Annual Reviews in Control 35 (2011) 123–136

Contents lists available at ScienceDirect

Annual Reviews in Control

journal homepage: www.elsevier.com/locate/arcontrol

A survey of dynamic positioning control systems

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ARTICLE INFO

Article history:
Received 4 January 2011
Accepted 27 February 2011

Keywords:
Marine systems
Dynamic positioning
Hydrodynamics
Control

ABSTRACT

Offshore exploration and exploitation of hydrocarbons have opened up an era of dynamically positioned (DP) vessels. DP control systems maintain floating structures in fixed position or pre-determined track for marine operation purposes exclusively by means of active thrusters. There are more than 2000 DP vessels of various kind operating worldwide. This paper gives a survey of some of the major technology advances in the DP controller design having taken place during more than 30 years of research and development. In addition some perspectives for the future with corresponding research challenges will be addressed.

1. Introduction

This paper is an updated version of the plenary paper by Sørensen (2010) presented at the IFAC Workshop CAMS 2010. A dynamically positioned (DP) vessel is by the International Maritime Organization (IMO) and the certifying class societies (DNV, ABS, LR, etc.) defined as a vessel that maintains its position and heading (fixed location or pre-determined track) exclusively by means of active thrusters. The real-time control hierarchy of a marine control system (Sørensen, 2005) may be divided into three levels: the *guidance system*, the *high-level plant control* (e.g. DP controller including thrust allocation), and the *low-level thruster control*. Description of DP systems including the early history can be found in Fay (1989). In the 1960s the first DP system was introduced for horizontal modes of motion (surge, sway and yaw) using single-input single-output PID control algorithms in combination with low-pass and/or notch filter. In the 1970s more advanced output control methods based on multivariable optimal control and Kalman filter theory were proposed by Balchen, Jenssen, and Saelid (1976). This work was later improved and extended by Balchen, Jenssen, Mathisen, and Sælid (1980), Jenssen (1981), Sørheim (1982), Saelid, Jenssen, and Balchen (1983), Fung and Grimble (1983), Grimble and Johnson (1988), Fossen (1994), Sørensen, Sagatun, and Fossen (1996), Fossen, Sagatun, and Sørensen (1996), Katebi, Grimble, and Zhang (1997, 1997), Mandzuka and Vukic (1995), Kijima, Murata, and Furukawa (1998), Tannuri and Donha (2000), Volovodov, Chernjaev, Kaverinsky, Volovodov, and Lampe (2004) and Perez and Donaire (2009). The introduction of observers with wave filtering techniques based on Kalman filter theory (Fossen & Perez, 2009) by Balchen, Jenssen and Sælid is regarded as a breakthrough in marine control systems in general, and has indeed been an inspiration for many other marine control applications as well.

In the 1990s nonlinear DP controller designs were proposed by several research groups. Stephens, Burnham, and Reeve (1995) proposed fuzzy controllers. Aarset, Strand, and Fossen (1998), Strand and Fossen (1998), Fossen and Grøvlen (1998), and Bertin, Bittanti, Meroni, and Savaresi (2000) proposed nonlinear feedback linearization and backstepping for DP. In the work of Fossen and Strand (1999), Strand and Fossen (1999) and Strand (1999) the important contribution of passive nonlinear observer with adaptive wave filtering is presented. One of the motivations using nonlinear passivity theory was to reduce the complexity in the control software getting rid of cumbersome linearizations and the corresponding logics. Pettersen and Fossen (2000), Pettersen, Mazenc, and Nijmeijer (2004) and Bertin et al. (2000) addressed DP control of under-actuated vessels. Agostinho, Tannuri, and Morishita (2009) and Tannuri, Agostinho, Morishita, and Moratelli (2010) proposed to use nonlinear sliding mode control for DP. Volovodov, Smolnikov, Volovodov, and Lampe (2007) proposed a controller for 3 dimensional DP operations of sea mobile objects (underwater vehicles) using a Lyapunov approach. DP of underwater vehicles like remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) has lately received increasing interest from offshore contractors, vendors and the research community.

As the DP technology became more mature research efforts were put into the integration of vessel control systems and the refinement of performance for the various vessel types and missions by including operational requirements into the design of both the guidance systems and the controllers. Sørensen and Strand (2000) proposed a DP control law for small-waterplane-area marine vessels like semisubmersibles with the inclusion of roll and pitch damping. Sørensen, Leira, Strand, and Larsen (2001) recommended

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1367-5788/$ - see front matter
doi:10.1016/j.arcontrol.2011.03.008

the concept of optimal setpoint chasing for deep-water drilling and intervention vessels. Leira, Sorensen, Berntsen, and Aamo (2006) extended this work and proposed to use structural reliability criteria of the drilling risers for the setpoint chasing. Jensen (2010) showed how proper modeling of pipe dynamics can be included in the DP guidance system. Fossen and Strand (2001) presented the nonlinear passive weather optimal positioning control system for ships and rigs increasing the operational window and reducing the fuel consumption.

Most of the current DP systems have been designed to operate up to a certain limit of weather condition limited by the thrust and power capacity. Due to the accuracy and availability of the inertia measurement units (IMU), Lindegaard (2003) proposed acceleration feedback (AFB) to increase the performance of DP systems in severe seas. AFB denotes here output acceleration feedback in addition to output PID controller. Sørensen, Strand, and Nyberg (2002) and Sørensen (2005) proposed passive nonlinear observer without wave-frequency (WF) filtering for output PID-controller in extreme seas, especially where swell becomes dominant.

Use of hybrid control theory as proposed by Hespanha (2001), Hespanha and Morse (2002), and Hespanha, Liberzon, and Morse (2003) and fault-tolerant control by Blanke, Kinnaert, Lunze, and Staroswiecki (2003) enabled the design of proper control architecture and formalism for the integration of multi-functional controllers combining discrete events and continuous control. Sørensen, Quek, and Nguyen (2005), Nguyen (2006), Nguyen, Sorensen, and Quek (2007, 2008) and Nguyen and Sørensen (2009b) proposed the design of supervisory-switched controllers for DP from calm to extreme sea conditions and from transit to station keeping operations. The main objective of the supervisory-switched control is to integrate an appropriate bank of controllers and models at the plant control level into a hybrid DP system being able to operate in varying environmental and operational conditions. Implementing the hybrid control concept will increase the so-called weather window making it possible to conduct all-year marine operations, such as subsea installation and intervention, drilling, and pipe laying in harsh environment. Concerning large changes in environmental conditions, in particular, when conducting marine operations in deep-water, the feature of hybrid control is important as the operations are more time consuming, and hence more sensitive to changes in sea states. Lately, with increasing interest for hydrocarbons in the arctic DP operations in various ice conditions like level ice, managed ice and ice ridges have been studied. In Nguyen, Sørbø, and Sørensen (2009) DP in level ice is presented. For DP vessels operating partly in ice and open water, see Fig. 1, switching between controllers and control settings on both the plant-level and low-level will be necessary.

Fig. 1. DP operations in arctic hydrocarbon exploration.

The number of the safety critical and demanding DP operations is increasing. As a consequence of this the system integrity and requirements to further physical and functional integration between the DP system, marine automation system, thruster and propulsion system and power plant will follow accordingly. It is believed that more research efforts will be directed into diagnostics and fault-tolerant control, see Blanke et al. (2003), Nguyen, Blanke, and Sørensen (2007), and Fang and Blanke (2009). As a part of this proper testing and verification of the DP system software are crucial for the safety and profitability (Johansen, Fossen, & Vik, 2005, 2007; Johansen & Sørensen, 2009; Smogeli, 2010).

The importance of the DP control system for the closed-loop performance of the station keeping operation is clearly demonstrated in several studies. Morishita and Cornet (1998), Morishita, Tannuri, and Bravin (2004), Tannuri and Morishita (2006), and Tannuri, Saad, and Morishita (2009) have conducted detailed performance studies of the DP operations for shuttle tanker and Floating Production Storage and Offloading (FPSO) units.

This paper will give a survey of some of the major technology advances of the DP control system having taken place during more than 30 years of research and development. Important areas of guidance and navigation are not covered in this paper. For further references on these topics the reader is referred to Fossen (2011), Skjetne (2005), Ihle (2006) and Breivik (2010).

Detailed information with complementary references to the literature for the major contributions in the field of DP of marine vessels can be obtained from Fossen (2000), Fossen (2002), Fossen (2011) and Sørensen (2011).

The paper is organized as follows. Section 2 contains an introduction to DP systems. In Section 3 mathematical modeling of DP vessels is presented. Sections 4 and 5 present DP observers and controllers, respectively. In Section 6 a brief overview of thrust allocation is presented. Section 7 is about low-level thruster control. Section 8 is about hybrid DP control with experimental results. In Section 9 failure and functional testing in the sense of hardware-in-the-loop (HIL) testing are shown. Finally, conclusions are made in Section 10.

2. Introduction to dynamic positioning

While in DP operated ships the thrusters are the sole source of station keeping, the assistance of thrusters are only complementary to the mooring system in the case of thruster assisted position mooring (PM) systems. Here, most of the station keeping is provided by a deployed anchor system. In severe environmental conditions the thrust assistance is used to minimize the vessel excursions and line tension by mainly increasing the damping in terms of velocity feedback control. Thruster assisted position mooring (PM) systems have been commercially available since the 1980s and provide a flexible solution for floating structures for drilling and oil&gas exploitation on the smaller and marginal fields. Modeling and control of turret-moored ships are treated in Strand, Sørensen, and Fossen (1998), Strand (1999), Sørensen, Strand, and Fossen (1999), Berntsen, Aamo, Leira, and Sørensen (2008), Berntsen (2008) and Nguyen and Sørensen (2009a, 2009b). For turret anchored ships without natural weather-vaning properties the thrusters are also used to automatic control of the heading, similarly to DP operated vessels.

DP systems have traditionally been a low-speed application, where the basic DP functionality is either to keep a fixed position and heading or to move slowly from one location to another. In addition specialized tracking functions for cable and pipe-layers, and remote operated vehicle (ROV) operations have been available. The traditional autopilot functionality has over the years become more sophisticated. Often a course correction function is available for correction of course set-point due to environmental disturbances and drifting, such that the vessel follows a straight line. Way-point tracking is used when a vessel is supposed to follow a pre-defined track, e.g. defined by several way-point coordinates. The trend today is that typical tracking functionality merges with the DP functionality, giving *one unified system* for all speed ranges and types of operations. Further research on hybrid control (Hespanha et al., 2003) will enable this.

2.1. System overview

DP and PM systems may comprise the following sub-systems (Fig. 2).

- Power generation (prime mover and generators), distribution system (switchboards), transformers, variable speed drives, motors and uninterruptable power supply (UPS) of sensitive equipment and automation systems. This comprises all units necessary to supply the DP system with power.
- DP control system:
  - Computer/joystick systems.
  - Sensors (gyros, wind sensors, motion reference units, etc.).
  - Position reference systems like Global Navigation Satellite Systems (GNSS), hydroacoustic systems, taut wires, micro wave systems, laser systems etc. Hardware, software and sensors to supply information and/or corrections necessary to give accurate position and heading references.
  - Display system and operator panels.
  - Associated cabling and cable routing.
- Thruster system. This involves all components and systems necessary to supply the DP system with thrust force and direction. The thruster system includes thrusters with drive units and necessary auxiliary systems including piping and main propellers and rudders that are under the control of the DP system.
- Mooring system (applicable for moored vessels only).
- Power management system (PMS) for handling of generators, black-out prevention, power limitation, load sharing and load shedding. For advanced vessels more sophisticated energy management systems are used for intelligent power scheduling and allocation.

2.2. Functionality

The various DP vendors may differ in design methods. However, the basic DP functionality are more or less based on the same principles, as outlined in Fig. 3.

The DP control system consists of several submodules dedicated for each task:

Signal processing: All signals from external sensors should be thoroughly analyzed and checked in a separate signal processing module. This comprises testing of the individual signals, and signal voting and weighting when redundant measurements are available.

Vessel observer: Wave filtering and state estimation are important features of the DP system. In case of lost sensor signals, the predictor is used to provide dead reckoning, which is required by class societies.

Controller logic: The DP system can be operated in different modes of operation. All kind of internal system status handling and mode transitions, model adaptation etc. are governed by the controller logic. This includes smooth transitions between the different modes of operation, issue alarm and warnings, and operator interactions.

Feedback control law: The DP controllers are often of multivariable PID type, where feedback is produced from the estimated low-frequency (LF) position and heading deviations and estimated LF velocities.

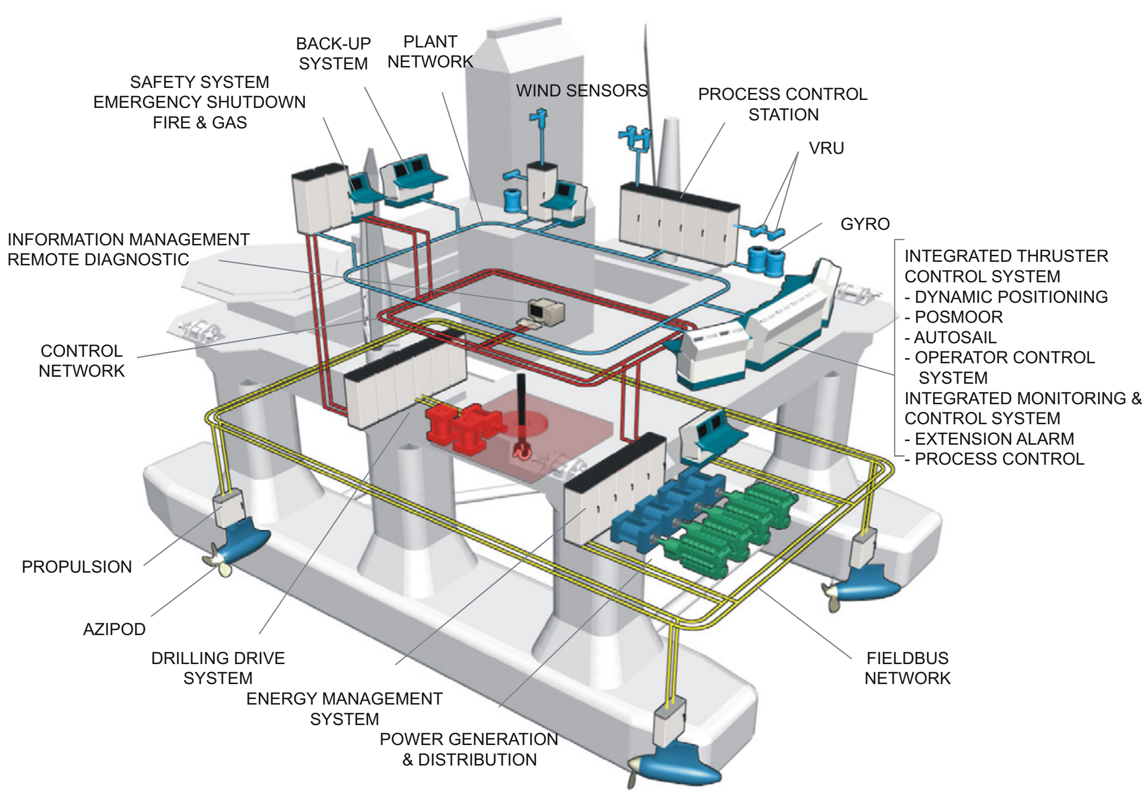

Fig. 2. Illustration of different systems on a DP rig (printed with kind permission from ABB Marine).

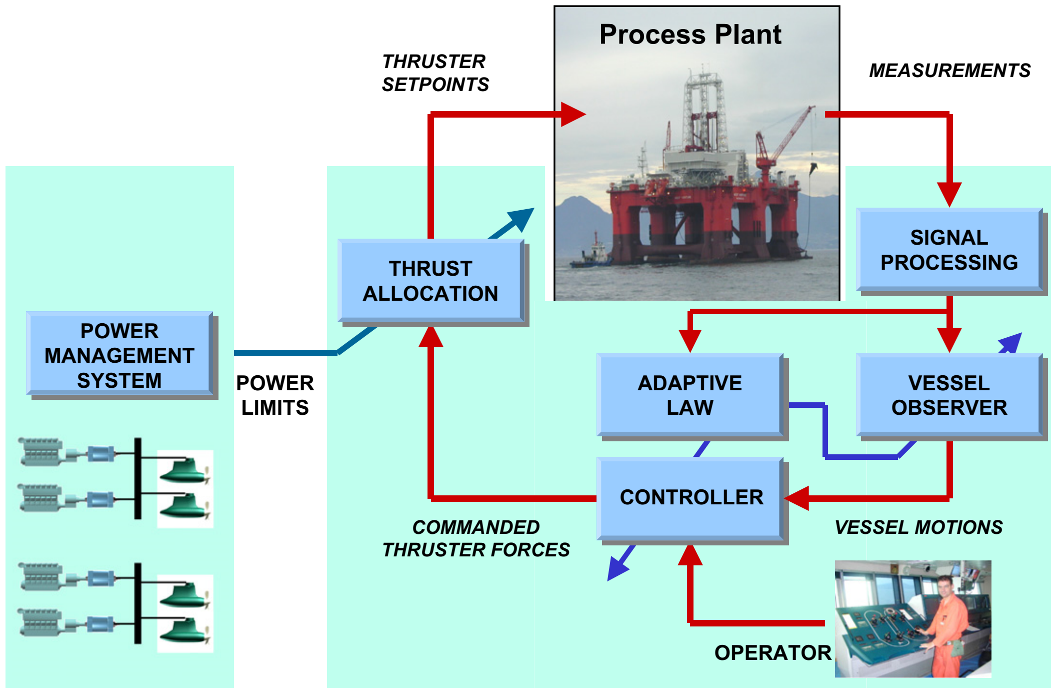

Fig. 3. DP SW modules integrated with PMS.

Feedforward control law: The most common feedforward control term is wind feedforward. For the different applications (pipe laying, ice operations, position mooring) tailor made feedforward control functions are used.

Guidance system and reference trajectories: In tracking operations, where the vessel moves from one position and heading to another, a reference model is needed for achieving a smooth transition. In the most basic case the operator specifies a new desired position and heading, and a reference model generates smooth reference trajectories/paths for the vessel to follow. A more advanced guidance system involves way-point tracking functionality, optimal path planning and weather routing for long distance sailing.

Thrust allocation: The high-level feedback and feedforward controllers compute commanded forces in surge and sway and moment in yaw. The thrust allocation module computes the corresponding force and direction commands to each thruster device. The low-level thruster controllers will then control the propeller pitch, speed, torque, and power satisfying the desired thrust demands.

Model adaptation: The parameters in the mathematical model describing the vessel dynamics will vary with the different operational and environmental conditions. In a model-based design, the DP system should automatically provide the necessary corrections of the vessel model and the controller settings subject to changes in the vessel draught, wind area and variations in the sea state.

3. Modeling of DP vessels

The mathematical models may be formulated in two complexity levels (Sørensen, 2005). The first level consists of a simplified mathematical description, low fidelity model, containing only the main physical properties of the process. This model may constitute a part of the controller and is here denoted as the *control plant model*. The second modeling level may be a comprehensive description of the actual process using high fidelity model formulations. The main purpose of this model, denoted as the *process plant model* or *simulation model* is to simulate the real plant dynamics including process disturbance, sensor outputs and control inputs.

3.1. Process plant model: hydrodynamics

3.1.1. Kinematics

The reference frames used are illustrated in Fig. 4. The Earth-fixed reference frame is denoted as the $X_E Y_E Z_E$-frame. The reference-parallel $X_R Y_R Z_R$-frame is also Earth-fixed but rotated to the desired heading angle ψ_d. The origin is translated to the desired x_d and y_d position coordinates. The body-fixed XYZ-frame is fixed to the body of the vessel.

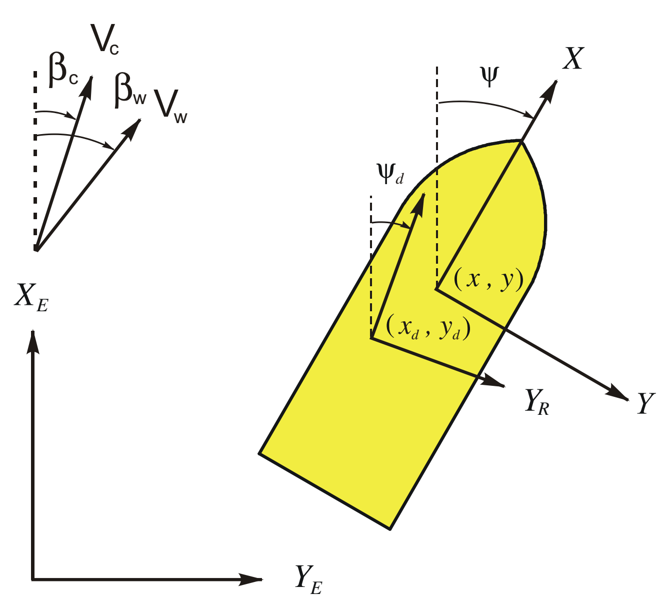

Fig. 4. Reference frames: Earth-fixed, reference parallel and body-fixed.

The rotation matrix $\mathbf{J}$ gives the linear and angular velocity of the vessel in the body-fixed frame relative to the Earth-fixed frame (Norrbin, 1970; Fossen, 1994)

$$\dot{\boldsymbol{\eta}} = \begin{bmatrix} \dot{\boldsymbol{\eta}}_1 \\ \dot{\boldsymbol{\eta}}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{J}_1(\boldsymbol{\eta}_2) & \mathbf{0}_{3\times3} \\ \mathbf{0}_{3\times3} & \mathbf{J}_2(\boldsymbol{\eta}_2) \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}, \\ = \mathbf{J}(\boldsymbol{\eta}_2)v. \tag{1}$$

The vectors defining the Earth-fixed vessel position and orientation, and the body-fixed translation and rotation velocities are given by

$$\boldsymbol{\eta}_1 = [x \quad y \quad z]^T, \quad \boldsymbol{\eta}_2 = [\phi \quad \theta \quad \psi]^T, \tag{2a}$$
$$\boldsymbol{v}_1 = [u \quad v \quad w]^T, \quad \boldsymbol{v}_2 = [p \quad q \quad r]^T. \tag{2b}$$

If only surge, sway and yaw (3DOF) are considered, the position vector and the velocity vector are reduced to $\boldsymbol{\eta} = [x, y, \psi]^\top$ and $\boldsymbol{v} = [u, v, r]^\top$, respectively, such that the kinematics is given as

$$\dot{\boldsymbol{\eta}} = \mathbf{R}(\psi)\boldsymbol{v}, \tag{3}$$

$$\text{where } \mathbf{R}(\psi) = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{4}$$

3.1.2. Vessel model

3.1.2.1. Nonlinear low-frequency vessel model. The nonlinear six degrees of freedom (DOFs) body-fixed coupled equations of the low-frequency (LF) motions in surge, sway, heave, roll, pitch and yaw (Fossen, 2002) and Sørensen (2011) are written

$$\mathbf{M}\dot{\boldsymbol{v}} + \mathbf{C}_{\mathrm{RB}}(\boldsymbol{v})\boldsymbol{v} + \mathbf{C}_{\mathrm{A}}(\boldsymbol{v}_{\mathrm{r}})\boldsymbol{v}_{\mathrm{r}} + \mathbf{D}(\boldsymbol{v}_{\mathrm{r}}) + \mathbf{G}(\boldsymbol{\eta}) \\ = \boldsymbol{\tau}_{\mathrm{wind}} + \boldsymbol{\tau}_{\mathrm{wave2}} + + \boldsymbol{\tau}_{\mathrm{moor}} + \boldsymbol{\tau}_{\mathrm{ice}} + \boldsymbol{\tau}_{\mathrm{thr}}. \tag{5}$$

where $\mathbf{M} \in \mathbb{R}^{6\times6}$ is the system inertia matrix including added mass; $\mathbf{C}_{RB}(\boldsymbol{v}) \in \mathbb{R}^{6\times6}$ and $\mathbf{C}_A(\boldsymbol{v}_r) \in \mathbb{R}^{6\times6}$ are the skew-symmetric Coriolis and centripetal matrices of the rigid body and the added mass; $\mathbf{G}(\boldsymbol{\eta}) \in \mathbb{R}^6$ is the generalized restoring vector caused by the buoyancy and gravitation; $\boldsymbol{\tau}_{\mathrm{thr}} \in \mathbb{R}^6$ is the real control vector consisting of forces and moments produced by the thruster system; $\boldsymbol{\tau}_{\mathrm{wind}}$ and $\boldsymbol{\tau}_{\mathrm{wave2}} \in \mathbb{R}^6$ are the wind and second-order wave load vectors, respectively; and $\mathbf{D}(\boldsymbol{v}_{\mathbf{r}}) \in \mathbb{R}^6$ is the damping vector including linear and nonlinear terms which are a function of the relative velocity vector, $\boldsymbol{v}_{\mathrm{r}} \in \mathbb{R}^6$, between the vessel and current. Details of these terms can be found in Faltinsen (1990) and Sørensen (2011). For operation in ice the corresponding loads from level ice, ice floes and ice ridges are modeled by $\boldsymbol{\tau}_{\mathrm{ice}} \in \mathbb{R}^6$. In Nguyen et al. (2009) models of level ice loads are presented.

The wave drift loads contribute to a significant part of the total excitation force in the low-frequency model. The second-order wave effects are divided into mean, slowly varying (difference frequencies) and rapidly varying (sum frequencies) wave loads. For the applications considered here the effect of the rapidly varying second order wave loads can be neglected. The determination of the second-order wave effects can be done by means of quadratic transfer functions for, $i = 1 \ldots 6$ (Newman, 1977 and Faltinsen, 1990)

$$\tau^i_{wave2} = \bar{\tau}^i_{wm} + \tau^i_{wsv} = \sum_{j=1}^{N}\sum_{k=1}^{N} A_j A_k \begin{bmatrix} T^{ic}_{jk}\cos\left((\omega_k - \omega_j)t + \varepsilon_k - \varepsilon_j\right) + \\ T^{is}_{jk}\sin\left((\omega_k - \omega_j)t + \varepsilon_k - \varepsilon_j\right) \end{bmatrix}, \tag{6}$$

where ω_j is the wave frequency, A_j is the wave amplitude, and ε_j is a random phase angle. The superscript c and s denote cos and sin, respectively. The quadratic transfer functions T_{jk} are dependent on both the first and second order velocity potentials, which require a nonlinear panel methodology. In addition, it is time-consuming to calculate the T_{jk} for all combinations of ω_k and ω_j. This motivates to derive some simplifications. One should notice that the transfer functions when $k = j, T_{jj}$, represents the mean wave loads, and can be calculated from the first order velocity potential only. The most interesting slowly-varying wave loads are those where $\omega_k - \omega_j$ is small and the loads are truly slowly-varying. Normally, T_{jk} will not vary significantly with the frequency. Then, the following approximation by Newman (1977) will give satisfactory results

$$T^{ic}_{jk} = T^{ic}_{kj} = \frac{1}{2}\left(T^{ic}_{jj} + T^{ic}_{kk}\right), \tag{7}$$
$$T^{is}_{jk} = T^{is}_{kj} = 0. \tag{8}$$

The slowly-varying loads are approximated by the mean drift loads, and hence, the computation becomes much simpler and less time consuming. This approximation based on frequency dependent wave drift coefficients will then further be applied. By dividing the sea wave spectrum into N equal frequency intervals with corresponding wave frequency, ω_j, and amplitude, A_j, the wave drift loads are found to be

$$\tau^i_{wave2} = \bar{\tau}^i_{wm} + \tau^i_{wsv} = 2\cdot \\ \left(\sum_{j=1}^{N} A_j \left(T^i_{jj}(\omega_j, \beta_{wave} - \psi)\right)^{1/2} \cos\left(\omega_j t + \varepsilon_j\right)\right)^2, \tag{9}$$

where $T^i_{jj} > 0$ is the frequency-dependent wave drift function, and β_{wave} is the mean wave direction (assumed to follow the same sign convention as wind and current). A disadvantage with this approximation is the numerical generation of high-frequency components of no physical meaning. By numerical filtering this can be avoided. Eq. (9) can also be extended to include wave spreading. In general, the second-order wave loads are smaller than the first-order wave loads. However, the second-order wave loads are proportional to the square of the wave amplitude, whereas the first-order wave loads are proportional to the wave amplitude. This means that the second-order wave loads have an increased importance for increasing sea states.

The mooring system contains a number of mooring lines connected to the vessel directly or through the turret. Mooring lines are subjected to three types of excitation (Triantafyllou, 1994): large amplitude LF motions, medium amplitude WF motions and small amplitude, very high frequency vortex-induced vibrations. For the purpose of PM control system design, the mooring lines' influence on the LF vessel model is considered. A horizontal-plane spread mooring model can be formulated as

$$\boldsymbol{\tau}_{\mathrm{moor}} = -\mathbf{J}^{-1}(\boldsymbol{\eta}_2)\mathbf{g}_{\mathrm{mo}}(\boldsymbol{\eta}) - \mathbf{d}_{\mathrm{mo}}(\boldsymbol{v}_{\mathrm{r}}), \tag{10}$$

where $\mathbf{d}_{\mathrm{mo}}$ and $\mathbf{g}_{\mathrm{mo}} \in \mathbb{R}^6$ are the additional damping and Earth-fixed restoring force vectors, respectively, due to the mooring system. The nonlinear mooring line characteristics can be found by dedicated software programs for marine slender structures, e.g. RIFLEX (2003) and others. For further details the reader is referred to Sørensen (2011).

3.1.2.2. Linear wave-frequency model. The WF motion is calculated in the Earth-fixed reference-parallel frame, here also denoted as the hydrodynamic frame, according to

$$\mathbf{M}(\omega)\ddot{\boldsymbol{\eta}}_{Rw} + \mathbf{D}_p(\omega)\dot{\boldsymbol{\eta}}_{Rw} + \mathbf{G}\boldsymbol{\eta}_{Rw} = \boldsymbol{\tau}_{\mathrm{wave1}}, \tag{11}$$
$$\dot{\boldsymbol{\eta}}_w = \mathbf{J}(\psi_d)\dot{\boldsymbol{\eta}}_{Rw}, \tag{12}$$

where $\boldsymbol{\eta}_{Rw} \in \mathbb{R}^6$ is the WF motion vector in the reference-parallel frame. $\boldsymbol{\tau}_{\mathrm{wave1}} \in \mathbb{R}^6$ is the first order wave excitation vector, which will be modified for varying vessel headings relative to the incident wave direction. $\mathbf{M}(\omega) \in \mathbb{R}^{6\times6}$ is the system inertia matrix containing frequency dependent added mass coefficients in addition to the vessel's mass and moment of inertia. $\mathbf{D}_p(\omega) \in \mathbb{R}^{6\times6}$ is the wave radiation (potential) damping matrix. $\mathbf{G} \in \mathbb{R}^{6\times6}$ is the linearized restoring coefficient matrix. For anchored vessels, it can be assumed that the mooring system will not influence the WF induced motions. Generally, a time domain equation cannot be expressed with frequency domain coefficient. However, this is a common used formulation denoted as a *pseudo-differential equation*. By using time-varying retardation function the fluid-memory effects can be solved, see Fossen (2011) and the references therein for details.

3.2. Control plant model: hydrodynamics

The control plant model for the WF model is obtained by assuming (11) to be a second-order linear model driven by white noise, $\mathbf{w}_{\mathrm{pw}} \in \mathbb{R}^3$, according to

$$\dot{\mathbf{p}}_{\mathrm{w}} = \mathbf{A}_{\mathrm{pw}}\mathbf{p}_{\mathrm{w}} + \mathbf{E}_{\mathrm{pw}}\mathbf{w}_{\mathrm{pw}}, \tag{13}$$

where $\mathbf{p}_{\mathrm{w}} \in \mathbb{R}^6$ is the state of the WF model, $\mathbf{A}_{\mathrm{pw}} \in \mathbb{R}^{6\times6}$ is assumed Hurwitz, and describes the first-order WF-induced motion as a mass-damper-spring system, according to

$$\mathbf{A}_{\mathrm{pw}} = \begin{bmatrix} \mathbf{0}_{3\times3} & \mathbf{I}_{3\times3} \\ -\boldsymbol{\Omega}^2 & -2\boldsymbol{\Lambda}\boldsymbol{\Omega} \end{bmatrix}, \tag{14}$$

where $\boldsymbol{\Omega} = \mathrm{diag}(\omega_1, \omega_2, \omega_3)$ is a diagonal matrix containing the dominating wave response frequencies, and $\boldsymbol{\Lambda} = \mathrm{diag}(\lambda_1, \lambda_2, \lambda_3)$ is a diagonal matrix of damping ratios (λ_i is often set between 0.05 and 0.2). As suggested by Strand and Fossen (1999) adaptive schemes may be used to update ω_i for the varying sea states. However, this should be done with care in heavy sea states with long wave lengths. As suggested in Sørensen et al. (2002) the wave filtering should be avoided for long waves length (low wave frequencies) appearing in extreme seas or in swell dominated seas.

By assuming fixed anchor line length, the generalized mooring forces in a working point may be approximated by a first-order Taylor expansion of the static restoring and damping forces about a working point $\boldsymbol{\eta} = \boldsymbol{\eta}_{\mathrm{o}}$ and $\boldsymbol{\nu}_{\mathrm{r}} = \boldsymbol{\nu} = \mathbf{0}$, according to

$$\boldsymbol{\tau}_{\mathrm{moor}} = -\mathbf{R}^{\top}(\psi)\mathbf{G}_{\mathrm{mo}}(\boldsymbol{\eta} - \boldsymbol{\eta}_{\mathrm{o}}) - \mathbf{D}_{\mathrm{mo}}\boldsymbol{\nu}, \tag{15}$$

where $\mathbf{G}_{\mathrm{mo}} = \frac{\partial \mathbf{g}_{\mathrm{mo}}}{\partial \boldsymbol{\eta}}\Big|_{\boldsymbol{\eta}=\boldsymbol{\eta}_{\mathrm{o}}}, \mathbf{D}_{\mathrm{mo}} = \frac{\partial \mathbf{d}_{\mathrm{mo}}}{\partial \boldsymbol{\nu}}\Big|_{\boldsymbol{\nu}=\mathbf{0}}$. Let us assume that $\mathbf{C}_{\mathrm{RB}}(\boldsymbol{\nu})\boldsymbol{\nu}$, $\mathbf{C}_{\mathrm{A}}(\boldsymbol{\nu}_{\mathrm{r}})\boldsymbol{\nu}_{\mathrm{r}}$ and the nonlinear damping are small in (5) since the vessel's velocity is small in station keeping. Based on these assumptions and considering only surge, sway and yaw motions, $\mathbf{v} = [u, v, r]^T, \boldsymbol{\eta} = [x, y, \psi]^T$, the LF model in (5) can be simplified such that

$$\begin{aligned} \dot{\boldsymbol{\eta}} &= \mathbf{R}(\psi)\boldsymbol{\nu}, \\ \dot{\mathbf{b}} &= -\mathbf{T}_{\mathrm{b}}^{-1}\mathbf{b} + \mathbf{E}_{\mathrm{b}}\mathbf{w}_{\mathrm{b}}, \\ \mathbf{M}\dot{\boldsymbol{\nu}} &= -\mathbf{D}\boldsymbol{\nu} + \mathbf{R}^{\top}(\psi)\mathbf{b} - \mathbf{G}_{\mathrm{mo}}\mathbf{R}^{\top}(\psi)\boldsymbol{\eta} + \boldsymbol{\tau}_{\mathrm{c}}, \end{aligned} \tag{16}$$

where $\mathbf{b} \in \mathbb{R}^3$ is the bias vector accounting for both slowly varying disturbances and unmodeled dynamics, and $\mathbf{E}_{\mathrm{b}}$ is a diagonal scaling matrix. The damping effect of the mooring system is included in the damping matrix, such that $\mathbf{D} = \mathbf{D}_{\mathrm{L}} + \mathbf{D}_{\mathrm{mo}}.\boldsymbol{\tau}_{\mathrm{c}} = [\tau_x, \tau_y, \tau_\psi]^T$ is the control input vector. For fully DP operated vessels $\mathbf{D}_{\mathrm{mo}}$ and $\mathbf{G}_{\mathrm{mo}}$ are set to zero. For inclusion of ice control plant models, please see Nguyen et al. (2009).

The output of the control plant model, $\mathbf{y} \in \mathbb{R}^3$, is the position and heading of the vessel, assumed to be a superposition of the WF and LF motion, according to

$$\mathbf{y} = \boldsymbol{\eta} + \mathbf{C}_{\mathrm{pw}}\mathbf{p}_{\mathrm{w}} + \mathbf{v}, \tag{17}$$

where $\mathbf{v} \in \mathbb{R}^3$ is the measurement noise vector, and $\mathbf{C}_{\mathrm{pw}} = [\mathbf{0}_{3\times3} \quad \mathbf{I}_{3\times3}]$.

4. Observer design

Inspired by Fossen and Strand (1999), the nonlinear passive observer operating in open water is found by copying the control plant model in (13)–(17) such that

$$\dot{\hat{\mathbf{p}}}_{\mathrm{w}} = \mathbf{A}_{\mathrm{pw}}\hat{\mathbf{p}}_{\mathrm{w}} + \mathbf{K}_1\tilde{\mathbf{y}}, \tag{18}$$

$$\dot{\hat{\boldsymbol{\eta}}} = \mathbf{R}(\psi_y)\hat{\boldsymbol{\nu}} + \mathbf{K}_2\tilde{\mathbf{y}}, \tag{19}$$

$$\dot{\hat{\mathbf{b}}} = -\mathbf{T}_{\mathrm{b}}^{-1}\hat{\mathbf{b}} + \mathbf{K}_3\tilde{\mathbf{y}}, \tag{20}$$

$$\mathbf{M}\dot{\hat{\boldsymbol{\nu}}} = -\mathbf{D}\hat{\boldsymbol{\nu}} + \mathbf{R}^{\top}(\psi_y)\hat{\mathbf{b}} - \mathbf{G}_{\mathrm{mo}}\mathbf{R}^{\top}(\psi_y)\hat{\boldsymbol{\eta}} + \boldsymbol{\tau}_{\mathrm{c}} + \mathbf{K}_4\mathbf{R}^{\top}(\psi_y)\tilde{\mathbf{y}}, \tag{21}$$

$$\hat{\mathbf{y}} = \hat{\boldsymbol{\eta}} + \mathbf{C}_{\mathrm{pw}}\hat{\mathbf{p}}_{\mathrm{w}}, \tag{22}$$

where $\tilde{\mathbf{y}} = \mathbf{y} - \hat{\mathbf{y}}$ is the estimation error (in the literature also denoted as the innovation or injection term); $\mathbf{K}_1 \in \mathbb{R}^{6\times3}$, $\mathbf{K}_2 \in \mathbb{R}^{3\times3}, \mathbf{K}_3 \in \mathbb{R}^{3\times3}$, and $\mathbf{K}_4 \in \mathbb{R}^{3\times3}$ are the observer gain matrices given by Fossen and Strand (1999). The stability analysis and tuning for the observer are very similar to those addressed in Fossen and Strand (1999) and Loria, Fossen, and Panteley (2000).

5. Plant control

5.1. Nonlinear horizontal-plane PID control law

A nonlinear horizontal-plane positioning feedback controller of PID type is formulated as

$$\boldsymbol{\tau}_{PID} = -\mathbf{R}_e^{\top}K_p\mathbf{e} - \mathbf{R}_e^{\top}\mathbf{K}_{p3}\mathbf{f}(\mathbf{e}) - \mathbf{K}_d\widetilde{\nu} - \mathbf{R}^{\top}\mathbf{K}_i\mathbf{z}, \tag{23}$$

where $\mathbf{e} \in \mathbb{R}^3$ is the position and heading deviation vector, $\widetilde{\boldsymbol{\nu}} \in \mathbb{R}^3$ is the velocity deviation vector, and $\mathbf{z} \in \mathbb{R}^3$ is the integrator states defined as

$$\mathbf{e} = [e_1 \quad e_2 \quad e_3]^T = \mathbf{R}^{\top}(\psi_d)(\hat{\boldsymbol{\eta}} - \boldsymbol{\eta}_d), \tag{24}$$

$$\widetilde{\boldsymbol{\nu}} = \hat{\nu} - \mathbf{R}^T(\psi_d)\dot{\boldsymbol{\eta}}_d, \tag{25}$$

$$\dot{\mathbf{z}} = \hat{\boldsymbol{\eta}} - \boldsymbol{\eta}_d, \tag{26}$$

$$\mathbf{R}_e = \mathbf{R}(\psi - \psi_d) \triangleq \mathbf{R}^T(\psi_d)\mathbf{R}(\psi). \tag{27}$$

A third order stiffness term is proposed

$$\mathbf{f}(\mathbf{e}) = [e_1^3 \quad e_2^3 \quad e_3^3]^T. \tag{28}$$

An advantage of this is the possibility to reduce the first order proportional gain matrix, resulting in reduced dynamic thruster action for smaller position and heading deviations. Moreover, the third order term will make the thrusters to work more aggressive for larger deviations. $\boldsymbol{\eta}_d \in \mathbb{R}^3$ is the vector defining the desired Earth-fixed position and heading coordinates. $\mathbf{K}_p, \mathbf{K}_{p3}, \mathbf{K}_d$ and $\mathbf{K}_i \in \mathbb{R}^{3\times3}$ are the non-negative controller gain matrices found by appropriate controller synthesis methods.

5.2. Roll-pitch control law

As proposed by Sørensen and Strand (2000) for small-water-plane-area vessels motion damping of roll and pitch may be achieved by using a roll-pitch control law according to

$$\boldsymbol{\tau}_{\mathrm{rpd}} = -\mathbf{G}_{\mathrm{rpd}}\begin{bmatrix} \hat{p} \\ \hat{q} \end{bmatrix}, \tag{29}$$

where $\hat{p}$ and $\hat{q}$ are the estimated pitch and roll angular velocities, and the roll-pitch controller gain matrix $\mathbf{G}_{\mathbf{rpd}} \in \mathbb{R}^{3\times2}$ is defined as

$$\mathbf{G}_{\mathrm{rpd}} = \begin{bmatrix} 0 & g_{xq} \\ g_{yp} & 0 \\ g_{\psi p} & 0 \end{bmatrix}, \tag{30}$$

and g_{xq}, g_{yp} and $g_{\psi p}$ are the corresponding non-negative roll-pitch controller gains. One of the challenges in implementation will be to design an observer for proper estimation of the pitch and roll angular velocities.

5.3. Resulting control law

The resulting positioning control law is written

$$\boldsymbol{\tau}_c = \boldsymbol{\tau}_{wFF} + \boldsymbol{\tau}_{PID} + \boldsymbol{\tau}_{rpd}, \tag{31}$$

where $\boldsymbol{\tau}_{wFF} \in \mathbb{R}^3$ is the wind feedforward control law.

5.4. Reference model

A reference model is used for obtaining smooth transitions between the various setpoints. Let

$$\boldsymbol{\eta}_r = [x_r \quad y_r \quad \psi_r]^T, \tag{32}$$

define the final Earth-fixed vector position and heading setpoint vector. This is input to a nonlinear third order reference model as presented in Fossen (1994, 2002, 2011) and Sørensen (2011), and is given as

$$(\mathbf{x}_{ref}, \mathbf{x}_d^e, \mathbf{v}_d^e, \mathbf{a}_d^e) = f(\boldsymbol{\eta}_r, \mathbf{x}_{ref}, \mathbf{x}_d^e, \mathbf{v}_d^e, \mathbf{a}_d^e; t). \tag{33}$$

This model produces a smooth desired acceleration, velocity and position reference that are inputs to the positioning control law (31). In Fossen (2002) and Breivik (2010) more details on reference models and guidance systems can be found. In Sørensen et al. (2001) and Nguyen and Sørensen (2009a) examples of local optimizations of setpoints in conjunction with reference models are shown.

6. Thrust allocation

The high-level positioning controller produces a commanded thrust vector $\boldsymbol{\tau}_c \in \mathbb{R}^3$ in surge, sway and yaw. The problem of finding the corresponding force and direction of the thrusters that meets the high-level thrust commands is called thrust allocation. References on thrust allocation are found in Sørdalen (1997), Sinding and Anderson (1998), Johansen, Fossen, and Berge (2004, 2005, 2007), Fossen (2002), Fossen and Johansen (2006), Ruth, Sørensen, and Perez (2007), Ruth (2008), Ruth and Sørensen (2009a, 2009b), Ruth, Smogeli, Perez, and Sørensen (2009) and Perez (2009).

6.1. Optimal thrust allocation

The relation between the control vector $\boldsymbol{\tau}_c \in \mathbb{R}^3$ and the produced thruster action $\mathbf{u}_c \in \mathbb{R}^r$ is defined by

$$\boldsymbol{\tau}_c = \mathbf{T}_{3\times r}(\boldsymbol{\alpha})\mathbf{T}_d = \mathbf{T}_{3\times r}(\boldsymbol{\alpha})\mathbf{K}\mathbf{u}_c, \tag{34}$$

where $\mathbf{T}_{3\times r}(\boldsymbol{\alpha}) \in \mathbb{R}^{3\times r}$ is the thrust configuration matrix, $\boldsymbol{\alpha} \in \mathbb{R}^r$ is the thruster orientation vector, and r is the number of thrusters. The corresponding desired thrust vector $\mathbf{T}_d \in \mathbb{R}^r$ is given by $\mathbf{T}_d = \mathbf{K}\mathbf{u}_c$, where $\mathbf{K} \in \mathbb{R}^{r\times r}$ is the diagonal matrix of thrust force coefficients written $\mathbf{K} = diag\{k_i\}$. The thrust provided by the thruster unit i is calculated to be

$$T_{\mathrm{d}i} = k_i u_{ci.} \tag{35}$$

For a fixed mounted propeller or thruster the corresponding orientation angle is set to a fixed value reflecting the actual orientation of the device itself. In case of an azimuthing thruster, α_i is an additional control input to be determined by the thrust allocation algorithm. $\mathbf{u}_c$ is the control vector of either pitch-controlled, revolution-controlled or torque- and power-controlled propeller inputs. The commanded control action and direction provided by the thrusters becomes

$$\mathbf{u}_c = \mathbf{K}^{-1}\mathbf{T}_{3\times r}^{+}(\boldsymbol{\alpha})\boldsymbol{\tau}_c, \tag{36}$$

where $\mathbf{T}_{3\times r}^{+}(\boldsymbol{\alpha}) \in \mathbb{R}^{r\times 3}$ is the pseudo-inverse thrust configuration matrix calculated using numerical optimization theory.

6.2. Geometrical thrust induction

The effect of the commanded thruster action provided by the thrusters in (36) on (5) can be calculated to be

$$\boldsymbol{\tau}_{\mathrm{thr}} = \mathbf{T}_{6\times r}(\boldsymbol{\alpha})\mathbf{K}\mathbf{u}_c, \tag{37}$$

where $\boldsymbol{\tau}_{\mathrm{thr}} \in \mathbb{R}^6$ is the corresponding actual control vector acting the vessel as shown in (5), and $\mathbf{T}_{6\times r}(\boldsymbol{\alpha}) \in \mathbb{R}^{6\times r}$ is the thrust configuration matrix accounting for both the horizontal and the vertical contribution of the produced thruster actions. The reader should notice that (37) will introduce roll and pitch moments, that may be important to consider for rigs as they may introduce unintentional roll and pitch motions. The effect of thrust losses on (5) and the design of the local thruster controllers are presented in the next section.

7. Low-level thruster control

Electrical propulsion has during the last decade become the preferred solution for DP vessels. This opened up for new control solutions combining the disciplines of hydrodynamics, electrical power, and control engineering. The thruster controllers may be divided in two control regimes, depending on the operational conditions:

(a) Thruster control in normal conditions, when experiencing low to moderate thrust losses.
(b) Thruster control in extreme conditions, when experiencing large and abrupt thrust losses due to ventilation and in-and-out-of-water effects.

The purpose of the low-level thruster controller is to relate the desired thrust T_d, given by the thrust allocation routine, to the commanded motor torque Q_c. The propulsion and thruster system is normally the main power consumer on marine vessels. The thruster control system performance is therefore critical for avoiding blackouts and harmonic distortions in the power generation and distribution system. In extreme conditions, the control systems designed for normal operating conditions may be inadequate, and lead to increased mechanical wear and tear and unpredictable power consumption. For surface vessels with fixed-pitch-propellers (FPP), shaft speed control has been the industry standard, whereas torque and power control was introduced by Sørensen, Ådnanes, Fossen, and Strand (1997) and further refined in Sørensen and Smogeli (2009). For control of diesel engines, shaft speed control is the most commonly used solution. However, both torque and power control have been proposed and implemented, see Blanke and Busk Nielsen (1987, 1990). In extreme seas with ventilation and motivated by the similar problem of a car wheel losing friction on a slippery surface during braking or acceleration, the concept of anti-spin thruster control was introduced in Smogeli, Aarseth, Overs, Sørensen, and Minsaas (2003), Smogeli, Sørensen, and Fossen (2004), Smogeli (2006), Bakkeheim, Johansen, Smogeli, and Sørensen (2008), Smogeli, Sørensen, and Minsaas (2008) and Smogeli and Sørensen (2009). In Ruth (2008) anti-spin thruster allocation was treated. Ruth shows in his work how thrust may be re-allocated to nonventilating propellers, increasing overall efficiency and improving thrust production. In Sørensen, Smogeli, and Ruth (2009), Smogeli (2006) and Ruth (2008) overview of the various low-level thrust controllers including control of controllable-pitch-propellers (CPP) can be found.

8. Hybrid control

Hybrid control has earlier been realized in the control of airplanes and other land-based vehicles. Although switching has been used in other applications, stability is a concern when switching among nonlinear controllers. Extensive work on the theory of supervisory switching control has been presented by Hespanha (2001), Hespanha and Morse (2002) and Hespanha et al. (2003). The work on hybrid DP control in Nguyen (2006), Nguyen et al. (2007, 2008) and Nguyen and Sørensen (2009b) are based on these results. Hybrid control enables switching either among linear or nonlinear controllers according to the prevailing operational regimes. While dwell-time switching logic is employed in the linear supervisory control, scale-independent hysteresis switching logic is used in nonlinear supervisory control ensuring stability of the whole system and to prevent chattering. Supervisory control used for DP system is more advantageous than gain scheduling control in terms of flexibility and modularity, and decoupling between supervision and control (Hespanha, 2001). In the supervisory control, the design of the candidate controllers is done separately with the adaptive mechanism (the supervisor) whereas in the gain scheduling control, the candidate controllers usually have to be particularly designed to satisfy the tuning mechanism. In the design of hybrid-controller DP system, the supervisory control allows the switching among the bank of controllers which are structurally different such as observer with WF filtering and PID controller in normal sea and observer without WF filtering, AFB controller in harsh environmental conditions, and inclusion of mooring models in the observer for thruster assisted position mooring. This is not allowed in the gain scheduling control due to the similarity requirement of the controller structure except the gains. This is important for the DP vessel that requires the design of structurally different controllers satisfying the structural changes in the hydrodynamics, and the performance requirements subject to varying environmental and operational conditions.

8.1. Vessel operational condition

As proposed in Perez, Sørensen, and Blanke (2006) the different control plant models subject to the various control objectives, constraints and dynamic response of the controlled system can be formulated. Based on this, the vessel operational condition (VOC) is defined as a space consisting of three main dimensions (Fig. 5), according to:

- Mode dependence (x axis),
- Speed dependence (y axis),
- Environmental dependence (z axis).

One may consider an additional dimension which is fault-tolerant control dependence. Changes in these dimensions result in changes in the fundamental components of the control problem (objectives, constraints and dynamic response of the controlled system).

Changes in operation mode: DP vessels operate in variety of modes, such as station keeping, setpoint changes, thruster assisted position mooring (PM), low speed maneuvering, and moderate to high speed transit operations.

Changes in speed: The changes in speed result in changes in the dynamic response of the vessel (high-level) and thrusters (low-level). The latter will be accounted in the control allocation scheme and the thruster and rudder controllers. In the high-level controller this can be captured as changes in the parameters of a model, and even in the structure of the model and the controller itself. For example, while the effects of nonlinear damping can be neglected in the zero speed regimes, e.g. DP applications, those should be included in the controller design for higher speed regimes.

Changes in environment: Changes in the environment result in changes of the disturbance characteristics (frequency and intensity). The control objective of a DP vessel from calm to moderate sea is to keep its position and heading by compensating for only LF motion. As the sea state increases, WF motion is induced by waves with lower dominant frequencies, especially swell in the North Sea and Barents Sea. For this reason, the control objective

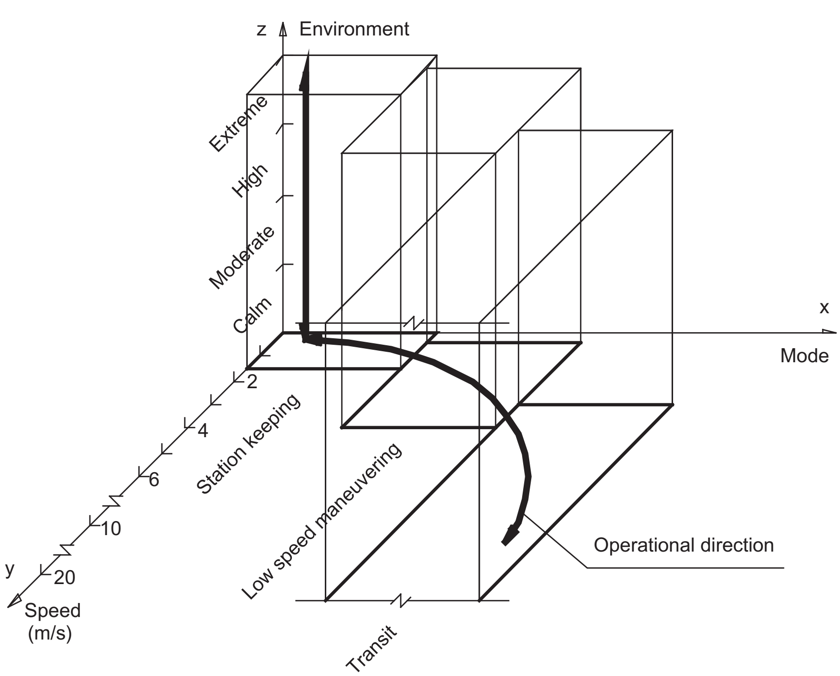

Fig. 5. Vessel operational conditions.

is to compensate both WF and LF motions instead of only LF in moderate sea. For the low-level thruster controllers, anti-spin control will be activated in high seas states.

8.2. Concept of hybrid control

8.2.1. Structure

The idea of hybrid-controller system is the ability to automatically switch among controllers. There are two main blocks in the hybrid-controller system: the supervisor and the controller set (Fig. 6).

In the estimator-based supervision, the supervisor compares the behaviors of some admissible models and the actual process, and decides which model is best to describe the ongoing process. The bank of models is given by

$$\dot{\mathbf{x}}_p = \mathbf{A}_p(\mathbf{x}_p, \mathbf{u}, \mathbf{y}), \mathbf{y}_p = \mathbf{C}_p(\mathbf{x}_p, \mathbf{u}, \mathbf{y}) : p \in P. \tag{38}$$

There will be at least one controller designed for each model. The set of controllers is denoted as

$$\dot{\mathbf{x}}_q = \mathbf{F}_q(\mathbf{x}_q, \mathbf{y}), \mathbf{u} = \mathbf{G}_q(\mathbf{x}_q, \mathbf{y}) : q \in Q, \tag{39}$$

where P and Q are the set of estimators and controllers, respectively; P and q denote the pth model and q^{th} controller, respectively; $\mathbf{x}_p$ is the state vector of model set; $\mathbf{y}_p$ is the estimation vector; $\mathbf{x}_q$ is the state vector of the controller; $\mathbf{y}$ is the output of the process plant; and $\mathbf{u}$ is the control force vector. When the switching is made, a switching signal, $\sigma \in \mathbb{Z}^+$, determines the selected model and the controller in the loop at each instant of time.

8.2.2. Hysteresis switching logic

The principle of switching is intuitive in the sense that the chosen controller in the closed loop is the one corresponding to the model behaving closest to the process plant. For this purpose, an estimation error is defined as

$$\mathbf{e}_p = \mathbf{y}_p - \mathbf{y}, \qquad p \in P. \tag{40}$$

Although switching based on the error vector is intuitive, this could cause the chattering (switching back and forth) of the controllers, hence destabilizing the whole system. One of the reasons is that the estimation error in (40) may contain noise. The effect of the noise can be reduced by introducing a monitoring signal (Hespanha et al., 2003), $\mu_p \in \mathbb{R}$, according to

$$\dot{\mu}_p = -\lambda\mu_p + \gamma(||\mathbf{e}_p||), \tag{41}$$

where $\lambda \in \mathbb{R}$ denotes a constant non-negative forgetting factor; γ is the class K function; $\mu_p(0) > 0$; and $||\cdot||$ denotes any norm.

According to Hespanha et al. (2003), in order to avoid chattering even more effectively, the switching is done on a slow-down basis of observing the growth of the estimation errors. This means that the switching is not toward $\mu_\sigma = \min(\mu_p)$, but toward $\mu_\sigma = (1+h)\min(\mu_p)$, where $h \in \mathbb{R}$ is a positive hysteresis constant. Such switching logic is called *hysteresis switching logic*.

In practice, the hysteresis parameter h is tuned such that it is positive. However, if h is too large, the switching will be frozen at previous operating regimes; and if h is too small, chattering may occasionally occur. The forgetting factor λ is chosen such that the monitoring signal, μ_p, is neither too sluggish nor aggressive.

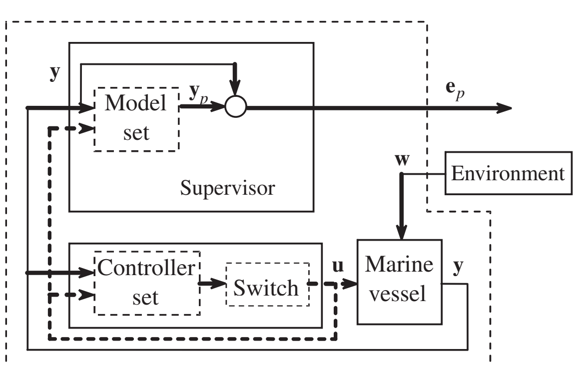

Fig. 6. Hybrid DP controller.

8.2.3. Properties

In the formal stability analysis of the whole system, it is convenient to have the following definition adopted from Hespanha (2001). The switched system includes the process, the controller set, and the model set

$$\dot{\mathbf{x}} = \mathbf{A}_\sigma(\mathbf{x}, \mathbf{w}), \tag{42}$$

$$\mathbf{e}_p = \mathbf{C}_p(\mathbf{z}, \mathbf{w}), p \in P, \tag{43}$$

where $\mathbf{x}$ denotes the state vector of the process, multi-controller, and multi-model; the nonlinear function $\mathbf{A}_\sigma$ is found by collecting the state space equations of the process, the multi-controller, and the multi-model; and $\mathbf{w}$ is the environmental disturbance vector. The input to the switched system is the disturbances caused by the wind, wave and current loads, and the output is the model error vector, $\mathbf{e}_p$.

According to Hespanha et al. (2003), the switched system must satisfy the matching and detectability properties.

Matching property: The multi-model should be designed such that each particular $\mathbf{y}_p$ provides a "good" approximation of the output $\mathbf{y}$. This means $\mathbf{e}_p$ is small whenever the process is inside the corresponding M.

Detectability property: For every fixed model, the switched system must be detectable with respect to the estimation error, $\mathbf{e}_p$, when the switching signal is frozen at σ. The detectability of the system guarantees that if the output of the system is small, then the state must be eventually small, no matter its initial state.

8.2.4. Example: switching control from DP to PM

This example of supervisory-switched control (SSC) is from Nguyen et al. (2008). In the example we consider moderate sea and low speed such that VOC = ⟨Mode = DP and PM, Speed, Environment = Moderate⟩, see Fig. 5.

We will here show station keeping operations of the shuttle tanker with switching from DP to thruster assisted position mooring (PM), that is switching between mode 3, 4 and 5 in Fig. (7). The shuttle tanker transits from port to/from offshore field using the autopilot controller (controller 1). The DP controller is controller 3. The smooth transformation from autopilot to/from DP is the controller 2. The single point mooring (SPM) or submerged turret loading (STL) mode to connect to the loading buoy or tower is the controller 5. The smooth transition between DP and SPM/STL is the controller 4. In the example shown here we will look into the station keeping operation only, that is modes 3–5. By collecting the states of the WF model in (13) and the LF model in (16), the state vector of the observer is reformulated:

$$\mathbf{x}_p = [\hat{\mathbf{p}}_w^\top, \hat{\boldsymbol{\eta}}^\top, \hat{\mathbf{b}}^\top, \hat{\boldsymbol{\nu}}^\top]^\top, \qquad \mathbf{x}_p \in \mathbb{R}^{15}, \tag{44}$$

then the model can be written compactly as,

$$\begin{aligned} \dot{\mathbf{x}}_p &= \mathbf{T}_p^\top(\psi)\mathbf{A}_p\mathbf{T}_p(\psi)\mathbf{x}_p + \mathbf{B}_p\boldsymbol{\tau}_c + \mathbf{K}_p(\mathbf{y} - \mathbf{y}_p), \\ \mathbf{y}_p &= \mathbf{C}_p\mathbf{x}_p. \end{aligned} \tag{45}$$

where $\mathbf{K}_p = [\mathbf{K}_1^\top, \mathbf{K}_2^\top, K_3^\top, \mathbf{K}_4^\top]^\top; \mathbf{K}_1 \in \mathbb{R}^{6\times3}$ is the observer gain matrix for the WF motion observer; $\mathbf{T}_p(\psi) = \mathrm{diag}(\mathbf{R}^\top(\psi), \ldots, \mathbf{R}^\top(\psi), \mathbf{I}_{3\times3}) \in \mathbb{R}^{15\times15}$ is the transformation matrix. $\mathbf{B}_p \in \mathbb{R}^{15\times3}$, $\mathbf{C}_p \in \mathbb{R}^{3\times15}$, and the system matrix $\mathbf{A}_p(\omega_{0p}) \in \mathbb{R}^{15\times15}$

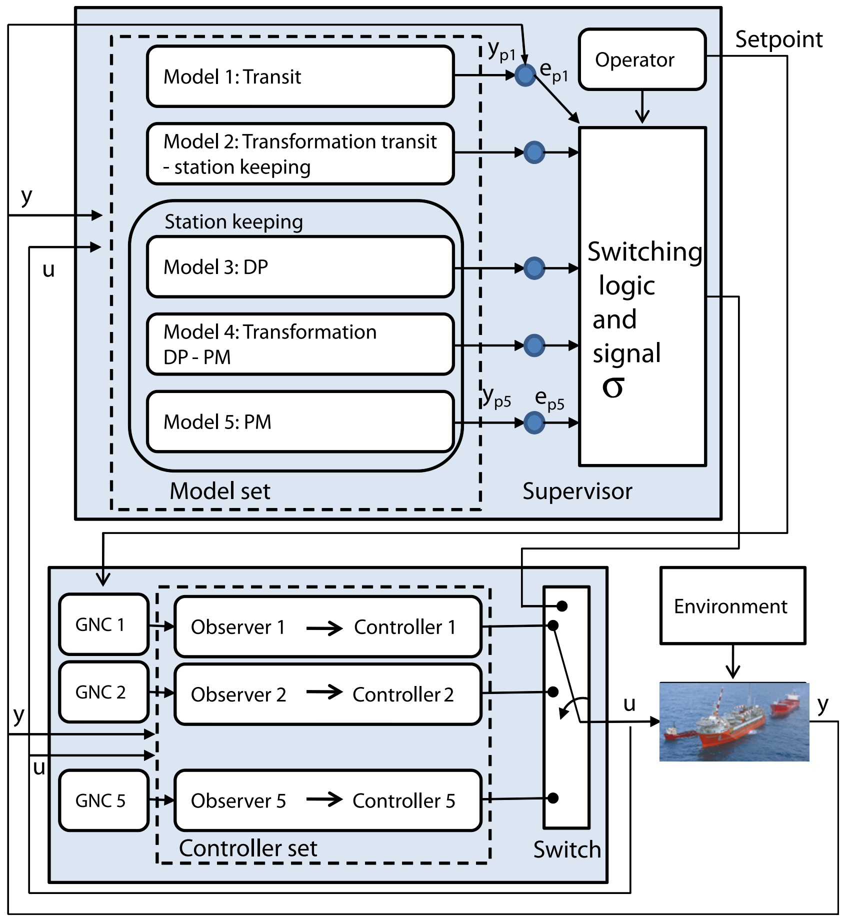

Fig. 7. Supervisory-switched control.

$$\mathbf{A}_p(\omega_{0p}) = \begin{bmatrix} \mathbf{A}_{\mathrm{pw}}(\omega_{0p}) & \mathbf{0}_{6\times 9} \\ \mathbf{0}_{9\times 6} & \mathbf{A}_{\mathrm{LF}} \end{bmatrix}, \tag{46}$$

are derived from (13) and the LF model in (16).

DP observer (mode 3): In DP the low-frequency system matrix $\mathbf{A}_{\mathrm{LF}} \in \mathbb{R}^{9\times 6}$ becomes

$$\mathbf{A}_{\mathrm{LF}} = \begin{bmatrix} \mathbf{0}_{3\times 3} & \mathbf{0}_{3\times 3} & \mathbf{I}_{3\times 3} \\ \mathbf{0}_{3\times 3} & -\mathbf{T}_{\mathrm{b}}^{-1} & \mathbf{0}_{3\times 3} \\ \mathbf{0}_{3\times 3} & \mathbf{M}^{-1} & -\mathbf{M}^{-1}\mathbf{D}_L \end{bmatrix}. \tag{47}$$

DP controller (mode 3): The nonlinear output-feedback PID controller is given by

$$\boldsymbol{\tau}_{\mathrm{cDP}} = \boldsymbol{\tau}_{wFF} + \boldsymbol{\tau}_{PID} + \boldsymbol{\tau}_{rpd}. \tag{48}$$

One should notice that roll-pitch damping (relevant for semi-submersibles) and wind feedforward control will be enabled/disabled by the operator. Hence, also these control terms needs to be phased in and out properly.

PM observer (mode 5): In PM the effect of the mooring must be included such that the system matrix becomes

$$\mathbf{A}_{\mathrm{LF}} = \begin{bmatrix} \mathbf{0}_{3\times 3} & \mathbf{0}_{3\times 3} & \mathbf{I}_{3\times 3} \\ \mathbf{0}_{3\times 3} & -\mathbf{T}_{\mathrm{b}}^{-1} & \mathbf{0}_{3\times 3} \\ -\mathbf{M}^{-1}\mathbf{G}_{\mathrm{mo}} & \mathbf{M}^{-1} & -\mathbf{M}^{-1}\mathbf{D} \end{bmatrix}. \tag{49}$$

PM controller (mode 5): The control objectives are (1) to keep the vessel in a desired heading angle, and (2) to add damping in surge and/or sway, when the resonant oscillatory motions happen due to environmental excitations. In Nguyen and Sørensen (2009b) the various PM control modes are given. Here, for simplicity we assume full station keeping control using PID.

$$\boldsymbol{\tau}_{\mathrm{cPM}} = \boldsymbol{\tau}_{PID} + \boldsymbol{\tau}_{rpd}. \tag{50}$$

Transition from DP to PM (mode 4): The switching from DP to PM can be done by proper weighting function α_c as follows

$$\boldsymbol{\tau}_{\mathrm{cPM2DP}} = \alpha_c(t-t_0)\boldsymbol{\tau}_{\mathrm{cDP}} + (1-\alpha_c(t-t_0))\boldsymbol{\tau}_{\mathrm{cPM}}, \tag{51}$$

where t is the time variable and t_0 is the instant time when the switching begins.

Design of supervisory switching control: The set of models and the set of controllers for the modes correspond to M in (38) and in (39), respectively. As shown in Fig. (7), the error vector, $\mathbf{e}_p$, can be formed from the estimation vector, $\mathbf{y}_p$, and process output, $\mathbf{y}$. From this error vector, the scale-independent hysteresis switching logic will decide the existing VOC so as to switch to the appropriate model and thereby the appropriate controller. Details of design and stability analysis for this supervisory switching control can be found in Nguyen et al. (2007).

Experimental results: The experiments for the switching from DP to single point mooring (here denoted as SPM) and vice versa are presented. The experiments were carried out using the model vessel, Cybership III (Fig. 8), which is a 1:90 scaled model of a shuttle tanker having a mass of m = 75 kg, length of L = 2.27 m and breadth of B = 0.4 m (in full scale: m = 54,675 ton, L = 204.3 m, B = 36 m). The vessel is equipped with two main azimuthing podded propellers, one tunnel thruster and one front azimuth thruster. The internal hardware architecture is controlled by an onboard computer

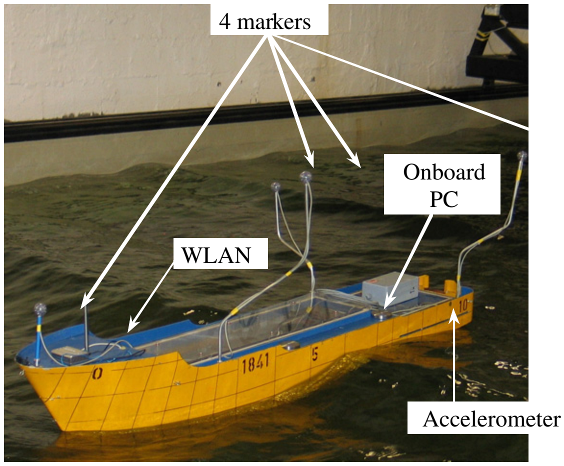

Fig. 8. Cybership III.

which can communicate with onshore PC through a WLAN. An onshore 4-camera measurement system provides Earth-fixed position and heading. The experiment was performed in the Marine Cybernetics Laboratory (MCLab) at NTNU. A wave maker system was used to simulate the different sea conditions.

The PM system is modeled by a mooring line. One end of the mooring line is connected to a fixed bridge; the other end to the bow of the Cybership III. This mooring line acts as a linear spring due to the linear behavior of the hawser and buoy. There are six tests carried out for three mooring line configurations: low, medium and high stiff mooring lines, under moderate and high seas. The stiffness of the low, medium and high stiff mooring lines are $K_{moor} = 40.5,\ 56.7$, and 81 kN/m, respectively. The vessel is subjected to JONSWAP irregular head seas. Since the switching is from DP to SPM, controllers 3, 4, and 5 will be used in the SSC.

Here, we only show the experimental result for Test 6 with high mooring stiffness and sea state: significant wave height $H_s = 3.96$ m and wave peak period $T_p = 10.4$ s. The other experiments showed similar results. Fig. 9 shows the position and heading of the vessel and the integral controller term from the control system during the switching procedure. Fig. 10 shows the switching signal. The sequence of the switching from DP to SPM and vice versa is as follows.

Stage 1. Controller 3: DP. The vessel is kept in fixed position and heading by the DP system.
Stage 2. Controller 4a: the smooth transformation in (51) is used.
Stage 3. Controller 5a: SPM with heading control. The vessel is connected to the SPM system.
Stage 4. Controller 5b: SPM with heading control and surge damping.
Stage 5. Controller 4b: the smooth switching from the SPM with heading control and surge damping to DP. The reference model provides the path from the existing position and heading of the vessel in SPM to the desired position and heading of the vessel in DP. The I controller is reset for the purpose of anti-windup, Nguyen and Sørensen (2009b). The smooth transformation (51) is used same as in Stage 2 but the reset of I controller has to be taken into account.

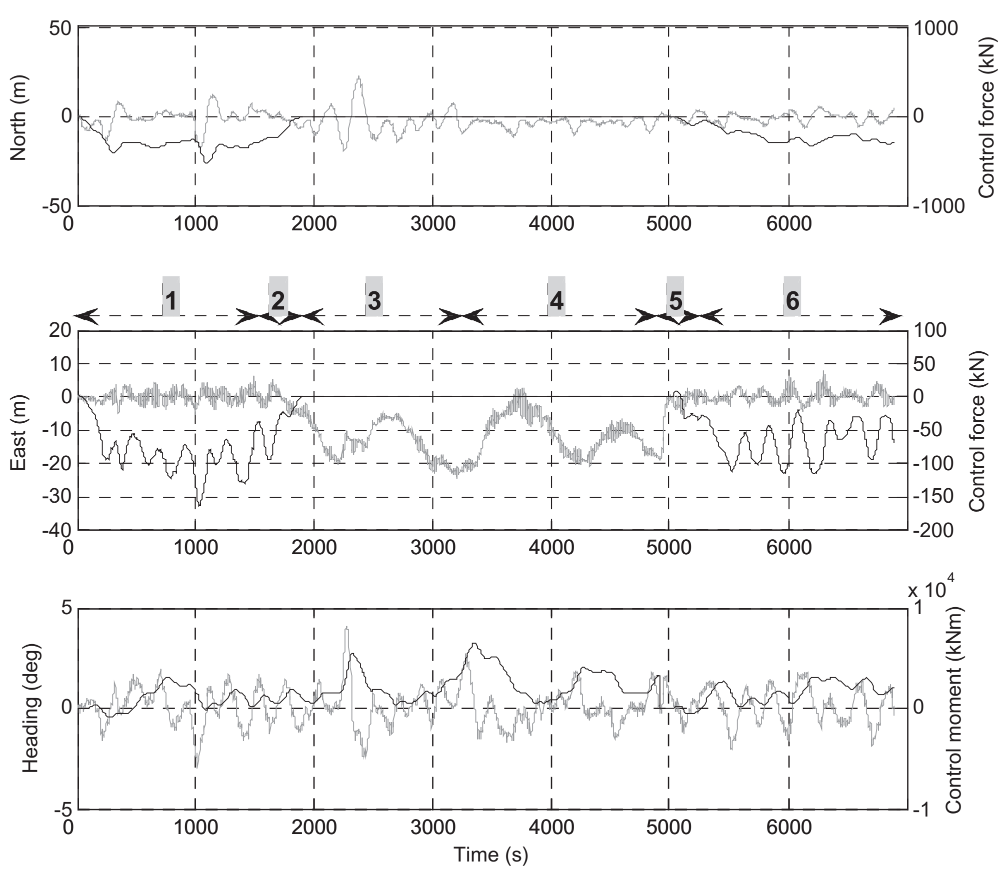

Fig. 9. Test 6: performance of switching from DP to SPM mode and vice versa of the shuttle tanker: measured position and heading (gray) and the integral term of the controller forces and moment (solid).

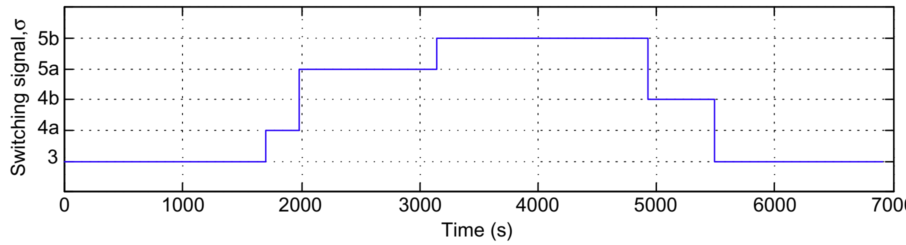

Fig. 10. Test 6: switching signal.

Stage 6. Controller 3: DP. The vessel returns to DP mode, same as Stage 1.

The six stages are shown with the numbers in Fig. 9. The experiments with the switching from PM to DP mode and vice versa in different sea conditions and different mooring system showed good performance. When the vessel was kept in a fixed heading, there existed oscillations in surge due to resonance (Stage 2). These oscillations were as expected reduced considerably by adding surge damping (Stage 3).

9. Hardware-in-the-loop testing of DP systems

As the DP vessels become more demanding and complex, safety, reliability and integration aspects with the navigation system, power plant, vessel automation, propulsion system and other consumers become more important. In order to reduce these risks, regulatory bodies, class societies and independent consultants have been continuously addressing advances in rules and regulations and testing and verification methodologies. In this context the safety and verification regime for DP systems may be seen as an example to be followed for other mission critical control systems as well.

The successful operation of DP vessels depends more and more on advanced integrated functionality of software-based control systems. Consequently, software related problems, often in conjunction with hardware and/or human errors, may lead to vessel construction delays, downtime during operation, reduced income for clients, increased cost, and reduced safety. In order to reduce these risks, independent third party hardware-in-the-loop (HIL) simulator testing has recently been applied for extensive software testing and verification of DP systems on several offshore vessels. In the work of Johansen et al. (2005, 2007), Johansen and Sørensen (2009) and Smogeli (2010) the concept of HIL testing is described, and the experiences and findings statistics are reported from HIL testing of DP computer systems, power management systems and steering, propulsion and thruster control systems on drilling vessels, offshore service and construction vessels, and shuttle tankers. The main idea is testing and verification of the computer software using a vessel specific simulator (Fig. 11) capable of simulating the dynamic response of the vessel, thruster and propulsion system, sensors, position reference systems, power generation, distribution, main consumers, and other relevant equipment (Sørensen, Pedersen, & Smogeli, 2003). The simulator is connected via network or bus interfaces to the targeted control system such that all relevant feedback and command signals are simulated. In order to achieve the test objective, the simulator is capable of simulating a wide range of realistic scenarios defined by operational modes, operational tasks and single, common mode and multiple failure modes in order to verify correct functionality and performance during normal, abnormal and faulty conditions.

HIL testing may be conducted in several phases during the construction. The first phase is usually an extensive software test

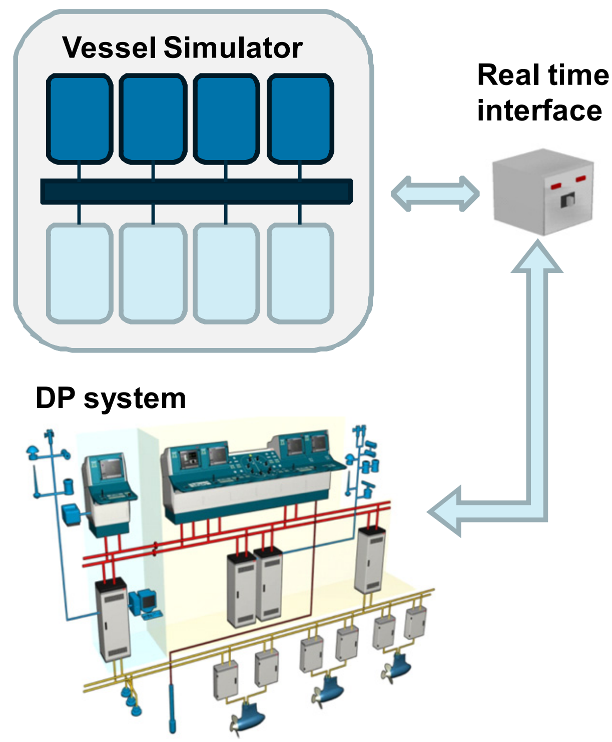

Fig. 11. HIL testing of DP computer system.

conducted at factory or using a lab facility before the control system software is installed on the vessel. By using HIL simulator technology a virtual sea trial with thorough testing is done before the vessel is built. The second phase is during commissioning at the yard or on replica hardware at the vendor. Finally, sea trials may be conducted to test the integration, and to verify the performance of the vessel.

10. Conclusions

The paper presented an overview of some of the main research results in the development of DP controllers during the last 30 years. It was shown how the first innovations were emerging from PID controllers to output feedback control, nonlinear control and hybrid control improving performance and operability of the DP vessels to a variety of operational missions and environmental conditions. As a part of this the DP system relied even more on other vessel systems like the thruster and propulsion system, the power generation and distribution system and the vessel automation system. Being able to operate in even more demanding areas with increased focus on availability and fuel consumption the physical and functional integration between systems and operational requirements will continue. As a consequence the control software will increase in complexity challenging both safety and reliability. Hence, proper testing and verification of functions and failure handling will be critical securing the integrity of the DP vessels.

Acknowledgments

This work has been carried out at the Centre for Ships and Ocean Structures (CeSOS) at NTNU. The Norwegian Research Council is acknowledged as the main sponsor of CeSOS.

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