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Coordinated weathervaning control of two surface vessels in a tandem configuration

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ABSTRACT

During a tandem offloading operation between a floating production storage and offloading (FPSO) unit and a connected shuttle tanker (ST), the control of the relative position and heading between two vessels is crucially important, since large relative motion may cause serious accidents such as collision or hose disconnection. Dynamic positioning (DP) systems can be used to control the motion of the vessels during the operation. Among various DP control strategies, weathervaning control enables each vessel to be oriented toward the direction of the mean environmental force induced by wind, wave and ocean current so as to improve the operational safety and reduce the overall thruster power consumption. This study proposes a controller design for DP in the task space of the vehicle dynamics that allows for weathervaning control without explicit measurements or accurate estimation of environmental disturbances. A coordinated control scheme assuming a reliable communication channel between two vessels is also introduced to ensure the safety of the vessels and continuous oil transfer by suppressing excessive relative heading changes under significant environmental disturbances. Numerical simulation results for several DP control scenarios under different control settings and environmental conditions are presented.

1. Introduction

In the last two decades, floating production, storage, and offloading units (FPSOs) have been the dominant floating offshore platform used in oil and gas fields, particularly in deep water sites and small reservoirs that are spread in adjacent areas. Shuttle tankers (STs) are used for offloading oil from FPSOs and bringing it to on-shore storage facilities. The offloading operation between the FPSO and the ST is usually carried out in a tandem offloading configuration (see Fig. 1).

Tandem offloading is a complex and challenging operation due to the relatively close distance between two large floating structures which are physically connected by a hawser and a loading hose between the FPSO's stern and the ST's bow loading system (BLS). The offloading operation may last from several to more than 24 h. During this long operation time, the environmental conditions continuously change, and thus the full attention by operators is required to avoid any dangerous situations such as ship collision, hose disconnection and hawser over-stress. The distance between the two vessels needs to be controlled by thrusters and the hawser's tension. The assistance of tug boats or standby vessels may also be required for supporting this configuration. Sudden changes in the environment and operating conditions may occur at any time during the operation, and thus the operators are subjected to considerable mental stress and fatigue that may lead to human errors and ultimately to accidents. All of the above conditions and difficulties increase the total operation time, cost and risk. The application of an automatic position control system, called dynamic positioning (DP), enables achieving more efficient and reliable operation with less human interference, reduced hawser loading and less force transmission between the two vessels.

DP systems have already been widely used to carry out various tasks such like cable laying, dredging, drilling and oil production. Especially, the weathervaning operation mode has been suggested as a mean to minimize the DP thrust power and fuel consumption under changing weather conditions by rotating the vessel's heading angle toward the direction of the mean environmental force. The DP system consists of various sensors, control algorithms, and thrusters. The sensors are used to measure the vessel's motion including the position and the heading. The control algorithms are used to calculate the required control reaction force inputs for counteracting environmental forces due to wind, wave and current. The thrusters including the ship's main propulsion system provide control forces and moments to counteract the environment forces.

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Fig. 1. Tandem offloading operation between a FPSO and a shuttle tanker (www.zebecmarine.com).

Various control algorithms have been developed for DP control since the 1960s. However, relatively few studies addressed weathervaning control. Pinkster and Nienhuis (1986) showed that the control forces can be minimized when the virtual mooring point for weathervaning is located near the bow of the vessel and presented a simple proportional-integral-derivative (PID) weathervaning control method with no proportional control of the ship's yaw motion. Fossen and Strand (2001) pointed out that it is difficult to accurately estimate the effects of environmental forces due to wind, wave and current in real situations, and proposed a non-linear weather optimal positioning control (WOPC) by expressing the vehicle dynamics in polar coordinates and employing an adaptive backstepping control design to compensate for unknown environmental forces.

Regarding the control of the FPSO and the ST in a tandem configuration, Hals (1999) introduced the concept of DP assisted tandem operation. The key idea of the concept is the separation of two relative motion modes into surge–sway and yaw modes. An improved tandem operation concept was addressed with the consideration of rapidly changing environmental conditions in Hals and Maritime (2004), and the coordination of an FPSO and a ST in offloading operation using a knowledge-based intelligent control was discussed by Millan et al. (2002). Bravin proposed a controller for tandem operation along with the definition of an allowable range for the hose connection between FPSO and ST, and its performance was compared with a traditional DP controller (Bravin and Tannuri, 2004). Nonlinear sliding mode control (SMC) for DP operation was suggested and its stability and robustness were shown in changing environmental conditions in Tannuri et al. (2010). More recently, a weathervaning control method based on the zero power control theory was proposed in Miyazaki and Tannuri (2013).

Full DP is not necessarily required for DP of turret-moored vessels. However, a recent trend in oil and gas fields is the requirement of DP applications in deep sea conditions and DP applications to small oil and gas reservoirs. Spread mooring lines may not be suitable in such applications, and oil and gas platforms may require proper self-propulsion and positioning systems to shift to another oil and gas field. In addition, there are some conceptual studies on the LNG offloading between full DP vessels in which weathervaning control may be applied. de Wilde et al. (2010) presented an experimental investigation using the models of the LNG stern-to-bow offloading with a shuttle tanker.

For conventional DP systems, in general, both a desired position and a desired heading angle need to be specified for directional stability and efficient power consumption. However, it is generally difficult to accurately estimate the desired heading angle, particularly when environmental forces due to wind, waves and currents are acting in different directions (not collinear) (Fossen and Strand, 2001). This study focuses on developing a new control algorithm for weathervaning DP of two vessels in a tandem configuration under ocean environmental disturbances. The proposed DP controller is designed in the task space associated with the surge and sway motion around a virtual pivot point, separated from the yaw motion in the null space. Therefore, weathervaning can be performed with no need for explicit disturbance observations. There is no or minimal requirement of sensors for observing environment conditions, which reduces the complexity of the DP system and also installation and maintenance cost. A similar control strategy was adopted by the WOPC presented in Fossen and Strand (2001), and its nonlinear controller is designed using the vehicle dynamics represented in polar coordinates. The proposed approach considers the separation of the vehicle dynamics into the task space and the null space dynamics to decouple the yaw motion from the surge-sway motion, which leads to a simple and systematic controller design procedure. Moreover, a coordinated control algorithm formulated in null space is also introduced to ensure the safety of the vessels and continuous oil transfer by suppressing excessive relative heading changes between the two vessels. In the proposed coordinated control scheme it is essential to have a robust and reliable communication channel between the two vessels in order to transmit required information.

The remainder of this paper is organized as follows. Section 2 describes the dynamic modeling of ship motion under ocean environmental disturbances. Section 3 describes the proposed weathervaning DP control approach, and Section 4 shows simulations results with discussions. Finally, the conclusions are made in Section 5.

2. Dynamic modeling

The dynamics of surface vessels and the effect of environmental disturbances due to wind, wave and current acting on floating vessels are modelled.

2.1. Dynamic model of a floating vessel

A marine vessel undergoes 6 degree-of-freedom (DOF) motions: 3 translational motions in surge, sway and heave, and 3 rotational motions in roll, pitch and yaw. However, DP generally focuses on 3 DOF motion on the horizontal plane, and hence the motion of the vessel is represented using a 3 DOF planar model covering surge, sway and yaw motions. Fig. 2 shows coordinate systems to represent the 3 DOF motion of a surface vessel on the horizontal surface.

The motion of a floating vessel is defined as

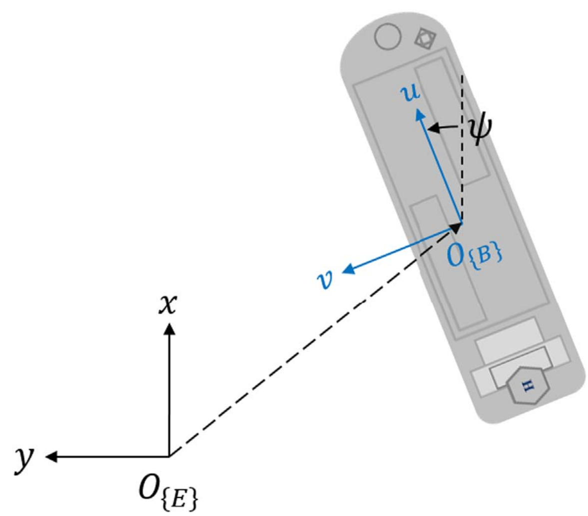

Fig. 2. Coordinate systems: the global reference frame $\{E\}$ and the body-fixed frame $\{B\}$.