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IFAC-PapersOnLine 48-16 (2015) 248–253

A Tension-based Position Estimation Approach for Moored Marine Vessels

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Abstract: This paper presents a novel idea on a tension-based localization approach as a redundancy measure to handle the situation when the position reference (posref) signals are not available or significant GNSS drifts occur, such as sudden ionospheric disturbances, for thruster-assisted moored vessels. The only information needed is the tension measurements from tension cells. This method can improve the redundancy and safety of offshore operation, by detecting and verifying posref failure modes. It can even take over the posref function if one no longer trust the main posref measurements. Based on a residual signal, a fault detection and estimation approach is introduced and verified through simulations.

Keywords: Thruster-assisted position mooring; Position mooring; Position reference systems; Fault diagnosis.

1 Introduction

Commercially available from the 1980s, thruster-assisted position mooring (TAPM) is an important offshore stationkeeping method for floating structures with an energy-efficient feature. The main difference between a TAPM and a dynamic positioning (DP) is that, while a DP system uses the thrusters directly to control the position and heading, a TAPM system uses the thrusters only to assist the mooring lines in keeping the heading in a favorable direction with respect to the environmental loads, and adding surge/sway damping (Skjetne et al., 2014). The position itself is allowed to move within an acceptable region. Innovative industrial tension units, such as the INTEGRIpod^{TM} and the Inter-MPulse^{TM}, are used to monitor and detect the line breakage through tension measurements (Gauthier et al., 2014). Fault detection and isolation (FDI), and reconfiguration control (RC) are two main categories in fault-tolerant control (FTC) (Blanke et al., 2006). Research on FTC schemes to TAPM systems is, for example, presented by Fang and Blanke (2011), Fang et al. (2015), and Nguyen and Blanke (2015).

The global navigation satellite system (GNSS) provides the Earth-fixed position information to surface-based motion systems. GPS, being the most widely used, has been a necessary part to navigation systems of modern marine systems in recent decades. The differential global positioning systems (DGPS) improves the positioning accuracy. However, the GPS signals may experience drifts during some extreme conditions, such as solar events and sudden ionospheric disturbances (SID). SID is a phenomenon with sudden increase of electron density in the ionosphere caused by solar flares, earthquake, storm, or tsunami. It results in a sudden decrease of the upper medium frequency and lower high frequency components in radiowaves (Afraimovich et al., 2000). Normally, SID happens simultaneously with ionospheric storms. These phenomena can last for 1-3 days, even 10 days, significantly degrading the reliability of marine control systems (Tsugawa et al., 2011).

A typical posref drift failure mode in a DP system is that all GPS measurements starts to drift due to SID (Zhao et al., 2012). The hydroacoustic position reference (HPR) system does not drift, but due to the superior signal quality of the GPS signals over the HPR signals, the DP control system chooses to believe in the GPS signals and automatically disables the HPR measurement, thus making the situation worse with a resulting DP system drive-off.

Considering the long-term duration of TAPM stationkeeping operations, the probability of experiencing such drift events is high. Doherty et al. (2004) reported that three very large sunspot clusters happened in October-November 2003 which caused strong magnetic storms. A Large amount of satellites failed, jeopardising the safety of the operations.

This paper proposes a localization algorithm based on the mooring line tension measurement. This provides extra detection capability of posref failure modes and a redundant position reference. Treated as a backup solution in abnormal conditions, this tension-based localization method can improve redundancy with only software updates. It is a companion paper to Ren et al. (2015), which considers the problem of efficient linebreak detection in the case when tension sensors are not available in the TAPM system. Here we consider the converse case when tension sensors are available and can be used as redundancy to the posref systems.

2 Problem Formulation

2.1 Vessel model

A surface vessel is moored by M mooring lines and is equipped with thrust assist. All the cables are indexed with an integer $i \in \mathcal{I}$ where $\mathcal{I} = \{1, 2, \cdots, M\}$ is an index set. Each cable is connected to the turret at a specific fairlead. The distance between the fairlead and the center of turret (COT) is r_t. The turret can rotate about a vertical axis at the COT (see Fig. 1). The vessel is considered to keep its position in 3DOF, including surge, sway, and yaw. The environmental loads are wind, waves, and currents.

Peer review under responsibility of International Federation of Automatic Control.
10.1016/j.ifacol.2015.10.288

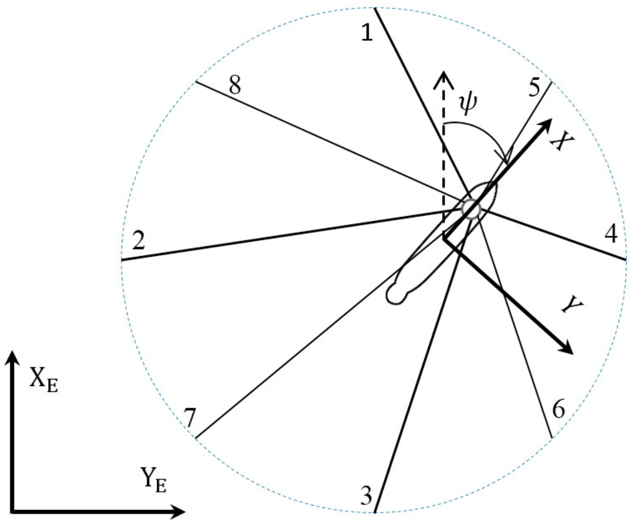

Fig. 1. System in Earth-fixed reference frame.

In what follows, the vessel model described in Fossen (2011) is presented. The stationkeeping model is given by

$$\dot{\boldsymbol{\eta}} = \boldsymbol{R}(\boldsymbol{\psi})\boldsymbol{\nu}, \tag{1a}$$

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{D}\boldsymbol{\nu} = \boldsymbol{R}(\psi)^\top \boldsymbol{b} + \boldsymbol{\tau_c} + \boldsymbol{\tau_m}, \tag{1b}$$

$$\dot{\boldsymbol{b}} = \boldsymbol{0}, \tag{1c}$$

where $\boldsymbol{\eta} = [x \ y \ \psi]^\top$ consists of the low frequency (LF) Earth-fixed position and heading orientation of the vessel relative to an Earth-fixed frame, $\boldsymbol{\nu} = [u \ v \ r]^\top$ represents the linear and rotational velocities decomposed in a vessel-fixed reference, $\boldsymbol{R}(\psi) \in \mathbb{R}^{3\times3}$ denotes the transformation matrix between the body-fixed frame and Earth-fixed frame(see Fig. 1), $\boldsymbol{M} \in \mathbb{R}^{3\times3}$ is the generalized system inertia matrix including zero frequency added mass components, $\boldsymbol{D} \in \mathbb{R}^{3\times3}$ denotes the linear damping matrix, $\boldsymbol{b} \in \mathbb{R}^3$ is a slow varying bias vector in the earth frame, $\boldsymbol{\tau_c} \in \mathbb{R}^3$ represents thruster induced forces vector, and $\boldsymbol{\tau_m} \in \mathbb{R}^3$ is the mooring load vector. See Fossen (2011) and Sørensen (2012) for details.

2.2 Mooring forces

The mooring system is modeled statically by catenary equations, disregarding the cable dynamics, the higher mode full-profile motion, nonlinear damping, and vibrations. For the LF model, a horizontal-plane spread mooring model is formulated as

$$\boldsymbol{\tau_m} = -\boldsymbol{R}(\psi)^\top \boldsymbol{g}_{mo}(\boldsymbol{\eta}) - \boldsymbol{d}_{mo}(\boldsymbol{\nu}), \tag{2}$$

where it is assumed that the mooring system is symmetrically arranged. Assuming fixed anchor line length, the damping effects of the mooring lines can be approximated by a linear damping model $\boldsymbol{D}_{mo}\boldsymbol{\nu}$. It is a common practice to estimate the linear damping of the mooring line by about $10 - 20\%$ of critical damping of the entire system (Nguyen et al., 2011). We have augmented the linear damping of the mooring system into the damping term $\boldsymbol{D}\boldsymbol{\nu}$. The Earth-fixed restoring force $\boldsymbol{g_{mo}}(\boldsymbol{\eta}) \in \mathbb{R}^3$ is given by

$$\boldsymbol{g}_{mo}(\boldsymbol{\eta}) = \boldsymbol{T}(\boldsymbol{\beta})\boldsymbol{\tau}_H, \tag{3}$$

where $\boldsymbol{\beta} \in \mathbb{R}^M$ is the mooring line orientation vector consisting of the angles between the mooring lines and the x-axis, $\boldsymbol{\tau}_H = [H_1, H_2, \cdots, H_M]^\top$ denotes the horizontal mooring force vector, and H_i represents the horizontal force component at TP_i. Suppose the moment provided by the mooring restoring forces is disregarded, the mooring line configuration matrix is

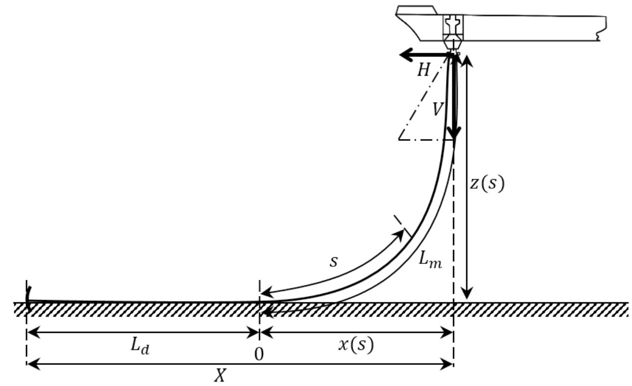

Fig. 2. Mooring line configuration.

$$\boldsymbol{T}(\boldsymbol{\beta}) = \begin{bmatrix} cos\beta_1 & \cdots & cos\beta_M \\ sin\beta_1 & \cdots & sin\beta_M \\ 0 & \cdots & 0 \end{bmatrix}. \tag{4}$$

Fig. 2 shows the configuration of a single mooring line. The 2D catenary equations (5a) and (5b) are used in this case to calculate H_i and the vertical mooring force component V_i (Aamo and Fossen, 2001).

$$x_i(s) = \frac{H_i}{E_m A_m} s + \frac{H_i}{\omega_m} \left\{ sinh^{-1} \left[\frac{V_i - \omega_m (L_m - s)}{H_i} \right] - sinh^{-1} \left[\frac{V_i - \omega_m L_m}{H_i} \right] \right\}, \tag{5a}$$

$$z_i(s) = \frac{1}{E_m A_m} \left[V_i s + \frac{\omega_m}{2} \left((L_m - s)^2 - L_m^2 \right) \right] + \frac{H_i}{\omega_m} \left[\sqrt{1 + \left(\frac{V_i - \omega_m (L_m - s)}{H_i} \right)^2} + \sqrt{1 + \left(\frac{V_i - \omega_m L_m}{H_i} \right)^2} \right], \tag{5b}$$

where s is the path parameter along the cable, $x_i(s)$ and $z_i(s)$ are the positions of each segment centred at length s along the i^{th} cable, L_m is the unstretched suspended segment length of the mooring lines, ω_m is the weight in water per unit length, E_m is the Young's modulus of elasticity, A_m stands for the cross-section area of the line, $T_i = \sqrt{V_i^2 + H_i^2}$ is tension at the end of the i^{th} mooring line, and $\phi_i = arctan(V_i/H_i)$ is the angle between the line tension and its vertical component. When the attachment point moves in either the horizontal plane or the vertical plane, L_m and the touchdown length L_d vary. The unstretched length of the mooring lines is supposed to be a constant, such that $L = L_d + L_m$.

2.3 Control law

The corresponding PID controller for thrust assist is designed to keep the LF heading and position at desired values. The PID controller is given by

$$\dot{\boldsymbol{\xi}} = \tilde{\boldsymbol{\eta}}, \tag{6a}$$

$$\boldsymbol{\tau}_c = -\boldsymbol{K}_i \boldsymbol{R}(\psi)^\top \boldsymbol{\xi} - \boldsymbol{K}_p \boldsymbol{R}(\psi)^\top \tilde{\boldsymbol{\eta}} - \boldsymbol{K}_d \tilde{\boldsymbol{\nu}}, \tag{6b}$$

where $\tilde{\boldsymbol{\eta}} = \hat{\boldsymbol{\eta}} - \boldsymbol{\eta}_d$ and $\tilde{\boldsymbol{\nu}} = \hat{\boldsymbol{\nu}} - \boldsymbol{\nu}_d$ are the position and velocity error vectors, $\boldsymbol{\eta}_d$ and $\boldsymbol{\nu}_d$ are the desired position and velocity vectors from the reference system, $\boldsymbol{K}_p$, $\boldsymbol{K}_i$, and $\boldsymbol{K}_d \in \mathbb{R}^{3\times3}$ are diagonal non-negative PID controller gain matrices (see Fossen (2011) for more details). The states $\hat{\boldsymbol{\eta}}$ and $\hat{\boldsymbol{\nu}}$ are later replaced by the estimated states $\hat{\boldsymbol{\eta}}_m$ and $\hat{\boldsymbol{\nu}}_m$ from an observer.