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Brief paper

Hybrid controller concept for dynamic positioning of marine vessels with experimental results ☆

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ABSTRACT

The next generation marine control systems will, as a step towards increased autonomy, have more automatic functionality in order to cope with a set of complex operations in unknown, challenging and varying environments while maintaining safety and keeping operational costs low. In this paper a hybrid control strategy for stationkeeping and maneuvering of marine vessels is proposed. The hybrid concept allows a structured way to develop a control system with a bank of controllers and observers improving dynamic positioning (DP) performance in stationary dynamics, changing dynamics including enhancing transient performance, and giving robustness to measurement errors. DP systems are used on marine vessels for automatic stationkeeping and tracking operations solely by use of the thrusters. In this paper a novel method improving the transient response of a vessel in DP is developed. The performance of the hybrid control system, including two observer candidates and one controller candidate, is demonstrated in model-scale experiments and on full-scale field data. The hybrid system has global stability properties.

1. Introduction

Marine operations are moving into harsher environments, and as a consequence, requirements for the vessel's operational window, safety functions, and energy-efficiency become stricter (Sørensen, 2011). As a result, the level of autonomy in marine control systems is increasing, with automatic performance monitoring and switching. During marine operations, both variations in stationary dynamics and transient behavior are important to account for in an all-year operation philosophy subject to changing weather, sea loads, and modes of operation (Perez, Sørensen, & Blanke, 2006). There are many unknown factors that may cause transients in the vessel response, both from the environment (e.g., wave trains and wind gusts) and triggered by the operation taking place (e.g., heading changes or crane operations of heavy goods). Fig. 1 shows a marine vessel with its operational conditions and a block diagram of a general hybrid marine control system. The vessel operational conditions with *use mode, speed*, and *environment* indicate how the vessel performs different tasks with varying speed in an unknown and changing environment. The use mode includes algorithms that satisfy different control objectives such as stationkeeping, maneuvering, and target tracking, which is closely linked with the vessel speed. Environment refers to the state of the environment consisting of wind, waves and current. Naturally, certain operations can only be performed in calm conditions. Because different physical effects matter for the various vessel operational conditions, there are distinct models and control strategies which are designed specifically for each operational condition. Nguyen, Sørensen, and Quek (2007) proposed to use supervisory switched control based on the methodology of Hespanha, Liberzon, and Morse (2003) and Hespanha and Morse (2002). In addition to handling different speed regimes, use modes and changing sea states, the proposed setup ensures redundancy in the (software) *design methodology* so that faults (Blanke, Kinnaert, Lunze, & Staroswiecki, 2003) may be detected early and alarms may be raised to operators, who are either on-site or remote. The performance monitoring and switching logic block includes monitoring of the environment, power system, observer performance, position precision, signal health, and more. In order to ensure

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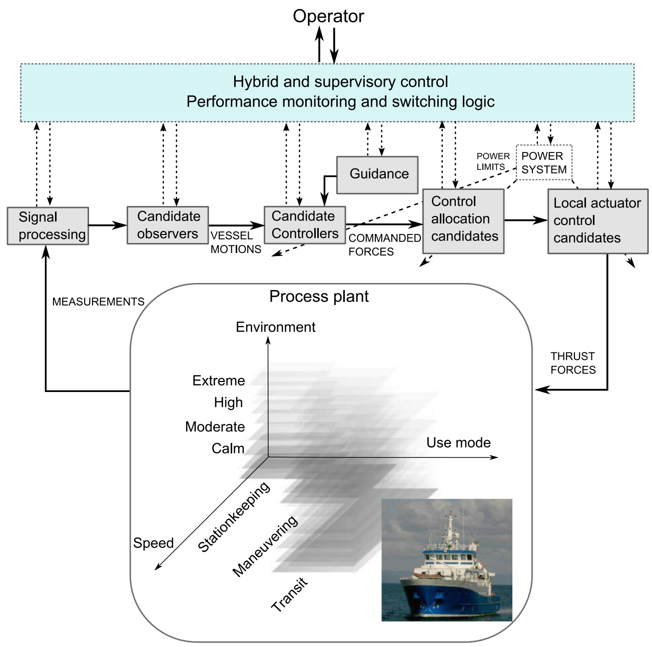

Fig. 1. Block diagram of a hybrid control system for a marine vessel in an unknown environment consisting of wind, waves and current. Sensors measure the operational status and vessel motions, and signal processing software filters, weights and votes between redundant measurements. The performance monitoring monitors the performance of the different blocks, and the switching logic chooses which algorithms to use in closed-loop control from the candidates. Here two observers and one controller are used.

safety, there are high requirements for system reconfiguration, fault tolerance and redundancy, and for testing and verification of performance (DNV-GL, 2014). Testing and verification of marine control systems with higher levels of autonomy are faced with a large (when not infinite) number of failure modes (Smogeli, Vik, Haugen, & Pivano, 2014); exhaustive testing is rarely possible. Therefore having modular design and proofs of subsystem properties may play a larger role in assuring safety (Kapinski, Deshmukh, Jin, Ito, & Butts, 2016). Systems with a wide range of dynamics and different modes that also use hybrid control approaches are for instance air traffic control (Hu, Prandini, & Sastry, 2005; Sastry et al., 1995), adaptive cruise control for the automotive industry (Girard, Howell, & Hedrick, 2005), autonomous docking operations of spacecraft (Malladi, Sanfelice, Butcher, & Wang, 2016), and in the marine industry hybrid power plants (Miyazaki, Sørensen, & Vartdal, 2016). The focus of this paper is on detecting and improving the transient performance of the DP control system using the hybrid system framework as proposed in Goebel, Sanfelice, and Teel (2012). As shown in Fig. 1, it is believed that the concept of hybrid control can provide a scalable and stringent methodology for the design of real industrial control applications dealing with several control objectives and changing environmental and operational conditions. A similar, or alternative, method may be to consider robust control by multiple model adaptive controllers as proposed by Hassani, Sørensen, Pascoal, and Athans (2017) and Hassani, Sørensen, Pascoal, and Dong (2012).

The main scientific contribution of this paper is the development of a hybrid control concept for proper switching of candidate observers and controllers, customized for transient and steady-state behavior of DP vessels. For particular observer candidates, this work combines a model-based observer (Fossen & Strand, 1999), a signal-based observer (Grip, Fossen, Johansen, & Saberi, 2015), a controller, and switching logic into a hybrid system with the goal of improving the transient response. The model-based observer, including wave filtering and bias force estimation, is especially suited in steady state, while the signal-based observer is more reactive during transients, even though it is more sensitive to signal noise. Stability analysis of the hybrid system applies results from Goebel, Sanfelice, and Teel (2009). Performance of the proposed concept is demonstrated experimentally through model-scale experiments with the hybrid observer estimates used in closed-loop output feedback control, and through estimation on full-scale field data. The paper is a continuation of Brodtkorb, Værnø, Teel, Sørensen, and Skjetne (2016), with the signal-based observer exchanged with one that has global stability properties, enhanced performance monitoring and switching logic, and new hybrid stability analysis.

The paper is organized as follows: The measurements and notation are introduced in Section 2, and the candidate observers and control algorithms are presented in Section 3. The hybrid system is assembled in Section 4, and stability is discussed in Section 5. The experimental setup and results are shown in Section 6. Section 7 concludes the paper.

2. Preliminaries

Common instrumentation in DP vessels includes position reference systems (typically GNSS[1]), compass, and inertial measurement units (IMU). The measurements, denoted with subscript m, are in this paper assumed to be of the form

$$p_m^n = [N, E]^\top \tag{1a}$$
$$\psi_m^n = \psi \tag{1b}$$
$$\omega_m^b = \omega^b + b_g \tag{1c}$$
$$f_m^b = R_\Theta^\top(\dot{v}^n - g^n), \tag{1d}$$

where the measurements in the North-East-Down (NED) frame (an Earth-fixed local reference frame assumed to be inertial) have superscript n, and measurements in the body-fixed frame have superscript b. For the purpose of stability analysis, the system is assumed to be deterministic such that noise is disregarded. This follows similar approaches as Fossen and Strand (1999) and Nguyen et al. (2007). The vector $p_m^n \in \mathbb{R}^2$ is the measured position in North and East. A vertical measurement may also be obtained through GNSS, but it is typically of low quality, and is not used here; see Section 3.2. The measured angle $\psi_m^n \in \mathbb{R}$ includes the low frequency yaw angle ψ and the wave-induced heading oscillations ψ_w, which are assumed to be small (Fossen & Strand, 1999). The angular velocity ω^b, which takes values in $\mathbb{R}^3$, is continuous and bounded, and the gyro bias is constant with a known bound $\|b_g\| \le M_b$. The vector $f_m^b \in \mathbb{R}^3$ is the measured specific force,[2] including the acceleration of the vessel $\dot{v}^n$ and the acceleration due to gravity $g^n \in \mathbb{R}^3$. $R_\Theta \in \mathbb{R}^{3\times3}$ is the rotation matrix about the z, y, x-axes (Fossen, 2011, Ch. 2). We assume f_m^b is non-biased, bounded $\|f_m^b\| \le M_f$, and the derivative of the actual specific force $\dot{f}^b$ is continuous and bounded. Furthermore, there exists a constant $c_{obs} > 0$ such that $\|c^b \times f_m^b\| > c_{obs}$, $c^b = [\cos(\psi_m^n), -\sin(\psi_m^n), 0]^\top$.

3. Candidate observers and controller

Two observers based on two philosophically different models of the same vessel are presented in the next sections. The relationship between the models is as follows:

$$\eta + \eta_w \equiv [p_{(1,1)}^n, p_{(2,1)}^n, \Theta_{(3,1)}]^\top \tag{2a}$$
$$\nu + \nu_w \equiv [v_{(1,1)}^b, v_{(2,1)}^b, \omega_{(3,1)}^b]^\top, \tag{2b}$$

1 Global Navigation Satellite System.

2 Specific force is the physical acceleration experienced by an object, consisting of the acceleration of the object and the acceleration due to gravity, i.e., it is the *measurable* acceleration, with unit $[\mathrm{m/s}^2]$.