Multi-Operational Controller Structure for Station Keeping and Transit Operations of Marine Vessels

Trong Dong Nguyen, Asgeir J. Sørensen, *Member, IEEE*, and Ser Tong Quek

***Abstract*—In this brief, a novel control system structure for integrated dynamic positioning, maneuvering, and transit operation of marine vessels is proposed. The proposed structure is based on supervisory switching control (SSC) using switching logics in conjunction with operator initiated commands. The SSC is a hybrid system consisting of continuous state multi-controllers and discrete state logics that allow switching among the various controllers for the particular operations. The switching between appropriately designed controllers facilitates operations from normal conditions to extreme situations such as severe seas and possible failure situations. Through this, it will be possible to extend the vessel operability under harsh environments, and increase the safety and performance in marine operations with greater fault-tolerance. One demonstrating example of the integrated marine control system verified by experiments is demonstrated.**

***Index Terms*—Extreme conditions, hybrid system, station keeping, supervisory switching control (SSC), transit.**

I. Introduction

MARINE business covers three main clusters including shipping, offshore exploration and exploitation of hydrocarbons, and aquaculture and fisheries. Marine vessels are the major element within these clusters. Nowadays, the marine vessels are required to operate in wider range of environmental conditions and different speed regimes with acceptable performance and safety. All-year marine operations are important for oil companies and contractors to conduct safe and cost effective explorations and exploitations of hydrocarbons. In particular, when conducting marine operations in deep water, the operations are more time consuming, and hence more sensitive to changes in the sea states. Therefore, marine control systems must be designed such that the marine vessel can operate under many different operational and environmental conditions with adequate reliability and economy.

This motivates nonlinear controller design since the dynamics of the process, the constraints and the control objectives vary subject to the different operational conditions. There are two major solutions for this nonlinear control strategy: either the design of a unique nonlinear controller or the integration of several simpler controllers. The single nonlinear controller may be complicated or even impossible to design for the applications in which the dynamics of the process changes significantly. In addition, it is difficult to satisfy the different control objectives within only one single controller.

In the second solution, several controllers are integrated into a system, and the switching is performed among the controllers by some automatic mechanisms. The design of controllers is based on the well-formulated linear and/or nonlinear models which are simplified from the process dynamics dependent on operational regimes. In addition, it is easier to satisfy the different control objectives with a multi-operational controller structure. Although the drawback could be a bundle of controllers with chattering problem, this control strategy has been already implemented widely in many industrial applications using ad hoc solutions. In the literature, similar approaches have been used, e.g., gain scheduling in flight control [25], in land-based vehicle control [11], and hybrid power/torque thruster control [17].

The switching between the various controllers may lead to instability. This can be prevented by the supervisory switching control (SSC) proposed by [8] and [9]. This control strategy makes it possible to switch either between linear or nonlinear controllers according to the prevailing operational conditions. The switching is done by a certain discrete logic to guarantee the stability of the whole system, therefore associated with the *switched system*. Readers can find examples of switching logics: scale-independent hysteresis switching logic (SIHSL) and hierarchical hysteresis switching logic (HHSL) in [10]. The SSC also associates with the hybrid system since it consists of continuous state multi-controllers and discrete state logics that allow switching among the various controllers. The SSC is more advantageous than adaptive control [2] in terms of rapid adaptation, flexibility and modularity, and decoupling between the supervision and control. One of the applications of SSC was illustrated by [4] on multi-model proportional–integral–differential (PID) controller for a nonlinear pH neutralization process.

Reference [7] proposed an SSC system for disassembling and reassembling with fault-tolerance consideration of the mobile offshore bases (MOB). Reference [13] proposed a SSC system to handle dynamic positioning (DP) operation in calm to extreme environmental conditions. In this brief, the SSC concept of [13] is extended to include the different speed assignments and the various control modes as well. Instead of having several separated controllers with inconvenient manual transfer and switching, the controllers can be integrated into one control system.

Thus, the objective of this brief is to introduce a novel concept for marine control system design to develop an *integrated*

Manuscript received June 2, 2006; revised November 24, 2006. Manuscript received in final form May 23, 2007. Recommended by Associate Editor R. Rajamani. This work was supported by the Centre for Offshore Research & Engineering at NUS in cooperation with the Centre for Ships and Ocean Structures (CeSOS) at Norwegian University of Science and Technology (NTNU). The work of T. D. Nguyen was supported by the Keppel Corporation.

T. D. Nguyen is with the Center for Ships and Ocean Structures (CeSOS), Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway (e-mail: trong.d.nguyen@ntnu.no).

A. J. Sørensen is with the Department of Marine Technology, Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway (e-mail: asgeir.sorensen@ntnu.no).

S. T. Quek is with the Department of Civil Engineering, National University of Singapore, Singapore 117576 (e-mail: cveqst@nus.edu.sg).

Color versions of one or more of the figures in this brief are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TCST.2007.906309

system (a so-called "*super system*") for integrated DP, maneuvering and transit operations subjected to changes of the environmental conditions. It will also establish the framework to support the integration of other controllers into the marine control system.

In this brief, the following definitions are used for the sake of clarification. hybrid system is a dynamic system containing continuous and discrete states; SSC system is a hybrid control system consisting of continuous state multi-controllers and discrete state logics that allow switching among the various controllers for the particular operational condition; and the term integrated marine control system (in short, integrated system) is the application of SSC system for the marine control system. This brief is organized as follows. The multi-operational conditions (see Section III) and multi-levels (see Section IV) of the marine control systems are presented so that they can be combined into the integrated system. Results on SSC are addressed in Section V. The SSC for marine operation from station keeping and transit operations is presented to demonstrate the integrated system in Section VI.

II. Modelling of Marine Vessels

The dynamics of marine vessels may be formulated in two complexity levels [20], [21], namely a process plant model and a control plant model. The *process plant model* is for numerical analysis of the stability and performance of the closed-loop system by simulating as close as possible the real plant dynamics including process disturbance, sensor outputs and control inputs. The *control plant model*, which is simplified from the process plant model, is used for controller design and analytical stability analysis (e.g., in the sense of Lyapunov). In this section, the process plant model including the kinematics and dynamics is discussed.

A. Kinematics

In station keeping and transit operations, the motions, and state variables of the control system are defined and measured with respect to some reference frames or coordinate systems as shown in Fig. 1 [20], [21].

- *The North-East-down (NED) reference frame* is Earth-fixed and given in local geographical coordinates. It is denoted as the $\mathrm{X_E Y_E Z_E}$-frame, in which the vessel's position and orientation coordinates are measured relative to a defined origin.
- *The body frame* XYZ is fixed to the vessel and thus moving along with it. For convenience, the body frame is often chosen at the vessel's center of gravity.
- *The hydrodynamic frame* $\mathrm{X_h Y_h Z_h}$*-frame* is generally moving along the path of the vessel which is assumed to oscillate with small amplitudes about this frame such that linear theory may apply when modelling the perturbations. In station keeping operations about the coordinates x_d, y_d, and ψ_d, the hydrodynamic frame is Earth-fixed and denoted as the *reference-parallel frame* $\mathrm{X_R Y_R Z_R}$.

Let the Earth-fixed position and orientation of a vessel be $\boldsymbol{\eta} \in \mathbb{R}^6$ and its body-fixed translation and rotation be $\boldsymbol{\upsilon} = [u,v,w,p,q,r]^{\mathrm{T}} \in \mathbb{R}^6$, where u, v, w, p, q, and r denote velocities in surge, sway, heave, roll, pitch and yaw, respectively. The Earth-fixed velocity vector is given through the transformation matrix $\mathbf{J}(\boldsymbol{\eta}) \in \mathbb{R}^{6\times 6}$, according to

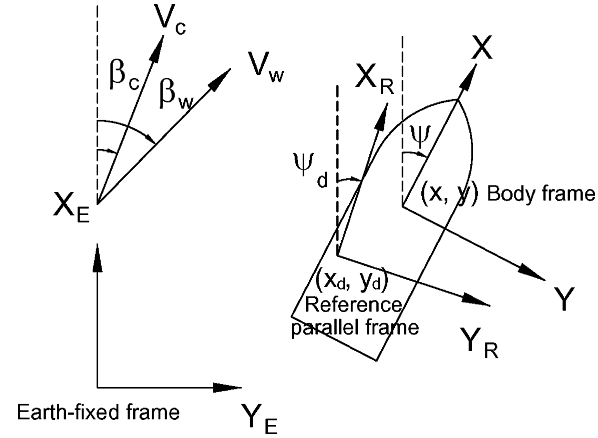

Fig. 1. Earth-fixed, reference-parallel and body-fixed frame.

$$\dot{\boldsymbol{\eta}} = \mathbf{J}(\boldsymbol{\eta})\boldsymbol{\upsilon}. \tag{1}$$

If only surge, sway, and yaw [3-degrees-of-freedom (DOF)] are considered, the kinematics and the state vectors are reduced to $\dot{\boldsymbol{\eta}}_{3\mathrm{DOF}} = \mathbf{R}(\psi)\boldsymbol{\upsilon}_{3\mathrm{DOF}}$. Details of $\mathbf{J}(\boldsymbol{\eta}) \in \mathbb{R}^{6\times 6}$ and $\mathbf{R}(\psi) \in \mathbb{R}^{3\times 3}$ are presented in [5].

B. Dynamics

In modelling of floating structure dynamics, the motion is assumed to be a superposition of the low-frequency (LF) and wave-frequency (WF) models [3], [5], [18]. The WF model is primarily for motions due to the first-order wave loads, whereas the LF model accounts predominantly for motions due to the second-order mean and slowly varying wave loads, currents and wind loads.

1) Low-Frequency Model: This 6-DOF LF model formulation is based on [20]. The equations of motion for the nonlinear LF model of a floating vessel is given by

$$\mathbf{M}\dot{\boldsymbol{\upsilon}} + \mathbf{C}_{RB}(\boldsymbol{\upsilon})\boldsymbol{\upsilon} + \mathbf{C}_A(\boldsymbol{\upsilon}_r)\boldsymbol{\upsilon}_r + \mathbf{D}(\boldsymbol{\upsilon}_r) + \mathbf{G}(\boldsymbol{\eta}) = \boldsymbol{\tau}_{\mathrm{wave2}} + \boldsymbol{\tau}_{\mathrm{wind}} + \boldsymbol{\tau} \tag{2}$$

where $\mathbf{M} \in \mathbb{R}^{6\times 6}$ is the system inertia matrix including added mass; $\mathbf{C}_{RB}(\boldsymbol{\upsilon}) \in \mathbb{R}^{6\times 6}$ and $\mathbf{C}_A(\boldsymbol{\upsilon}_r) \in \mathbb{R}^{6\times 6}$ 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 mooring lines (if any), buoyancy and gravitation; $\boldsymbol{\tau} \in \mathbb{R}^6$ is the 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 $\mathbf{D}(\boldsymbol{\upsilon}_r) \in \mathbb{R}^6$ is the damping vector which is a function of the relative velocity vector ($\boldsymbol{\upsilon}_r$).

2) Linear Wave-Frequency Model: The coupled equations of WF motions in surge, sway, heave, roll, pitch and yaw are

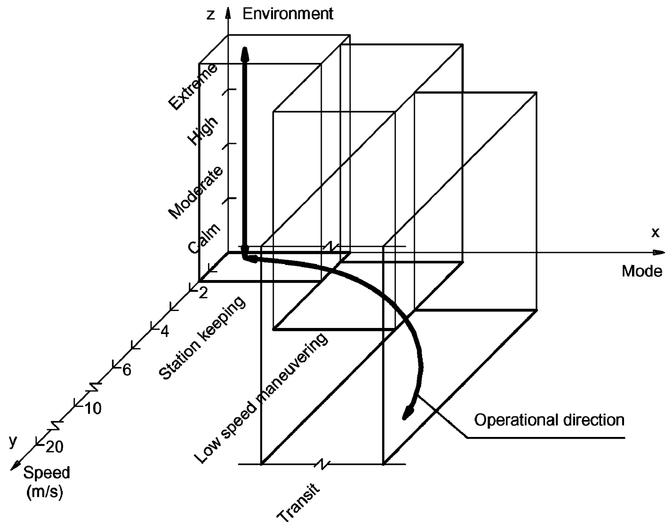

Fig. 2. Vessel operational condition is defined in three dimensions: use mode, speed, and environment.

assumed to be linear, and can in the body-fixed frame be formulated as

$$\mathbf{M}(\omega)\ddot{\boldsymbol{\eta}}_{Rw} + \mathbf{D}_p(\omega)\dot{\boldsymbol{\eta}}_{Rw} + \mathbf{G}\boldsymbol{\eta}_{Rw} = \boldsymbol{\tau}_{\text{wave1}} \quad (3)$$

$$\dot{\boldsymbol{\eta}}_w = \mathbf{J}(\overline{\boldsymbol{\eta}}_2)\dot{\boldsymbol{\eta}}_{Rw} \quad (4)$$

where $\boldsymbol{\eta}_{Rw} \in \mathbb{R}^6$ is the WF motion vector in the hydrodynamics frame; $\boldsymbol{\eta}_w \in \mathbb{R}^6$ is the WF motion vector in the Earth-fixed frame; $\boldsymbol{\tau}_{\text{wave1}} \in \mathbb{R}^6$ is the first order wave excitation vector, which will be modified for varying vessel headings relative to the incident wave direction; $\mathbf{M}(\omega) \in \mathbb{R}^{6\times 6}$ is the system inertia matrix including frequency dependent added mass; $\mathbf{D}_p(\omega) \in \mathbb{R}^{6\times 6}$ is the wave radiation (potential) damping matrix. The linearized restoring coefficient matrix $\mathbf{G} \in \mathbb{R}^{6\times 6}$ is due to gravity and buoyancy affecting heave, roll and pitch only. The readers may find the details of vessel modelling in [20].

III. Multi-Vessel Operational Conditions

As shown in Section II, the model of marine vessel is a highly nonlinear system. This can be simplified to different control plant models dependent on control objectives, constraints and dynamic response of the controlled system. Based on this, the vessel operational condition (VOC) is defined as a space consisting of the following three main dimensions (see Fig. 2), 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).

A. Changes in Operation Mode

Marine vessels operate in variety of modes, such as station keeping including DP and thruster assisted position mooring (PM), low speed maneuvering, and moderate to high speed transit operations. Several operation modes of typical vessels are shown in Table I. Changes in the modes result in changes in the control objective. For example, PM mode may require heading control, damping control, or line tension control [1], [23], while DP mode requires station keeping or setpoint chasing exclusively by the thruster system [3], [18]. The objectives of the low speed maneuvering mode are: 1) to force the vessel to follow a path, while 2) satisfying time, speed, or acceleration assignment (dynamic task) along the path [16]. Reference [6] proposed a controller that may satisfy the objectives for both station keeping and low speed maneuvering by using a unified mathematical model. A vessel in transit, on the other hand, may require heading control, heading plus cross-error control, and piece-wise rectilinear path following with active leg switching guidance [5], [14], [15]. A summary of the control objectives for the different operation modes is shown in Table II.

TABLE I
Typical Operational Profiles of a PSV, a Shuttle Tanker, an FPSO, and Drilling and Well-Intervention Vessel

	Station keeping/ Standby	Transit	Port	Low speed
PSV	30 – 50%	30 – 40%	5 – 10%	5 – 10%
FPSO	90 – 99%	1 – 5%	–	–
Shuttle tanker	20 – 40%	40 – 60%	5 – 15%	–
Drilling and well intervention	70 – 90%	5 – 20%	1 – 5%	–

TABLE II
Marine Operational Objectives of Sub-Modes

Station keeping
- PM/POSMOOR system: station keeping, change of setpoint, damping control, line break detection and compensation.
- DP system: single point mooring, station keeping, change of set point (marked position), optimal heading control, roll and pitch damping

Low speed maneuvering
- Follow target, e.g. remotely operated underwater vehicle (ROV)
- Low speed way point tracking

Transit (autopilot)
- Course keeping
- Course change
- High speed way point tracking (guidance and navigation control)
- Path following
- Line of sight

B. 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, e.g., low speed maneuvering and autopilot [5], [14]–[16].

C. Changes in Environment

Changes in the environment result in changes of the disturbance characteristics (frequency and intensity). However, these changes can also result in changes of the control objective. 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 (see [13] and the references therein). As the sea state increases, WF motion is induced by waves with lower dominant frequencies, especially swell in the North Sea and Barents Sea [24]. For this reason, the control objective is to compensate both WF and LF motions instead of only LF in moderate sea [19]. Reference [13] integrated a bank of controllers into a SSC system at plant control level for DP in order to extend the weather window from calm to extreme seas. The concept of SSC in [13] could also be extended and generalized for other modes and thereby the general marine control systems.

IV. Control Structure

Reference [21] addressed the different control levels of marine control systems. For the real-time control, the local optimization control provides the plant control system setpoints to follow. The plant controller calculates the necessary commanded forces and moment which are sent to the actuator control block.

A. Actuator Controller (Low Level)

The actuators of marine systems are normally thrusters, propellers, rudders, interceptors, fins, flaps, T-foils, and mooring systems. Other actuators include pumps, separators, compressors, drilling drives, cranes, and winches. These actuators often are associated with a local control system which ensures the correct implementation of the control action. Dependent on whether the actuators are mechanically, hydraulically, and/or electrically driven, controllers with different properties will be used.

B. Plant Controller (High Level)

At this level, the control systems focus on the ship operational objectives, and generate the desired control command. For example, in station keeping operations, the DP system is supposed to counteract the disturbances such as wave (mean and slowly varying), wind, and currents loads acting on the vessel. The plant controller calculates the necessary surge and sway forces and yaw moment needed to compensate the disturbances. These force commands are the input of the thrust allocation system, which determines the command of each actuator so as to obtain the desired forces.

C. Local Optimization

Depending of the actual marine operation that the vessel is involved in (such as drilling, weather vaning, pipe laying, tracking operations, and transit), different optimization of desired setpoints in conjunction with the appropriate reference models are used. At this level, we also find the guidance block used in the so-called guidance, navigation, and control system (GNC) used in transit operations [5].

V. Results on Supervisory Switching Control

This section is based on [8]. The design of SSC system consists of the designs of controllers and switching logic to assure the stability and performance during and after switching. In some cases, the operator may initiate the switching command but the SSC still undertakes the switching process and the smooth transition between controllers.

A. Concept

There are two main blocks in the SSC system: the *supervisor* and the *controller sets*. The supervisor compares the behaviors of some admissible models (multi-estimators) and the actual process, and decides which model is best to describe the ongoing process.

The multi-estimator is a set of estimators to model the process in different operational regimes, according to

$$\begin{aligned}\mathcal{M} &:= \bigcup_{p\in\mathcal{P}} \mathcal{M}_p \\ &= \{\dot{\mathbf{x}}_p = \mathbf{A}_p(\mathbf{x}_p, \mathbf{u}, \mathbf{y}), \mathbf{y}_p = \mathbf{C}_p(\mathbf{x}_p, \mathbf{u}, \mathbf{y}), \\ &\quad \mathbf{e}_p = \mathbf{y}_p - \mathbf{y} : p \in \mathcal{P}\}. \end{aligned} \tag{5}$$

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

$$\mathcal{C} := \bigcup_{q\in\mathcal{Q}} \mathcal{C}_q = \{\dot{\mathbf{x}}_q = \mathbf{F}_q(\mathbf{x}_q, \mathbf{y}), \mathbf{u} = \mathbf{G}_q(\mathbf{x}_q, \mathbf{y}) : q \in \mathcal{Q}\} \tag{6}$$

where $\mathcal{P}$ and $\mathcal{Q}$ are the set of estimators and controllers, respectively; $\mathbf{x}_p$ is the state of model set; $\mathbf{y}_p$ is the estimation vector; $\mathbf{x}_q$ is the state of the controller; $\mathbf{y}$ is the output of the process plant; and $\mathbf{u}$ is the control force. When the switching is made, a *process switching signal* ρ determines the selected model, and a *switching signal* σ determines the controller in the loop at each instant of time. Selecting the controller with respect to the estimator is performed by the mapping $\sigma = \chi(\rho) \in \mathcal{Q}$, $\rho \in \mathcal{P}$. In this brief, a simple mapping is used, that is, $\sigma = \rho \in \mathcal{P}, \mathcal{P} \equiv \mathcal{Q}$.

In the formal stability analysis of the SSC system, it is convenient to have the following definition.

Definition 1 (Switched System—[8]): The switched system includes the process, controller set, and the estimator set,

$$\dot{\mathbf{x}} = \mathbf{A}_\sigma(\mathbf{x}, \mathbf{w}), \tag{7}$$

$$\mathbf{e}_p = \mathbf{C}_p(\mathbf{x}, \mathbf{w}), \quad p \in \mathcal{P} \tag{8}$$

where $\mathbf{x}$ denotes the state vector of the process, multi-controller, and multi-estimator; and $\mathbf{w}$ 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 $\mathbf{e}_p$.

B. Properties

According to [9], the two important properties of the switched systems are *matching* and *detectability*. Two properties, *small error* and *non-destabilization*, must be satisfied by the switching logic.

Matching Property: The multi-estimator must 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 $\mathcal{M}_p$.

Detectability Property: For every fixed estimator, the switched system must be detectable with respect to the estimator error $\mathbf{e}_\rho$ when the switching signal is frozen at $\sigma = \chi(\rho) \in \mathcal{Q}$. The detectability of a system guarantees that if the output of the system is small, then the state must eventually be small, no matter its initial state.

Small Error Property: The switching logic must guarantee the bound on $\mathbf{e}_\rho$ (the "smallest" sub-vector using any norm of the model error vector, $\mathbf{e}_p$) for a process switching signal ρ which satisfies $\sigma = \chi(\rho)$, or simply $\sigma = \rho$.

Non-Destabilization Property: Preserves the detectability property of the switched system when the switching is performed among a bank of controllers.

The matching property and the detectability property are important for the multi-estimator and multi-controller, respectively. The small error property makes sure that the selected controller is the "best." In the case of the switching, the switching logic, e.g., dwell-time switching, SIHSL, HHSL, etc., in [8]–[10] will ensure the non-destabilization property, and hence will prevent chattering.

C. *Anti-Windup for Inactive Controllers*

The switching between controllers may lead to windup of the inactive controllers during or after transition unless proper precautions are taken. For instance, in the PID controller used in DP applications, the I term is used to compensate the mean drift loads. The I term of the inactive controllers may exceed the physical limitation of the control system because the inactive controllers are not designed to compensate the existing mean environmental drift loads. The solution to prevent windup for the inactive controllers depends on the type of switching. In particular, the switching between autopilot (high speed) and station keeping (low speed) may require the integrator re-set and fast integration during the start-up since the direction and magnitude of the environmental loads in those VOCs are significantly different. The switching between the controllers in the SSC system for DP [13] requires some synchronization with integrator anti-windup. This is an important topic that is not further treated here. In the next section, a SSC system is developed for changes of modes from transit to station keeping operations of a shuttle tanker, in which the operator initiates the command.

VI. Case Study—SSC for Shuttle Tanker Operations From Transit to Station Keeping

This section shows the case study of the design of integrated system for marine operations at a fixed environmental condition, varying speeds and modes. Thus, VOC $= \langle \text{Mode}, \text{Speed}, \text{Environment} = \text{Moderate}\rangle$ (see Section III and Fig. 2). Readers can find the design of the integrated system for a fixed mode (DP) and speed regime (zero speed) and varying environmental conditions in [13].

The typical operations of a shuttle tanker involve transit, low speed maneuvering and station keeping modes as shown in Table I. In order to have operations crossing these modes and speed regimes, the integration of controllers need to be implemented at each level of control structure (see Section IV). Readers can find the integration of the controllers at actuator control level for several VOCs in [17]. This section will focus on the integration of the controllers at plant control and GNC levels for transit and station keeping. The proposed integrated system using SSC is shown in Fig. 3. 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.

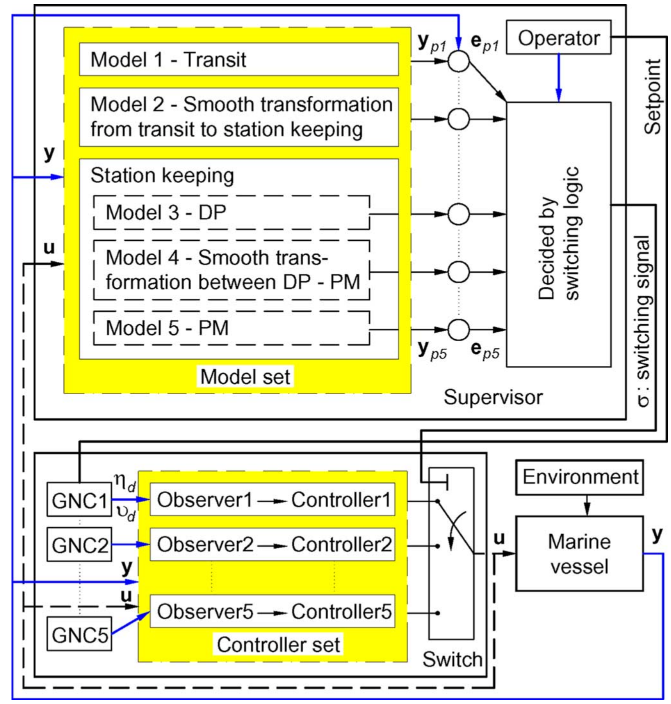

Fig. 3. Concept of SSC for marine operations from transit to station keeping.

The purpose of this section is to show the feasibility of the SSC system. The set of the controllers may be different from above. For example, the low speed maneuvering control [16] can be inserted between the DP and the autopilot. Furthermore, the DP and low speed maneuvering controllers can be replaced by the unified controller proposed in [6].

A. *Autopilot in Transit Regime*

The objective of the autopilot is to keep the heading and yaw rate of the vessel in fixed or new setpoints commanded by the guidance, navigation and control (GNC) system.

1) Observer Design: If the WF model in (3) is simplified by assuming it to be a second-order linear model driven by white noise, w_w, and only yaw are considered, then the control plant models for (3) and (2) are

$$\begin{bmatrix} \dot{\xi}_w \\ \dot{\psi}_w \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\omega_p^2 & -2\lambda\omega_p \end{bmatrix} \begin{bmatrix} \xi_w \\ \psi_w \end{bmatrix} + \begin{bmatrix} 0 \\ K_w \end{bmatrix} w_w \tag{9}$$

$$\begin{bmatrix} \dot{\psi} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 0 & -1/T \end{bmatrix} \begin{bmatrix} \psi \\ r \end{bmatrix} + \begin{bmatrix} 0 \\ -K/T \end{bmatrix} b + \begin{bmatrix} 0 \\ K/T \end{bmatrix} \tau_{q1} \tag{10}$$

where ξ_w and ψ_w are the states of WF model for yaw; ψ_w is WF yaw; ω_p and λ are the dominating frequency and damping ratio of the WF model [5], respectively; ψ is LF yaw; T and K are known as the Nomoto [14] time and gain constants, respectively; r is yaw rate; τ_{q1} is rudder angle; and b is bias term for slowly-varying environmental disturbances which are modelled as a 1st-order Markov process driven by white noise, w_b, according to

$$\dot{b} = -(1/T_b)b + w_b \tag{11}$$

where T_b is time constant for the bias model. By collecting the state $\mathbf{z}_1 = [\xi_w \ \psi_w \ \psi \ r \ b]^T \in \mathbb{R}^5$, the control plant model is given by

$$\dot{\mathbf{z}}_1 = \mathbf{A}_{p1}\mathbf{z}_1 + \mathbf{B}_{q1}\tau_{q1} + \mathbf{E}_1\mathbf{w}_1 \tag{12}$$
$$y_1 = \mathbf{C}_{p1}\mathbf{z}_1 \tag{13}$$

where $\mathbf{C}_{p1} = [0\ 1\ 1\ 0\ 0]$. Details of this control plant model can be found in [5].

By copying the control plant model (12), the passive observer can be adopted to develop the observer for the heading angle [5], according to

$$\dot{\mathbf{z}}_{p1} = \mathbf{A}_{p1}\mathbf{z}_1 + \mathbf{B}_{q1}\tau_{q1} + \mathbf{K}_{p1}(y_1 - y_{p1}) \tag{14}$$
$$\mathbf{y}_{p1} = \mathbf{C}_{p1}\mathbf{z}_{p1}. \tag{15}$$

The state vector for observer $\mathbf{z}_{p1} \in \mathbb{R}^5$ is written as

$$\mathbf{z}_{p1} = [\hat{\xi}_w \quad \hat{\psi}_w \quad \hat{\psi} \quad \hat{r} \quad \hat{b}]^T \tag{16}$$

where $\hat{\xi}_w$, $\hat{\psi}_w$, $\hat{\psi}$, $\hat{r}$, and $\hat{b}$ are the estimated states.

The observer gain $\mathbf{K}_{p1} \in \mathbb{R}^{5\times 1}$ can be calculated by passivity requirements according to [5].

2) Controller Design: A PID controller for heading control is used

$$\dot{\xi}_{q1} = \tilde{\psi} \tag{17}$$
$$\tau_{q1} = \tau_{FF1} - K_{p1}\tilde{\psi} - K_{d1}\tilde{r} - K_{i1}\xi_{q1} \tag{18}$$

where τ_{FF1} is the feedforward term; K_{p1}, K_{i1}, and K_{d1} are the nonnegative PID controller gains, respectively; and $\tilde{\psi}$ and $\tilde{r}$ are the output feedback error dynamics of the heading angle and yaw rate, respectively, given by

$$\tilde{\psi} = \hat{\psi} - \psi_d, \quad \tilde{r} = \hat{r} - r_d \tag{19}$$

where ψ_d and r_d are the desired heading angle and yaw rate, respectively, provided by GNC system (see [5] and [20]).

It is noted that more sophisticated observer and controller designs may be used, but for the purpose of illustration we have used conventional well-known designs.

B. Station Keeping—Dynamic Positioning

1) Observer Design: The observer design of DP is similarly to that of autopilot except that 3 DOFs (surge sway and yaw) are considered. In particular, the WF model in (3) is simplified by assuming it to be a second-order linear model driven by white noise. The slowly-varying environmental disturbances are modeled as a bias term through a 1st-order Markov process driven by white noise. It is noted that $\mathbf{C}_{RB}(\boldsymbol{\upsilon})$, $\mathbf{C}_A(\boldsymbol{\upsilon}_r)$, and nonlinear damping are negligible in (2) since the vessel's velocity is small in station keeping. Based on these assumptions, the passive nonlinear observer proposed by [5] is given by

$$\dot{\mathbf{z}}_{p3} = \mathbf{T}_{p3}^T(\psi_y)\mathbf{A}_{p3}\mathbf{T}_{p3}(\psi_y)\mathbf{z}_{p3} + \mathbf{B}_{q3}\boldsymbol{\tau}_{q3} + \mathbf{K}_{p3}(\mathbf{y}_3 - \mathbf{y}_{p3}) \tag{20}$$
$$\mathbf{y}_{p3} = \mathbf{C}_{p3}\mathbf{z}_{p3}. \tag{21}$$

The state vector for observer $\mathbf{z}_{p3} \in \mathbb{R}^{15}$ is written as

$$\mathbf{z}_{p3} = \left[\hat{\mathbf{p}}_w^T \quad \hat{\boldsymbol{\eta}}^T \quad \hat{\mathbf{b}}^T \quad \hat{\boldsymbol{\upsilon}}^T\right]^T \tag{22}$$

where $\hat{\mathbf{p}}_w \in \mathbb{R}^6$, $\hat{\boldsymbol{\eta}} \in \mathbb{R}^3$, $\hat{\mathbf{b}} \in \mathbb{R}^3$, and $\hat{\boldsymbol{\upsilon}} \in \mathbb{R}^3$ are the estimated states of WF model, LF position and heading, bias, and LF velocity, respectively; and the transformation matrix $\mathbf{T}_{p3} \in \mathbb{R}^{15\times 15}$ is given by

$$\mathbf{T}_{p3}(\psi) = \mathrm{diag}\left(\mathbf{R}^T(\psi), \ldots, \mathbf{R}^T(\psi), \mathbf{I}_{3\times 3}\right). \tag{23}$$

The system matrices $\mathbf{A}_{p3}$, $\mathbf{B}_{q3}$, and $\mathbf{C}_{p3}$ are derived from (2) and (3) through the assumptions presented in the beginning of the subsection. Readers can find the details in [5] and [12]. The tuning of the observer gain matrix $\mathbf{K}_{p3} \in \mathbb{R}^{15\times 3}$ is based on the passivity requirements [5].

2) Controller Design: The control objective is to keep the vessel in a fixed position and heading $\boldsymbol{\eta}_d \in \mathbb{R}^3$ such that

$$\boldsymbol{\eta}_d = [x_d, y_d, \psi_d]^T. \tag{24}$$

The reference model (see [5] and [20]) provides the desired velocity $\boldsymbol{\upsilon}_d \in \mathbb{R}^3$ and acceleration $\dot{\boldsymbol{\upsilon}}_d \in \mathbb{R}^3$. The output feedback error dynamics are given by

$$\tilde{\boldsymbol{\eta}} = \hat{\boldsymbol{\eta}} - \boldsymbol{\eta}_d, \quad \tilde{\boldsymbol{\upsilon}} = \hat{\boldsymbol{\upsilon}} - \boldsymbol{\upsilon}_d. \tag{25}$$

The nonlinear output-feedback PID control law for model 3 could be written as

$$\dot{\boldsymbol{\xi}}_{q3} = \tilde{\boldsymbol{\eta}} \tag{26}$$
$$\hat{\boldsymbol{\tau}}_{q3} = \boldsymbol{\tau}_{FF3} - \mathbf{K}_{i3}\mathbf{R}^T(\psi_y)\boldsymbol{\xi}_{q3} - \mathbf{K}_{p3}\mathbf{R}^T(\psi_y)\tilde{\boldsymbol{\eta}} - \mathbf{K}_{d3}\tilde{\boldsymbol{\upsilon}} \tag{27}$$

where $\boldsymbol{\tau}_{FF3}$ is feedforward term; and $\mathbf{K}_{p3} \in \mathbb{R}^{3\times 3}$, $\mathbf{K}_{i3} \in \mathbb{R}^{3\times 3}$, and $\mathbf{K}_{d3} \in \mathbb{R}^{3\times 3}$ are the non-negative P, I, and D controller gain matrices, respectively.

C. Controller for Transition From Autopilot to DP

In the transition regime from/to autopilot to/from DP, the controller is combined by the DP and autopilot controllers according to

$$\boldsymbol{\tau}_{q2} = \alpha_1(U)\mathbf{H}\tau_{q1} + \alpha_2(U)\boldsymbol{\tau}_{q3} \tag{28}$$

where the weighting functions α_1 and α_2, which are used to smoothly transform the controller from transit speed to low speed are the function of the vessel's speed, according to

$$U = \sqrt{u^2 + v^2}. \quad (29)$$

In this regime, the GNC provide the desired vessel's speed from high to zero. The mapping from control action in yaw, τ_{q1}, to 3-DOF is done by the matrix $\mathbf{H}$.

The weighting functions are assumed to have the following properties:

- $\alpha_i \rightarrow 1$ when the operation is close to the i^{th} regime;
- $\alpha_1(\theta) + \alpha_2(\theta) = 1 \ \forall\theta$;
- α_i is slowly varying, such that $d\alpha_i/dt = \dot{\alpha}_i \approx 0$.

Examples of appropriate α_1 and α_2 are

$$\alpha_1(\theta) = 1 - \exp\left[-k(p\theta)^r\right] \quad (30)$$

$$\alpha_2(\theta) = \exp\left[-k(p\theta)^r\right]. \quad (31)$$

D. Station Keeping—Position Mooring System

1) Observer Design: The observer for a PM vessel is similar to that for a DP vessel, but the restoring loads due to the mooring system must be taken into account [23], such that

$$\begin{aligned} \dot{\mathbf{z}}_{p5} &= \mathbf{T}_{p5}^T(\psi_y)\mathbf{A}_{p5}\mathbf{T}_{p5}(\psi_y)\mathbf{z}_{p5} \\ &\quad + \mathbf{B}_{q5}(\mathbf{g}_{\mathrm{moor}}(\mathbf{x}_{\mathrm{tur}}, \boldsymbol{\eta}) + \boldsymbol{\tau}_{q5}) + \mathbf{K}_{p5}(\mathbf{y}_3 - \mathbf{y}_{p5}) \quad (32) \\ \mathbf{y}_{p5} &= \mathbf{C}_{p5}\mathbf{z}_{p5}. \quad (33) \end{aligned}$$

where $\mathbf{z}_{p5} \in \mathbb{R}^{15}$ is the state; $\mathbf{T}_{p5} \in \mathbb{R}^{15\times15}$ is the transformation matrix; $\mathbf{g}_{\mathrm{moor}}(\mathbf{x}_{\mathrm{tur}}, \boldsymbol{\eta})$ is the restoring contribution of the mooring system to the vessel's dynamics; $\mathbf{x}_{\mathrm{tur}}$ is the position of the center of turret in body-fixed frame; the system matrices $\mathbf{A}_{p5} \in \mathbb{R}^{15\times15}$, $\mathbf{B}_{q5} \in \mathbb{R}^{15\times3}$, $\mathbf{E}_5 \in \mathbb{R}^{15\times6}$; and the projection matrix $\mathbf{C}_{p5} \in \mathbb{R}^{3\times15}$ are same as in DP mode.

2) Controller Design: The control objectives are 1) to keep the vessel in a desired heading angle ψ_d and 2) to add damping in surge and/or sway $[u_d, v_d] = [0, 0]$, when the resonant oscillatory motions happen due to environmental excitations.

E. Station Keeping—Transition From DP to PM and Vice Versa

The process of switching from DP to PM is smoothly switching off the surge and sway control while keeping the heading angle control. This can be done by the weighting function as follows

$$\boldsymbol{\tau}_{q4}^{\mathrm{DP2PM}} = \alpha_1(t - t_0)\boldsymbol{\tau}_{q3} + \alpha_2(t - t_0)\boldsymbol{\tau}_{q5} \quad (34)$$

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

The process of switching from PM to DP is more complicated such that the PM mode smoothly transforms to DP while at the same time, the reference model provides the path from the setpoint of the PM mode to the setpoint of the DP mode.

TABLE III
SUMMARY OF EXPERIMENTS: SWITCHING FROM DP TO SPM MODE

	Mooring line's stiffness	Sea state	
Test 1	low	moderate:	H_s = 2.52m, T_p = 9.2s.
Test 2	low	high:	H_s = 3.96m, T_p = 10.44s.
Test 3	medium	moderate:	H_s = 2.52m, T_p = 9.2s.
Test 4	medium	high:	H_s = 3.96m, T_p = 10.44s.
Test 5	high	moderate:	H_s = 2.52m, T_p = 9.2s.
Test 6	high	high:	H_s = 3.96m, T_p = 10.44s.

F. Design of Supervisory Switching Control

The set of models and the set of controllers presented in Subsections from B to E correspond to $\mathcal{M}$ in (5) and $\mathcal{C}$ in (6), respectively. The error vector $\mathbf{e}_p$ can be formed from the estimation vector, $\mathbf{y}_p$ and process output $\mathbf{y}$ (see Fig. 3). From this error vector, the SIHSL will decide the existing VOC so as to switch to the appropriate model and thereby the appropriate controller. Readers can find the details of design and stability analysis for this SSC in [12].

G. Experimental Results

In this section, the experiments for the switching from DP to SPM and *vice versa* are presented. The experiments were carried out using the model vessel, Cybership III, 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 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 SPM system is modelled 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 since the restoring forces acting on the ship due to the linearity behavior of the whole SPM system (hawser and buoy), [22]. There are six tests carried out for three mooring line configurations: low, medium and high stiff mooring line, under moderate and high seas. The stiffness of the low, medium and high stiff mooring line are $\mathbf{K}_{\mathrm{moor}} = 40.5, 56.7$, and 81 kN/m, respectively. The summary of the experiments are shown in Table III. The vessel is subjected to JONSWAP irregular head seas with the significant wave height (H_s) and the peak period of wave (T_p). 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. The other experiments showed similar results. Fig. 4 shows the position and heading of the vessel and the I controller load from control system during the switching procedure. Fig. 5 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.

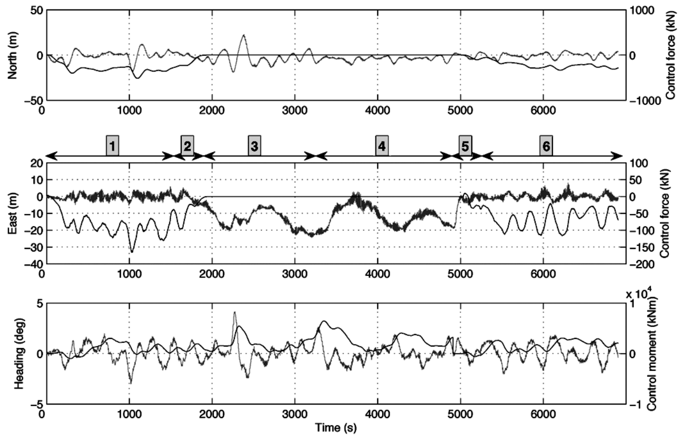

Fig. 4. Test 6: performance of switching from DP to SPM mode and *vice versa* of the shuttle tanker: measured position and heading (grey) and I controller forces and moment (solid).

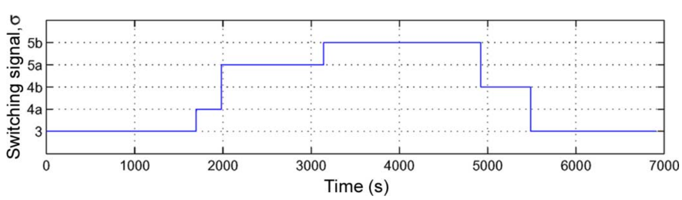

Fig. 5. Test 6: switching signal.

Stage 2) Controller 4a: The smooth transformation in (34) 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 presented in Section V-C. The smooth transformation (34) is used same as in Stage 2 but the reset of I controller has to be taken into account.

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. 4. The experiments with the switching from PM to DP mode and *vice versa* in different sea conditions and different mooring systems showed good performance. When the vessel was kept in a fixed heading, there existed oscillations in surge due to resonance (Stage 3). These oscillations were as expected reduced considerably by adding surge damping (Stage 4). The performance of the SSC strategy indicates that the integrated control system can indeed expand the marine operation from transit speed to station keeping and vice versa.

VII. Conclusion

This brief presented a novel concept of SSC for the marine control system by showing the feasibilities of integration of different controllers at different control levels. The concept of SSC allowed the integration of modes for DP, low speed maneuvering, and transit operations. The proposed integrated system were demonstrated by experiments.

References

[1] O. M. Aamo and T. I. Fossen, "Controlling line tension in thruster assisted mooring systems," in *Proc. IEEE, Int. Conf. Control Appl.*, Aug. 1999, pp. 1104–1109.
[2] K. J. Åström and B. Wittenmark, *Adaptive Control*, 2nd ed. Reading, MA: Addison-Wesley, 1995.
[3] J. G. Balchen, N. A. Jenssen, and S. Sælid, "Dynamic positioning using Kalman filtering and optimal control theory," in *IFAC/IFIP Symp. Autom. Offshore Oil Field Oper.*, Amsterdam, The Netherlands, 1976, pp. 183–186.
[4] J. M. Böling, D. Seborg, and J. Hespanha, "Multi-model control of a simulated pH," in *Proc. 16th World Congress Int. Fed. Autom. Control*, 2005, pp. 663–672.
[5] T. I. Fossen, *Marine Control Systems: Guidance Navigation and Control of Ships Rigs and Underwater Vehicles*. Trondheim, Norway: Marine Cybernetics, 2002.
[6] T. I. Fossen, "A nonlinear unified state-space model for ship maneuvering and control in a seaway," *J. Bifurcation Chaos (ENOC'05 Plenary)*, vol. 15, no. 9, pp. 2717–2746, Sep. 2005.
[7] A. R. Girard, J. Sousa, and J. K. Hedrick, "A hierarchical control architecture for the mobile offshore base," *Marine Structures J.*, vol. 13, no. 4/5, pp. 459–476, Jul. 2000.
[8] J. P. Hespanha, "Tutorial on supervisory control," in *Proc. Lecture Notes Workshop Control Using Logic Switching 40th Conf. Dec. Control*, 2001, pp. 1–46.
[9] J. P. Hespanha and A. S. Morse, "Switching between stabilizing controllers," *Automatica*, vol. 38, no. 11, pp. 1905–1917, 2002.
[10] J. P. Hespanha, D. Liberzon, and A. S. Morse, "Hysteresis-based switching algorithms for supervisory control of uncertain systems," *Automatica*, vol. 39, no. 2, pp. 263–272, 2003.
[11] K. J. Hunt and T. A. Johansen, "Design and analysis of gain-scheduled control using local controller networks," *Int. J. Control*, vol. 66, no. 5, pp. 619–651, 1997.
[12] T. D. Nguyen, "Design of hybrid marine control systems for dynamic positioning," Ph.D. dissertation, Dept. Civil Eng., NUS, Singapore, 2006.
[13] T. D. Nguyen, A. J. Sørensen, and S. T. Quek, "Design of hybrid controller for dynamic positioning from calm to extreme sea conditions," *Automatica*, vol. 43, no. 5, pp. 768–785, 2007.
[14] K. Nomoto, T. Taguchi, K. Honda, and S. Hirano, "On the steering qualities of ships," Tech. Rep. Int. Shipbuilding Progr. vol. 4, 1957.
[15] N. H. Norrbin, "Theory and observation on the use of a mathematical model for ship maneuvering in deep and confined waters," in *Proc. 8th Symp. Naval Hydrodyn.*, 1970, pp. 807–904.
[16] R. Skjetne, T. I. Fossen, and P. V. Kokotovic, "Adaptive output maneuvering with experiments for a model ship in a marine control laboratory," *Automatica*, vol. 41, no. 4, pp. 289–298, 2005.
[17] Ø. N. Smogeli, "Control of marine propellers: From normal to extreme conditions," Ph.D. dissertation, Dept. Marine Technol., NTNU, Trondheim, Norway, 2006.
[18] A. J. Sørensen, S. I. Sagatun, and T. I. Fossen, "Design of a dynamic positioning system using model-based control," *Control Eng. Practice*, vol. 4, no. 3, pp. 359–368, 1996.
[19] A. J. Sørensen, J. P. Strand, and H. Nyberg, "Dynamic positioning of ships and floaters in extreme seas," in *Proc. OCEANS MTS/IEEE*, 2002, pp. 1849–1854.
[20] A. J. Sørensen, *Marine Cybernetics: Modelling and Control*, 5th ed. Trondheim, Norway: Dept. Marine Technology, NTNU, 2005.
[21] A. J. Sørensen, Elsevier Ltd, "Structural issues in the design and operation of marine control systems," *IFAC J. Ann. Rev. Control*, vol. 29, no. 1, pp. 125–149, 2005.
[22] H. R. Sørheim, "Dynamic positioning in single point—A theoretical analysis of motions, and design and evaluation of an optimal control system," Ph.D. dissertation, Dept. Eng. Cybern., the Norwegian Inst. Technol., Univ. Trondheim, Trondheim, Norway, 1981.
[23] J. P. Strand, A. J. Sørensen, and T. I. Fossen, "Modelling and control of thruster assisted position mooring system for ships," *Modelling, Id. Control*, vol. 19, no. 2, pp. 65–71, 1998.
[24] K. Torsethaugen, Model for a doubly peaked wave spectrum SINTEF, Trondheim, Norway, Tech. Rep. STF22A96204, 1996.
[25] F. Wang and V. Balakrishnan, "Improved stability analysis and gain synthesis for parameter-dependent systems," *IEEE Trans. Autom. Control*, vol. 47, no. 5, pp. 720–734, Sep. 2002.