Energy efficient propulsion system for dynamic positioning application: design and assessment

Dr Andrea Coraddu[a], Dr Silvia Donnarumma[b*], Mr Ken Chu[a], Prof Massimo Figari[b]

[a] *Naval Architecture, Ocean & Marine Engineering Strathclyde University, Glasgow G1 1XW, UK;*
[b] *Department of Naval Architecture, Electric, Electronic, and Telecommunication Engineering, University of Genoa, Genoa 16145, Italy*
*Corresponding author. Email: donnarumma@dime.unige.it

Synopsis

Dynamic positioning systems are most commonly used in offshore operations. They provide an automated controlling of position and heading of the vessel using its own thrusters to compensate environmental disturbances. The allocation of total required force over the available actuators is a complex task, as DP-systems are over-actuated. Therefore, one of the main challenges faced by the industry is constantly seeking to improve the systems efficiency for both sustainability and economic reasons. Furthermore, it is important to evaluate the performance of a DP vessel under critical conditions. In this paper, the authors aim to compare different thrust allocation logics based on the optimisation of different objective functions. Using a simple validation tool, the authors were able to investigate the overall efficiency of a dynamic positioning propulsion system and its ability to operate when a failure occurs.

Keywords: Dynamic positioning; thrust allocation logic; failure analysis

1 Introduction

The ever increasing demand for oil and gas along with the depletion of such resources motivates drilling operations at ultra-deep water depths. A consequence of this exploration is the increasing use of Dynamic Positioning (DP) systems for station-keeping, as opposed to passive mooring systems. DP systems are also playing an important role in the renewable industry, e.g. for installation and maintenance of offshore wind farms. Unmanned marine vehicles are of broad and current interests within the industry in recent years, and DP systems, the most reliable fully autonomous ship control, are undoubtedly the foundation for such progress.

The need to increase efficiency by reducing power and/or fuel consumption comes from the need to operate at deeper sea levels for long periods, saving costs as well as minimising environmental pollution. Therefore, there is a continuous demand and effort being put into improving efficiency, positioning accuracy and safety in DP systems [11]. A DP system is over-actuated when the number of available output is higher that the number of control inputs. In particular, for DP purposes, the number of available thrusters on board is over-estimated in order to allow the system to compensate extreme environmental disturbances, as reported in [8] and [16], as well as to manage failures.

Advanced allocation algorithms for DP systems has been an active area of research in recent decades. In [9], the authors provides an overview of control allocation methods for a range of applications from the aerospace to maritime industries, while in [6] the authors placed more emphasis on marine engineering applications. There has been numerous development of thrust allocation algorithms aimed at reducing power consumption of thrusters. The Lagrange Multiplier was one of the most popular methods used to solve this problem. However, in [4] the authors compared the suitability of the Lagrange method with a Quadratic Programming (QP) approach. In particular the authors stated that one of the characteristics of Lagrange Multiplier is that it does not take into account thrust limits; saturation handling is required which branches into smaller problems, whereas a QP allocator eliminates such issues and generates optimal solutions. In [10] the authors used a sequential quadratic programming (SQP) to avoid singularity which is a situation where actuator configuration failed to produce thrust force/moment in every direction and could result in a loss of controllability. The study includes a term in the objective function to penalize such singularity.

Authors' Biographies

Dr Andrea Coraddu currently is Lecturer at the Department of Naval Architecture, Ocean and Marine Engineering at the University of Strathclyde. His research interests focus on improving the understanding, design, and performance of propulsion plants simulations and control, mainly through the application of numerical models, data mining, statistics, and performance evaluation.

Dr. Silvia Donnarumma is currently a postdoctoral researcher at the Department of Naval Architecture Marine Engineering at University of Genoa. Her research interest include automatic steering/positioning systems, LMI based control, convex optimization, and control of systems with saturation.

Mr. Ken Fui Chu is a 5th year Naval Architecture and Marine Engineering student at the University of Strathclyde. His research interests focus on dynamic positioning systems and autonomous marine vehicles.

Prof. Massimo Figari currently is Associate Professor in Marine Engineering and Coordinator of both Bachelor and Master degrees in Naval Architecture and Marine Engineering. His research activity focus on numerical simulation of ship propulsion systems and ship control systems.

http://doi.org/10.24868/issn.2631-8741.2018.012

Ruth [14] proposed a convex thrust allocation problem. This produces an adjustable system in on-line testing making it possible to reconfigure constraints by switching between different thrust allocation logic during operation to fit the environmental conditions. A modification was also proposed which is an anti-spin strategy to overcome the problem of thrust loss due to ventilation and surfacing of propellers for increased power savings and lifespan.

In addition to thrust forces and azimuth angles, Jenssen and Realfsen [8] describes a strategy which takes into account available switchboard power to solve for an optimal thrust allocation solution. This was done with balancing the load on power buses and switchboard by introducing power limitations.

In [13] the authors introduced a more special case of optimisation where minimization of fuel consumption is explicitly set as the cost function instead of minimization of power. This was done by implementing the fuel consumption model of a diesel generator as a function of its delivered power. The resulted thrust allocation produced solutions which require less fuel compared to the conventional thrust allocation based on power minimization .

DP vessels also have to be effective in case of system failure. Depending on the class notation, single failures of active components (i.e. generators, thrusters, switchboards, remote controlled valves, etc.) as well as static components (i.e cables, pipes) have to be verified. Each failure case correspond to a new system configuration that has to be analysed. According to IMCA, the predominant cause for dynamic positioning incidents in 2015 was thruster/propulsion failure. This repeats the 2012, 2013 and 2014 findings. For operations such as drilling, diving and heavy lifting, loss of position during a critical activity may result in damage to vessel or facilities, pollution, injuries or even fatalities. Such incidents underlined the importance of determining the design limits of the vessel during an early stage of production

The proposed study investigates two optimal control allocation strategies and their relationships with the vessel DP capability in intact and failure conditions. The proposed approach is tested on a case study drillship; DP capability assessment by means of minimum thrusts are compared with minimum torque. Further, different single failure analysis has been carried out in order to verify the algorithm robustness.

The paper is organized as follows. Section 2 reports a general description of the vessels, Section 3 presents a description of the mathematical model utilised for the optmisation problem. The thrust allocation algorithm for dynamic positioning is reported in Section 4, and the results are reported in Section 5. Finally in Section 6, the conclusions are drawn.

2 Vessel Description

The methods proposed in this paper for the DP capability assessment of the propulsion configuration are applied on a specific case study. A typical 7^{th} generation ultra-deepwater drillship was employed to validate the optimisation algortihm and verify the single failure mode. Drillshps are widely used for ultra-deepwater drilling operation for their higher transit speed, load capacity and storage volumes due to its ship-like shape; while semi-submersible units are tailored for multi-purpose offshore applications, i.e. Floating production storage and offloading (FPSOs). However, this trait sacrifices better wave motion characteristics, making it more susceptible to environmental forces, especially from the sway direction. This is why efficient dynamic positioning system is crucial especially during drilling operations. A conceptual representation of the vessel propulsion system is shown in Figure 1, while the main particulars of the vessels are presented in Table 1.

Table 1: Main particulars of vessel

Ship feature	Value	Unit
Length overall	232	[m]
Length between Perpendicular	228	$[m]$
Breadth Moulded	40	$[m]$
Draught (Lightship)	12	$[m]$
Frontal Area Projection	2093	$[m^2]$
Lateral Area Projection	7500	$[m^2]$

The drillship propulsion plant consists of six azimuth thrusters, positioned three fore and three aft, with a maximum total available power of 36000 kW. The main power source of the vessel consists of six diesel engines @720 rpm, each connected to a generator set which can produce up to 8600 kW. The gensets are distributed in three engine rooms and provide a total power of 51600 kW for the whole vessel. Table 2 provides a geometric description of the thrusters' position referred to the vessel center of gravity (CoG).

http://doi.org/10.24868/issn.2631-8741.2018.012

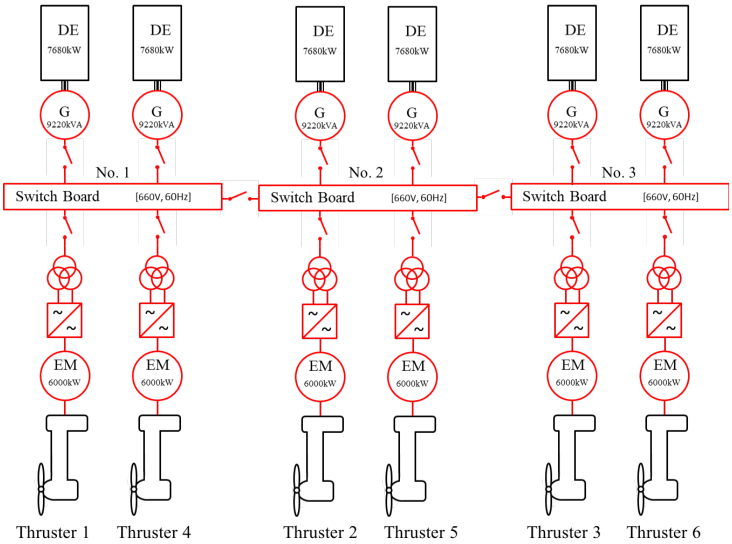

Figure 1: Drillship power distribution system

Table 2: Thruster position and Switch Board connection

Thruster	Switch Board	$x\ [m]$	$y\ [m]$
1	1	96.1	0
2	2	84.1	9.9
3	3	84.1	-9.9
4	1	-104.8	0
5	2	-89.2	-14.9
6	3	-89.2	14.9

3 Mathematical Model of the DP System

3.1 Vessel Modelling

In this section the mathematical model implemented by the authors for the simulation of the drillship vessel is reported. In Figure 2 a schematic of the drillship thruster arrangement is reported together with the sign conventions for the forces X and Y and the momentum M. The scheme shows $\mathbf{X} = \sum_{i=0}^{n} F_x$, $\mathbf{Y} = \sum_{i=0}^{n} F_y$ and $\mathbf{N} = \sum_{i=0}^{n} N_z$ which are the total forces required in the longitudinal (x-axis) and transverse (y-axis) directions, and the total required moment about the vertical axis (z-axis) respectively. Figure 3 depicts the $2D$ coordinate system that has been used as reference frame for the vessel. The x-axis is defined positive forwards, y-axis is dened positive to starboard side and z-axis is dened positive downwards. The origin is placed at centre of gravity. It is worth noting that the problem is considered in 3 degrees of freedom (DOF), but has been solved in a 2-dimensional space. Such complexity-reduced problem results exhaustive by means of the suggested design approach. Indeed, almost all preliminary DP-capability assessments are carried out by means of $3-DOF$ rigid-bodies dynamics.

3.2 Environmental Disturbances

In order to accomplish the proposed static analysis, environmental disturbances (X_{env}, Y_{env}, N_{env}) have been modeled by taking into account the linear superposition principle of the different contribution actions, similarly as reported in [5]:

- Waves contribution: X_{waves}, Y_{waves}, N_{waves}
- Wind contribution: X_{wind}, Y_{wind}, N_{wind}
- Current contribution: X_{curr}, Y_{curr}, N_{curr}

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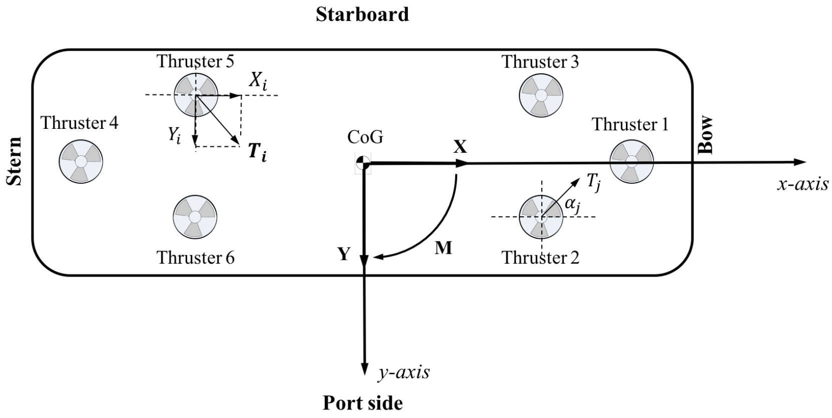

Figure 2: Schematic of thruster allocation

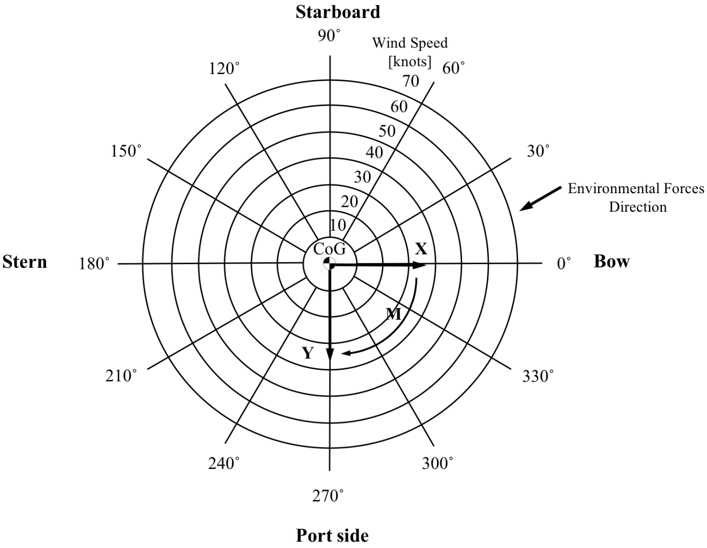

Figure 3: Considered reference frame

Under this assumption the following equtions apply:

$$X_{env} = X_{waves} + X_{wind} + X_{curr} \tag{1a}$$

$$Y_{env} = Y_{waves} + Y_{wind} + Y_{curr} \tag{1b}$$

$$N_{env} = N_{waves} + N_{wind} + N_{curr} \tag{1c}$$

$$\tag{1d}$$

3.2.1 Wave Drift Forces and Moment

The wave drift forces can be described by a wave spectrum, usually evaluated based on operating location. In this study, the JONSWAP spectrum is modeled. Wave loads are divided into two components, first order wave frequency model and second order low frequency model. First order wave drift forces and moments are characterised by a large amplitude and high frequency disturbances with zero mean force, ship will have no horizontal movement and is not of interest. The low frequency model is driven by wave drift forces and moment which will cause drifting of vessel, therefore only second order wave drift forces and moments are to be considered in this case. Such forces and moments are proportional to the squared of significant wave height, H_S.

$$X_{wave} = K_X^{sea} H_S^2 \cos\psi_s \tag{2a}$$
$$Y_{wave} = K_Y^{sea} H_S^2 \sin\psi_s \tag{2b}$$
$$N_{wave} = K_N^{sea} H_S^2 \sin 2\psi_s \tag{2c}$$
$$\tag{2d}$$

where K_X^{sea}, K_Y^{sea}, K_N^{sea} are coefficients of the wave drift force and moment for surge, sway and yaw directions respectively, and ψ_s represents the angle of incoming wave. Wave drift forces can only be calculated using appropriate hydrodynamic analysis software or model tests. The values provided for this study were the average values carried out with time domain simulation, performed for sea state 4 according to the World Wide Sea State and for all the headings.

3.2.2 Wind Forces and Moment

In this paper, wind forces are modeled as a linear superposition of mean force and moments from a mean wind speed V_W. Based on IMCA specification for DP capability plots [3], forces on a hull are calculated from the following formulae:

$$X_{wind} = \frac{1}{2}\rho_w V_w^2 C_X^w \cos\psi_w A_f T \tag{3a}$$
$$Y_{wind} = \frac{1}{2}\rho_w V_w^2 C_Y^w \sin\psi_w A_l L_{BP} \tag{3b}$$
$$N_{wind} = \frac{1}{2}\rho_w V_w^2 C_N^w \sin 2\psi_w A_l L_{BP}^2 \tag{3c}$$

where ψ_w wind direction, $\{C_X^w(\psi_w), C_Y^w(\psi_w), C_N^w(\psi_w)\}$ are wind coefficients for given wind directions, ρ_w is air density, V_w is the wind speed.

3.2.3 Current Forces and Moment

The current model is similar to wind force calculations based on IMCA specification for DP capability plots.

$$X_{current} = \frac{1}{2}\rho_c V_c^2 C_X^c \cos\psi_c BT \tag{4a}$$
$$Y_{current} = \frac{1}{2}\rho_c V_c^2 C_Y^c \sin\psi_c L_{BP} T \tag{4b}$$
$$N_{current} = \frac{1}{2}\rho_c V_c^2 C_N^c \sin 2\psi_c T L_{BP}^2 \tag{4c}$$

where ψ_c represents current direction, $\{C_X^c(\psi_c), C_Y^c(\psi_c), C_N^c(\psi_c)\}$ are current coefficients for given current directions, ρ_c is water density, V_c is the current speed.

4 Thrust Allocation for Dynamic Positioning

The thruster system plays a pivotal role for a drillship vessel in maintaining its position and heading, providing longitudinal X and transversal Y thrust. As the truster systems are generally over-actuated, the thrust allocation problem needs to be formulated as constrained optimisation. For the DP capability assessment of the propulsion configuration, a control allocation logic needs to be validated. The proposed case study is an over-actuated vessel, see [12] and [15]. For such a reason, the authors express the allocation algorithm through an optimisation problem. The variables in the problem are thrust magnitude and orientation for each thruster. In order to avoid non-linear trigonometric constraints, the problem has been formulated in a larger domain where unknowns are the thrust magnitudes and their components, for each thruster. In particular, two objective functions have been validated and compared.

In this study the optimization problem of variables x, subject to some suitable constraints, is formulated as follows:

$$\begin{aligned} \underset{x}{\text{minimize}} \quad & f(x) \\ \text{subject to} \quad & h_i(x) = 0,\ i = 1,\ldots,m \\ & g_i(x) \le 0,\ i = 1,\ldots,n. \end{aligned}$$

where $f(x)$ is the objective function to be minimized, $h_i(x)$ and g_i refer to the equality and inequality constraints, respectively.

In accordance with literature, the first objective function (f_1) with variables $x = [T_j, X_j, Y_j] \in \Re^n$ can be expressed as:

$$f_1(x) = \sum_{j=1}^{k} \frac{X_j^2 + Y_j^2}{T_{max_j}^2} \tag{5}$$

where k is the number of thrusters; X_j and Y_j are the longitudinal and lateral components of the thrust, respectively; T_{max_j} is the maximum allowable thrust for each thruster. The equality constraints in this problem regards: the balance of forces and momentum to be verified with respect to the environmental disturbances; by defining T_j as the modulus of the deliverable thrust by each propeller [1], the subsequent constraints guarantee the correct relationship between the thrust modulus and its components.

$$h_1(x) = \begin{cases} X_{env} - \sum\limits_{j=1}^{k} X_j \\ Y_{env} - \sum\limits_{j=1}^{k} Y_j \\ N_{env} - \sum\limits_{j=1}^{k} (\mathrm{x}_j Y_j - \mathrm{y}_j X_j) \\ T_j^2 - X_j^2 - Y_j^2, \quad j = 1, \dots, k \end{cases} \tag{6}$$

where x_j, and y_j are the longitudinal and transverse locations of each thruster. Regarding inequality constraints it is necessary to impose the thrust modulus to be positive and lower than the maximum deliverable thrust per each thruster. Then,

$$g_1(x) = \begin{cases} -T_j \\ T_j - T_{max} \end{cases} \tag{7}$$

The second objective function ($f_2(x)$) has been proposed to determine a different optimisation problem where the required power is minimized through the shaft speed, [2]. The main idea is to take into account for the fuel consumption in a preliminary way.

$$f_2(x) = \sum_{j=1}^{k} \left(\frac{n_j}{n_{max_j}} \right)^3 \tag{8}$$

where k is the number of thrusters, n_j is the shaft rate for each propeller, and n_{max_j} is the maximum shaft speed. The balance of forces and momentum in this configuration requires the introduction of propeller thrust and torque coefficients.

$$h_2(x) = \begin{cases} X_{env} - \sum\limits_{j=1}^{k} \rho_c K_{T_j} n_j^2 D^4 \cos\alpha_j \\ Y_{env} - \sum\limits_{j=1}^{k} \rho_c K_{T_j} n_j^2 D^4 \sin\alpha_j \\ N_{env} - \sum\limits_{j=1}^{k} \rho_c K_{T_j} n_j^2 D^4 (\mathrm{x}_j \sin\alpha_j - \mathrm{y}_j \cos\alpha_j) \end{cases} \tag{9}$$

where K_{T_j} is the thrust coefficient and D is the propeller diameter. Regarding inequality constraints regards lower and upper constraints of the variables.

$$g_2(x) = \begin{cases} -n_j \\ n_j - n_{max} \end{cases} \tag{10}$$

5 Results

In this section results for the proposed control allocation logic are presented for both the intact and damaged conditions. Results have been carried out by means of a multi-start method [7] for the validation of the optimisation algorithm.

5.1 *Intact Condition Results*

A comparison between results of thrust allocation optimisation obtained with two objective function approach (minimum thrust and minimum power), are shown in Figure 4. The polar plot displays the operational wind limits in knots in the radial direction, while the angle represents the incoming direction of disturbances. In particular, Figure 4 shows compared results for two cases: the left-hand side draws comparisons for the case where environmental disturbances are aligned versus misaligned by 15 and 30 degrees, while, on the right-hand side, the case where all the environmental forces have been considered aligned and the optimisation algorithms are compared. Due to the static environmental forces model, useful for the DP propulsion layout preliminary design and validation, misaligning the disturbances leads to decrease the amplitude of disturbances without giving additional information about the real effect on the algorithm. On the other hand, considering all environmental disturbances coming form the same direction allows to apply the maximum environmental force for any direction. For this test, current speed is considered constant at $1\,kn$ and wave drift forces have been evaluated by their mean value time histories for $2.5\,m$ wave main height and a modal period of $9\,s$. Both optimisation approach converge to close solutions. Results are saturated by means of wind speed at $50\,knots$ even though the algorithm is able to produce solutions for higher wind speeds for both bow and stern seas, which is numerically accurate. However, in reality vessels will not be allowed to operate in such extreme conditions.

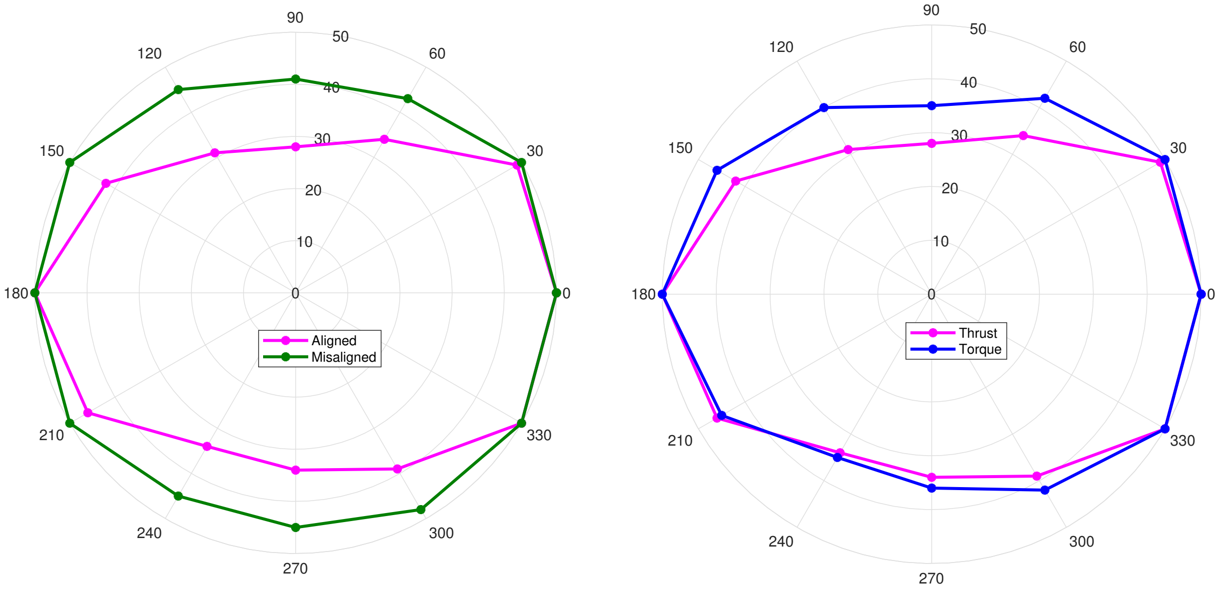

Figure 4: DP Capability Plot for intact condition.

5.2 *Failure Analysis Results*

Figure 5 shows results obtained with the single failure analysis criteria applied to the switchboards. The main idea is to consider that the loss of a main switchboard entails the loss of two propellers. The green line depicts the optimisation results as a consequence of failure in switchboard 1, while the dashed black line represents the result due to failure in switchboard 3. As expected, the symmetry of the superimposed failure leads to symmetrical results as depicted in Figure 5.

6 Conclusions and further research

Dynamic Positioning systems represent a continuous test bed for industry and research. The authors developed from scratch a thrust allocation algorithm for station keeping based on the minimization of two different objective functions, overall thrust and overall power. The algorithm was tested on a drillship to validate results and robustness. The test case included both intact as well as damaged configurations. The validation showed good algorithm performance for both objective functions and for both configurations. Performances are intended as a good compromise between the results' numerical reliability (strengthened by the symmetry of the DP capability polar plots) and the code time consumption. This was the first step toward the minimum overall consumption and emission objective function.

http://doi.org/10.24868/issn.2631-8741.2018.012

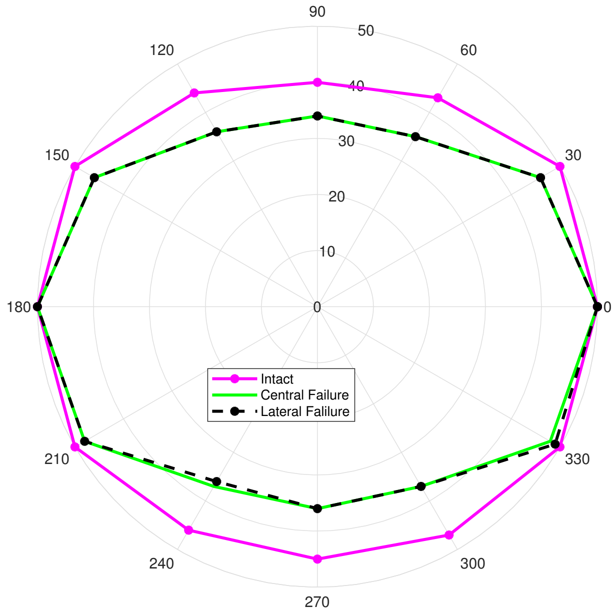

Figure 5: DP Capability Plot for single failure condition.

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