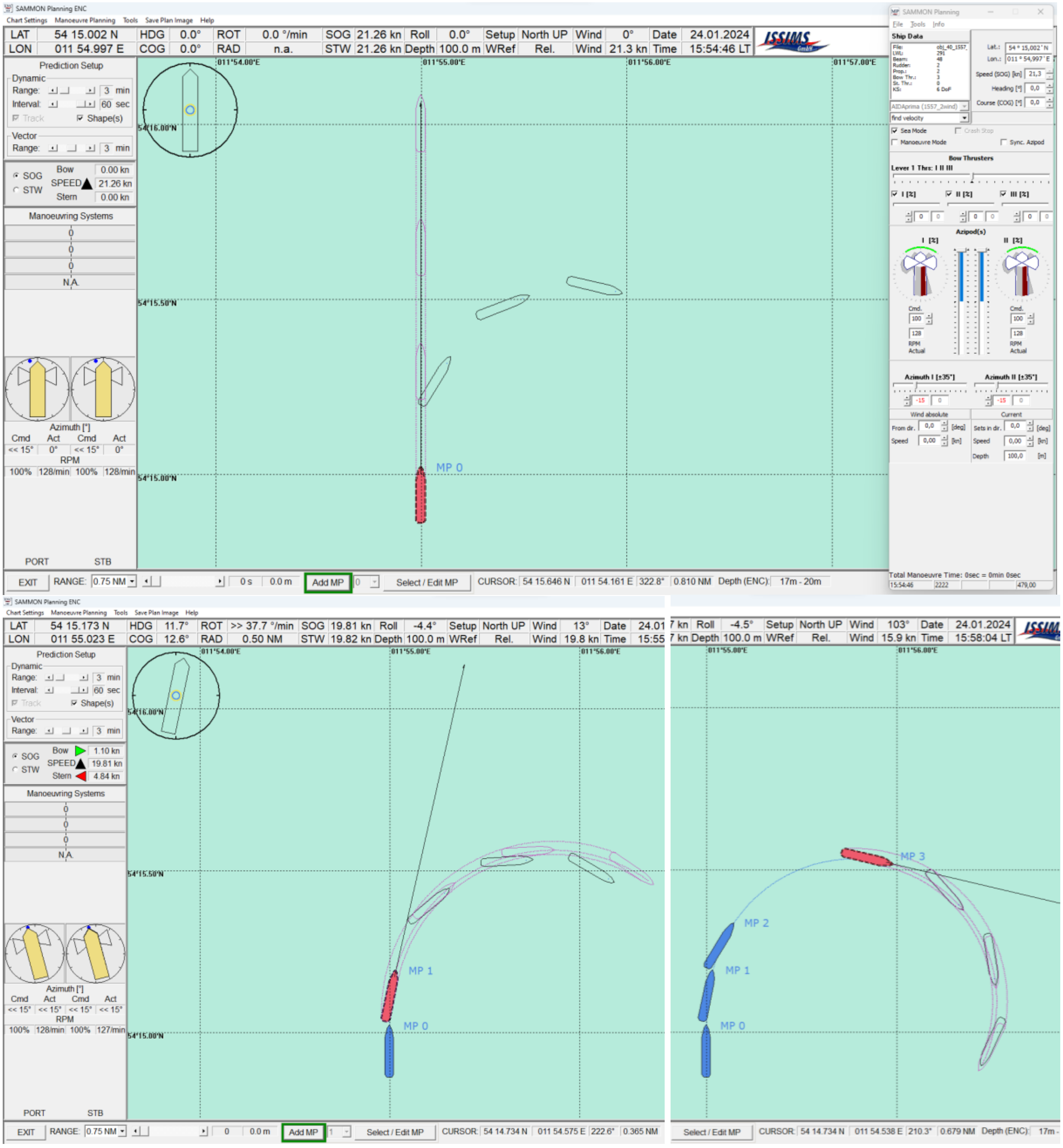
- Left: Start of the manoeuvre – the prediction is still straight line
- Centre and Right: Beginning of turning after 1 min and 2 min – The predicted track shows a circle segment with increasing rate of turn and shapes in equal distances according to the momentary ship speed taken as constant along the predicted track

4 DYNAMIC MANOEUVRING PREDICTION AS DESCRIPTION OF FUTURE MOTION OF SHIP

In contrast to the static prediction, the dynamic prediction immediately shows the future track following the command input given, even if the pod has not changed its position.

In Fig. 6. a sample is shown comparing both static and dynamic prediction methods for the start of a turning manoeuvre with a cruise ship with azimuth propellers: at the beginning of the turning manoeuvre when the rate of turn is still zero (top) both predictions are totally different because only the dynamic prediction shows the future track. The more the ship starts turning (bottom), the static prediction changes and the track and the distances of the shapes becomes more and more identical with the dynamic prediction and are equal when the steady state condition are reached with constant speed and turning rate.

In case the rudder will be changed (Fig. 7) then the dynamic prediction immediately shows the reaction and the future track: the dynamic prediction shows immediately the decrease of turning due to the TOE-IN 15° position, whereas the static prediction remains a circle for a certain time, according to the existing rate of turn.



SAMMON Planning ENC

LAT 54 15.002 N | HDG 0.0° | ROT 0.0 °/min | SOG 21.26 kn | Roll 0.0° | Setup North UP | Wind 0° | Date 24.01.2024
LON 011 54.997 E | COG 0.0° | RAD n.a. | STW 21.26 kn | Depth 100.0 m | WRef Rel. | Wind 21.3 kn | Time 15:54:46 LT

EXIT | RANGE: 0.75 NM | 0 s | 0.0 m | Add MP | Select / Edit MP | CURSOR: 54 15.646 N | 011 54.161 E | 322.8° | 0.810 NM | Depth (ENC): 17m - 20m

Total Manoeuvre Time: 0sec = 0min 0sec

LAT 54 15.173 N | HDG 11.7° | ROT >> 37.7 °/min | SOG 19.81 kn | Roll -4.4° | Setup North UP | Wind 13° | Date 24.01
LON 011 55.023 E | COG 12.6° | RAD 0.50 NM | STW 19.82 kn | Depth 100.0 m | WRef Rel. | Wind 19.8 kn | Time 15:55

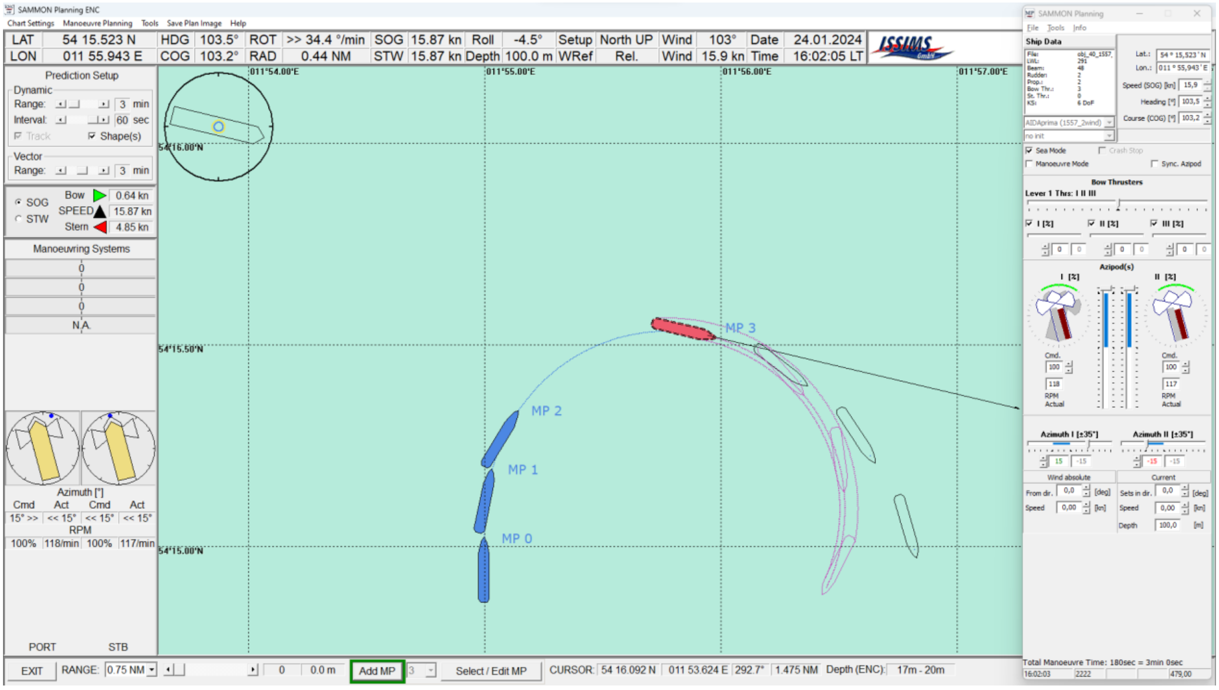
Roll -4.5° | Setup North UP | Wind 103° | Date 24.01.2024
Depth 100.0 m | WRef Rel. | Wind 15.9 kn | Time 15:58:04 LT

EXIT | RANGE: 0.75 NM | 0 | 0.0 m | Add MP | Select / Edit MP | CURSOR: 54 14.734 N | 011 54.575 E | 222.6° | 0.365 NM

Select / Edit MP | CURSOR: 54 14.734 N | 011 54.538 E | 210.3° | 0.679 NM | Depth (ENC): 17m

Fig. 6 Presentation of dynamic prediction (black shapes) and comparison with the static prediction (magenta shapes) in SAMMON Planning for a turning manoeuvre of a ship with Azimuth Propellers 15° PT

- Top: Situation at the beginning of the turning manoeuvre right after the rudder command
- Bottom: Situation after 30s (left) and 180s (right) after initiating the manoeuvre at MP0



SAMMON Planning ENC

LAT 54 15.523 N | HDG 103.5° | ROT >> 34.4 °/min | SOG 15.87 kn | Roll -4.5° | Setup North UP | Wind 103° | Date 24.01.2024
LON 011 55.943 E | COG 103.2° | RAD 0.44 NM | STW 15.87 kn | Depth 100.0 m | WRef Rel. | Wind 15.9 kn | Time 16:02:05 LT

Prediction Setup
Dynamic Range: 3 min
Interval: 60 sec
☑ Track ☑ Shape(s)
Vector Range: 3 min
● SOG ○ STW
Bow 0.64 kn
SPEED 15.87 kn
Stern 4.85 kn

RANGE: 0.75 NM
CURSOR: 54 16.092 N 011 53.624 E 292.7° 1.475 NM Depth (ENC): 17m - 20m
Total Manoeuvre Time: 180sec = 3min 0sec

Fig. 7 Presentation of dynamic prediction (black shapes) and comparison with the static prediction (magenta shapes) in SAMMON Planning for a turning manoeuvre of a ship with Azimuth Propellers 15° PT: Rudder manoeuvre from steady state turning only with the PT pod commanded 15° SB to starboard to TOE-IN 15°

The SAMMON Planning tool allows with its dynamic predictions an unrivalled opportunity for demonstrating ship dynamics during lecturing and also individual student training on laptops using the on-screen manoeuvring handles. It is unique in providing more predictions at the same time and with this functionality to build up a full manoeuvring plan for arrival / departure manoeuvre for the approach and in ports as in the following chapter.

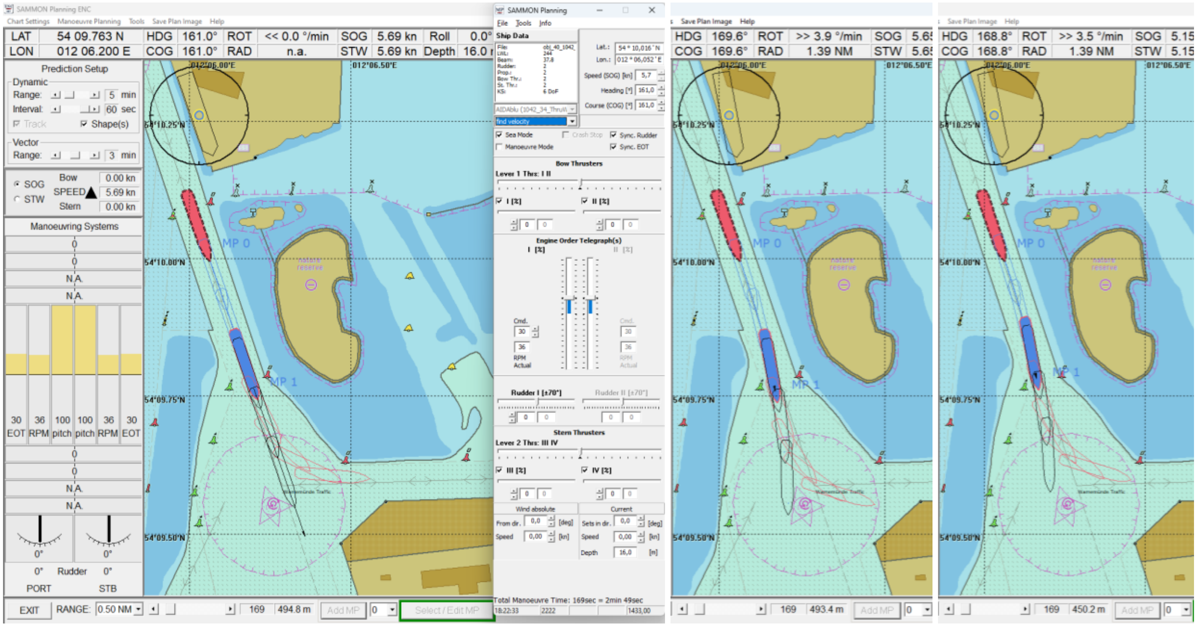
5 EXTENDED PREDICTION FOR WIDER HORIZON IN MANOEUVRING PROCESSES

The predictions discussed above are providing the look ahead for the next manoeuvre only. However, it happens quiet often that the previous manoeuvre was not sufficient and therefore the next manoeuvre ahead cannot be performed successfully. Therefore, the so called "Edit Mode" was developed as feature of the Planning tool in order to allow to jump back on previous MPs to correct the commands there sufficiently.

A great support can be given by presenting the prediction for not only one but at least two manoeuvring segments ahead as shown in Fig. 8 for the approach to the turning area of Rostock Port. In the left figure the black shapes represent the prediction from the current position MP 0 with command settings shown in the manoeuvring panel on the right side set to Rudder Midships and both engines EOT +30%. The red shapes represent the prediction for the next manoeuvre, planned from the blue shape to turn in the side arm which is pre-planned with split engines and rudders 20° PT (see Fig. 9 left). Both predictions are calculated in parallel, therefore the whole manoeuvre can be controlled at MP0: for instance, by changing the rudder (centre) the whole prediction chain will turn, or by changing the engine then the starting position of the next manoeuvre will be moved and comes closer for reducing the EOT (right). This is a good opportunity to adjust commands for instance when wind or other forces are coming into the scenario.

In Fig. 9 the turning into the side arm is shown together with proceeding until the end and prepare for turning into the basin for berthing. In Fig. 10 the final phase is shown for a stopping manoeuvre to prepare for berthing and for the final approach to the berth. The second prediction in red always gives a good indication whether the manoeuvre is suitable. In the left figure the stopping manoeuvre is shown and specifically where the transverse motion can be started. In the right figure the transverse motion is started by using bow and stern thruster and it is to be seen that the concept is successful, because the red shapes are squeezed together close to the berth indicating that the ship is to be stopped there safely by reversing the thrusters.

This series of actions in Fig. 8 to Fig. 10 shows how easy it is to prepare a full manoeuvring plan and the benefits to get information and learn about the manoeuvring behaviour of the ship. The operational interface on the screen allows for comfortable use on a laptop, both for lecturers and for trainees, in simulators or on board.



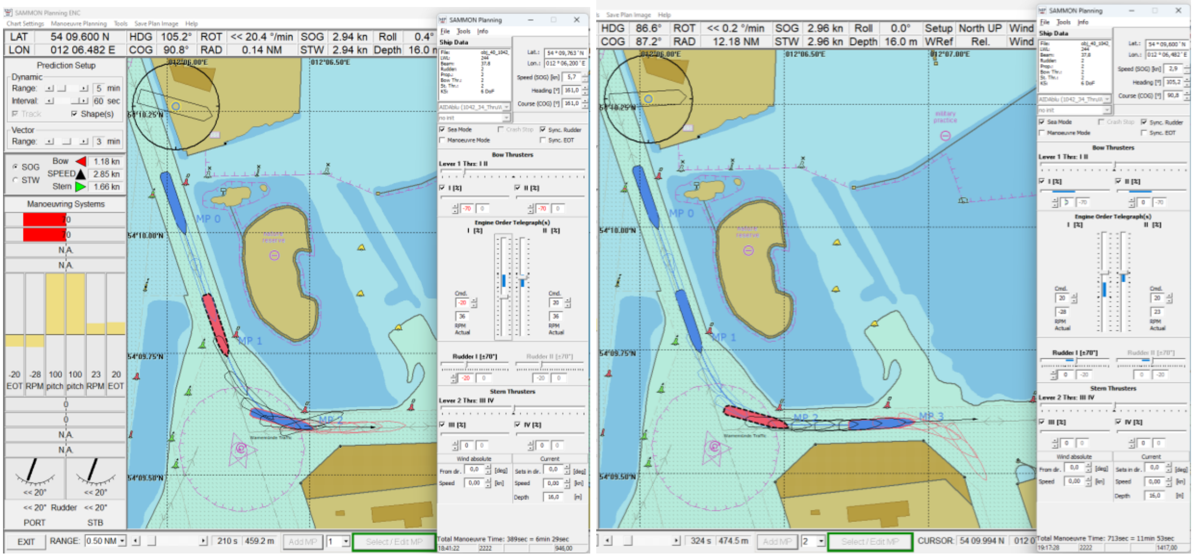
LAT 54 09.763 N HDG 161.0° ROT << 0.0 °/min SOG 5.69 kn Roll 0.0°
LON 012 06.200 E COG 161.0° RAD n.a. STW 5.69 kn Depth 16.0

HDG 169.6° ROT >> 3.9 °/min
COG 169.6° RAD 1.39 NM

HDG 168.8° ROT >> 3.5 °/min SOG 5.15
COG 168.8° RAD 1.39 NM STW 5.15

Fig. 8 Sample for Intelligent prediction with two simulated steps ahead for a turning manoeuvre into the side arm at Rostock Port (Black shapes: first prediction at current position; Red shapes: second prediction from the blue shape reference position)

- Left: Approach to the turning area and Rudder Midships at MP0, next manoeuvre is the turning manoeuvre at MP1 prepared with commands to achieve the track ahead with red shapes
- Centre: control action at MP0 - Change of Rudder to 3°SB
- Right: additional control action at MP0 - EOT 28% was reduced on top of Rudder to 3°SB

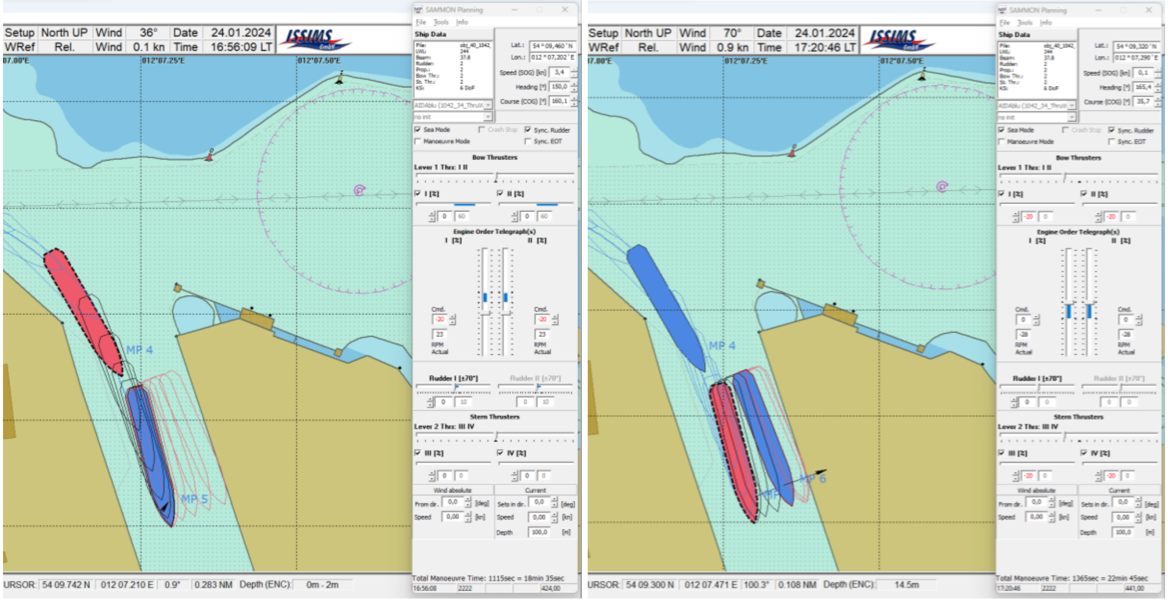


LAT 54 09.600 N HDG 105.2° ROT << 20.4 °/min SOG 2.94 kn Roll 0.4°
LON 012 06.482 E COG 90.8° RAD 0.14 NM STW 2.94 kn Depth 16.0

HDG 86.6° ROT << 0.2 °/min SOG 2.96 kn Roll 0.0° Setup North UP
COG 87.2° RAD 12.18 NM STW 2.96 kn Depth 16.0 m WRef Rel.

Fig. 9 Second sample for Intelligent prediction with two simulated steps ahead for a turning manoeuvre and proceeding in the side arm at Rostock Port (Black shapes: first prediction at current position (full red shapes); Red shapes: second prediction from the blue shape reference position)

- Left: Turning manoeuvre at MP1 with split engines and rudders 20° PT (black), next manoeuvre is to stop the turning by midships at MP2 (red)
- Right: Stop the turning in side arm by midships at MP2 (black), next manoeuvre is to initiate turning by 20° SB at MP3 (red)



Setup North UP Wind 36° Date 24.01.2024
WRef Rel. Wind 0.1 kn Time 16:56:09 LT

Lat.: 54 ° 09,460 ' N
Lon.: 012 ° 07,202 ' E
Speed (SOG) [kn] 3,4
Heading [°] 150,0
Course (COG) [°] 160,1

☑ Sea Mode ☐ Crash Stop ☑ Sync. Rudder
☐ Manoeuvre Mode ☐ Sync. EOT

URSOR 54 09.742 N 012 07.210 E 0.9° 0.283 NM Depth (ENC): 0m - 2m

Total Manoeuvre Time: 1115sec = 18min 35sec

Setup North UP Wind 70° Date 24.01.2024
WRef Rel. Wind 0.9 kn Time 17:20:46 LT

Lat.: 54 ° 09,320 ' N
Lon.: 012 ° 07,290 ' E
Speed (SOG) [kn] 0,1
Heading [°] 165,4
Course (COG) [°] 35,7

☑ Sea Mode ☐ Crash Stop ☑ Sync. Rudder
☐ Manoeuvre Mode ☐ Sync. EOT

URSOR 54 09.300 N 012 07.471 E 100.3° 0.108 NM Depth (ENC): 14.5m

Total Manoeuvre Time: 1365sec = 22min 45sec

Fig. 10 Third sample for Intelligent prediction with two simulated steps ahead for a stopping manoeuvre to prepare for berthing at Rostock Port (Black shapes: first prediction at current position at full red shapes; Red shapes: second prediction from the full blue shape at reference position)

- Left: Stopping manoeuvre at MP4 with engines EOT -10% and rudders Midships (black), next manoeuvre is starting approach to the berth by both Thrusters to PT -20% at MP5 (red)
- Right: Starting transverse motion to berth by both Thrusters -20% to PT at MP5 (red), next manoeuvre is stop transverse motion by reversing both thrusters to SB +20% at MP6 (red)

6 PREDICTION FOR EFFICIENCY CONSIDERATION DURING MANOEUVRES

In research projects an extension of the SAMMON system is under preparation for adding energy consumption into the fast time simulation. Previous research has shown that an efficient ship operation is not only depending on the provided technical equipment, but also on the efficient handling. Measurement on board of a real vessel showed a variety of required energy for the same port approach but with different manoeuvring concepts [16]. Measurements under controlled conditions in a simulated environment showed that proper assistance tools could lead to an effective manoeuvring while reducing the amount of engine orders and rudder commands given and using alternative manoeuvring concepts [5]. In these publications and in the following example the energy reduction regarding the simulations was only determined by the calculation of the propeller energy - without taking into account the drive train yet. In Fig. 11 an example is given for two initial manoeuvring conditions with different variations of propulsion for a double-end ferry with four azimuth propellers. The required power in kW at MP0 (red ship contour) can be seen in the new manoeuvring handle interface on the right side with the green bar display: for the propulsion condition by using the two pairs of azimuth propellers at front and aft with equal EOT 40% the power is equally distributed indicated with bars of same length and an initial speed of 6.5kn can be observed. For the condition where the aft propellers are used (bottom) with EOT 50% a speed of 7.6 kn can be seen and a smaller power requirement at the front propellers, obviously the propeller load is reduced at these azimuth propellers.

In future it is planned to consider the drive train energy into the simulation in the same way as in the on-board measurements where the total energy has been directly calculated by integrating the power of installed azimuthal drives. Future economic and sustainability demands and respective regulations will require a more efficient operation of ships. Therefore, a suitable assistant tool must be able not only to predict the ships motion, but also requires to provide information about the necessary drive power. This will be especially important if the ship is driving with a limited energy reserve, e.g. with batteries, and within restricted emission areas like Norwegian heritage fjords in the foreseeable future. Therefore, the project SimpleShip was initiated by various institutions and funded by the German government. Considering that one of the largest consumers on a passenger ship is the propulsion, the main target is to give the nautical crew innovative assistance for navigating with higher safety and efficiency, to calculate and predict the total energy consumption within the manoeuvring time.

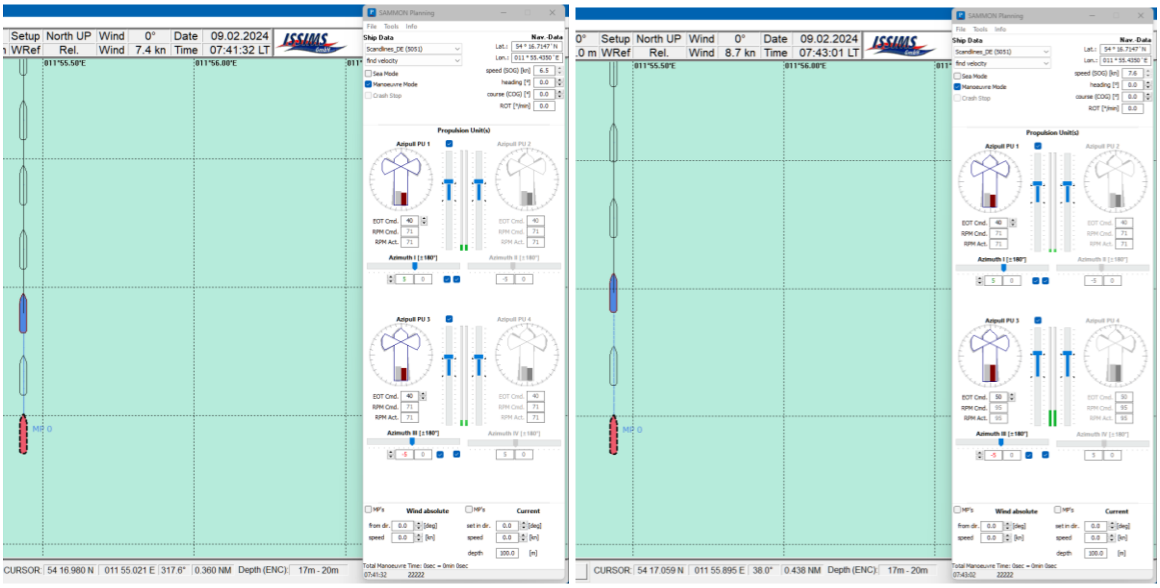


Fig. 11 Examples of prediction of power requirement (green bar display, in kW) for a double-end ferry with four azimuth propellers (left: both pairs of azimuth propellers are active with EOT 40%, right: aft propellers increased to EOT 50%)

7 PARALLEL PREDICTION FOR DIRECT STEERING WITH HANDLES ON BRIDGE

For hands-on experiences it is of advantage to use the SAMMON Monitoring and Conning tool because it allows the input to the prediction using the bridge handles – both in simulators or on-board ships.

In Fig. 12 the handles on the bridge console represent a typical configuration for Azimuth Propeller steering. Because of the complexity of the response of the vessel as result of the 360° azimuth thrusters in combination with bow and stern thrusters there is a big variety of options. The prediction can be used either in freeze mode when the simulator exercise is stopped (left) to familiarise with different manoeuvring strategies and also during the run of the exercise where the predictions are shown during the run (right).

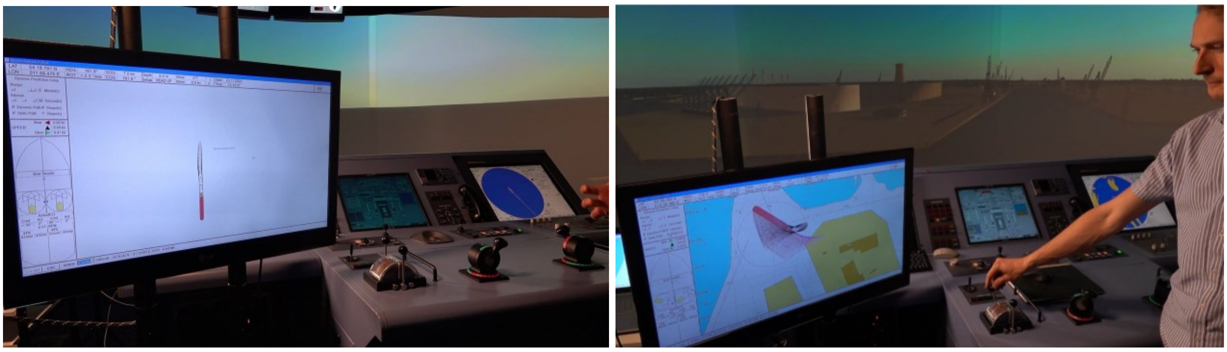


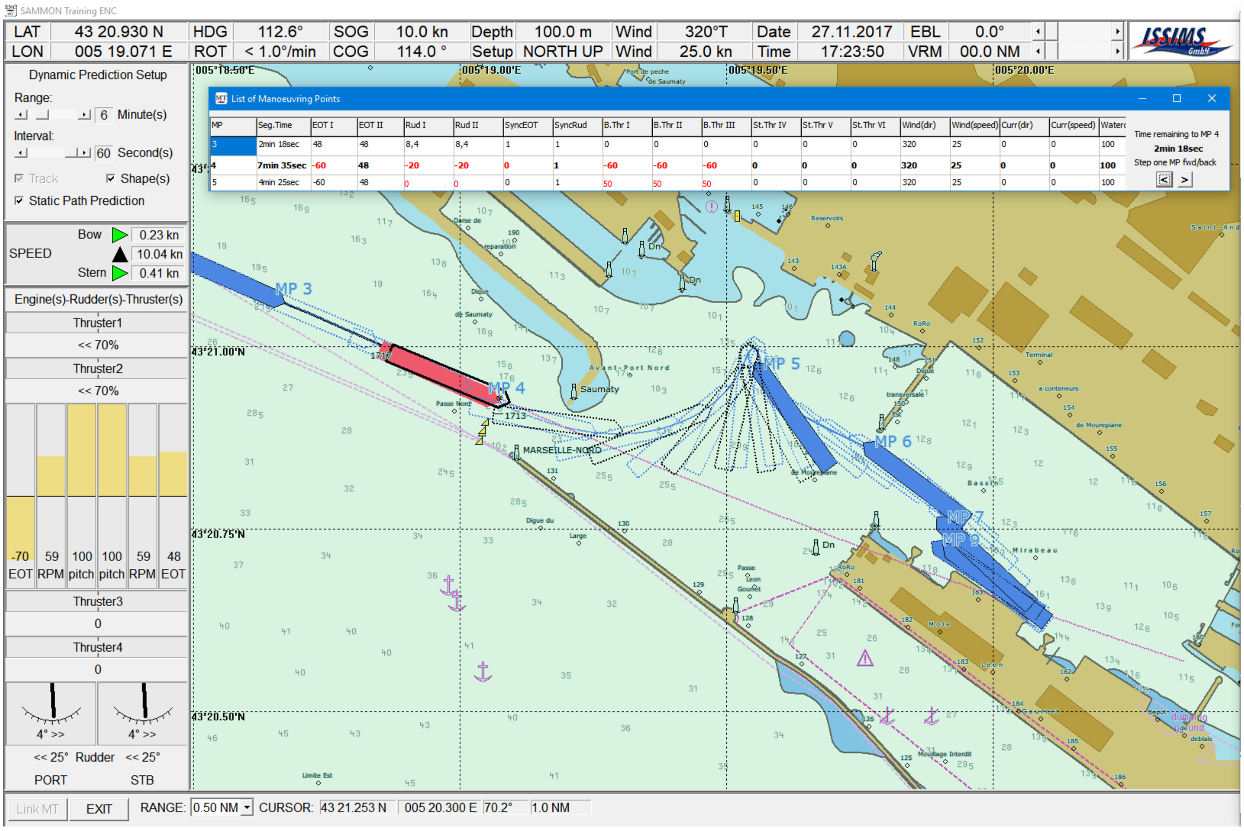
Fig. 12 SAMMON Monitoring & Conning Tool with Multiple predictions used in Ship Handling Simulator for Training used in familiarisation exercise for Podded Ships (Full Dynamic Predictions: black dotted ship contours; Static Path Prediction: Magenta ship contours)

- Left: Exercise in Freeze Mode for TOE IN method for Stopping Manoeuvre with dynamic prediction
- Right: Turning manoeuvre during simulator run using static and dynamic prediction in parallel

Using the Monitoring & Conning tool, several predictions can be shown in parallel for steering the ship. In Fig. 13 the interface is displayed for a sample steering a Cruise ship during arrival at Marseille and berthing. The main features provided with this module are:

- Display of Manoeuvring Plan, together with current position and Predicted Manoeuvres in parallel;
- Calculation and display of new Multiple Dynamic Prediction tracks:
  - Dynamic Prediction, based on full ship dynamic simulation for future ships motion – due to the input from actual bridges handle settings
  - "Path Prediction" Presentation, same as existing Look Ahead in navigation or pilotage systems, simply taking the current rate of turn and speed as constant for the prediction time period.

This feature allows for more safe and efficient manoeuvring which has been proven in several tests see e.g. [4]



LAT 43 20.930 N
LON 005 19.071 E
HDG 112.6°
ROT < 1.0°/min
SOG 10.0 kn
COG 114.0 °
Depth 100.0 m
Setup NORTH UP
Wind 320°T
Wind 25.0 kn
Date 27.11.2017
Time 17:23:50
EBL 0.0°
VRM 00.0 NM

Dynamic Prediction Setup
Range: 6 Minute(s)
Interval: 60 Second(s)
☑ Track ☑ Shape(s)
☑ Static Path Prediction

SPEED
Bow 0.23 kn
10.04 kn
Stern 0.41 kn

Thruster1 << 70%
Thruster2 << 70%

-70	59	100	100	59	48
EOT	RPM	pitch	pitch	RPM	EOT

Thruster3 0
Thruster4 0
4° >> 4° >>
<< 25° Rudder << 25°

List of Manoeuvring Points

MP	Seg.Time	EOT I	EOT II	Rud I	Rud II	SyncEOT	SyncRud	B.Thr I	B.Thr II	B.Thr III	St.Thr IV	St.Thr V	St.Thr VI	Wind(dir)	Wind(speed)	Curr(dir)	Curr(speed)	Waterd
3	2min 18sec	48	48	8,4	8,4	1	1	0	0	0	0	0	0	320	25	0	0	100
4	**7min 35sec**	**-60**	**48**	**-20**	**-20**	**0**	**1**	**-60**	**-60**	**-60**	**0**	**0**	**0**	**320**	**25**	**0**	**0**	**100**
5	4min 25sec	-60	48	0	0	0	1	50	50	50	0	0	0	320	25	0	0	100

Time remaining to MP 4
2min 18sec
Step one MP fwd/back
< >

RANGE: 0.50 NM CURSOR: 43 21.253 N 005 20.300 E 70.2° 1.0 NM

Fig. 13 SAMMON Monitoring & Conning Tool with Multiple predictions: Real time simulation and Manoeuvring Prediction integrated into ENC with comparison of Full Dynamic Predictions (black dotted ship contours) and the simple static prediction (magenta curve, no shapes) together with planned manoeuvring track (blue line and ship shapes) for a Cruise ship arrival at Marseille and berthing at Pier 163

8 MULTIPLE PREDICTION FOR COLLISION AVOIDANCE

However, FTS can provide also very detailed estimations for Collision Avoidance Manoeuvres, e.g. of the time needed for any manoeuvre intended for an escape action in case of crossing traffic as Stand-on-Vessel. Using these decision-making capabilities for the selection of a course and/or speed alteration respectively could be performed on a much more profound and reasonable basis than it is done in today's practice.

For the purposes of collision avoidance there are three main relevant application cases for predictions:

1. determination of the time and position for the initiation of the defined maximum rudder angle to pass at a given safe distance,
2. determination of the "Last Line of Defence" as the time and position for the initiation of the maximum technical feasible manoeuvre to just avoid a collision (passing not at a safe distance, but without touches of the hull) and
3. support to decision making on the basis of manoeuvring zones, as a visualization of the navigable space, that is technically feasible by combinations of steering controls.

Predictions of the expected path, e.g. with maximum possible rudder angles provides profound input for decision making. The space needed for advance and transfer movement for the planned turn under current conditions (considering the present draft and trim as well as wind (force and direction) and available water depth) to avoid a potential collision or a dangerous encounter can simply be displayed in dedicated screens.

When the navigator assesses the risk of collision, the prediction helps to visualize the lower and the utmost technically feasible action limit. Applying e.g. the risk model for onboard situation assessment (developed in [6]) this first limit is suggested to be the time that is needed for a 90° course change. This limit suggests a safety reserve, e.g. not using hard rudder to avoid heavy list, while the other limit suggests the last technically feasible action. In this way, position and remaining time to initiate an evasive manoeuvre that will just avoid the touch of the ship hulls can be visualized as well. All these considerations assume, that the "give-way-vessel" is not taking an appropriate action and continues without any course or speed alteration.

Therefore, by means of FTS and dynamic prediction it is possible to give enhanced advice when and where the so called "Last line of defence - LLoD" will be reached. The further development and implementation of the concept for defining and using the LLoD has been already discussed earlier. Many research works are dealing with this exact problem (to give just one dominant sample, see [9]). Now, in the following example its implementation can be demonstrated.

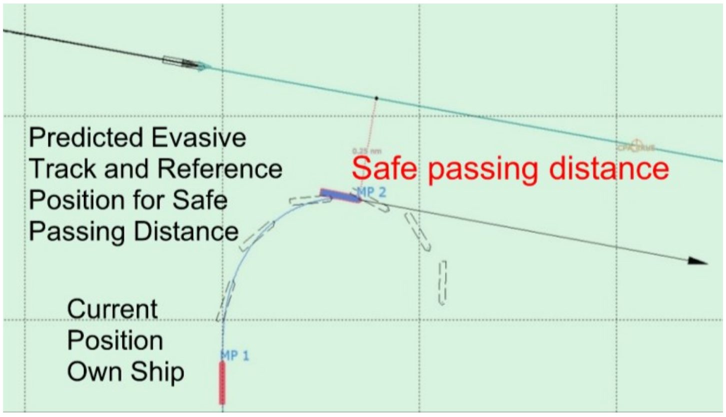


Fig. 14 Concept for „Last Line of Defence – LLoD" for a given safe passing distance of 0.25 nm at the moment when ships are moving on parallel course: Sample for Lower Limit of manoeuvre of "Stand on Vessel" (1,3 nm)

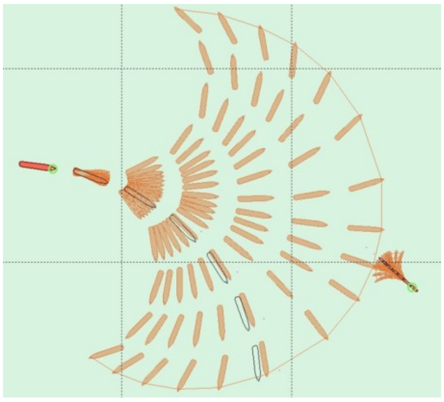


Fig. 15 Manoeuvre zones represented by ship domains for collisions avoidance calculated by FTS to support operator's decision making

Fig. 14 shows a visualization of an encounter situation in a chart environment. The own ship (marked by the red ship shape in the lower centre of the screenshot) is on a north-easterly course and is approaching another vessel on her port side sailing on a south-easterly course and crossing the bow of the own ship at a very short distance. By means of the prediction it is highlighted, that the closest approach will be reached when the heading of the own ship equals to the course over ground of the target ship. To achieve a pre-defined safe passing distance provided e.g. by standing orders MP 1 indicates the corresponding position, where the own ship at the latest, has to initiate the hard wheel over command to ensure a minimum passing distance of 0.25 nm at the CPA (marked MP 2).

A new alternative concept is to use multiple predictions to enable the prediction of all potential positions of a manoeuvring ship for a given time period. In this way complete manoeuvring zones can be calculated and visualized as well. Different from and contrary to ship domain areas the manoeuvring zones are areas a ship may cover by using all potential combinations of the control settings of a specific ship. The idea of manoeuvring zones is based on and derived from the concept of potential areas of water ([7] & [8]) and may contribute and enhance conventional situation assessment for collision avoidance on board as also suggested in [9]-[12].

Fig. 15 shows such a sample for the manoeuvring zones for Collision Avoidance by calculating a series of potential manoeuvres of two involved ships using FTS as an application of the concepts described in [5] for the use of manoeuvring zones for purposes of risk assessment of offshore windmill installations or from a shore-based VTS perspective. The expansion and the overlapping of the zones indicate, that the vessel with a smaller zone has lesser options to avoid a collision by her manoeuvre alone.

It becomes obvious that this technology allows for dynamically adapted limit values for collision avoidance. The use of fast time simulation is able to provide situation dependent support. This, especially, will be needed in a critical situation with less available time and increasing pressure to take a right decision (see also [6]).

As described above, the prediction of ship motions can tremendously contribute for understanding of collision situations and potential countermeasures in teaching and training [17]. Moreover, it also has great potential for further enhancement in collision avoidance systems. FTS-based collisions avoidance systems can be used on-board ships and from ashore [13] when there will be encounter situations with autonomous ships. Additionally, it has potential for assessing risks when passing wind mill farms [14], as well.

9 CONCLUSIONS

Prediction of ship motions is an essential part of safety of navigation in general, for manoeuvring in coastal or narrow waters - and particularly when approaching terminals and ports for berthing. In this paper a survey of historic developments and recent achievements of simulation-based manoeuvring predictions is provided.

Digitalization and modern information and communication technologies are main prerequisites for advancements of predictions. The invention of Fast Time Simulation and its implementation for more exact and reliable manoeuvre planning is a big advantage - not only for simple course changes but very complex manoeuvring for berthing operations in narrow harbour basins.

Regulatory boundaries and prices for carbon dioxide-emissions calls for economic measures in all aspects of ship operations. An efficient ship operation by the crew itself is a large mosaic piece for reaching climate-change reducing and economic operation measures. A powerful and reliable prediction tool for manoeuvring operation including energy and fuel consumption is a path to include the crew and provide them with proper information.

Moreover, situation assessment and decision making for manoeuvring with purposes of collision avoidance can be supported much more comprehensively and easily than just 5 or 10 years ago. It is possible to provide situation-dependent limit values for triggering collision warnings precisely - considering the manoeuvring behaviour for determination of the latest moment to take action.

The developments and technical implementations focussing on the support of the Officer of the watch on a ship's navigational bridge, are very beneficial for training purposes in maritime education and training of navigating officers. In this way manoeuvring predictions improve simulation training and shall be integrated accordingly.

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