# Manoeuvring Automation towards Autonomous Shipping

A U Schubert*[1] Dr.-Ing., M Kurowski[2], M Gluch[1] Dr.-Ing., O Simanski[1] Prof. Dr.-Ing., T Jeinsch[2] Prof. Dr.-Ing.

[1] *University of Applied Sciences Wismar, Department of Maritime Studies, ISSIMS, Germany*
[2] *University of Rostock, Institute of Automation, Germany*
* Corresponding Author. Email: agnes.schubert@uni-rostock.de

**Synopsis**

The German joint project *GALILEOnautic* aims to develop systems for autonomous navigation and optimised manoeuvring of vessels cooperating in areas with high safety and efficiency requirements, such as harbours or narrow waterways. In the conception of this project, the SAE levels of the automotive industry were applied for classification of intended levels in automation of already being used manoeuvring vessels. It fairly soon became apparent that the conditions in development of new autonomous road vehicles and the appropriate infrastructure are significantly different in comparison to adaption of navigation and manoeuvring of watercrafts which are part of a complex transport network. Therefor and in relation to the few orientating guidelines addressing autonomous maritime applications, a specific concept for manoeuvring automation in high safety areas was developed. It defines the automation levels towards autonomous shipping considering the current practice and the technical equipment on such vessels, the legal framework for automatic shipping as well as the requirements for integrating automatic manoeuvring in the traditional shipping traffic. The contribution introduces this automation concept and the necessary infrastructure for each level. Additionally, the results of the first project phase are presented. It implies the essential sensor equipment and subsequent data fusion to describe completely the dynamic ship motion and to recognise the close surrounding of the vessel. A hybrid control scheme is applied including feedforward and feedback modules. The control approach is illustrated by interfered encounter situations in ship handling simulator and for unmanned surface vehicles. The paper gives a prospect on the future investigations for higher manoeuvre automation.

*Keywords:* Marine systems, automatic control, guidance, navigation, hybrid control, manoeuvring ships

## 1. Introduction

The joint project *GALILEOnautic* studies and develops necessary requirements and control structure to establish fully automated ships cooperating in areas with little space to manoeuvre and high safety standards, such as harbours, narrow waterways or zones with denser traffic. The surveys address explicitly the larger vessels without dynamic positioning (DP) system, merchant ships or ferries. These types are characterised by an effective transport volume, but only less manoeuvrability and basic sensor equipment. In the mentioned areas, the vehicles need to move with low velocities. The motion is affected by different forces from the environment, e.g. wind, current, banking, shadowing areas or shallow water. In general, their routes and the harbour situations are repetitive. During the transit phase in open sea, simple speed and course controllers are already applied. In consequence, there are even economic interests and great potential to optimise and automate the manoeuvring process in the harbours according to the actual conditions.

During the conception of automation for manoeuvring vessels already being in use, generally must be answered how the given infrastructure needs to be adapted and advanced for automated functionalities without interrupting the operation of the vessel.

**Authors' Biographies**

**Dr.-Ing. Agnes U. Schubert** works as a research assistant in the field of marine control applications with a focus on modelling and model predictive control as well as the development of ergonomic assistance systems. Her earlier experiences encompass chemical and medical automation which also included the development of assistance systems.

**Dipl.-Ing. M Kurowski** is scientific head of the research group marine control applications at the Institute of Automation at the University of Rostock. The research is focused on modelling and hybrid control of vessels and unmanned surface vehicles as well as the development of guidance systems.

**Dr.-Ing. Michael Gluch** is deputy director of Institute of Innovative Ship-Simulation and Maritime Systems (ISSIMS) at the University of Applied Sciences Wismar. His research interests include satellite-based and terrestrial maritime navigation, hybrid sensor systems and data fusion, ship motion models, simulation and track prediction in manoeuvre assistance systems.

**Prof. Dr.-Ing. Olaf Simanski** is professor of Automation at the University of Applied Sciences Wismar in the research group Automation and Mechatronics in the Computational Engineering and Automation Group. His focus in marine research lies on real-time embedded systems.

**Prof. Dr.-Ing. Torsten Jeinsch** is professor of Control Engineering and head of the Control Application Centre in the Institute of Automation at the University of Rostock. The research focus of institute lies in control applications in marine systems using fault tolerant algorithms.


http://doi.org/10.24868/issn.2631-8741.2018.020

The new conception based on the SAE (Society of Automotive Engineers) definitions of automation level for on-road motor vehicles but the prerequisites for automation of traditional maritime vehicles for the motion in high safety areas are significantly different. Therefore, the first section deduces the definitions of manoeuvre automation levels (MAL) in contrast to other maritime guidelines for automation. In the following sections, each level is described by necessary infrastructure and technological progress. It is illustrated by previous solutions in project *GALILEOnautic*. A prospect is given for the planned investigations in higher levels. In the conclusion, the practical relevance of the new stringent automation concept is proved.

## 2. Classification of manoeuvring automation

SAE International defines the levels of automation for on-road motor vehicles first in 2014 with six levels from level (0) 'No Automation' to the highest level (5) 'Full Automation', i.e. autonomy (SAE, 2016). In autonomy, the car doesn't need any more a human driver for the fall-back solution in a dynamic driving task under any circumstances. Despite the rapid development of automotive automation, the complete concept in level with high (4) or full automation (5) is only roughly described except in geofenced areas with the corresponding environment.

Unlike the targeted automotive developments, the number of initiatives for autonomous shipping is modest and with different strong relations to the SAE definition. Lloyd's Register released the first procedure guidance for autonomous ships (LR Groupe, 2017). It describes seven autonomy levels ranging from 'AL 0 – manual/ no autonomous function' to 'AL 6 – fully autonomous/ unsupervised'. Between them, the guidance distinguishes levels with decision support on and off-board (AL 1 and 2), 'AL 3 – active human in the loop' and 'AL 4 – human on the loop'. The decisions and actions are performed with different degrees of human supervision. The two highest level AL 5 and AL 6 are defined as fully autonomous whereby a rarely supervision by human operator is intended in AL 5.

The Norwegian Forum for Autonomous Ships (NFAS) defines clearly four operational levels specific for autonomous merchant ships (NFAS, 2017). In the first level, all systems are summarised that use today's or tomorrow's advanced *decision support*, starting with electronic chart systems, autopilot or track pilots. The human operator is fully responsible without system autonomy. The level '*Automatic*' includes selected automatic demanding operations without human interaction, e.g. automatic berthing. For the operations, predefined sequences are applied but in unexpected events the human operators onboard or in the shore control centre are always available to intervene by direct or remote control. The third level '*Constrained autonomous*' means fully automatic operations in most situations. Human operators supervise the process still continuously. A ship is called '*Fully autonomous*' if there is no supervision at all either onboard or onshore. The authors of NFAS notice that fully autonomy is in shorter time perspective only realistic for shorter distances and very controlled environments.

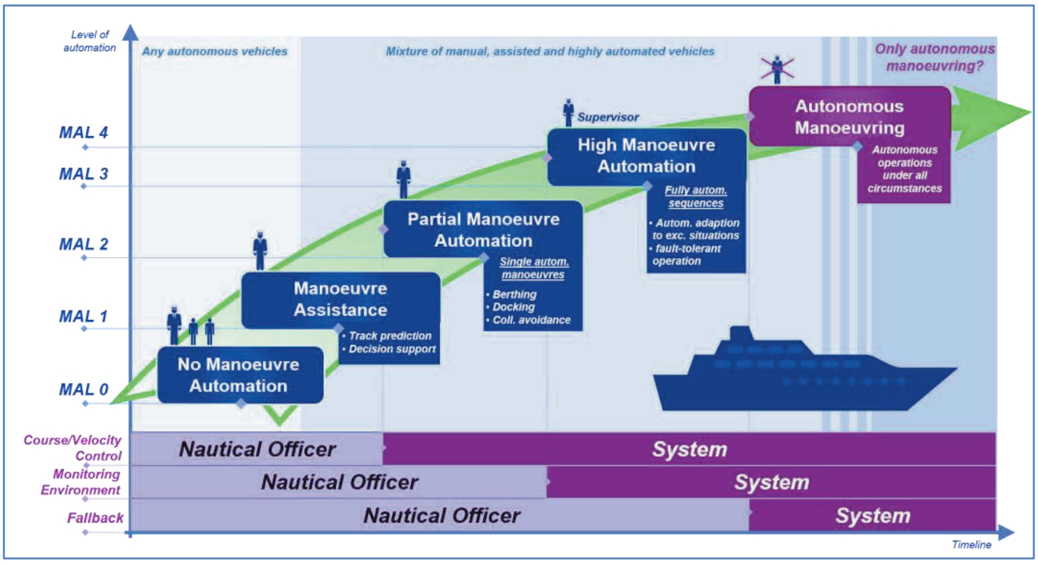


Figure 1: Automation levels of manoeuvring of maritime surface vehicles

The challenge in increasing automation level consists in handling of unexpected situations, especially with little space to manoeuvre. The project *GALILEOnautic* aims specially on such situations. The SAE levels were adapted to classify automation of manoeuvring mode in manoeuvre automation level (MAL), seen in Figure 1. The classification is similar to the NFAS levels except that the lower level *Decision support* is split in *No manoeuvre automation* (MAL 0) and *Manoeuvre assistance* (MAL 1) because, e.g., the claimed autopilot is not


http://doi.org/10.24868/issn.2631-8741.2018.020

available for manoeuvring in high safety areas. Additionally, the manoeuvre assistance has the strong potential to mediate the professional skills of nautical officers. Therefore, a modular manoeuvre assistance system (MAS) should be stepwise advanced by customisable functionalities. Sufficient specific models of vessel motion, harbour characteristics and the environmental data are the requirements to provide relevant notes and warnings for assistance of classic manoeuvring process. Advanced sensor equipment is the basis for such features.

In level MAL 2 *Partial Manoeuvre Automation*, single manoeuvre sequences are automated, e.g. automatic berthing. Control functions need to be integrated in the MAS which the responsible operator initialises. Optimised trajectories, adaptive control strategies and safe fall-back procedures are absolutely required for the automation.

In level MAL 3 *High Manoeuvre Automation*, these manoeuvre sequences are automatically combined to complete tracks in geographically-restricted areas, e.g. a specific port. The system decides which manoeuvre has highest priority in an actual situation. An additional module ensures fault-tolerant operation as part of the control strategy. The operator assumes the role of a supervisor but he doesn't act as an initiator of single operations.

MAL 4 corresponds to *Autonomous Manoeuvring*. No operator cares neither onboard nor ashore. This short classification gives an idea how many requirements and data are relevant to realise not only higher manoeuvre automation but global autonomous shipping traffic. However, already highly automated shipping in limited areas provides a great potential to increase effectivity, safety for man, machine and environment.

## 3. Development chain of manoeuvre automation

The concept provides on one hand that the next higher level includes all functionalities of the lower levels and on the other hand in using the automated system that the next lower level system acts as fall-back solution for the actual level.

### *3.1. Manoeuvre assistance – MAL 1*

Providing more and more precise information is the basic assistance in classic manoeuvring to ensure the watchkeeping officer (WO) in his own estimations. Relevant information concerns all states of the own ship and details about the environment with influence on the ship motion or potential track. In Figure 2, the inputs are summarised to identify a dynamic motion model: *sufficient accurate position data, the relevant environmental data and the proximity recognition* especially in the harbour where classic positioning systems do not provide enough accuracy. A dynamic motion model forms the basis for extended assistance by prediction as well as the further automation. It represents the relation between the current actuator settings, the affecting environmental forces and the resulting dynamic motion of the vehicle which is described completely in the equations of motion in at least 3 degrees of freedom. A generic model suitable for controller development has a simple structure with various lookup tables for the parameters. The several sensor and actuator data have different timestamps and sampling rates so they need to be *synchronised and fused* with model-based weights according to their current quality. The weighted sensor fusion is closely linked with the dynamic motion model to verify the motion states by the actuator settings.

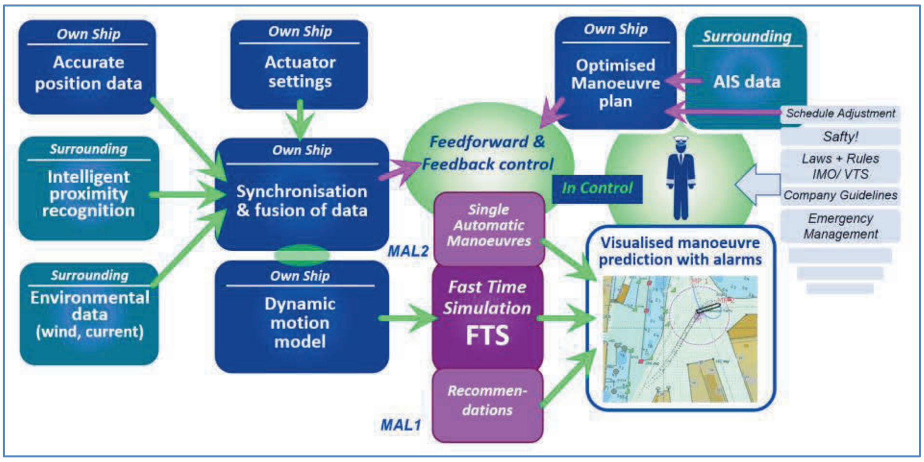



Figure 2: Necessary infrastructures for manoeuvre assistance – MAL 1
and partial manoeuvre automation – MAL 2


http://doi.org/10.24868/issn.2631-8741.2018.020

Originating from the known high-precise position, the *prediction* in MAL 1 shows the resulting motion from the current actuator settings and the environmental forces by fast time simulation (FTS) with prediction horizon up to 24 minutes. The operator gets the feedback whether the actuator settings are adequate to reach his subsequent mentally planned position. Additionally, warnings can be given if the predicted path presents significant risks of collision or grounding (Baldauf et al., 2017). Simultaneously, the operator can reduce strong variations in actuator settings because of visualised prediction. The MAS developed by ISSIMS institute of the Wismar University of Applied Sciences realises this prediction and supports the operator in his own estimations (Schubert et al., 2018).

The sensor equipment in shipping automation is oriented strongly to automotive developments already for manoeuvre assistance. An automatic system with responsibility for perception of the complete surrounding environment needs sufficient accuracy of the information at all time. The measurements of multiple sensors have to be combined and analysed to perform this challenging task (AAWA, 2016). The KONGSBERG project YARA Birkeland will equip the autonomous, area limited transport vessel with an array of radar, lidar, AIS, cameras and IR cameras (YARA Birkeland, 2017). These sensors are partially supplementary and redundant because of their availability is depending on weather conditions or they will be applicated in different situations depending on the distance to other objects to be collected.

In the project *GALILEOnautic*, it was investigated onboard a ferry which advanced sensors are useful to supplement the quality of existing ship sensors. An additional GNSS (Global Navigation Satellite System) receiver (AsteRx3 HDC) and two IMUs (Inertial Measurement Unit) of different precision in comparison have been applied (Crossbow AHRS440, Xsens MTi-G-710) to increase the precision of position in 6 DOF (Degrees of Freedom). The measured positions in the harbour and in relation to the facilities show precision in range of centimetres or maximal 1-2 decimetres in contrast to several meters in the data of Voyage Data Recorder (VDR). Commonly, position data are illustrated in Electronic Nautical Chart (ENC) without knowledge of its accuracy. Additionally, it was observed that radar detections of the harbour facilities don't fit with the ENC arising from many potential sources. Especially in reduced visibility during night or adverse weather, such tools generate an additional risk. Therefore, proximity recognition is essential to assist or automate manoeuvres in harbour by accurate positions (Schubert et al. OCEANS, 2018).

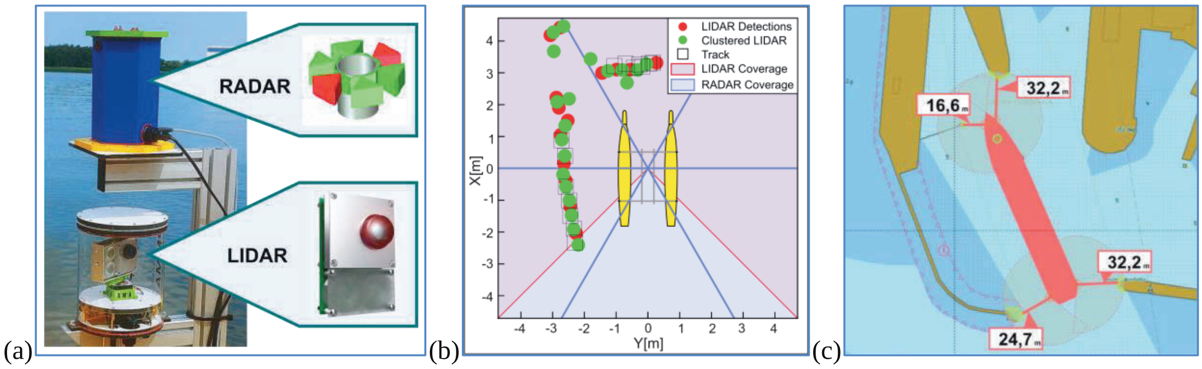



Figure 3: (a) Radar-lidar-system installed on USV, (b) Scatterplot of proximity distances around the USV, (c) Concept of presentation of proximity distances on larger vessels in ENC

In the project, a new *proximity recognition system* was developed which is suitable in the maritime environment. For first tests, it was installed on an unmanned surface vehicle (USV) as shown in figure 3. The system combines radar with lower frequencies and lidar modules to detect the objects in a 360°-view around the vehicle in a range of 40 meters. The quality of the radar measurements depends on the bundling of the beams, the shape and the material of the reflecting objects. They are only slightly attenuated by rain. The inhouse developed radar sensor module combines 6 single-chip radar sensors TRX_120_001 (Silicon Radar). The centrepiece of the lidar module builds the M16 Eval Kit by Leddartech. The module is mounted in a case which is rotated by a step motor control. The lidar module provides an accuracy of 5cm depending on the distance to the target. Laser beams are strongly attenuated by environmental impacts. The distance data of lidar and radar system are fused locally on a microcontroller board. In the first stage, the result is displayed only in scatter plot for manoeuvre assistance. The high accuracy of the sensor system offers further applications such as object identification and direct distance control for automatic docking. For application on larger vessels, the sensor configuration has to be expanded according to the vessel size. Figure 3(c) shows the concept to present the real distances measured by proximity recognition system on larger vessels in the ENC. In the fusion of all sensor signals in harbours, the proximity recognition data get the highest weighting because of their highest reliability.

Important components in maritime sensor equipment are the *sensors for environmental impacts* on the dynamic ship motion. Commonly wind, depth and current are measured because of their especially strong effect. During

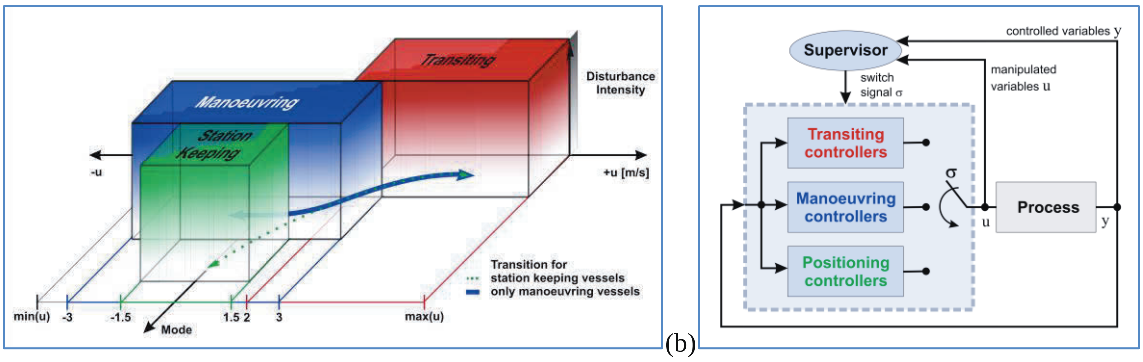

http://doi.org/10.24868/issn.2631-8741.2018.020

classic manoeuvring, the operator estimates the environmental conditions, as the distances to other objects, and considers them in subsequent manoeuvres. Additionally, the WO can use individual sensors onboard or external to measure the current or the wind but with a few or only one measurement point on the vehicle. To consider these data together with the observations in the manoeuvring process, the pilot needs a mental model of their impact on the dynamic motion. The quality of this model depends strongly on the practical experience of the nautical officer. Particularly, extreme conditions are often not covered by individual mental models. An advanced assistance system offers the opportunity to integrate the sum of environmental impacts in the dynamic motion model.

### *3.2. Partial Manoeuvre Automation – MAL 2*

In MAL 2 as shown in figure 2, the manoeuvre assistance system is being expanded by single automatic manoeuvres with relatively low space requirement. The specific manoeuvre is initialised by the operator but controlled by an integrated system for automatic velocity control and path following (Kurowski et al., 2017). The operator acts as supervisor and can intervene at any point during the operation. He uses the visualisation of FTS to watch and evaluate the actual controller output. The controller utilises the same inputs like the FTS. Additionally, digitally planned and continuously optimised trajectories are provided to the controller to minimise the difference between planned and actual path. The AIS data of other vehicles in relevant distance are included in the trajectory optimisation for collision avoidance. Other legal or company guidelines can also be considered as constraints of the trajectory optimisation to support the WO. Examples for such specifications are the fuel consumption or emission standards (Schaub et al., 2015). It is obvious to applicate the already existing dynamic motion model for controller design. On the one hand, the actuator settings should be integrated in digital manoeuvre plan and can be used as feedforward controller. On the other hand, the parameters of the feedback controller can be deduced from dynamic behaviour of the model for disturbance attenuation.

Besides the essential sensor equipment, advanced guidance, navigation and control systems (GNC) are necessary to operate ships at higher automation levels. For the target vessels with conventional propeller rudder combinations, classical systems for heading control and path following are applied during transit mode. The requirements of each manoeuvre in high safety areas significantly differ in working range of longitudinal velocity u and dynamic behaviour which is illustrated in figure 4(a). Therefore, each function needs a different control approach combined in a hybrid control scheme with linear and nonlinear controllers. According to the current process and environmental conditions, a supervisor discretely switches from the given set to the suitable controller, figure 4(b). The GNC design has a simple structure using complex parameter setups and is strongly associated with the generic model concept described above. The controller concept is explained in detail in (Kurowski et al., 2017).



(a) (b)
Figure 4: (a) Vehicle motion modes (b) Scheme of a switching control system

In general, the vehicle dependent velocity control loop consists of feedforward and feedback control terms as well as the allocation as shown in figure 5. At this level, effective nonlinearities of the vehicle dynamics are regarded by the feedforward terms. Consequently, simple linear feedback control structures can be used. Furthermore, this concept separates the reference tracking performance from the disturbance attenuation behaviour, which is essential for vehicles manoeuvre in limited fairways, where disturbances have the major impact. The inputs of the feedforward component are the command signals $\mathbf{x_c}$ to generate forces and moments $\mathbf{H_{ff}}$, which lead to the corresponding manipulated variables $\mathbf{u}$ provided by the allocation. The feedforward parameters of the velocity control system can be calculated by inversion of the parameterised model. In contrast to the feedforward control, the feedback control term evaluates and minimises the difference between commanded and controlled variable of the vehicle motion disturbed by environmental or intrinsic process disturbances $\mathbf{w}$. Hence, the feedback controllers including integral parts have to be used for each degree of freedom to compensate the


http://doi.org/10.24868/issn.2631-8741.2018.020

deviations arising from the neglected cross-couplings as well as the external disturbances or faults. The outputs of the controller are the correcting forces and torques $\mathbf{H}_{\mathbf{fb}}$. The disturbances acting on the vehicle have both stationary and stochastic nature, and their statistical characteristics are not known exactly during the design procedure. Furthermore, due to manoeuvring of the vehicle, there are substantial and rapid changes in the statistical properties of disturbances. For these reasons, robust controllers are suitable, which ensure sufficient performance in the different operation modes.

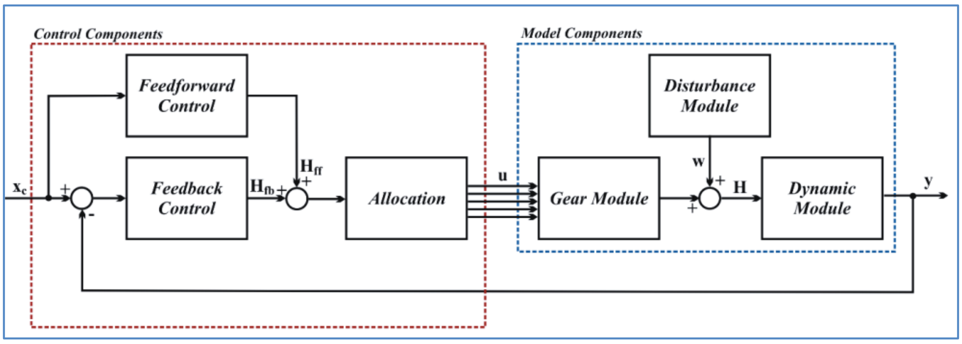



Figure 5: Modular velocity control loop structure

The hybrid control concept was evaluated in the ship handling simulator (SHS) for ferries and during experimental trials in the port of Rostock using USVs (Kurowski et al., 2018). In each case, the encounter situation of two autonomous navigated vehicles is interrupted by a third non-automatic vehicle (figure 6). This interference must be included in the autonomous trajectory optimisation used for feedforward control. The feedback controller located on the vehicle or the simulator bridge minimises the difference between the optimised and the actual trajectory caused by environmental disturbances. The demonstrations show promising results. In prospect control systems, the robustness against major disturbances and system faults should be realised.

(a)



Figure 6: Test for autonomous navigation in encounter situations (a) in SHS and (b) by USVs

### *3.3. Prospect for higher manoeuvre automation – MAL 3 and 4*

In the second stage of the project, high manoeuvre automation - MAL 3 should be realised. MAL 3 was defined above by complex manoeuvre sequences in geographically-restricted areas. Typically for this level is ferry manoeuvre automation with two included harbours and therefore a specific manoeuvring space or effective manoeuvres but variating weather or traffic conditions. For automation of manoeuvre sequences in most situations, e.g. entering into the harbour, turning and berthing, an effective system needs at least the technological profile of a high-qualified, experienced human operator with redundant sensor equipment as well as real-time reactions. Certain rules must be followed, restrictions must be respected and the safety of passengers and the ship must be guaranteed. It is planned to realise this technological profile by a fault-tolerant (FT) GNC system with a structure shown in figure 7.

 http://doi.org/10.24868/issn.2631-8741.2018.020

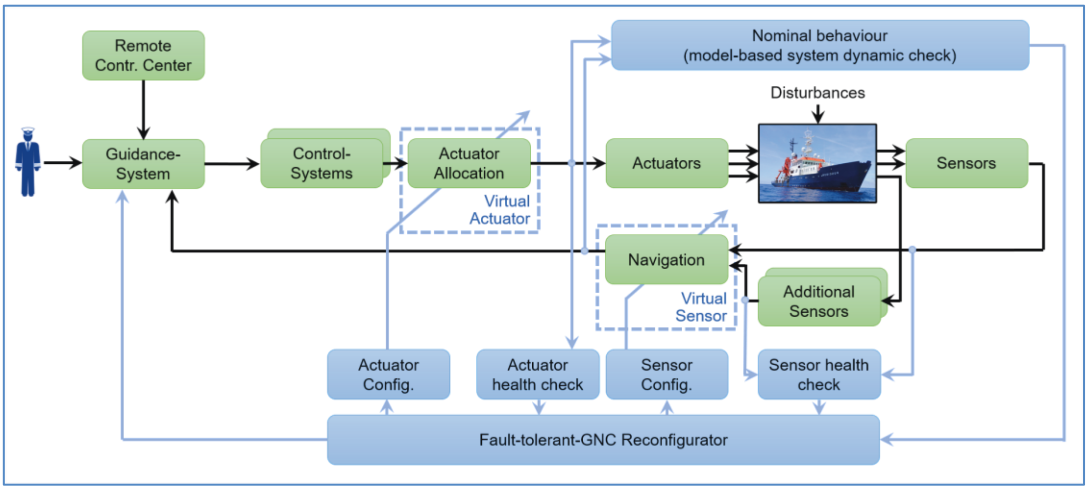



Figure 7: Advanced application of FT-GNC reconfigurator in MAL 3

The FT-GNC system (blue blocks) supplement the common modules for guidance, navigation, and control of the ship (green blocks). Methods for autonomous fault diagnosis, isolation and identification as well as robust fault-tolerant control are developed to ensure safe ship management in every operating condition. The health status of the individual sensors and actuators is checked continuously by the system. Secondly, the actual motion dynamics will be compared with the expected nominal behaviour by simulations. The FT-GNC Reconfigurator evaluates the deviations and adapts the sensor and actuator configuration if necessary. In autonomous ships (MAL 4), the FT-GNC unit works without the supervision of an operator. Simultaneously with suitable interfaces, it is an effective tool for external system monitoring.

## 4. Conclusions

This paper introduces the required infrastructure and generic control approaches to increase the level of automation for manoeuvring marine vehicles. A classification of manoeuvre automation in four levels is presented which ranges from manoeuvre assistance to autonomous manoeuvring. In all level of automation, an advanced sensor equipment is necessary for an accurate state, position and distance measurement as well as the corresponding guidance and motion control. The complex sensor system integrates different technologies to provide reliable data under all circumstances and weather conditions. The fused position, environment and actuator data form the basis for identification of a dynamic motion model and its application in motion prediction as an assistance system in manual manoeuvring. A hybrid control scheme has been presented that can be used for all operation modes and the transition between the modes. The entire system was applied successfully in SHS and USV manoeuvring. Future developments will focus on adaption of this concept for larger vessels to establish automatic manoeuvring in areas with high safety requirements. The application of fault-tolerant control methods is essential for higher manoeuvre automation. The contribution shows that manoeuvre assistance as a baseline system for automation offers both the transmission of nautical expert knowledge as well as a stable fall-back solution for higher automated or autonomous vessels.

## 5. Acknowledgements

The authors would like to thank the German Federal Ministry of Economics and Technology (BMWi) and the Project Management DLR for supporting the GALILEOnautic project under registration number FKZ 50NA1612.

## 6. References

AAWA, 2016. Remote and autonomous ships: the next steps. London: Rolls-Royce.

Baldauf M., Mehdi R., Fischer S., GLUCH M.: “A perfect warning to avoid collisions at sea?”, Scientific Journals of the Maritime University of Szczecin, ISSN 2392-0378 (Online), 49 (121), pp. 53-64, 2017.

Kurowski M., Schubert A.U., Jeinsch T.: “Generic Control Strategy for Future Autonomous Ship Operations”, 16th Conference on Computer and IT Applications in the Maritime Industries (COMPIT), Cardiff (UK), pp. 401-412, 2017.


http://doi.org/10.24868/issn.2631-8741.2018.020

Kurowski M., Damerius R., Jeinsch T.: “Generic Navigation and Control Methods for Classes of Unmanned Surface Vehicles”, MTS/IEEE OCEANS‘18 Conference, Kobe, Japan, May 28-31, 2018.

Lloyd’s Register Groupe: “Design Code for Unmanned Marine Systems”, February 2017.

Morse A.S.: “Control using logic-based switching”, In A. Isidori (Ed.), Trends in control: An European perspective, Springer, London, pp. 69–113, 1995.

NFAS - Norwegian Forum for Autonomous Ships, Rødseth Ø.J. & Nordahl H.: “Definitions for Autonomous Merchant Ships”, October10 2017.

SAE International: “SAE J3016: Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems”, Revision September 2016.

Schaub M., Benedict K., Klaes S., Baldauf M.: “Fast-Time Simulation for Prediction of Fuel Consumption and Emissions during Ship Manoeuvres”, International Conference on Shipping in Changing Climates (SCC), Glasgow (UK), Vol. 1, pp.171-183, 2015.

Schubert A.U., Gluch M., Benedict K., Kupas H., Hagendorf O., Simanski O.: „Conception of Navigation Assistance System Integrating New Sensor Technologies and Model-based Prediction”, 17th Conference on Computer and IT Applications in the Maritime Industries (COMPIT), Pavone (Italy), pp. 61-68, 2018.

Schubert A.U., Gluch M., Simanski O., Hagendorf O., Kupas H., Baldauf M., An assistance system for manoeuvring vessels in high safety areas, OCEANS - MTS/IEEE, Kobe/ Japan, May 28-31, 2018.

YARA Birkeland KONGSBERG project facts https://www.km.kongsberg.com, 2017.


http://doi.org/10.24868/issn.2631-8741.2018.020