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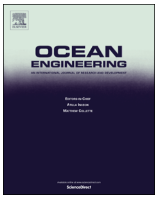

Advanced control for fault-tolerant dynamic positioning of an offshore supply vessel

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ABSTRACT

The paper presents a solution to guarantee a fault-tolerant robust control for the dynamic positioning of an over-actuated offshore supply vessel. Fault detection is obtained by a combination of two model-based techniques: the parity space approach and the Luenberger observer. The dynamic positioning system is provided by a bank of reconfigurable Discrete-Time Variable-Structure Controllers (DTVSC), selected by a supervisor, based on a fault isolation logic. The control system is combined with a wave compensation based on a Multi-rate Extended Kalman Filter (MREKF). The proposed solution is compared with a standard Proportional-Integral-Derivative (PID) control system and a passive nonlinear wave filter to assess its robustness to input disturbances and uncertainties in the model parameters. The simulation tests developed for a scale model of an offshore supply vessel show that, in the case of actuators faults, dynamic positioning is guaranteed by the proposed solution.

1. Introduction

Offshore exploration and exploitation of hydrocarbons have opened up an era of dynamically positioned vessels. Dynamic positioning (DP) is an autonomous control system that acts to maintain vessel position and the angle of direction at a reference point by means of the vessel propulsion and maneuvering thrusters. To calculate the steering angle and the thrust of each thruster, information from sensors (GPS, gyroscopes, etc.) and from the thruster allocation algorithm is combined. The control action maintains the desired position and orientation according to a navigation path or a specific task (absolute or relative DP). The dynamic positioning system is decisive in those situations in which the position of the unit is either bound to a specific point on the seabed (absolute DP), or is related to a moving unit, such as when the ship is operating with other vessels or with remotely operated underwater vehicles. A dynamically positioned vessel is defined by the International Maritime Organization (IMO) and the certifying class societies (DNV, ABS, LR, etc.) as a vessel that maintains its position and heading (fixed location or predetermined track) exclusively by means of active thrusters (Sørensen, 2011; Johansen et al., 2014). Other solutions, like position mooring, consider the aid of mooring lines, as described by Nguyen and Sørensen (2009), Fang et al. (2015), and Chen et al. (2013). The evaluation of structural responses is key element in the design of ships and offshore structures and Hirdaris et al. (2014) review some of the recent advances in the assessment of loads for ships and offshore structures.

To date most dynamic positioning systems have been used for positioning drill ships in deep water, and for other offshore operations, such as diving support and anchor handling. Furthermore, DP systems have been applied increasingly to shuttle tankers during offloading operations using a floating production, storage and offloading unit (see Sørensen, 2011; Fossen, 2011). The first DP systems were designed using conventional PID controllers in a cascade with low pass and/or notch filters to suppress the wave induced motion components. From 1980 onwards, a new model-based control concept, which exploits stochastic optimal control theory and Kalman filtering techniques, has been employed to address the DP problem (Balchen et al., 1980). Subsequent extensions and modifications of the latter work have been proposed by numerous authors, including Sørensen (2011), Fossen (2000), Strand and Fossen (1999), Fang et al. (2011) and references therein. In Xia et al. (2005) and in Tannuri and Agostinho (2010) the sliding mode control is used with a Passive Nonlinear Observer for the DP problem. A procedure for attenuating the control law of a vessel dynamic positioning system, based on the observer backstepping methodology, is proposed in Morishita and Souza (2014) and a port-Hamiltonian framework to design a nonlinear set-point-regulation controller with integral action is presented in Donaire and Perez (2012). A family of passivity-based controllers for dynamic positioning of ships is considered in Muhammad and Dòria-Cerezo (2012).

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As with other technological systems, a DP system is subject to fault (e.g. loss of position) which may be caused by computer, electrical, hydraulic or thruster failures. The International Marine Contractors Association (IMCA) has defined guidelines for fault-tolerant system design (MSC/IMCA, 1994): a requirement for a DP Class 2 vessel is that loss of position is not to occur in the event of a single failure in any active component or system (generators, thrusters, switchboards, remote controlled valves, etc.). However thrusters cause 21% of the incidents related to DP, according to the report in IMCA (1994), and thruster reliability for DP has been addressed by Phillips (1996) as a problem to be solved. It is very important to recover control authority in case of any thruster failure and the IMCA guidelines for vessels equipped with dynamic positioning systems, MSC/IMCA (1994) require the redundancy of all active components, thrusters included, to meet the single failure criteria given above. Redundancy, as an alternative means of providing the same function, is intended as fault tolerance, which is the ability of a system to continue operating following a failure, and is more general than having at least two of each thruster component.

Single point thruster failures in DP applications are extensively described in Phillips (1998) and early diagnosis and fault-tolerant control for safe operation of floating platforms where mooring systems maintain vessel position and must withstand environmental loads are considered in Fang et al. (2015). Systematic fault-tolerant control was studied for the station keeping of a marine vessel by Blanke (2005) and a structure-graph approach for fault diagnosis and control reconfiguration was validated by sea tests. Fault-tolerant approaches to handle thrust failures have recently been proposed in Fu et al. (2010, 2011): classical PID controls are used and reconfiguration after faults is implemented by means of the virtual actuator approach in Blanke et al. (2006). With this approach the PID controllers may not be sufficiently robust to handle reconfiguration transients during non-steady state maneuvering.

This paper presents an innovative solution for the DP control system of a vessel, based on a bank of reconfigurable Discrete-Time Variable Structure Control (DTVSC) systems selected by a logic supervisor and wave filtering using a Multi-rate Extended Kalman Filter. The introduction of DTVSC allows the issue of control law digitalization to be taken into account directly and it ensures robustness with respect to model uncertainties and input disturbances acting on the actuators. An Extended Kalman Filter (EKF) is designed for the purpose of estimating the disturbances induced by the first order wave forces on the thruster. This is done to minimize the thruster efforts. The estimation is improved by means of a Multi-rate Extended Kalman Filter (MREKF) which allows differences in the working frequency of the sensors to be considered (Wang et al., 2013, 2014). A fault diagnosis module and a control reconfiguration structure are used to handle thruster failures. The proposed solution is compared to a standard PID control system tuned using an LQR algorithm (Fossen, 2011) equipped with a Passive Nonlinear Observer to filter waves (Strand and Fossen, 1999). Tests are based on numerical results.

The paper is organized as follows. The kinematic and dynamic vessel equations, the thruster allocation and the wave model are presented in Section 2. The filter techniques are discussed in Section 3. The fault diagnosis system is presented in Section 4. The control system is reported in Section 5. Simulation results are presented in Section 6. The paper ends with conclusions and comments.

2. Mathematical model of the DP vessel

Motion superposition is the most commonly adopted model for ship motion control system design (Perez and Fossen, 2004). Motion can be conceptually decomposed as the superposition of three contributions:

- slowly varying disturbance motion produced by second order wave effects, current and wind;
- control-induced motion described by a maneuvering model, clarifying the relationship between control action and its effects on the motion. These dynamics are referred to as Low Frequency (LF) dynamics;
- wave-induced motion where the wave frequency oscillatory motion induced by first order waves is described by a sea-keeping model. These dynamics are referred to as Wave Frequency (WF) dynamics.

2.1. Maneuvering model

The generalized displacement and body-fixed velocities are defined as $\boldsymbol{\eta}$ and $\boldsymbol{\nu}$, respectively, where $\boldsymbol{\nu}$ is defined in the ship body-fixed frame $\{b\}$, while $\boldsymbol{\eta}$ is defined in the local geographical inertial north-east-down frame $\{n\}$, fixed to the Earth (Fossen, 2011). The kinematics equations, which express the relationship between the generalized displacements in the $\{n\}$ frame and the velocities in the $\{b\}$ frame, are

$$\dot{\boldsymbol{\eta}} = \boldsymbol{J}(\boldsymbol{\eta})\boldsymbol{\nu} \tag{1}$$

where $\boldsymbol{J}$ is the transformation matrix from the $\{b\}$ to the $\{n\}$ frame.

In case of irrotational and constant ocean currents (Fossen, 2011), the 6 degrees of freedom (DOF) maneuvering equations of motions can be expressed in the $\{b\}$ frame as

$$\boldsymbol{M}\dot{\boldsymbol{\nu}}_r + \boldsymbol{C}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \boldsymbol{D}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r + \boldsymbol{G}\boldsymbol{\eta} = \boldsymbol{\tau}_c + \boldsymbol{\tau}_{env} \tag{2}$$

where $\boldsymbol{\nu}_r = [u-u_c, v-v_c, w, p, q, r]^T$ is the relative velocity vector between the vessel and the current (see Section 2.2.3); $\boldsymbol{M} = (\boldsymbol{M}_{RB} + \boldsymbol{M}_A)$ is the system inertia matrix, including the rigid-body and the added mass matrices; $\boldsymbol{C} = \boldsymbol{C}_{RB} + \boldsymbol{C}_A(\nu_r)$ is the Coriolis–centripetal matrix, including both rigid-body ($\boldsymbol{C}_{RB}$) and added mass $\boldsymbol{C}_A(\nu_r)$; $\boldsymbol{D}(\nu_r) = \boldsymbol{D}_L + \boldsymbol{D}_{NL}(\nu_r, \gamma_r)$ is the damping matrix, which may be divided into a linear component ($\boldsymbol{D}_L$), accounting for linear wave drift damping and laminar skin frictions and a non-linear component ($\boldsymbol{D}_{NL}(\nu_r, \gamma_r)$) accounting for the effects of ocean currents. It is important to notice that, for velocities of vessel close to zero, the linear damping becomes more significant than the nonlinear damping. The restoring term is assumed to be $\boldsymbol{G}(\eta) = \boldsymbol{G}\eta$ under the assumption of small roll and pitch angles. The terms $\boldsymbol{\tau}_c$ are the control forces and moments to be produced by the actuators, while $\boldsymbol{\tau}_{env}$ are the environmental loads.

2.2. Environmental forces and moments

A ship in a seaway is mainly affected by the following types of environmental disturbances: waves, currents, and wind. The environmental disturbances contain both slowly varying and high-frequency forces. Control forces and moments due to environmental disturbances are caused by wind and waves. Using the principle of superposition, they are added to the right side of (2) by defining $\boldsymbol{\tau}_{env} = \boldsymbol{\tau}_{wind} + \boldsymbol{\tau}_{wave}$.

2.2.1. Wind forces and moments

The wind force on a marine vessel is proportional to the projected area above the waterline and to the square of the wind speed relative to the vessel. The total relative wind speed can be defined as

$$U_{rw} = \sqrt{u_{rw}^2 + v_{rw}^2} \tag{3}$$