From Manoeuvre Assistance to Manoeuvre Automation

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Abstract. One of the greatest challenges in shipping automation is the automatic manoeuvring in areas with high safety standards which are executed today exclusively by nautical officers with appropriate expertise. Precise manoeuvre plans and suitable control solutions are missing because the human operators act according their mental strategies. The presented approach for automated manoeuvring primarily bases on a complex dynamic motion model of a specific vessel. This model is adapted and used to plan a complete manoeuvre sequence considering the common nautical guidelines and the vessel characteristics. The resulting digital manoeuvre plan forms the basis for the assistance during manual manoeuvring as well as the automatic manoeuvring. Prognosticated weather conditions can be involved already during the planning. For automatic manoeuvring, the deduced manoeuvre trajectory is implemented into the feed-forward part of velocity control. The entire control structure is cascaded in outer trajectory controller and inner velocity controller. The described approach was successfully applied for large vessels in ship handling simulator for automatic collision avoidance and port manoeuvres.

1. Introduction

The objective of ship automation or even autonomy is in particular the increase of safety and efficiency to protect human life, environment and the giant economic values associated already with a single ship. Therefore, a sustainable and realistic agenda of ship automation has to taken into account the large number of ships of the existing global merchant fleet that cannot be simply replaced by highly automated ships in the next decades. In the last Equasis Statistic [1], almost 91 thousand ships of different types and sizes are reported. Only one third of them are highly manoeuvrable and equipped with precise sensors according to their task, in order to be able to operate near structures or the land. But the majority of vessels in service has neither performant drive systems nor reliable navigation sensors for safer or more efficient track control.

In addition to sensors and drive technology, control technology also plays a decisive role in advancing the automation of shipping. Autopilots and track pilots are the most common automatic applications in shipping today. Both are only used when the ship is on the open sea and sufficient manoeuvring space is available. In principle, an autopilot can also be used for a collision avoidance (CA) manoeuvre, but in practice CA is usually performed manually. In [2], Rolls-Royce and FinFerries presented autonomous and remote controlled ferry operations. The route is defined by way points of a ferry connection. Three different potential collision
situations were solved. The obstacles are detected by additional intelligent awareness sensors and an autonomous navigation system installed on the standard ferry in Plug & Play container. The successful demonstration shows the technological progress in situational awareness and autonomous navigation but the technological effort and the costs for future automatic shipping as well. The situation is similar for other current projects with the aim of autonomous shipping. The best-known example is probably the YARA Birkeland project, in which a completely new ship is build to autonomously connect three ports in southern Norway to free the road from truck traffic and to enable green shipping technology [3]. After the intermediate steps of manned and remote-controlled shipping, it was planned to allow the ship to operate autonomously from 2022. There’s supposed to be three operation centre on land which will handle emergency and exception handling, observation of conditions, operational monitoring and decision support. It is therefore not clear to what extent the ship actually acts autonomously and which control functionalities are implemented. The developments in watercraft automation especially for safety-critical manoeuvre areas are often limited to small unmanned vehicles [17] or simulation approaches. One of the reasons for this is also the legal situation.

This contribution shows a gradual, user-centred approach for manoeuvre automation based on analysis of manual process as it takes place on board today. For assisted manoeuvring, the watch officer will be supported by own digital manoeuvre plans which can give guidance during manual manoeuvring. In addition, there is a prediction of future motion path, automatic calculation of manoeuvre plans and further functionalities. At the level of partial automation, single manoeuvres and manoeuvre sequences are automatically calculated and executed after initialization by the watch officer. Automatic manoeuvres on the open sea for collision avoidance and in the port are presented. The necessary technological framework for such automatic manoeuvres is identified for the application on unmanned surface vehicles (USVs) with advanced equipment as well as on classic merchant ships with basic actuator and sensor equipment initially in simulation in ship handling simulator. Based on complex dynamic motion model, a generic controller approach with cascaded structure and hybrid velocity controller is applied to execute automatically the manoeuvres.

2. Systematics of manoeuvre automation

In order to classify future project work, the authors have developed a systematics for maneuver automation, described in more detail in [14]. Based on SAE automation level for the automotive industry [5] and the classification of Norwegian Forum for Autonomous Ships (NFAS, [6]), the manoeuvre automation levels (MAL) shown in Fig. 1, were developed. The system takes into account the current legal situation in which a captain bears full responsibility for his vessel. Therefore, the automation must be user-centered and transparent so that the watch officer can take over manual ship control again at any time during automatic mode as the lowest fallback solution in the automation hierarchy. By this strategy, the functionalities of manoeuvre assistance system (MAS) can be introduced successively into practice and the MAS can accompany the nautical officers up to the higher automation levels. In addition, the nautical experts can be involved in the development process of the human machine interface.

Ship manoeuvres can be distinguished according to different aspects. One aspect is the available manoeuvre space. The available space determines the necessary precision of manoeuvring. Tight structures such as ports offer further challenges for ships with less manoeuvrability. Depending on the size of vessel and the determined berthing position, manoeuvres in a certain order have to pass within the port specific speed limit. The planned manoeuvre sequence can be disturbed by other vehicles or their transmitted forces. A variety of interactions with port facilities affect the motion by hydrodynamic and aerodynamic forces as well.

The effort required for automation depends largely on the manual process itself and the
Figure 1. Systematics of manoeuvre automation

general conditions. In fact, navigating and controlling a ship is a much more complex process than controlling a car. Nautical officers need a long time of theoretical and practical training before they can be fully responsible for a ship. During manual manoeuvring, in addition to the actual task of keeping on the planned track, the officer must consider all relevant conditions on board, in the environmental and traffic situation, IMO and shipping company guidelines as well as captain’s instructions. He must have a mental model of the ship movement and all forces acting on it by the actuators under the local environmental conditions. The motion is influenced by effects of shallow water, banking, shadowing by other objects or varying weather conditions in current and wind. These effects are partially measured by instruments integrated in the bridge system, but these measurements are related to only one or few points on the ship’s hull and often they are unreliable. In addition, the officer therefore incorporates estimates by his own observations of the situation into the mental model. Of course, this individual model is based on his experience and therefore does not cover extreme situations. For increasing safety and efficiency of manoeuvring, a general automation approach needs a prioritised list of automatic functionalities.

From an automation point of view, a difference is made between vehicle types, operating modes, and velocity ranges. The classical systems for heading control and path following applied to standard vessels like ferries, cargo or cruise vessels are designed according to [4]. These systems work as follow-up controllers using classical control approaches for transiting, explained in [7]. But, these systems are not suitable for manoeuvre operations.

It is obvious that the dynamic behaviour and the control requirements significantly differ between the operation modes. Therefore, each mode needs potentially a different control approach combined in a hybrid control scheme with linear and non-linear controllers or robust control structures. The idea is that there is a supervisor who selects the appropriate controller from a controller set, depending on the current operating conditions of the process [8]. The supervisor works in a feedback loop and generates the switching signal based on the control variables of the controller and the process output similar to an adaptive structure. The difference lies in the generation of the switching signal. While adaptive systems use continuously working
tuning algorithms, the hybrid structure combines the continuous control loop with a discrete switching logic [9]. Hybrid systems are developed in the maritime area mainly for special ships able of dynamic positioning (DP) [10].

3. Nautical frameworks for manoeuvre planning
As mentioned above, the necessary precision of a manoeuvre depends mainly on the available space. While a few meters on the open sea have no consequences, centimetres in the vicinity of solid structures are decisive. In port manoeuvres, the attention of watch officer is massively increased to estimate continuously the surrounding situation, the distance to other vessels, navigation marks and harbour facilities. Commonly, he operates in the small bridge wing at the docking side. The relevant measuring displays and control levers are close together so that the officer can see and handle everything from one position. Often, he is assisted by a second officer who gives him auditory information about the relative location of the vessel and communicates with other assistants onboard.

In order to support this manual control in simple manner, availability and quality of measurement data should be increased and supplemented with missing information. By questionnaire based survey with a ferry crew [11], the authors could specified this information. Individually, officers use the ship’s speeds such as speed over ground (SOG), rate of turn (ROT) and rarer transversal velocity. Especially under rough environmental conditions, they would like to know if their control interventions are sufficient to keep the vessel on mental path. Secondly, reliable distances to the harbour facilities are important particularly under poor visibility conditions. Another survey shows low quality and reliability of classic navigation data onboard [12]. A human operator can compensate for the missing values or inaccuracies with his own observations and experience, but automatic operations have to base on reliable data. This objective can be reached by integration of more precise sensors and advanced data processing, ideally based on specific dynamic ship motion model. In ship handling simulators (SHS), dynamic motion models are established already, so that SHS present a good starting point for automation by manoeuvre planning and prediction.

3.1. Manoeuvre planning for collision avoidance
Manual manoeuvre data was analysed to deduce general algorithms for the automatic procedure. For collision avoidance manoeuvres, the regulations of IMO, of shipping company and the captain’s order are relevant. They determine the closest point of approach (CPA), time to CPA (T-CPA) and maximal rudder angle at the usual speed on the open sea. According to these specifications, a developed automatic procedure is initiated if a target vessel is identified by an automatic radar plotting aid (ARPA), which determines beside CPA and T-CPA also course and speed of target vessels. The new procedure calculates firstly the geometrical path of the suitable CA manoeuvre corresponding to COLREG rules number 16 and 17. Secondly, the associated manoeuvre plan is calculated to realise this geometrical path. The entire procedure is described more detailed in [13].

3.2. Manoeuvre planning for port manoeuvres
For deducing of automatic port manoeuvres, the specifications of shipping company as well and the analysis of several manual manoeuvre sequences in the concerning area form the basis. Nowadays, no exact manoeuvre plan exists for port manoeuvres but a rough way point list. An example is shown in Fig. 2 by the red dotted line which presents the last two way points of a ferry to moor in the port of Rostock. The black lines demonstrate different real berthing manoeuvre sequences which were manually controlled under various environmental conditions. From the nautical point of view, the most efficient route nearest to recommended way points was selected to plan digitally the manoeuvre sequence. Using the manoeuvre planning tool of
**Figure 2.** Five different manual controlled berthing routes of a ferry in port of Rostock

ISSIMS (Innovative Ship Simulation and Maritime Systems) institute, this planned sequence contains manoeuvre points (MP) defined by new commands for at least one of the actuators associated with the geographical position and the set of vessel motion states such as speeds, course and heading angles.

**Figure 3.** Comparison of manual controlled and digital planned manoeuvre sequence in the port of Rostock with routes (plan-left, real manual-right), manipulated variables, SOG and ROT

In Fig. 3, this manoeuvre plan (blue plots) is presented and compared with the selected manual manoeuvre sequence (red plots). It can be seen that the planned control interventions are more infrequent as in free manual control. Additionally, the planned sequence is shorter than the manual. SOG and ROT show smoother curves. All three characteristics of the digital manoeuvre plan can contribute to decrease the fuel consumption, emission as well as maintenance
costs. Therefore, the shipping companies have a high interest on algorithms for digital planning. The two methods, automatic calculation of CA and digital re-planning of port manoeuvres, outline an approach to transfer the nautical expert knowledge into an assistance system as well as in an automatic controlled manoeuvring. Plans of port manoeuvres can be used as an overlay in electronic chart display (ECD) to show the watch officer the next manoeuvre point with the changes in commands to minimize the manual interventions and increase the efficiency. It is planned further to define so called nautical algorithms for already specified manoeuvres. An example is a docking manoeuvre at determined berth place. Beside a recommended manoeuvre plan, an area with geographical and nautical parameters can be given from where safe docking manoeuvres are available. For automatic application, the manoeuvre plan has to be transferred to a trajectory that is used as a direct controller input.

4. Assistance during manual manoeuvring
Based on digital manoeuvre plans, the manual manoeuvring can be assisted by different functionalities. In a real ship application, assistance requires beside the specific dynamic ship motion model an online interface to the voyage data recorder and a software module to synchronise and fuse the current ship’s sensor data. Synchronisation is needed because of different sample rates and locations of sensors. Data fusion takes into account the different quality and reliability of data, also in consequence of the changing environmental conditions during measurement. The authors developed different methods for sensor fusion for assisted or automated manoeuvre processing [12], [16]. The developed manoeuvre assistance system comprises two modules: the monitoring tool and the function display, presented with basic functions in Fig. 4.

![Figure 4. Manoeuvre assistance system with monitoring tool and function display](image)

Monitoring tool bases on electronic chart system (ECS) and displays in the electronic navigational chart (ENC) actual vessel position, manoeuvre plan, nautical algorithms optionally, past track and predicted motion determined by the current settings for propulsion and steering units. ENC is a common nautical tool and the officers being able to correlate their own mental
model with the movement of the shape in the ENC. For motion prediction, the simplified dynamic motion model is applied in Rapid Advanced Prediction and Interface Technology (RAPIT) to present the future track by ship shapes. The distance between the shapes complies with the actual speed. The prediction horizon can be chosen between 1 to 24 minutes but also automatically adapted with the current speed. This functionality, in comparison of planned and actual route, can give the watch officer security in his control decisions.

The function display is a summarised presentation of all necessary information during manual manoeuvring. As mentioned above, important information are the speeds SOG, ROT, the transversal velocity as well as the heading (HDG) and course over ground (COG) angle. Further data for displaying are the engine states, current settings and environmental measurements such as wind and current. In the future MAS, also alarms for significant disturbances in the propulsion system have to be displayed. In order to cover the individual strategies during manual manoeuvring, the future assistance system should be customisable.

5. Vehicle control framework

The automation of manoeuvring in confined waters is one key factor to achieve a high automation level in shipping. The well-known structure of guidance, navigation and control (GNC) provides a solid framework for this. GNC systems work like a closed control loop at the highest hierarchical level. The ship’s movement process is detected by navigation sensors. The sensor data is processed and fused in a navigation filter and distributed to the other modules. The guidance module generates the command values for the motion control system of the vehicle. Basically, it solves an optimisation problem, where parameters like fuel, time, weather situation but also rules for collision avoidance or coordinated movement of several ships can be considered. In addition, the guidance system serves as human-machine interface. The control module summarises the automatic motion controllers to generate the necessary forces and torques translated by the propulsion and steering gears of the specific vehicle.

5.1. Hybrid approach

Especially for standard ships without DP capability, an adapted hybrid system structure is necessary to adequately map the operational domains. Therefore, the motion is modularised and divided into different operation ranges, which are characterised mainly by its velocity. The main motion modes are transiting on open sea with higher speeds and manoeuvring with lower or negative velocities. There are subdomains to describe further effects, e.g. at negative longitudinal velocities because of the significant changes in efficiency of the propulsion units and in the hull resistance. However, the parameters of the motion models can continuously change within one domain and between two different domains. Independently from the motion mode, the disturbances affect the process in varying degrees by wind, current and other environmental factors.

5.2. Generalised model

For vehicle control, the choice of vehicle model is a matter of the utmost importance mostly motivated by the type of control approach as well as by the type of vehicle and its operational domains. Especially, model structures for manoeuvring mode are still a research area because of the difficult parametrisation. In order to overcome these difficulties, a so-called generalised model describing also the state transitions has been developed. It has been generated by consequent abstraction of the hydrodynamic effects influencing the vehicle motion. In this way, the model structure was changed from a parameter-intensive to a parameter-minimal approach but with non-linear characteristic of parameters. A further abstraction arises by straightforward connection between the system inputs and outputs. The existing cross-couplings between the internal states and the manipulated variables are included in the external forces and torques.
Finally, the interacting forces and torques of the actuators and the disturbances generate a predictable stationary value of the respective state variable. This stationary value is indirectly influenced by the cross-couplings and changes with the motion states. The abstraction is achieved by linearising the differential equation of motion around various operating points, which results in the description of the transition behaviour between equilibrium points of the vehicle motion. The adapted methodology has been introduced in [15] and applied in [16] to USVs presenting the parametrisation of the model approach with experimental results.

5.3. Control structure

The feedback control objective is to keep the vessel on a given trajectory, heading, velocity or to compensate for disturbances. According to identified operational domains and expected disturbance ranges, different controllers have been provided in a controller set switched by a supervisor. Therefore, a modular control concept is established using a unified inner loop and a variable outer loop, as introduced in [18]. The inner loop is designed as multiple input multiple output (MIMO) velocity control system. These outer controllers generate the target velocities for the inner loops. The input variables of the outer control system are provided by the guidance system and can include different target but also error values. The motion states in the earth-fixed frame are calculated by the vehicle navigation system. The velocity control system corresponds to the vehicle-specific cascade and controls the available actuators to realise the desired translational and rotational components. Therefore, it combines the modules feed-forward, feedback and actuator allocation (Fig. 5), what is essential for manoeuvring vehicles utilising different actuator configurations and a significant advantage with low performance of navigation sensors and signal processing, as is the case with standard ships. The feedback controller considers environmental and system disturbances as well as deviations due to parameter uncertainties of the underlying models. It can be shown that the different disturbance sources have similar impact on the motion behaviour. Integral behaviour is required since constant or slowly varying disturbances are to be expected. According to the degrees of freedom of the underlying generalised model, a decentralised multi-variable controller has been designed. The parameter space method is used for controller synthesis, because of the strongly changing parameters during vessel manoeuvring. The resulting controllers are generally less complex, but provide a robust parametrisation. The control approach was demonstrated in [16], where the velocity control of USVs in moderate sea conditions achieved good control results.

![Cascaded control structure](image)

**Figure 5.** Cascaded structure and inner loop of control system
6. Automatic manoeuvring by ship handling simulator

The developed methods were validated with one of the SHS bridges in the Maritime Simulation Centre Warnemünde (MSCW). A SHS bridge is a certified tool to educate and train nautical officers in full ship missions. The realistic representation of the ship bridges, environmental conditions and ship movements in the SHS enable complex tests of the developed modules under almost real nautical conditions. In the SHS, topology and positions of sea marks such as buoys, correspond to real situation in the selected sea area. In preparation of a SHS trial, a specific ship is positioned in a selected sea area. For manoeuvre assistance, the ships are manually controlled by the bridge handles. For automatic manoeuvring, additional software modules are needed to extract the relevant NMEA data from the entire data set of SHS for characterising the ship motion and actuator commands. The controller output respectively output of allocation is transmitted directly to the bridge instead of manual commands. The signal routing for both manoeuvre assistance and automation is shown in Fig. 6.

![Diagram](attachment:image.png)

**Figure 6.** System conception for manoeuvre assistance and automation by SHS trials

### 6.1. Automatic collision avoidance

The automatic CA procedure bases on the manually initialised target identification by ARPA system and the subsequent calculation of geometrical solution and manoeuvre plan for CA as described in section 3.1. In order to use the manoeuvre plan in controller, a trajectory is generated as time series of positions, velocities and actuator commands. The actuator settings are applied to the control oriented model to estimate the appropriate target velocities for 2 DOF velocity controller in the inner loop. Deduced from geographical path, velocity differences are calculated to keep the vessel on path in real time by the trajectory controller in the outer cascade. The method description can be found with more details in [13].

Fig. 7 presents a map section of trials in SHS with ferry Mecklenburg-Vorpommern in starting position of automatic CA manoeuvre. In consideration of COLREG rule 16, the controlled vessel has to give way to avoid the collision with the crossing target vessel from starboard. The orange dotted line shows the geometrical solution considering the CPA of 0.54 nm and T-CPA of 5 min. The manoeuvre plan is sign in blue and is characterised by manoeuvre points where only the rudder angle is varied to change the course, hold it and return to the original course after solving the collision risk. The manoeuvre plan is equal to controller trajectory which starts in the current
Figure 7. Encounter situation in SHS with automatically calculated geometrical CA solution (orange) and deduced manoeuvre point plan (blue) for realisation.

6.2. Automatic port operations

The cruise ship MV Europa was used in the SHS to validate the hybrid manoeuvring control, studied so far. The vehicle is equipped with two pod drives and a bow transverse thruster. The manipulating values for the control system are the propulsion commands in EOT (engine order telegraph) and turning angle $\delta$ as well as THR for the bow thruster. The vessel has a length of about 200 m, a width of 24 m and a draught of 6 m. For the evaluation of the control performance while manoeuvring, a turning manoeuvre on the turning plate in port of Rostock was chosen as simulation scenario. The trajectory was deduced from a manually controlled manoeuvre as already was described above. Fig. 8 shows the simulations results. The manoeuvre starts at the port entrance with a longitudinal velocity $u$ of about 6.5 kn. After $t = 270$ s the ship starts to decelerate to about 0 kn while approaching the turning plate. During that deceleration the hybrid structure switches three times to different controller sets as well as considering different actuator configurations and allocation constraints. Switching is done using the signal $\sigma$ due to the explained operating domain models used for controller parametrisation. During $590 < t < 1245$ s the vessel turns with a yaw rate $r$ of about $40^\circ/\text{min}$ using the bow thruster and one of the pods which has been turned 70° to compensate for the transversal velocity $v$. Hence, only small manoeuvring space is used for the turning manoeuvre. Finally, the vessel accelerates and moves to its docking place.
7. Conclusions and outlook

This contribution elucidates an innovative approach for assisted and automatic ship manoeuvring which combines both nautical expert knowledge and performant hybrid control methods. The different requirements for automatic track control on open sea or port manoeuvres are implemented from nautical planning to controller design. While a collision avoidance manoeuvre has to be planned immediately in the risk situation under actual environment conditions, a repeated port manoeuvre, such as docking of a ferry line, can be planned or adapted for prognosticated weather before the voyage is started. In comparison to today’s used way points for berth-to-berth declaration, the advantages of manoeuvre plans are concrete actuator commands in geographical positions. This increases the manoeuvring accuracy and efficiency of a complete voyage. By overlaying the plan in ENC, the self-developed plan can be used by the watch officer to keep the ship on planned track. RAPIT prediction is an additional support during manual manoeuvring by showing the future motion of a vessel based on current manual control.

In order to transfer the manual to automatic procedure, the manoeuvre plan is converted to a time series with geographical positions, motion and actuator values. This trajectory is applied in two respects within the cascaded controller structure. On one hand the actuator commands are converted into velocities by a simple control-oriented motion model to use them as target values for hybrid velocity control in the inner loop. On the other hand, velocities are deduced from differences between geographical and actual path to execute the given manoeuvre trajectory in real time. The simulated trials in ship handling simulator show good results even in case of constant external disturbances. First experiments with USVs confirm the control approach where the environmental forces are varying.

By progress of the joint project GALILEOnautic 2, different applications of the presented methods are planned. The manoeuvre assistance system will be tested on a real ferry for assistance during manual control. Therefore, the ferry will be equipped with an additional sensor network for proximity recognition. The sensor data will be highly weighted involved in data synchronisation and fusion to increase the precision of position measurement especially near the harbour facilities. In consequence, the RAPIT prediction should be more reliable. On this
ferry, the nautical officers will test and validate the planning and monitoring tool of assistance system to optimise the human-machine interface functionalities. Additionally, the methods of planning, assistance and control will be applied on USV MESSIN and further on the research ship Deneb to proof the scalability of approaches as well as the transferability into the real world. All trials on real vehicles will be prepared by tests in ship handling simulator.

Acknowledgments
The authors would like to thank the German Federal Ministry for Economic Affairs and Energy (BMWi) and the Project Management DLR for supporting the GALILEOnautic 2 project under registration number FKZ 50NA1811 and 50NA1809.

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