Prediction Control Systems in Marine Applications

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ABSTRACT: The paper presents one of the modern control methods used for steering of the ship motion. The different automatic systems used to navigate the vessels are described at the beginning. Next, prediction control methodology is presented and multidimensional MPC regulator applied to steering of the training ship is shown as a technical product. Tests results from the real-time experiments with the mentioned controller are presented at the end of the article.

1 CONTROL SYSTEMS APPLIED TO STEERING OF THE SHIP MOTION

The regulation of the motion of a merchant ship seems to be one of the most difficult control problems. In fact, the ship is the multidimensional, strongly non-linear and non-stationary object (Fossen 2011). External disturbances like waves and wind play an important role in the whole regulation process therewithal. They can change reaction of the vessel to steering signals.

There are a few methods to classify control systems used for steering of the vessel movement. One of them is the classification in view of the ship's speed. From this point of view the control systems can be divided into three types:

1 for speed close to zero:
  − dynamic stabilization of position DSP (Fossen 2002),
  − stabilization of ship placement in relation to the hydrodynamic structure, position mooring (e.g. Weather Vaning) (Hals 2004).

2 for small speed i.e. 'Slow or Very Slow ahead' and 'Slow or Very Slow Astern' used mainly in harbours, navigation channels etc.:
  − controlled motion with any drift angle (crab-wise motion) (Gierusz at al. 2007, Rybczak 2018),
  − controlled movement following ROV unit (Fossen 2002).

3 for large speed i.e 'Full ahead' or a similar one used on open sea:
  − stabilization of heading (Tomera 2016),
  − the trajectory keeping (Tomera 2018, Łebkowski 2018),
  − steering during turning operations (Zhogui & Xiuyan 2011),
  − roll minimization (Perez 2005),
  − UNREP operations (Bowman 2009),

Another classification can be built taking into account the propulsion units and their mutual cooperation. The following cases can be recognized:

1 conventional propeller and blade rudder used for very small speed (Shouji 1990),

2　two or more pods installed close to each other when any pod (pods) are under accelerated water stream from another pod (pods) (Gierusz 2016),

3　two or more fins used for roll stabilization with two blade rudders (iSSMC 2014)

4　active trim tabs or active interceptors used with any propulsion devices (e.g. screws or waterjets) (Ride Control Systems 2015)

From control theory point of view the one-dimensional regulators (SISO ones) and the multi-dimensional types of regulators (the MIMO ones) can be recognized.

One-dimensional regulators (SISO ones) can be applied only for a few control systems (e.g. heading or trajectory stabilizations). They seem to be rather simple regulators but due to non-linear and non-stationary properties of the ship they often lead to modern and very sophisticated solutions e.g. adaptive or robust controllers.

The majority of cases presented above belong to the multi-dimensional types of regulators (the MIMO ones) due to the necessity to steer a few of ship's velocities simultaneously. The review of such solutions can be found in (Fossen 2011).

2　USED PREDICTIVE CONTROL METHODOLOGY

2.1　*Main features of the Model Predictive Control*

Historically MPC (Model Predictive Control) regulator comes from LQR (Linear Quadratic Regulator) designed by Kalman in 1960, which is an optimal control with the objective function minimization (Kalman et al. 1960). This mathematical operation gives a proportional controller in which constraints cannot be incorporated. First MPC regulators, in form in which they are known nowadays, were designed in the 1970s. They are based on MPHC (Model Predictive Heuristic Control) presented by Richalet in (Testud et al. 1978).

MPC is an algorithm which determines optimal control values taking into account constraints. When it is applied to the real plant these constraints (saturation of the actuators, technological and safety constraints and control signals rate of change) are very useful. First MPC controllers were applied to the slow-changing processes such as ratification of fuel, polymer production (Zavala & Biegler 2009) wood cellulose and paper production. Computers evolution and increase of their computing power caused an increase in interest in the predictive regulators in other areas as well. Nowadays they are used to control linear, nonlinear, one-dimensional and multidimensional plants.

MPC regulators are discrete-time systems in which control signals are computed on-line. Therefore computations effort and time is proportional to the degree of systems complication. This is the reason why in marine applications MPC controller works with linearized internal model. Because of use of the internal model predictive controller can deal with plants in which number of inputs is not equal to the number of controlled variables. It also considers

internal interactions and cross-coupling which occur in the ship dynamics (Miller 2016a).

2.2　*Idea of the ship motion predictive control*

Ship is a highly nonlinear plant characterized by large inertia. Moreover it moves in an environment with wind and waves disturbances. MPC algorithms are dedicated for such plants, because they incorporate process model, deal with physical constraints and use past and predicted future outputs to compute control signals. Ship's trajectory tracking controller works based on Equations 1 and 2.

$$u(k) = \left[u(k|k), u(k+1|k), \ldots, u(k+N_u-1|k) \right] \quad (1)$$

$$u(k+p|k) = u(k+N_u-1|k) \Leftrightarrow (p \geq N_u \wedge p = 1, 2, \ldots, N) \quad (2)$$

where:
N_u – control horizon,
N – prediction horizon
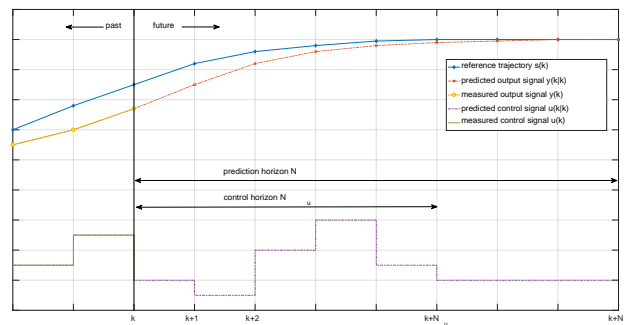$u(k+1|k)$ – control signal predicted in *k*-time for *(k+1)*-time

Figure 1. Predictive trajectory tracking idea.

Figure 1 illustrates predictive trajectory tracking problem. Optimization is done on-line to allow for the fastest possible convergence of the reference trajectory and predicted output signal. Algorithm computes output signals in control horizon and beyond it control is constant and equal to the last one estimated in the control horizon. Figure 2 illustrates a block diagram of the MPC controller used in ships for the trajectory tracking. It is connected in series to the plant.
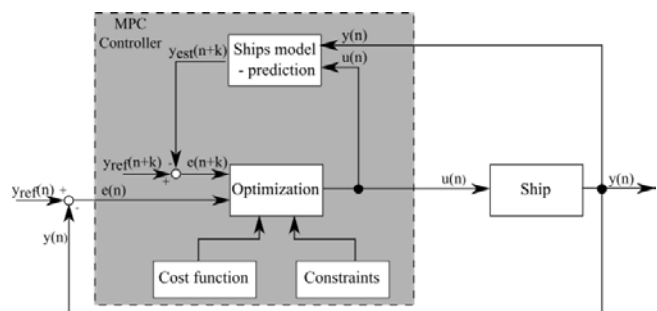

Figure 2. Predictive trajectory tracking controller block diagram.

Ship is a MIMO (Multiple Input Multiple Output) plant, when taking into account trajectory tracking problem. So optimization problem is a multidimensional one. Its cost function *J* has the following form described by Equation 3.

$$J = \sum_{p=N_1}^{N} \left\| \boldsymbol{M}x(k+p|k) - y(k+p) \right\|_{\boldsymbol{Q}(p)}^2 + \sum_{p=0}^{N_u-1} \left\| \Delta u(k+p) \right\|_{\boldsymbol{R}(p)}^2 \quad (3)$$

where:
x(k) – state space vector,
M – output matrix,
y(k+p) – output signals vector in *(k+p)*-time,
Δu(k+p) – control signal increments vector in *(k+p)*-time,
Q(p) – output signal weights matrix,
R(p) – control signal increment weights matrix.

Control signals optimization process is based on the information about ship included in its dynamics model, knowledge about constraints and predicted disturbances, past and future predicted outputs. In case of a ship steering process we define constraints as physical ones for the actuators and their real rates of turn. Weight matrix of control signals penalizes for fast and big changes of input signals, that lead to increased ships operating costs and actuators exhaustion. In turn, output signal weights matrix enforces accuracy of the trajectory tracking. Trajectory should be known and provided to the algorithm in whole prediction horizon for a better performance. Otherwise, it is treated as constant which can degrade control quality.

Plant dynamics model is very important, when control quality is taken into account. Incremental state-space model was used in presented MPC system for Underway Replenishment operations (Miller 2016a). In the mentioned above system output and control signals defined as deviations.

2.3 *Model predictive algorithms in marine applications*

MPC is a group of model-based control algorithms that have been developed since early 1970s. They come from Dynamic Matrix Control (DMC), which is known as first generation of the MPC, developed for Shell Oil (Holkar & Waghmare 2010). This control strategy may be applied to the stable linear objects and does not work with nonlinear plants having cross-couplings between several channels in their dynamics. It is useless to control ship motion, but can be applied to the ships diesel engine and regulate emission (Kozlik 2016).

Model Predictive Heuristic Control (MPHC) uses FIR linear model to estimate future control signal. Richalet in 1978 proposed extended version of predictive algorithm that includes reference trajectory (Testud et al. 1978). It defines plants closed-loop behavior and is treated as an output signal. Algorithm estimates control signals iteratively and chooses these that ensure minimization of the error between reference and set point trajectory. MPHC is a base for ships predictive regulators, despite the fact that it incorporates FIR model which is better for chemical processes control.

Generalized Predictive Control (GPC) is the most popular and widely used MPC algorithm. Its first version was proposed by Clarke in 1987 (Clarke, Mohtadi & Tuffs 1987). GPC algorithm predicts future output signals based on polynomial or state-space models. It can be used for MIMO plants that are non-minimal phase, unstable and having variable dead-times. It is also possible to add predictive feedforward controller object deals with measurable disturbances. This is common situation in ships motion control, where wind and waves are present. In GPC optimization is done on-line. The values of future controls are determined based on predefined quality indicator by solving quadrating programing task. According to the Equation 3 (see section 2.3) summands are squares of the differences between set-points and output signals estimated in prediction horizon and control signals deviations in the last sample time. During MPC controller synthesis length of the horizons, cost function form and constraints are modified. Moreover, in GPC changing predictor may be used (Camacho & Alba 2013), which extends algorithm application capabilities.

Rapid evolution of the GPC algorithm is proved by its usage in developing Intelligent Transport Systems to follow a line and guide unmanned vehicle along it (Horiuchi, Tamatsukuri & Nohtomi 2000). GPC algorithm is also a part of Scientific Environments like MATLAB, LabVIEW and SciLab, which shows its usage in industrial applications and research.

3 PREDICTION CONTROL IN UNREP OPERATIONS

3.1 *Underway Replenishment (UNREP)*

Underway Replenishment (UNREP) derives from navy. It is a form of Ship to Ship transfer that is undertaken when 2 ships are moving close to each other. Nowadays it has also found application in merchant navy. Two ships – Ship To Be Lightered (STBL) and Service Ship (SS) are moving close to each other in order to allow for fast cargo shipment between them. STBL is a guiding ship which means it moves with constant speed and course. SS is an approaching ship that changes course and speed to bring them to the STBL's motion parameters. UNREP procedure allows STBL to change course and speed not more than 10^0 and 1kn.

During commercial UNREP maneuver navigator controls ship manually and estimates distance between vessels using markers placed on boards and line connecting them. Furthermore, radar, GPS and AIS are used for distance and ships' relative position assessment. But their accuracy is too small to use them in automatic control systems.

Increasing number of VLCCs and big gas carriers that cannot enter smaller harbors. They have to be reloaded in open waters due to their big draught and restricted maneuverability. In Arctic areas feeders having an ice class are used to transport petroleum and LNG products. In this case also Ship to Ship operations are carried out. It leads to UNREP companies (e.g. STP Inc., STS Limited UK, Teakey) arising.

Regardless of the type of ships participating in UNREP, manoeuver is carried out in the same way. It is divided into three phases: approach, parallel motion, departure. Figure 3 illustrates them schematically.
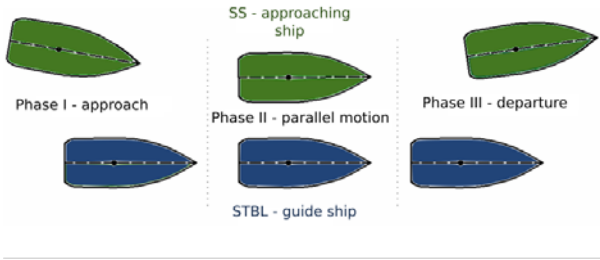

Figure 3. UNREP phases schematic.

In approach phase SS ship adjusts speed and course to the STBL, approaching it from the aft with an absolute course difference smaller than 20^0. Navigator monitors and controls their relative position in order to decrease relative speed and course difference to zero while maintaining a constant transverse difference between their sides. During parallel motion SS sails near STBL with zero course difference and longitudinal shift, maintaining constant transversal shift. During departure phase both ships should return to their previous or any other particular course. STBL should maintain its course and speed while SS maneuvers the course and speed.

3.2 MPC based UNREP control system

Ship in automatic control system is an autonomous surface vessel (ASV). UNREP MPC algorithm creation involved the same methods as in autonomous ships' formation or mobile robot control. Main difference requiring special attention are: constraints due to merchant ships inertia; relatively small powers and performance of the propellers; restricted maneuverability compared with tugs or off-shore vessels. Developed MPC algorithm uses leader-follower (Wang 1991) approach, where SS follows up STBL ship.

In order to implement predictive control, approaching ship has to be positioned relatively to guide ship. Figure 4 illustrates how SS is placed in coordinate system associated with the STBLs center of gravity. In this system are three output variables: transversal deviation (Δx), longitudinal deviation (Δy) and course difference ($\Delta \psi$).
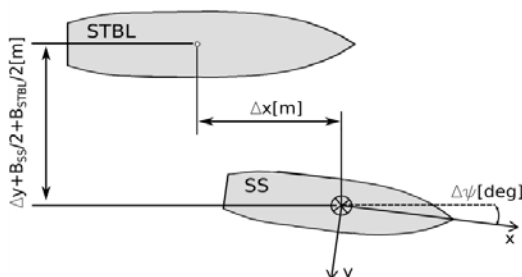

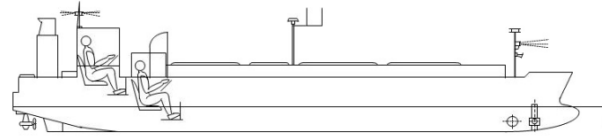Figure 4. Relative ships placement during UNREP.

Figure 5. LNG carrier "Dorchester Lady" silhouette (Gierusz 2015).

MPC regulator is used to control SS training LNG carrier "Dorchester Lady" presented in Figure 5 and virtual ship whose dynamics is adequate to training VLCC "Blue Lady". Both ships (owned by Foundation for Safety of Navigation and Environment Protection) are built in scale 1:24. LNG carrier is equipped with azipods and manipulated variables in the control system are their set-points (Δn) and angles of rotation ($\Delta \delta$) changes.

Ship dynamics forced prediction horizons, control horizons and constraints values (presented in Table 1) to guarantee the possibility of finding a solution by solving the square programming task.

Table 1. MPC weights and horizons.

Parameter	Value	
Prediction horizon	55	[samples]
Prediction horizon	4	[samples]
Δn rate of change weight	1	[-]
$\Delta \delta$ rate of change weight	53	[-]
Δx weight	20	[-]
Δy weight	220	[-]
$\Delta \psi$ weight	10	[-]

This research gave a technical product – MPC controller applied to the training LNG carrier. It proved that there is a possibility to build a predictive controller used to steer SS ship during UNREP maneuver. The difficulty in its application is requirement of the identification of ship dynamics linear incremental model (Miller 2016a). Also interaction forces and moments acting on both vessels should be taken into account. They have to be measured or estimated before the model identification (Miller 2016b).

4 RESULTS

All time responses are results of the MPC control of LNG carrier "Dorchester Lady" (SS) sailing in the vicinity of the virtual VLCC "Blue Lady" on the Silm Lake. All trials are real-time experiments recorded with the use of Simulink Real Time Toolbox. We present two trials: first phase UNREP maneuver – approach and its second phase – parallel motion. Both of them are illustrated by two figures, namely time trials and ships' trajectories marked by their silhouettes. First position of each vessel is indicated by a red ship. Measured values are indicated by the solid and set points by the dotted lines in all time trials.
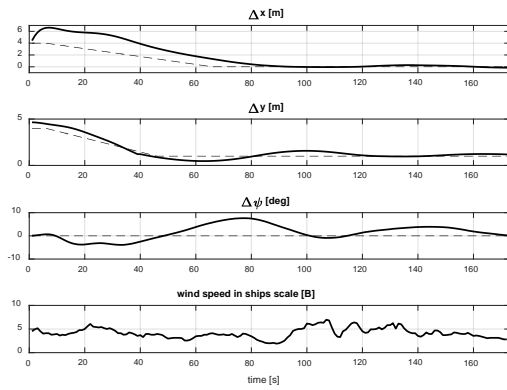
Figure 6. Transversal, longitudinal and course deviation trials for the approach phase of UNREP.
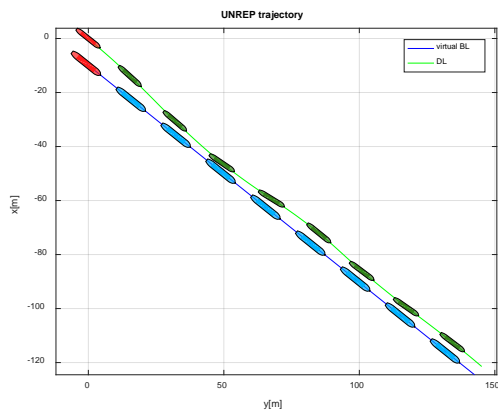

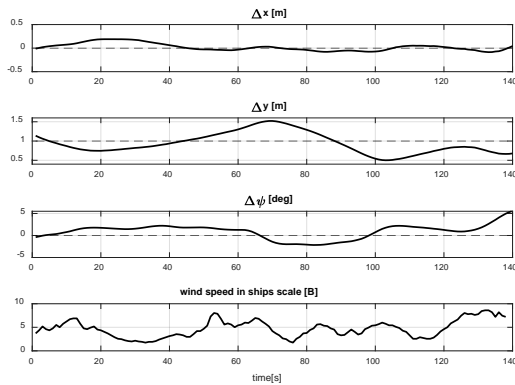Figure 7. Approach UNREP phase trajectory.

Figure 8. Transversal, longitudinal and course deviation trials for the parallel motion of UNREP.
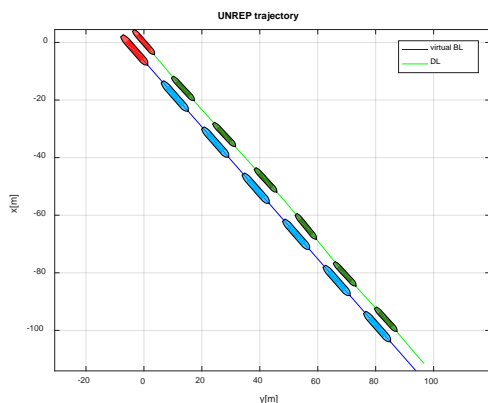

Figure 9. Parallel motion UNREP phase trajectory.

In the first phase STBL moves at constant course and speed of 1.05[m/s]. SS ship decreases the longitudinal and transversal distance and enters second phase of maneuver, parallel motion, in 50th second of the trial presented in Figure 6. There are oscillations in transversal shift (Δy) due to the increased speed of wind that is an unmeasured disturbance in this system. Increased course deviations ($\Delta \delta$) are the result of constant transversal distance between ship boards maintenance. Figure 7 illustrates vessels' trajectories during approach phase of UNREP. SS significantly approached STBL in 1/3th of the trial, which responds to Δy decrease almost to zero in 60th second presented in Figure 6.

During parallel motion both ships are moving at constant course and speed of 1.05[m/s]. MPC controlled SSs position to guarantee longitudinal deviation $\Delta x = 0 [m]$ and transversal deviation $\Delta y = 1 [m]$ (see Figure 8). Wind speed change caused oscillations in lateral distance. They are indicated by the change of Δy and DL (SS) position in trajectory (see Figure 9).

Presented results show that MPC for UNREP operations fulfills its role in different weather conditions. It was applied to the real sailing training ship whose dynamics is heavy nonlinear and pods have limitations in power and angle setting accuracy.

5 CONCLUSIONS

The main purpose of presented work was to show the application of the modern control method to steering of the ship motion.

A few conclusions can be formulated in relation to the MPC approach in marine industry. MPC control strategy was invented for petrochemical industry, but it can be successfully used to control ship. Its main advantages are: ability to generate sub-optimal control sequence in the presence of wind and wave disturbances, possibility to incorporate actuators' constraints directly in the algorithm and probability of getting better performance and smoother control signal than in conventional control methods. his is connected with control signals determination based on the internal ship dynamics model.

Real-time trial results show that it is possible to maintain the Service Ship's motion parallel to the STBL one during UNREP operation by means of the multidimensional MPC regulator. Presented MPC automatic control system works also in the presence of wind disturbances. Even if the wind speed in squalls exceeds 8B in ship's scale which appropriate to gale or strong gale. These are conditions where in normal exploitation underway replenishment cannot be done due to regulation restrictions. The usage of the MPC approach enables also addition of the predictive feedforward controller for measurable disturbances. It will decrease large influence of the wind on steering accuracy what will be the aim of the future work.

Predictive control system applied to UNREP control needs three coordinates reference frames to properly describe steering process and incremental

discrete state-space liner mathematical model of the ship for synthesis. This approach fastens and simplifies MPC algorithm operation compared with nonlinear ship's model incorporation into MPC structure. But quality of the identified model determines the quality of control. Linearized model is a key element of the whole UNREP automatic control system. It should be adequate, minimize bias and it parameters should be reliable in whole input signal range and used in algorithm prediction horizon. Identification of the reliable linearized model is a clue of the whole regulator synthesis.

The use of modern control methods is the future of ship automation. It leads to the better performance, lower costs and less environmental pollution associated with reduced energy consumption in the control process.

REFERENCES

Bowman, M. L. 2009. Navy tactics, techniques and procedures underway replenishment. NTTP 4-01.4 Tech, Rep. Departament of the Navy Office of the Chief of Naval Operations

Camacho, E. F., & Alba, C. B. 2013. Model predictive control. Springer Science & Business Media.

Clarke, D. W., Mohtadi, C., & Tuffs, P. S. 1987. Generalized predictive control—Part I. The basic algorithm. Automatica 23(2): 137-148.

Fossen, T. I. 2002. Marine Control Systems. Marine Cybernetics. Trondheim Norway.

Fossen, T. I. 2011. Marine Craft Hydrodynamics and Motion Control. J. Wiley & Sons Ltd.

Gierusz, W., Vinh, N. C. & Rak, A., 2007, Maneuvering control and trajectory tracking of very large crude carrier. Ocean Engineering 34: 932-945.

Gierusz, W. 2015. Simulation model of the LNG carrier with podded propulsion Part 1: Forces generated by pods. Ocean Engineering 108: 105-114.

Gierusz, W. 2016. Simulation model of the LNG carrier with podded propulsion Part 2: Full model and experimental results. Ocean Engineering 123: pp. 28-44.

Hals, T. Tandem Loading and Drilling Operations Under Changing Environmental Conditions. Dynamic Positioning Conference, Houston, USA, 09, 2004.

Holkar, K. & Waghmare, L. 2010. An overview of model predictive control. International Journal of Control and Automation 3(4): 47-63.

Horiuchi, S., Tamatsukuri, T., & Nohtomi, S. 2000. An automotive lateral controller based on generalized predictive control theory. JSAE review 21(1): 53-59.

Kalman, R. E. et al. 1960. Contributions to the theory of optimal control. Boletin de la Sociedad Matemática Mexicana 5(2): 102-119.

Kozlik, C. et al. 2016. Dynamic matrix control applied to emission control of a diesel engine. *International Journal of Engine Research* 17(5): 556-75

Lisowski, J. 2012. Game control methods in avoidance of ship collisions, Polish Maritime Research Special Issue 19(1): 3-11

Łebkowski, A. 2018. Design of an Autonomous Transport System for Coastal Areas. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation 12(1): 117-124.

Miller, A. 2016a. Identification of a multivariable incremental model of the vessel. 21st International Conference on Methods and Models in Automation and Robotics, IEEE: 218-224.

Miller, A. 2016b. Interaction Forces Between Two Ships During Underway Replenishment. The Journal of Navigation 69(6): 1197-1214.

Perez, T. 2005. Ship Motion Control: Course Keeping and Roll Stabilisation Using Rudder and Fins. Springer Verlag: London

Rybczak, M. 2018. Improvement of control precision for ship movement using a multidimensional controller. Automatika 59(1): 63-70.

Shouji, T., Ishiguro, T. & Mizoguchi. S. Hydrodynamic forces by propeller and rudder interaction at low speed. Int. IFAC Conference MARSIM and ICSM, Tokyo, Japan, June 1990.

Testud, J. et al. 1978. Model predictive heuristic control. Applications to industrial processes. Automatica 14(5): 413-428.

Tomera, M. 2016, Hybrid real-time way-point controller for ships. In 21th International Conference on Methods and Models in Automation and Robotics (MMAR), pp. 630-635.

Tomera, M. 2018. Multi-operational control of the ship motion in a system with switchable structure. Gdynia

Wang, P. K. 1991. Navigation strategies for multiple autonomous mobile robots moving in formation. Journal of Robotic Systems 8(2): 177-195.

Zavala, V. M. & Biegler, L. T. 2009. Optimization-based strategies for the operation of low-density polyethylene tubular reactors: nonlinear model predictive control. Computers & Chemical Engineering 33(10): 1735-1746.

Zhoghui, H. & Xiuyan, P. 2011. Integral nested sliding mode control for ship turning. 3rd IEEE International Conference on Communication Software and Networks (ICCSN), Xi'an, China

iSSMC - Ship Stabilization and Motion Control System. 2014 IMAR Navigation & Control GmbH. Information Brochure

Ride Control Systems, Advanced Ship Motion Reduction in Five Degrees of Freedom. Naiad Dynamics 2015, Infmation Brochure