

Consumption Optimised Manoeuvring Method for Ship Automation

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Synopsis

The paper presents a method for gradual automation of ship manoeuvring, focusing on ships already in service. The approach involves the expert knowledge of both nautical officers and ship engineers to optimise the operational behaviour and reduce fuel consumption and emissions. Detailed models of dynamic ship motion and engine processes form the basis of various software tools to assist the manual planning and execution of effective voyages. The results of a study in ship handling simulator show that the manual manoeuvring efficiency of experienced nautical officers has also been significantly increased by these assistance instruments. With regard to automatic shipping, the generated optimal plan is transferred to the automatic control system as a target trajectory. Based on a simplified motion model, the controller structure with feed-forward and feedback modules was developed to realise velocity, heading and track control. Results of controller application in simulator tests with and without wind disturbances are presented. In addition, the paper describes the development of necessary framework conditions for safety-critical areas for the application of automatically controlled manoeuvres in today's practice with the so-called nautical algorithms according to the research project GALILEOnautic 2.

Keywords: Consumption optimisation; Model-based prediction; Manoeuvring automation

1 Introduction

The measures for reduction of fuel consumption and greenhouse gas (GHG) emission in shipping can be distinguished in technical and operational measures. The technical and economic applicability of a single measure depends strongly on type and age of a considered ship. The technological intervention options, such as hull design, efficient propulsion and engine systems, alternative fuels or energy sources, are particularly interesting when a ship is newly designed and built due to the immense costs of a reconstruction. Speed optimisation, capacity utilisation, voyage optimization by planning or weather routing, and the optimisation of trim, draft or maintenance belong to the operational measures. Bouman et al. (2017) determined in a review of around 150 studies the highest CO₂ reduction potential through the use of biofuels. The speed optimization achieves between 20% and 35% reduction per transported freight unit and thus belongs to the group of the second most effective measures. These results show the great, promptly available potential of operational measures, which do not require technological changes.

Today, the automation of vessels already in operation is a lesser regarded research topic. Beside the dynamic positioning (DP) control for vessels with special tasks (a survey is found in Sørensen (2011)), the autopilots are widely used for standard vessels with classic propulsion configuration but only at transit speed in the open sea. An overview in Roberts et al. (2003) addresses also the specific approaches with fuzzy and neural networks. Both DP and autopilot solutions do not cover manoeuvring behaviour of vessels in safety-critical areas. A practical oriented example is described in Alessandri et al. (2015) with optimised autopilot design for a patrol vessel. The controllers were synthesised by linear matrix inequalities considering the external disturbances of wind and waves. A linear

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model predictive controller was used for a model ship of an LNG carrier in Miller (2014). In Mizuno et al. (2012) also predictive control was developed for automatic berthing of a training ship. As described in Källström (2000), various control tasks were realised on high-speed catamarans with water-jet propulsion, which were used as ferries by *Stena* for several years. The track autopilot predictor from *KAMEWA/SSPA* combines the functionalities for keeping course and turning as well as automatic navigation and track keeping based on a non-linear manoeuvring model. A harbour mode for narrow waterways is conceived with highly accurate motion control under wind, current and wave disturbances and additional stop-on-track control in emergency situations.

This paper focuses on how assistance and automation functionalities can achieve significant savings in fuel consumption and GHG emissions. The expert knowledge for the dynamic ship motion and engine processes is contained in basic models that have been published in detail earlier. These models are integrated into assistance systems for the analysis, planning and execution of effective manoeuvre sequences, which can be operated intuitively by every nautical officer and are useful for training purposes. In order to realise an optimal plan also automatically, a suitable motion model for the controller development is required. The contribution explains this model concept shortly and its application in an innovative controller approach. Results of trials in ship handling simulator (SHS) for both assistance and automation are presented. Further conceptional requirements for the introduction of automatic manoeuvres in safety-critical areas are identified to document the current progress in the research project *GALILEOnautic 2*.

2 Basic Models

2.1 Ship simulator models

The method development has its origin in a strong connection to the practical education and training of nautical personnel with simulators. For the presented research and the tests, the certified *SHS ANS6000* for ship handling and the *SES7* for ship engine simulations (SES), both from *Rheinmetall Electronics*, are used. They represent the on-board systems with a high degree of precision and many generic and manufacturer-specific modules that meet the requirements of experienced officers and engineers. The ship and port models of SHS have to be detailed replicas in 3D-geometry to cover the key hydro- and aerodynamic effects of the ship motion, but there are only simplified models to represent the delayed engine response to bridge commands. The ship motion models combine the common physical motion equations with various numerical parameter sets for the entire operating range of all actuators. They are consistently applied in the tools for ship's manoeuvre planning and monitoring *SAM-MON* (Benedict et al. (2014)) and for ship's motion prediction *RAPIT* (Rapid Advanced Prediction and Interface Technology).

The thermodynamic engine processes of SES are represented by differential equations, which allow real diagnosis as on board. But there are no measurements for inner processes and emissions amounts of CO₂, SO_x, NO_x or soot. An engine test bed was used to develop a model basis for it. Trials addressed the typical transient thermodynamic states of manoeuvring mode, which contribute significantly to high fuel consumption and high emission amounts. The resulting purely physical model is described in Finger et al. (2019) and alternative data-based models, e.g. with a neural network in Schaub et al. (2019). These models can be linked with the ship handling data to evaluate the efficiency of manoeuvring sequences. A more detailed analysis is provided by the software tool *ShiB-DAT*, which allows a deduction of the best manoeuvres under specific weather conditions in repeatedly approached sea areas. Further information to this tool can be found in Finger et al. (2020).

2.2 Parameter space model for controller development

Although the complex motion model with numerous parameters used in SHS is not suitable for developing controller approaches, these models provide a good starting point for the identification through rapid simulation. Suitable models for an inverted generic approach are characterised by a simple structure and a minimal number of parameters. Only the relationships between actuator commands and resulting state variables are considered. Further internal effects are included in the parameter tables. External forces are treated as disturbances. In this manner, the identified model can be applied in a feed-forward control and an allocation module as well as for the parametrization of controllers.

The used process model corresponds to a first-order delay element. Both the gain factor $K(\cdot)$ and the time constant $T(\cdot)$ are complex parameters represented by look-up tables (see Kurowski et al. (2020)). The model describes the relationship between the manipulated variables \mathbf{a} and the resulting surge velocity u , sway velocity v and yaw rate r . The dimension of \mathbf{a} therefore depends on the actuator configuration of the specific vessel. Typical inputs are the value of engine order telegraph (EOT) for propulsion propellers and thrusters as well as the angles for azimuth thrusters and rudders, as stated in Kurowski et al. (2017). The generic model is divided into a static and a dynamic part. Each actuator contributes in its own way to the static force in the respective degree of freedom. Based on given manipulated variables, the associated stationary virtual force X_{stat} can be determined by

$$X_{stat} = h(\mathbf{a}, \mathbf{x}) \quad (1)$$

where $\mathbf{x} = (u, v, r)^T$ is the velocity state vector. Usually, $h(\mathbf{a}, \mathbf{x})$ depends only on the manipulated variables \mathbf{a} and the surge velocity u . The stationary surge velocity can then be calculated by

$$u_{stat} = g(X_{stat}) . \quad (2)$$

The functions $h(\mathbf{a}, \mathbf{x})$ and $g(X_{stat})$ are nonlinear analytical functions or look-up tables and together they produce a nonlinear gain factor $K(\cdot)$. The same procedure can be used for the remaining degrees of freedom, that is, the sway velocity and the yaw rate. For the dynamic part of the model, a first-order delay element is assumed, where the time constant is mapped with a look-up table that depends on both the current velocity and the setpoint velocity.

3 Assisted manoeuvring

The developed manoeuvre assistance system (MAS) supports the officer of the watch (OOW) with additional information to make the ship handling more confident and effective. The system also takes into account the advancing automation in shipping, the growing number of sensors on board and larger data volumes to be processed. In MAS on board a real ship, the same complex motion models are used as in simulation, but the pre-processing validation, synchronisation and fusion of the sensor data in the real world is much more demanding. The latest MAS version consists of a planning and a monitoring tool.

3.1 Seamanship Compliant Manoeuvre Planning

Two methods of manoeuvre planning are envisaged, manual pre-planning for a manoeuvre sequence the planning tool *SAMMON*, e.g. a complete berth-to-berth voyage, and automatic in-situ planning for collision avoidance (CA). With a specific ship model, a detailed manoeuvre plan can be created manually in the selected sea area in an electronic navigation chart (ENC) under forecasted environmental conditions. For pre-planning, a nautically trained user sets manoeuvre points (MP) stepwise shown in Figure 1. The MPs are based on the legally required waypoints. Since these waypoints only give a rough orientation, it is useful to refer to previously recorded manoeuvres of this situation for the digital planning of a safety-critical manoeuvre, e.g. for ferry dockings. A single MP is defined by at least one change in the actuator commands, e.g. changing of rudder angle, or in the environmental variables, e.g. the onset of current at the breakwater, in a geographical position. The command settings are realised by handles of the graphical user interface. By way of illustration, future ship movement is represented by the RAPIT prediction based on the specific ship model. The movement depends on the changed commands, the current motion states and the environmental forces. Output of the planning tool is a complete manoeuvre plan with MPs containing commands, geographical positions and state variables such as speed over ground (SOG), rate of turn (ROT), heading angle (HDG) or course over ground (COG). The planning in ENC is familiar to the navigators. This data is identical to those in a conning display. For the execution of the plan it can be loaded as an overlay in the ENC.

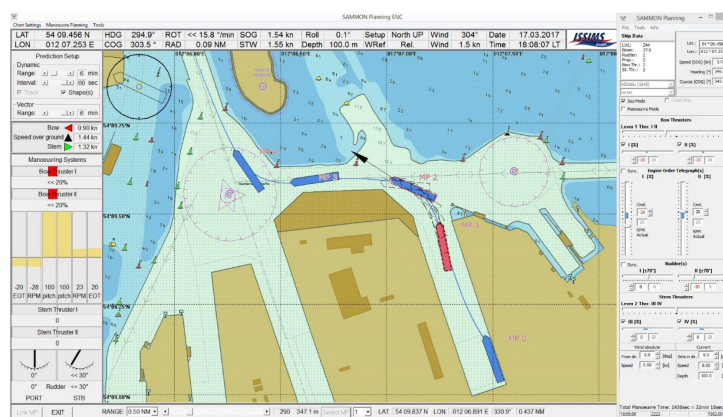


Figure 1: User-interface of the manoeuvre planning tool *SAMMON*

For the purpose of automatic CA manoeuvres, the plan can already be calculated automatically according to the situation, the COLREGs, the instructions of ship owner and master. The waypoints calculated first represent a geometric solution that takes into account the closest point of approach, the required change of course and the maximum rudder angle. The calculation of the manoeuvre plan is based on this geometric solution, whereby the ship's course is kept close to the waypoint route or returned to the original course only by a minimum number of rudder angle changes. Therefore, these CA manoeuvres are also highly efficient. The method is described in more detail in Schubert et al. (2019).

3.2 Manoeuvring Assistance by MAS

During the execution of planned manoeuvre sequences, the monitoring mode of the MAS is applied as shown exemplarily in the current version of MAS in Figure 2. This MAS is specified for a ferry with two Azipods, a centre-propeller with rudder and a bow thruster. In monitoring mode, the interface comprises two parts: a monitoring tool and a function display.



Figure 2: Sample view of MAS with ENC monitoring and function tool

In the monitoring tool, the current vessel position, the selected manoeuvre plan and the RAPIT prediction are displayed in the ENC. In the plan, preferably self-created, the changing commands are displayed near the geographical MPs. The prediction horizon can be manually selected from 1 to 24 minutes or automatically adjusted according to the current SOG. The comparison between planned route and predicted path can increase the decision reliability of OOW. The function display is a summarised presentation of all necessary information during manual manoeuvring. Beside the variables already used during planning, engine states and environmental measurements, such as wind and current, are displayed. In the future MAS, also alarms for significant disturbances in the propulsion system and the initial conditions for automatic manoeuvres have to be displayed. In order to cover the individual strategies during manual manoeuvring, the future assistance system should be customisable.

3.3 Simulator trials with assistance

The efficiency increase through the application of MAS was evaluated with SHS trials. Nine experienced nautical officers and masters commanded a ship in three different short scenarios in sea or port areas with different equipment, without any assistance (group 1), with online RAPIT prediction (group 2) and with RAPIT prediction and a self-made digital manoeuvre plan (group 3) as presented in Figure 3. The usage of bow thrusters was only allowed for the docking scenario. Each officer executes each scenario and equipment situation only once, so that a total of 27 attempts were made and the learning effect does not distort the results. The experimental design was comprehensively described in Finger et al. (2020).

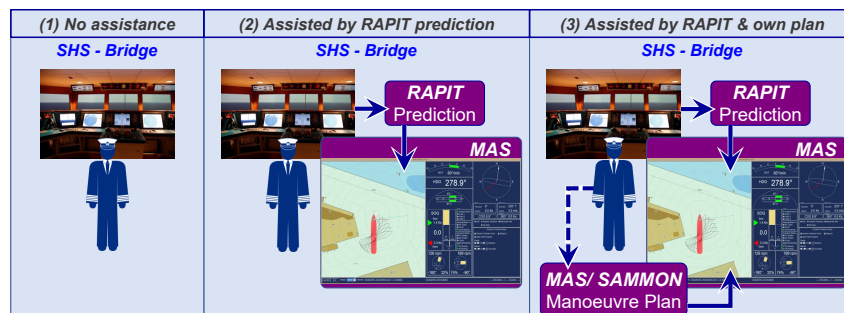


Figure 3: Conception of SHS trials in three groups

The ShiBDAT tool is used to compare the results of the three groups in terms of actuator use, power consumption and emission values. The first two are summarised in Table 1. The greatest efficiency increases can be seen in all categories in group 3, although the plan cannot be fully adhered to. The respective power consumption of

propeller and thruster has been reduced by almost 40%. Both assistance functionalities support the OOW in a more focused use of actuators. The prediction shows him immediately how the current commands will affect the future movement of the ship and he can correct them appropriately. This positive effect is intensified by a prior conscious planning of efficient manoeuvres. Therefore, the reduced power consumption in groups 2 and 3 can be explained by the greater reserve of the EOT and the more focused use of the rudder. The EOT reserve depicts how much power is left from the maximum continuous rating of the main engine. The 21.4 % increase in this value in group 2 and 46.4% in group 3 proves that the officers use lower EOT commands to achieve the manoeuvre objectives. The differences in rudder usage are documented by the number of changes per angular range. In the three lower ranges in Table 1, the usage number is reduced on average by 24.7% in group 2 and even by 49.5% in group 3. This result also confirms the great influence of the use of the rudder on the ship drag and thus on the fuel consumption.

Table 1: Results of SHS trials for the efficiency evaluation of manoeuvre assistance functionalities

	Propeller Power [kWh]	Thruster Power [kWh]	Min. EOT reserve [%]	Number of Rudder Angle δ [°] Changes			
				$0.5 \leq \delta < 5$	$5 \leq \delta < 10$	$10 \leq \delta < 20$	$20 \leq \delta \leq 30$
Group 1 No Assistance	6179	466	28	165	53	32	10
Group 2 RAPIT Pred.	5025 (-18.7%)	343 (-26.4%)	34 (+21.4%)	147	35	22	7
Group 3 RAPIT & Plan	3764 (-39%)	286 (-38.6%)	41 (+46.4%)	100	22	15	4

Table 2 shows the average duration in each scenario and group of assistance functionalities used. Only for scenario 2 the manoeuvring in group 2 using the prediction takes much longer than without assistance. But especially the significant reduction of the duration of the docking manoeuvre (scenario 1) both in group 2 (-17%) and in group 3 (-25%) shows the advantages of these assistance systems for the manoeuvre mode. The reduced power requirement is not caused by lower speeds but by the targeted use of all actuators.

Table 2: Average duration of the SHS trials ordered by scenario and the assistance functionalities used

	Scenario 1 Berthing in port of Rostock	Scenario 2 Sail between Islands	Scenario 3 Sail to Anchor Position
Group 1 No Assistance	1833 s	932 s	3317 s
Group 2 RAPIT Pred.	1519 s	1170 s	2901 s
Group 3 RAPIT & Plan	1366 s	965 s	3348 s

The emissions of CO₂ and SO_x are directly linked to the fuel consumption. The emissions of NO_x and soot are correlated with the phases of acceleration and of upper load ranges identified by the extensive actuator usage and a little EOT reserve. Therefore, the NO_x emission is on average by 64% higher in the trial group 1 with any assistance. Soot is also produced in middle load ranges so that the difference compared to group 1 is smaller with 16%. In general, the difference between these emission values of groups 2 and 3 is minimal.

4 Automated manoeuvring

The significant increase in efficiency already achieved by the manoeuvring assistance confirms the user-centred strategy for manoeuvre mode automation. This user-centred automation concept is presented in Figure 4 with the basic modules. According to the systematics of the manoeuvre automation level (MAL) published in Schubert et al. (2018), the next level after manoeuvre assistance (MAL1) is the partial manoeuvre automation (MAL2). At this level it is intended that single manoeuvres or short manoeuvre sequences are realised automatically. In the current project *GALILEOnautic 2*, the planned examples for this kind of automatic manoeuvres are docking, CA and manoeuvring in encounter situations in ports. Due to the necessary transparency of the control algorithms for the nautical personnel and their legal responsibility, it must be possible to initialise and supervise the automatic manoeuvres in MAS with measurable parameters.

These parameters are summarised in the concept of so called nautical algorithms (NA). Similar to the manoeuvre plan, these NA have to be created manually by experienced nautical officers defined for a specific vessel and area. They contain a geographical area for the initialisation of an automatic manoeuvre respectively a corridor for the manoeuvre sequence alongside the plan with MPs. The parts of this area can be further specified by different ranges of motion states, such as velocities or orientation angles, e.g. according to the distance to the final position of berthing. Both the potential initialisation area and the compliance with the corresponding parameters will be displayed in MAS to support the decision of OOW to switch between manual and automatic manoeuvring. The

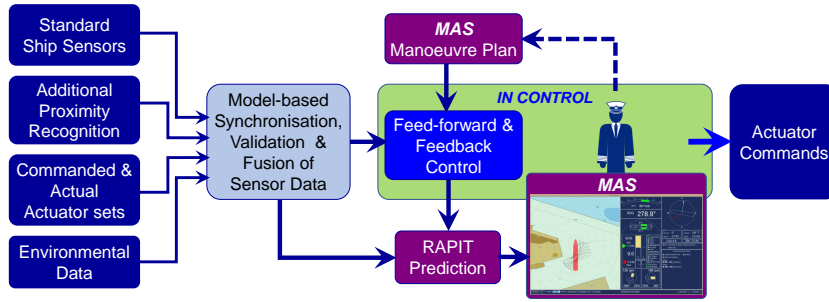


Figure 4: Concept of user-centred ship automation with MAS

geographical initialisation area of NA for an automatic berthing manoeuvre is shown in Figure 5. This manoeuvre is planned for the research vessel DENEK of the German Federal Maritime and Hydrographic Agency (BSH) in the port of Rostock. The schematic diagram on the left presents the area outline with three sub-areas and the nautical manoeuvre plan with MPs. The shapes and lines marked in green represent possible actual initialisation positions for automatic berthing and optimized trajectories to the final position. On the right, the implementation of the NA in the planning tool SAMMON is shown.

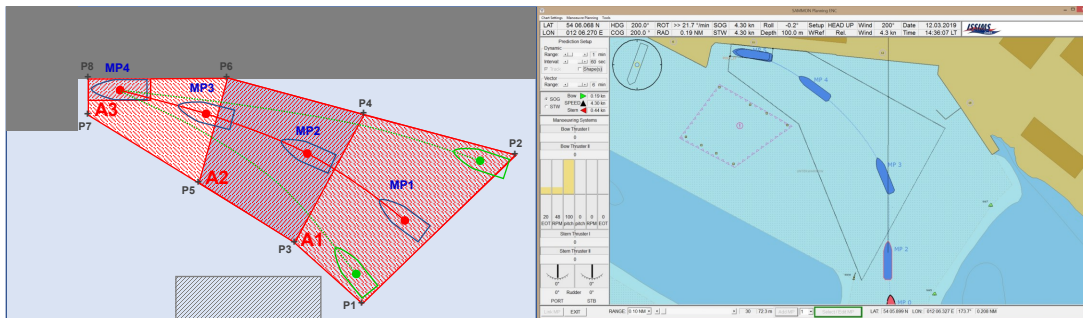


Figure 5: Geographical initialisation area of NA for automatic berthing with schematic (left) presentation and planned in SAMMON

After initialisation, a usable trajectory has to be optimised based on current position and motion states as well as on the given manoeuvre plan. An example for such an optimisation method is given in Kurowski et al. (2019). An alternative is the direct application of the trajectory of the manoeuvre plan in closed loop control. In any case, the automated manoeuvring uses the trajectory deduced from the plan in the feed-forward module. In the following subsection the applied controller structure is explained.

4.1 Controller structure

For the controller design, the functions of the parameter space modes described in section 2.2 are inverted with

$$\mathbf{a} = h^{-1}(X_{stat}, \mathbf{x}) \tag{3}$$

and

$$X_{stat} = g^{-1}(u_{stat}) \tag{4}$$

and defined by look-up tables as well.

A reference trajectory contains both the motion state, which includes the geographical position, heading angle and body-fixed velocities and the manipulated variables at any time. If the manipulated variables are transferred to the system, the ideal result would be a position curve that corresponds exactly to the trajectory. Due to external disturbances and model uncertainties, however, control is necessary to keep the vessel on the track. Since manipulated variables cannot be superimposed due to non-linearity of the process, suitable transformations are required so that the feedback control can add a differential force to the feed-forward control. The feed-forward control calculates the virtual force from the manipulated variables of the trajectory according to

$$X_{Traj} = h(\mathbf{a}_{Traj}, \mathbf{x}_{Traj}) \tag{5}$$

A feedback controller calculates a surge velocity error

$$\Delta u_{fb} = u_{Traj} - u \quad (6)$$

from the reference velocity u_{Traj} of the trajectory and the current velocity u . This velocity error has to be transformed to a corresponding virtual force error ΔX that can be added to (5). The transformation is given by

$$\Delta X_{fb} = g^{-1}(g(X_{Traj}) + \Delta u_{fb}) - X_{Traj} \quad (7)$$

where X_{Traj} can be seen as an operating point. In this way, velocity errors between the velocity specified by the trajectory and the current velocity can be compensated. In order to be able to compensate for position errors, an outer control loop is required, which evaluates the position error to the trajectory and converts it into an additional differential velocity command Δu_{ff} for the internal velocity control loop. By using (7), the differential velocity Δu_{ff} can be transformed into a corresponding differential force ΔX_{ff} . The total virtual force is then given by

$$X_{stat} = X_{Traj} + \Delta X_{ff} + \Delta X_{fb} \quad (8)$$

and can be transformed to actuator commands using (3).

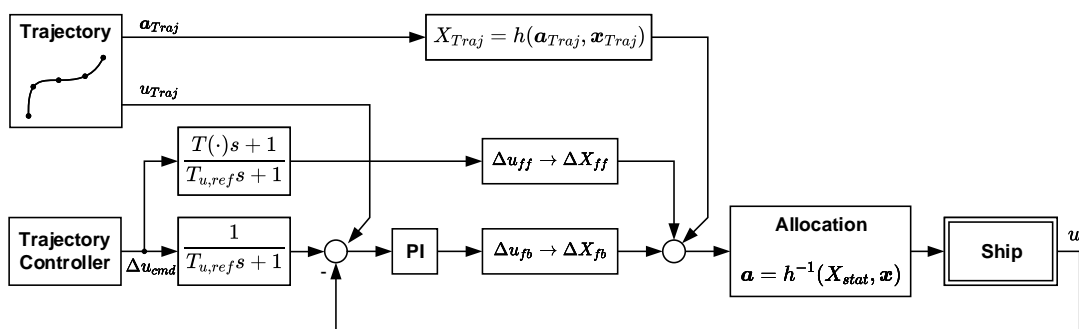


Figure 6: Velocity control structure

Figure 6 shows the structure of the velocity controller for one degree of freedom. While the feed-forward module linearises the process in the relation between input and output, a PI controller is used for disturbance attenuation. The time constant from the look-up table $T(\cdot)$ can be compensated and replaced with a reference time constant T_{ref} . The same procedure can be used for the yaw rate.

The outer trajectory controller sees a first-order delay with a unit gain and a time constant of T_{ref} . The manipulated variables from the trajectory are already used for feed-forward control. The position error, which results for example from disturbances, must be reduced by the trajectory controller. Since the position data are available in geographical coordinates, they first must be converted into earth-fixed coordinates in north and east direction. The ships position according to the trajectory is selected as reference coordinate system. The measured or estimated vehicle states can then be converted into this reference coordinate system as follows.

$$\Delta x^b = (x - x_{Traj}) \cos \psi_{Traj} + (y - y_{Traj}) \sin \psi_{Traj} \quad (9)$$

$$\Delta y^b = -(x - x_{Traj}) \sin \psi_{Traj} + (y - y_{Traj}) \cos \psi_{Traj} \quad (10)$$

$$\Delta \psi = \psi - \psi_{Traj} \quad (11)$$

$$\Delta u = u - u_{Traj} \quad (12)$$

$$\Delta r = r - r_{Traj} \quad (13)$$

Δx^b and Δy^b correspond to a longitudinal and lateral offset, respectively, and are minimized by two different controller approaches. Both approaches are considered independently of each other. It is assumed that possible cross-couplings have only a minimal influence and can be added to the disturbances. Δx^b can be affected by a change in the differential surge velocity Δu_{cmd} , which is the input to the inner velocity controller. For a given reference time constant $T_{u,ref}$ for the surge velocity model a continuous-time state space model can be constructed.

$$\begin{bmatrix} \Delta \dot{x}^b \\ \Delta \dot{u} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -1/T_{u,ref} \end{bmatrix} \begin{bmatrix} \Delta x^b \\ \Delta u \end{bmatrix} + \begin{bmatrix} 0 \\ 1/T_{u,ref} \end{bmatrix} \Delta u_{cmd} \quad (14)$$

$$y = \begin{bmatrix} 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta x^b \\ \Delta u \end{bmatrix} \quad (15)$$

A conventional state controller with integral action can be used to compensate for position errors along the trajectory. For the compensation of the lateral deviation, a differential yaw rate Δr_{cmd} must be commanded to the inner velocity controller. For this purpose, a classic PI track controller with an underlying PID heading controller can be used. The heading controller then generates the commanded differential yaw rate Δr_{cmd} . The track controller uses Δy^b from (10) to generate a differential heading command $\Delta \psi_{cmd}$ for the heading controller that compares this command to the current differential heading according to (11).

4.2 Simulator trials with automatic control

In the project *GALILEOnautic*, this control structure in simulator and for unmanned surface vehicles (USV) has been used so far, for both automatic CA and port manoeuvres. The detailed results for the automatic CA are published in Schubert et al. (2019) and for the automatic port manoeuvres with the model of cruise ship MV Europa in Kurowski et al. (2020). Figure 7 shows the results of the complete method application for a CA manoeuvre according to COLREG rule 16 under two different wind conditions. The risk of collision with the target *OXRA6-10* from northeast was detected by the automatic radar plotting aid (ARPA). This is followed successively by the automatic calculation of the geometric avoidance path (orange dotted line) and manoeuvre plan with MPs (blue line and ship shapes), presented on the left. This plan was generated without wind disturbances. For the control application, it has been converted into a reference trajectory, represented by the black dashed line on the right side of Figure 7. The blue line shows the trajectory of the automatic manoeuvre without external disturbances, while the red line shows the result with winds of 10 knots from the west. Therefore, the red trajectory shows a larger error to the reference in east direction. In the case of the open sea, the small deviations are negligible, but for safety critical areas a more precise solution is required. The environmental conditions must therefore either be considered in a hybrid controller approach, where a supervisor switches between different controllers depending on the operating conditions, or these conditions must already be taken into account when creating the plan.

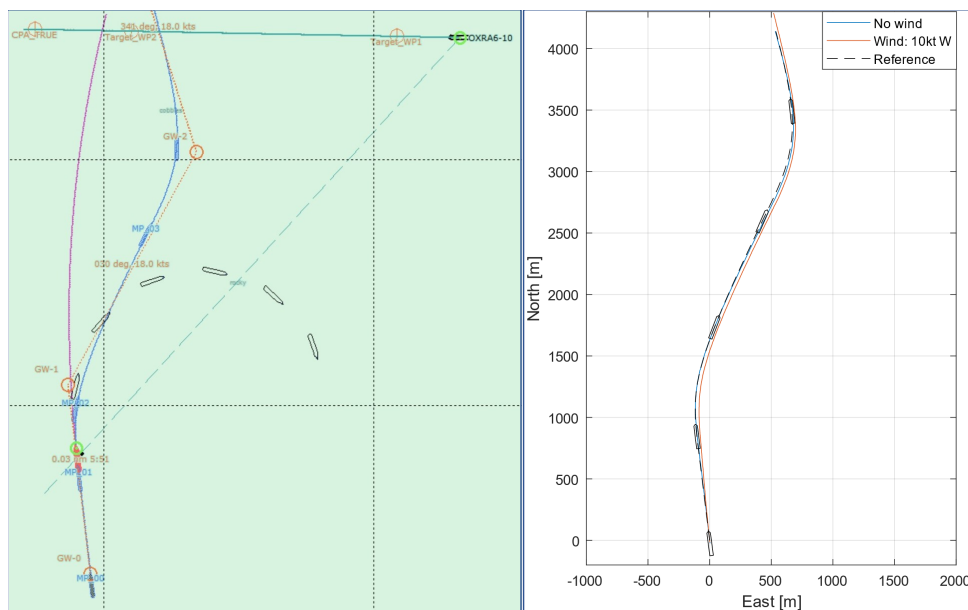


Figure 7: Automatic CA manoeuvre with geometric avoidance path (in orange), manoeuvre plan (in blue) on the left and controlled trajectories without and with wind on the right side

5 Conclusion and outlook

The contribution presents a comprehensive strategy to automate today's operating vessels. It is focussed on gradual automation accompanied by an assistance system that guarantees a user-centric methodology and control transparency for nautical officers to continue to meet their legal responsibility. Simultaneously, MAS is a well-suited tool to educate and train nautical officers for both manual and future automatic ship handling. It was shown that assistance alone can significantly increase the efficiency of manoeuvring. By including engine models, power and fuel consumption as well as emission values can be consciously taken into account during manoeuvre planning. The application of both the planning and prediction tools in SHS trials has contributed to more targeted control interventions. The advantage of a nautically and energetically validated manoeuvre plan can be transferred to the automatic approach by converting it into a control trajectory that is used in the feed-forward and allocation

module. Furthermore, the development of the entire controller structure is based on a control oriented-model, which is deduced from the comprehensive dynamic motion model used in simulator.

In the project GALILEOnautic2, the introduced methods will be further optimised in SHS, in particular as pre-integration tests of the automatic functionalities on USVs and finally on board the research vessel. The constantly evolving MAS will be involved in the daily manoeuvre routines of an operating ferry to assist the OOW's in increasing safety and efficiency of their manoeuvring. The application behaviour with MAS will be observed and analysed again to incorporate their criticism and suggestions into an improved design and function of the human machine interface.

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