SCIENTIFIC JOURNAL OF POLISH NAVAL ACADEMY
ZESZYTY NAUKOWE AKADEMII MARYNARKI WOJENNEJ

2018 (LIX) 4 (215)

DOI: 10.2478/sjpna-2018-0031

MODERN DYNAMIC POSITIONING (DP) SYSTEM OF ORP 'KORMORAN' — CLASS MINE DESTROYER

Paweł Zalewski*, Roman Haberek, Mirosław Chmieliński*****

* *Maritime University of Szczecin, Faculty of Navigation, Wały Chrobrego 1-2 Str., 70-500 Szczecin, Poland; e-mail: p.zalewski@am.szczecin.pl*

** *Autocomp Management Ltd., 1 Maja 36 Str., 71-627 Szczecin, Poland; e-mail: r.haberek@autocomp.com.pl*

*** *Polish Naval Academy, Faculty of Navigation and Naval Weapons, Śmidowicza 69 Str., 81-127 Gdynia, Poland; e-mail: m.chmielinski@amw.gdynia.pl*

ABSTRACT

The paper presents the dynamic positioning system (DP), particularly its thruster allocation model, designed for ORP 'Kormoran', a Polish mine destroyer built for the Polish Navy in Remontowa Shipbuilding S.A. in Gdańsk. The ORP 'Kormoran' ship is the newest and best equipped minehunter ship in Europe. The main task of the new Polish mine destroyer is to search for, classify, identify and combat marine mines and improvised underwater explosives, recognize waterways, transport mines, deploy mines and provide remote control of self-propelled anti-mine platforms. The dynamic positioning control system of the ship presented in the article was constructed by Autocomp Management Ltd. from Szczecin, the only in Poland and one of the few producers of dynamic ship positioning systems in the world.

Key words:

DP, dynamic positioning, thrust allocation, constrained convex optimization, ORP 'Kormoran'.

Research article

INTRODUCTION

Dynamic positioning (DP) system can be defined as a system which automatically controls a vessel, influenced by external excitations, to maintain her position and heading (fixed location, relative location or planned track) exclusively by means of active thrust. DP system divides forces among ship's thrusters to achieve resultant force and momentum equal to the one set by the control system. Optimization of thrust allocation is based on minimization of energy usage (need for power or fuel if feasible), additionally taking into account limitations like forbidden zones for thrusters' settings (individual and relative to each other like opposing thruster pairs).

The optimal allocation of forces generated by thrusters in DP systems is a problem that can be solved by several convex optimization methods depending on criteria and constraints used [4, 7, 8]. In this paper, the quadratic programming (QP) method described in [9, 10] has been further extended to include real constraints of ORP 'Kormoran' propulsion.

GENERATION OF FORCES WITH THRUSTERS

For a DP control a ship's hull can be treated as a rigid body with the centre of gravity (CG) at origin $p = 0 \in \mathbb{R}^2$. Measurements of the present position and heading (three degrees of freedom) are compared with the required position and heading setpoints. The difference is fed into the vessel's hydrodynamical model and PID-FL (Proportional-Integral-Derivative-Fuzzy-Logic) controller to convert this to the resultant force and momentum required to achieve the position and heading setpoints [2]. The allocation unit controls the thrusters, which must generate the component forces of the resultant one. Therefore, the model of thrust allocation used for a vessel with i^{th} number of azimuth thrusters can be built following the geometrical relations presented in the fig. 1.

The assumptions of the model are:

- The vessel's position is stabilized at low speed (less than 3 kts or 1.55 m/s), and the CG (force reference origin) is the fixed rotation centre (for higher speeds the effects of water flow around the hull impact generated thrust non-linearly).

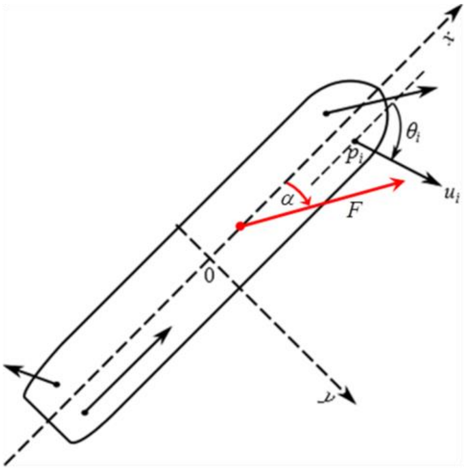


Fig. 1. Thrust forces acting on a vessel with i^{th} number of azimuth thrusters

- The vessel is class mine destroyer (fig. 2) of parameters:
  - length between perpendiculars (LPP) 55.58 m;
  - breadth moulded (B) 9.75 m;
  - draught fore & aft 2.7 m;
  - two main diesel engines rating 1000 kW each;
  - two stern VSP Voith Turbo 21GH/160 thrusters rating 950 kW, each generating max force 104.4 kN (10.7 tf) with interceptor;
  - one bow Schottel tunnel thruster rating 100 kW, generating max force 16.8 kN (1.7 tf).

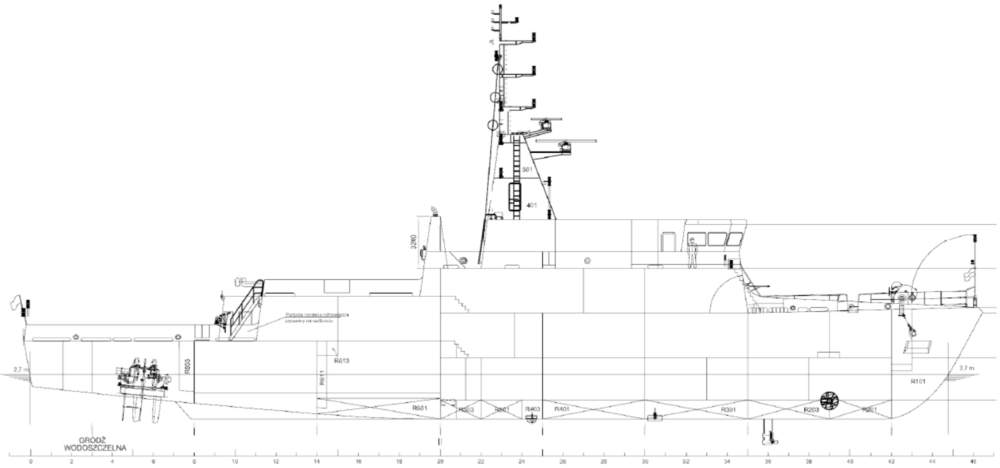


Fig. 2. General arrangement of ORP 'Kormoran' [Remontowa Shipbuilding S.A.]

- There are $n = 3$ component forces of magnitude u_i [kN] or [tf], acting at $p_i = (p_{xi}, p_{yi})$ [m, m], in direction θ_i [°], $i = 1, 2, \ldots, n$ (fig. 3):

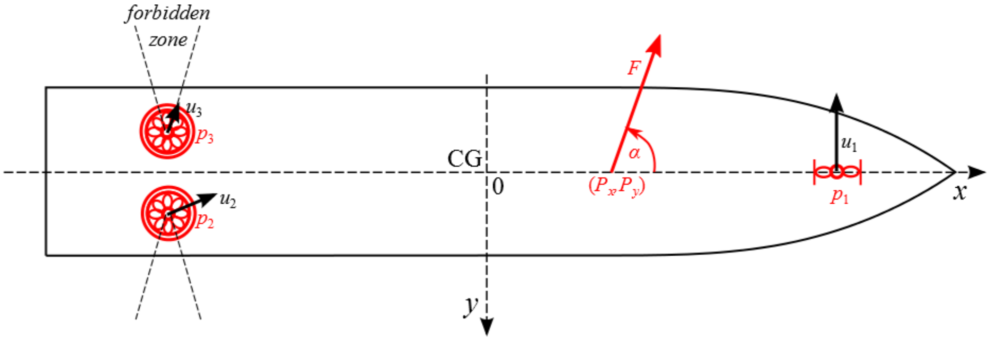


Fig. 3. Position of thrusters and forces in ship-body reference frame

$$p_x = [p_{x1}, p_{x2}, \ldots, p_{xn}]^{\mathrm{T}} = [17.77, -18.84, -18.84]^{\mathrm{T}}; \tag{1}$$

$$p_y = [p_{y1}, p_{y2}, \ldots, p_{yn}]^{\mathrm{T}} = [0.00, 2.30, -2.30]^{\mathrm{T}}. \tag{2}$$

Hydrodynamical forces generated by VSPs are presented in the fig. 4. R1 to R5 are the hydrodynamical forces generated at each blade when the intersection point of normal lines is at the point N' and the blades are rotating in the direction of the blue arrow. Summing up these hydrodynamical forces gives the resulting thrust vector T or the component force u_i of i^{th} VSP in the direction θ_i.

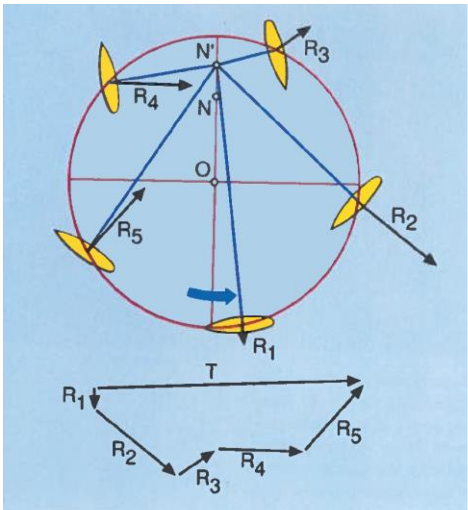


Fig. 4. Forces generated by Voith Schneider propeller [6]

- The resultant force [kN] or [tf] is:

$$F = \sqrt{F_x^2 + F_y^2} \; . \tag{3}$$

- The resultant longitudinal force (horizontal in ship-body coordinate system) [kN] or [tf]:

$$F_x = \sum_{i=1}^{n} u_i \cos\theta_i \; . \tag{4}$$

- The resultant transverse force (vertical in ship-body coordinate system) [kN] or [tf]:

$$F_y = \sum_{i=1}^{n} u_i \sin\theta_i \; . \tag{5}$$

- The resultant torque (moment of the resultant force) [kNm] or [tfm]:

$$M_z = \sum_{i=1}^{n} (p_{yi} u_i \cos\theta_i - p_{xi} u_i \sin\theta_i) \; . \tag{6}$$

- The force limits [kN] or [tf]:

$$0 \le u_i \le u_{\max i}; \tag{7}$$

  in [tf]:

$$u_{\max} = [u_{\max 1}, u_{\max 2}, \dots, u_{\max n}] = [1.7, 10.7, 10.7]^{\mathrm{T}} \; . \tag{8}$$

- The thruster angle limits or allowed zones [°]:

$$\begin{array}{l} \theta_1 = 90 \text{ or } \theta_1 = 270 \\ 0 \le \theta_2 < 360 \\ 0 \le \theta_3 < 360 \end{array} \; . \tag{9}$$

- The energy or fuel usage E_i is strictly dependent on u_i and is assumed to be linearly correlated to:

$$\sum_{i=1}^{n} u_i^2 = u_1^2 + u_2^2 + \dots + u_n^2 \; . \tag{10}$$

The problem to solve is: find u_i and θ_i that yield desired resultant force and moment and minimize the fuel or energy usage. Note that the problem is considered to be 3-DOF (degrees of freedom) or solved in 2-dimensional space. In fact, any movement in the z-direction (up/down) or around *x*- and *y*-axis is ignored because common actuators in offshore vessels do not have the ability to produce thrust in these directions. This clearly reduces the complexity of the problem. The remaining challenge is to rotate the vessel around fixed rotation centre so to keep the pivot point steady. The pivot point position in ship's body reference coordinate system was analysed in [1]. To keep it steady while turning at spot or with lateral and forward speed the u_i and θ_i must be changed dynamically in correlation to deviation of rotation centre from setpoint in local or global reference frame. This is done by the PID-FL controller and setpoint moving on pre-set trajectory (so called carrot) [2].

QP PROBLEM SOLUTION

For the thruster allocation problem with variables u_i and θ_i transformed to f_{xi} and f_{yi} (longitudinal and transverse components of forces u_i) the formulation of the objective function and constraints in the form of QP constrained optimization problem can be given in matrix notation as:

$$\begin{aligned} \text{minimize} \quad & \mathbf{1}\left(f_x^2 + f_y^2\right) \\ \text{subject to} \quad & F_x = \mathbf{1} f_x \\ & F_y = \mathbf{1} f_y \\ & M_z = \mathbf{1}\left(p_x \bullet f_y - p_y \bullet f_x\right) \\ & f_x^2 + f_y^2 \le f_{\max}^2 \\ & \begin{bmatrix} \sin\theta_{start} & -\cos\theta_{start} \\ -\sin\theta_{end} & \cos\theta_{end} \end{bmatrix} \begin{bmatrix} f_x \\ f_y \end{bmatrix} \le \begin{bmatrix} 0^{\mathrm{T}} \\ 0^{\mathrm{T}} \end{bmatrix} \end{aligned} \tag{11}$$

where:

$$\begin{aligned} \mathbf{0} &= [0_1, 0_2, \ldots, 0_n] \\ \mathbf{1} &= [1_1, 1_2, \ldots, 1_n] \end{aligned}; \tag{12}$$

$$\begin{aligned} f_x &= [f_{x1}, f_{x2}, \ldots, f_{xn}]^{\mathrm{T}} \\ f_y &= [f_{y1}, f_{y2}, \ldots, f_{yn}]^{\mathrm{T}} \end{aligned}; \tag{13}$$

$$\begin{aligned} \theta_{start} &= [\theta_{start1}, \theta_{start2}, \ldots, \theta_{startn}]^{\mathrm{T}} \\ \theta_{end} &= [\theta_{end1}, \theta_{end2}, \ldots, \theta_{endn}]^{\mathrm{T}} \end{aligned}; \tag{14}$$

$$\begin{aligned} f_{xi} &= u_i \cos\theta_i \\ f_{yi} &= u_i \sin\theta_i \\ u_i^2 &= f_{xi}^2 + f_{yi}^2 \end{aligned}; \tag{15}$$

$\bullet$ — Hadamard product (elementwise multiplication of matrices or vectors);

^{2} — Hadamard second power;

$^{\mathrm{T}}$ — matrix transposition;

θ_{starti} — start angle of allowed i^{th} thruster azimuth limit;

θ_{endi} — clockwise end angle of allowed i^{th} thruster azimuth limit;

F_x, F_y, M_z — designated constraints of longitudinal and transverse forces, and moment (torque) acting on ship's hull.

If the final constraints worked out by hydrodynamical model and PID-FL controller are in the form of (see fig. 1):

F — resultant force;
α — orientation of the resultant force;
M_z — resultant momentum;
f_{max} — maximum individual thruster force,

then:

$$\begin{aligned} F_x &= F\cos\alpha \\ F_y &= F\sin\alpha \end{aligned} \tag{16}$$

and the ordinates of the application point of the resultant force F can be calculated as:

$$\begin{aligned} P_x &= M_z / F_y \\ P_y &= 0 \end{aligned} \tag{17}$$

or

$$\begin{aligned} P_x &= 0 \\ P_y &= -M_z / F_x \end{aligned} . \tag{18}$$

The formula (11) has been extended by additional constraints on thrusters' work sectors (limits of θ_i). These constraints are defined by two additional hyperplanes, limiting the sector angle similarly to the method elaborated in [8]. Such formula can be used directly in case of azimuth or VSP thrusters (the thrusters should not generate thrust towards each other or straight into interceptor plate), but cannot be applied in case of lateral thrusters. The limits of ship propulsion system (9) indicate non-convexity in case of lateral thruster working either to port or starboard. There are two disjunctive thrust regions defined by two equality constraints. The method to deal with disjunctive thrust regions of lateral thruster is to replace the alternative geometrical equalities with one conjunctive dual equality:

$$f_{x1} = 0. \tag{19}$$

Then the optimization problem (11) considering (19) can be modified to:

$$\begin{aligned}
&\text{minimize } \mathbf{1}\left(f_x^2 + f_y^2\right)\\
&\text{subject to}\\
&\qquad f_{x1} = 0\\
&\qquad F_x = \mathbf{1} f_x\\
&\qquad F_y = \mathbf{1} f_y\\
&\qquad M_z = \mathbf{1}\left(p_x \bullet f_y - p_y \bullet f_x\right)\\
&\qquad f_x^2 + f_y^2 \le f_{\max}^2\\
&\qquad \begin{bmatrix} \sin\theta_{start} & -\cos\theta_{start} \\ -\sin\theta_{end} & \cos\theta_{end} \end{bmatrix} \begin{bmatrix} f_x \\ f_y \end{bmatrix} \le \begin{bmatrix} 0^{\mathrm{T}} \\ 0^{\mathrm{T}} \end{bmatrix}
\end{aligned} \tag{20}$$

IMPLEMENTATION IN DP SIMULATOR

The algorithms, solving (20) by applying interior-point method to a sequence of equality constrained problems [3], have been developed in Matlab with CVX Toolbox [5] and afterwards translated to C++ / C#.

The example of thrust allocation to ORP 'Kormoran', calculated by the model adopted by Autocomp, with the resultant force in ship-body fixed co-ordinate system, is presented in the fig. 5 (corresponding to the fig. 1: angles 360° clockwise, *x*-axis up, *y*-axis right, ordinates in [m] in ship-body fixed co-ordinate system from the centre of gravity marked as green cross, the resultant force in red, the component forces in blue). The allocated thrust corresponds to the resultant force of 2.0 tf, 340.0° and torque of 6.0 tfm (clockwise). The detailed numerical values of the component forces are presented in the tab. 1.

The fig. 6 presents the graphical operator's console within ORP 'Kormoran' navigation bridge.

Tab. 1. Numerical data of the allocated thrust as in fig. 5

F [tf]	*α* [°]	M_z [tfm]	P_x [m]	P_y [m]
2.00	340.0	6.00	–8.77	0
i	u_i [tf]	θ_i [°]		
1	0.18	270.0		
2	0.97	345.2		
3	0.98	345.3		

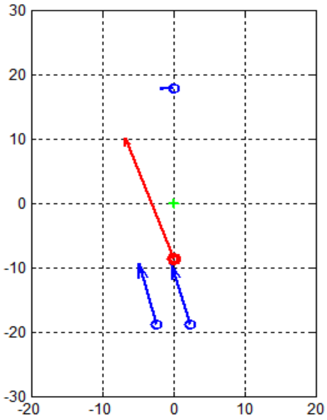
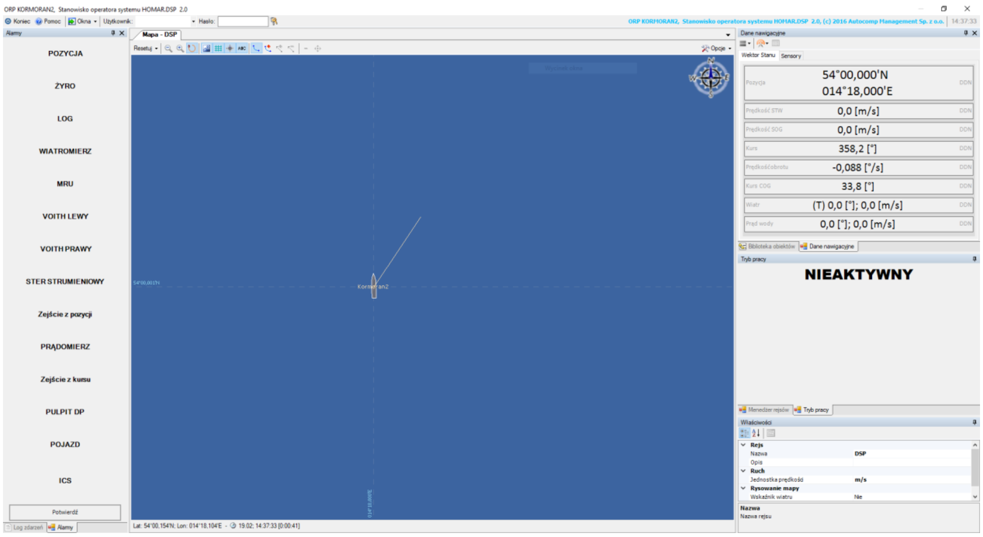


Fig. 5. Example of thrust allocation to ORP ‘Kormoran’



Pozycja: 54°00,000'N 014°18,000'E DDN
Prędkość STW: 0,0 [m/s] DDN
Prędkość SOG: 0,0 [m/s] DDN
Kurs: 358,2 [°] DDN
Prędkośćobrotu: -0,088 [°/s] DDN
Kurs COG: 33,8 [°] DDN
Wiatr: (T) 0,0 [°]; 0,0 [m/s] DDN
Prąd wody: 0,0 [°]; 0,0 [m/s] DDN

Tryb pracy: NIEAKTYWNY

Rejs
Nazwa: DSP
Opis:
Ruch
Jednostka prędkości: m/s
Rysowanie mapy
Wskaźnik wiatru: Nie

Nazwa
Nazwa rejsu

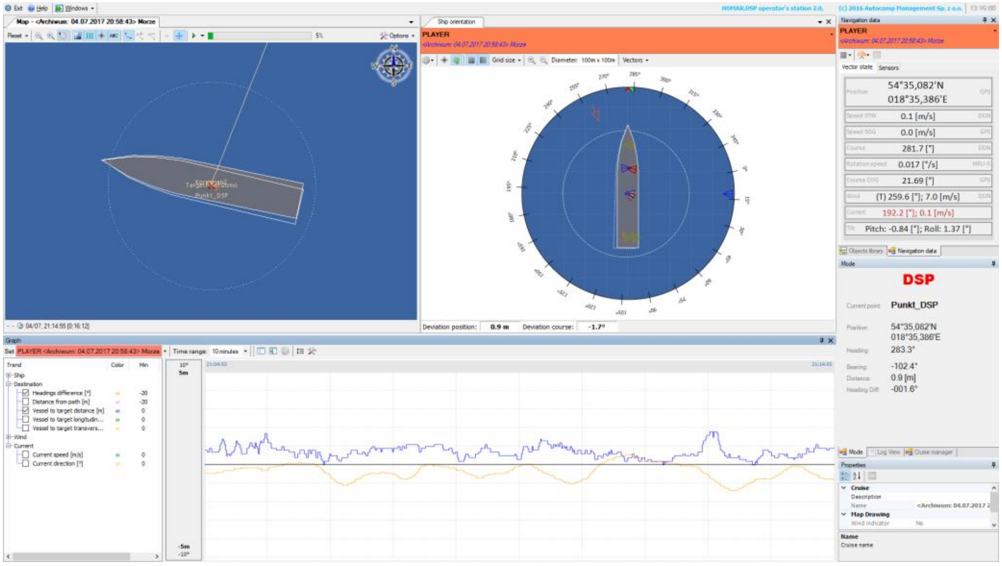
Lat: 54°00.154'N; Lon: 014°18.104'E - 19.02; 14:37:33 [0:00:41]

Fig. 6. DP system graphical operator’s console within ORP ‘Kormoran’ [2]

SEA TRIAL RESULTS

The algorithms implemented in DP system has been tested thoroughly in the course of sea trials and acceptance tests. Manoeuvres proceeded in various environmental conditions proved the quality of the system and mathematics principles employed.

The fig. 7 presents the recorded progress of vessel maintaining her position and heading fixed over ground. The trends show changes in vessel to target location (blue — scaled +/−5 m) and rotation distance (orange — scaled +/−10°).



Deviation position: 0.9 m
Deviation course: -1.7°

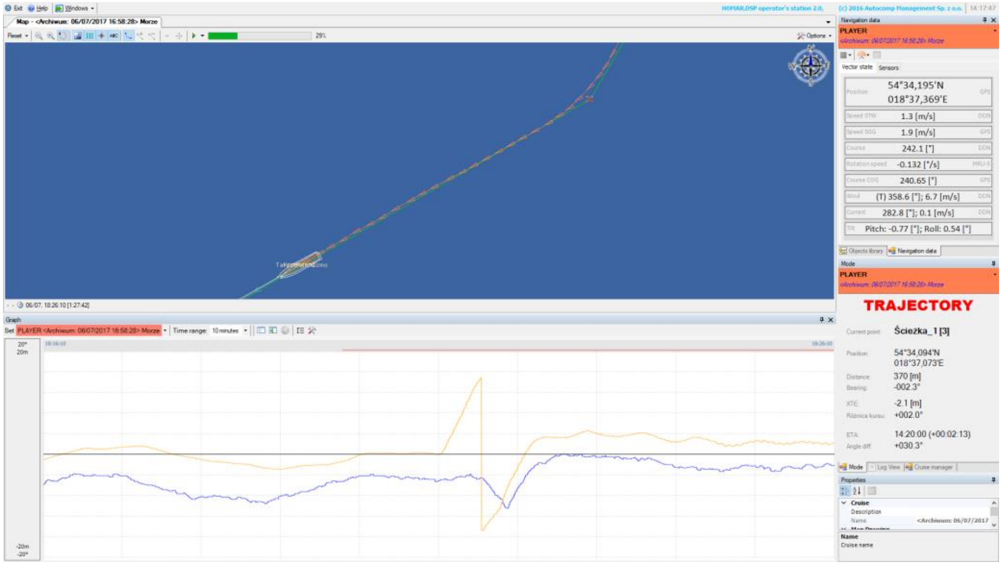
Position: 54°35,082'N 018°35,386'E
Speed STW: 0.1 [m/s]
Speed SOG: 0.0 [m/s]
Course: 281.7 [°]
Rotation speed: 0.017 [°/s]
Course COG: 21.69 [°]
Wind: (T) 259.6 [°]; 7.0 [m/s]
Current: 192.2 [°]; 0.1 [m/s]
Tilt: Pitch: -0.84 [°]; Roll: 1.37 [°]

DSP

Current point: Punkt_DSP
Position: 54°35,082'N 018°35,386'E
Heading: 283.3°
Bearing: -102.4°
Distance: 0.9 [m]
Heading Diff: -001.6°

Fig. 7. DP positioning manoeuvre progress example

The fig. 8 presents the recorded progress of vessel following trajectory of fixed waypoints. The trends show changes in XTE (blue — scaled +/–10 m) and heading variation (orange — scaled +/–20°) from momentary value pointing always along the current segment.



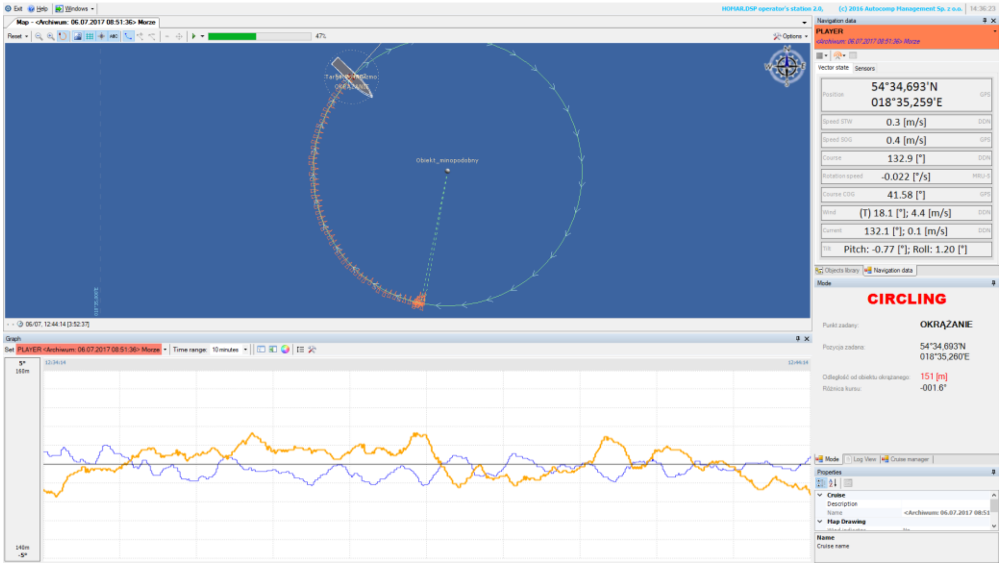
Position: 54°34,195'N 018°37,369'E
Speed STW: 1.3 [m/s]
Speed SOG: 1.9 [m/s]
Course: 242.1 [°]
Rotation speed: -0.132 [°/s]
Course COG: 240.65 [°]
Wind: (T) 358.6 [°]; 6.7 [m/s]
Current: 282.8 [°]; 0.1 [m/s]
Tilt: Pitch: -0.77 [°]; Roll: 0.54 [°]

TRAJECTORY

Current point: Ścieżka_1 [3]
Position: 54°34,094'N 018°37,073'E
Distance: 370 [m]
Bearing: -002.3°
XTE: -2.1 [m]
Różnica kursu: +002.0°
ETA: 14:20:00 (+00:02:13)
Angle diff: +030.3°

Fig. 8. DP trajectory manoeuvre progress example

The fig. 9 presents the recorded progress of vessel rotating around fixed location over ground with radius 150 m. The trends show changes in distance from rotation centre (blue — scaled 140–160 m) and heading variation (orange — scaled +/–5 [°]) from momentary heading value pointing always at the rotation centre.



PLAYER <Archiwum: 06.07.2017 08:51:36> Morze

Position: 54°34,693'N 018°35,259'E (GPS)
Speed STW: 0.3 [m/s] (DDN)
Speed SOG: 0.4 [m/s] (GPS)
Course: 132.9 [°] (DDN)
Rotation speed: -0.022 [°/s] (MRU-5)
Course COG: 41.58 [°] (GPS)
Wind: (T) 18.1 [°]; 4.4 [m/s] (DDN)
Current: 132.1 [°]; 0.1 [m/s] (DDN)
Tilt: Pitch: -0.77 [°]; Roll: 1.20 [°]

CIRCLING

Punkt zadany: OKRĄŻANIE
Pozycja zadana: 54°34,693'N 018°35,260'E
Odległość od obiektu okrążanego: 151 [m]
Różnica kursu: -001.6°

Cruise
Description
Name: <Archiwum: 06.07.2017 08:51
Map Drawing
Name
Cruise name

Fig. 9. DP rotation manoeuvre progress example

CONCLUSIONS

A thrust allocation system must be used to distribute the control actions determined by the DP controller among the thrusters. The allocation problem can be translated to a constrained optimization problem. The quadratic programming (QP) method has been tested for this purpose in DP system of ORP 'Kormoran'. The tests proved that the optimization algorithm translated into C++ / C# programming language works efficiently using interior-point methods [3] to solve the problem. The system includes extra constraints like limits to the thrusters' work sector (forbidden zones) and non-azimuth thrusters. From a critical point of view concerning safety it is also important that system can take into account actuator limitations such as saturation, wear, tear and rotation time following methodology presented in [4] and [7].

REFERENCES

[1] Artyszuk J., *Pivot point in ship manoeuvring*, 'Scientific Journals of the Maritime University of Szczecin', 2010, 20(92), pp. 13–24.

[2] Autocomp Management Sp. z o.o., *Sterowanie ruchem okrętu 258 ORP „Kormoran II"*, Szczecin 2015 [*Control of the ship's movement 258 ORP 'Kormoran II'* — available in Polish].

[3] Boyd S., Vandenberghe L., *Convex Optimization*, Cambridge University Press, 7th printing, New York 2009.

[4] Fossen Thor I., *Handbook of Marine Craft Hydrodynamics and Motion Control*, John Wiley & Sons Ltd., United Kingdom, 2011.

[5] Grant M., Boyd S., *CVX: Matlab software for disciplined convex programming, version 2.0 beta*, September 2013, [online], http://cvxr.com/cvx [access 17.04.2018].

[6] Jurgens B., Fork W., *The Fascination of the Voith-Schneider Propeller — History and Engineering*, Koehlers Verlagsgesellschaft, Hamburg 2002.

[7] Ruth E., *Propulsion control and thrust allocation on marine vessels*, PhD thesis, 'Doctoral Theses at NTNU', 2008:203, Norwegian University of Science and Technology, 2008.

[8] Wit C. D., *Optimal Thrust Allocation Methods for Dynamic Positioning of Ships*, M.Sc. thesis, Delft University of Technology, Netherlands, 2009.

[9] Zalewski P., *Convex optimization of thrust allocation in a dynamic positioning simulation system*, 'Scientific Journals of the Maritime University of Szczecin', 2016, 48(120), pp. 58–62.

[10] Zalewski P., *Constraints in allocation of thrusters in a DP simulator*, 'Scientific Journals of the Maritime University of Szczecin', 2017, 52(124), pp. 45–50.

NOWOCZESNY SYSTEM DYNAMICZNEGO POZYCJONOWANIA (DP) NISZCZYCIELA MIN ORP „KORMORAN"

STRESZCZENIE

W artykule zaprezentowano system dynamicznego pozycjonowania statku (DP) zaprojektowany dla ORP „Kormoran", polskiego niszczyciela min zbudowanego dla Marynarki Wojennej RP w Gdańskiej Stoczni Remontowej Shipbuilding S.A. Okręt ORP „Kormoran" to najnowszy i najlepiej obecnie wyposażony okręt przeciwminowy w Europie. Głównym zadaniem nowego polskiego niszczyciela min jest poszukiwanie, klasyfikacja, identyfikacja i zwalczanie min morskich oraz improwizowanych podwodnych ładunków wybuchowych, rozpoznanie torów wodnych, przeprowadzanie jednostek przez akweny zagrożenia minowego, stawianie min oraz zdalne sterowanie samobieżnymi platformami przeciwminowymi. Przedstawiony w artykule system dynamicznego pozycjonowania statku został wykonany przez Autocomp Management Sp. z o.o. ze Szczecina, jedynego w Polsce i jednego z nielicznych na świecie producentów systemów dynamicznego pozycjonowania statku.

Słowa kluczowe:

DP, pozycjonowanie dynamiczne, alokacja pędników, optymalizacja wypukła z ograniczeniami, ORP „Kormoran”.

Article history

Received:	21.05.2018
Reviewed:	19.10.2018
Revised:	12.12.2018
Accepted:	14.12.2018