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A Tension-based Position Estimation Solution of a Moored Structure and its Uncertain Anchor Positions ⋆

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Abstract: Thruster-assisted position mooring (TAPM) is an attractive stationkeeping solution for long-term operation. Due to the complex environmental loads and system structure, increasing attention has been paid to improve the redundancy and reliability. This paper summaries the key research results when introducing the simultaneous localization and mapping algorithm to moored structures, which can provide an additional position reference system with uncertain anchor positions. It is especially cost-efficient for some applications alleviating the need for special sensors, such as, hydroacoustic sensors. The line-of-sight range mapping from tension measurements is discussed. Fairleads, the turret dynamics, and loading effects are considered to provide a more realistic and robust solution. A sensor network scheme and a state-space model are proposed, and an extended Kalman filter (EKF) is employed to estimate the uncertain anchor position.

Keywords: Thruster-assisted position mooring; map aided localization; SLAM

1. INTRODUCTION

Since oil exploration moves towards deeper waters, thruster-assisted position mooring (TAPM) has become an attractive stationkeeping solution for long-term operation (Skjetne et al., 2014). With the increasing attention to safety and new technological innovations, newly built TAPMs tend to be equipped with tension cells, which gives availability of tension measurements. A winch load monitoring system can enhance the systematic autonomy, as well as detect fatigue and line breakage (May et al., 2008). Aamo and Fossen (1999) theoretically addresses a robust dynamic mooring tension control scheme. The experimental verifications are conducted in Nguyen et al. (2011) and Ji et al. (2015). Furthermore, tension measurements may potentially be used to estimate the current profile (Ren and Skjetne, 2016).

It has been reported by the main class societies that one anchor is lost per 100 ships each year (Gard News, 2011). The risk of losing anchors and chains is tremendous when considering the service life in more than 20 years. The broken chains and anchors are considered as wrecks. According to the IMO convention, shipowners has the financial responsibility to the wreck removal (Ratcovich, 2008). Therefore, techniques which can quickly locate and remove the lost anchors are valuable.

Collaborative position location is a localization technique. Nodes in a sensor network can determine their locations collaboratively. It can be classified into deterministic and probabilistic methods. Approaches based on the maximum likelihood, such as the second-order cone programing (SOCP) and semi-definite programming (SDP), are widely-applied deterministic optimization-based approaches (Naddafzadeh-Shirazi et al., 2014; Tseng, 2007). Ren et al. (2015) applies a tension-based scheme to locate the position of the moored vessel with known anchor positions. The anchors are then regarded as landmarks. However, the application of the algorithm is limited by the precise knowledge of the positions of the anchors. The above-mentioned methods are not robust enough, since a moored structure can only move in a limited region much smaller than the footprints of the mooring lines. Hence, the anchor positions may not be distinguishable. Simultaneous localization and mapping (SLAM) is a relatively new technique applied in robotics to locate the robot with uncertain landmarks and no access to position reference (posref) through a joint estimation of pose and landmarks (Gustafsson, 2010). Normally, extended Kalman filter (EKF), particle filter, and FastSLAM are the most popular approaches (Durrant-Whyte and Bailey, 2006).

This paper adapts the map aided localization technique to the TAPM system. The key application is to locate the vessel with tension measurements. In addition, a simplified model is used to track the uncertain anchor positions for any vessels equipped with tension cells. With precise localization and short operation period, the costs to remove the lost anchors will be reduced.

1.1 Terminology

In this paper, an *anchor* and an *anchor node* are two different terms with unlike meanings. We define them as follows:

Definition 1. (Anchor). An anchor is a heavy device attached to a cable or chain which is used to prevent the craft from drifting due to environmental loads (Oxford Advanced Learner's Dictionary, n.d.).

Definition 2. (Anchor node). An anchor node is a node in a sensor network whose position is expected to have been known (Zekavat and Buehrer, 2011). We can also call it a landmark.

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2. SYSTEM MODELING

A surface vessel is spreadly moored by M anchor lines and equipped with thruster assist. Each mooring line is connected to the turret through the corresponding fairlead (see Fig. 1(a)). The vessel motion is assumed to be represented in 3DOF by surge, sway, and yaw. The environmental loads are wind, waves, and currents. The Earth-fixed north-east-down (NED) and body-fixed coordinate systems, $\{E\}$ and $\{B\}$, are employed in this paper. The origin of the NED frame is located at the field zero point (FZP) which is the equilibrium position where the vessel comes to rest without any environmental and thruster loads. The turret can rotate about a vertical axis at the center of turret (COT) for simplification. The motion can be superposed by the low-frequency (LF) model and the wave-frequency (WF) model (Fossen, 2011).

2.1 Vessel model

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

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

$$\dot{\boldsymbol{b}} = -\boldsymbol{T}_b^{-1}\boldsymbol{b} + \boldsymbol{E}_b\boldsymbol{w}_b, \tag{1b}$$

$$\boldsymbol{M}\dot{\boldsymbol{\nu}} = -\boldsymbol{D}\boldsymbol{\nu} + \boldsymbol{R}(\psi)^\top\boldsymbol{b} + \boldsymbol{\tau}_m + \boldsymbol{\tau}_c \tag{1c}$$

$$\dot{\boldsymbol{\xi}} = \boldsymbol{A}_w\boldsymbol{\xi} + \boldsymbol{E}_w\boldsymbol{w}_w, \tag{1d}$$

$$\boldsymbol{\eta}_w = \boldsymbol{C}_w\boldsymbol{\xi}, \tag{1e}$$

where $\boldsymbol{\eta} = [x \ y \ \psi]^\top$ consists of LF position and heading orientation of the vessel relative to the NED frame, $\boldsymbol{\nu} = [u \ v \ r]^\top$ represents the vector of transverse and angular velocities decomposed in the body-fixed reference, $\boldsymbol{R}(\psi) \in \mathbb{R}^{3\times3}$ denotes the rotation matrix between the body-fixed frame and the NED frame (see Fig. 1(a)), $\boldsymbol{E}_b \in \mathbb{R}^{3\times3}$ is a diagonal scaling matrix, $\boldsymbol{M} \in \mathbb{R}^{3\times3}$ 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 slowly varying bias vector in the NED frame, $\boldsymbol{\tau}_c \in \mathbb{R}^3$ represents the thruster-induced loads, and $\boldsymbol{\tau}_m \in \mathbb{R}^3$ is the mooring loads. $\boldsymbol{\xi} = [\xi_1, \xi_2, \xi_3, \xi_4, \xi_5, \xi_6]^\top \in \mathbb{R}^6$, $\boldsymbol{\eta}_w \in \mathbb{R}^3$ is the WF motion vector, $\boldsymbol{w}_w \in \mathbb{R}^3$ is a zero-mean Gaussian white noise vector, $\boldsymbol{A}_w \in \mathbb{R}^{6\times6}$, $\boldsymbol{C}_w \in \mathbb{R}^{3\times6}$, and $\boldsymbol{E}_w \in \mathbb{R}^{6\times3}$ are the system matrix, measurement matrix, and diagonal scaling matrix of the linear filter. See Fossen (2011) for details.

2.2 Mooring forces

The mooring system is simulated by a FEM model. A horizontal-plane spread mooring model is formulated as

$$\boldsymbol{\tau}_m = -\boldsymbol{R}(\psi)^\top\boldsymbol{g}_{mo} - \boldsymbol{D}_{mo}\boldsymbol{\nu}, \tag{2}$$

where it is assumed that the mooring system is symmetrically arranged. The Earth-fixed restoring force and moment vector acting at the moored vessel is given by

$$\boldsymbol{g}_{mo} = \begin{bmatrix} \boldsymbol{g}^t_{mo,1:2} \\ D^t_z\dot{\tilde{\psi}}_t \end{bmatrix}, \tag{3}$$

where $\boldsymbol{g}^t_{mo}$ is the restoring force and moment vector acting at the turret, the subscript $1:2$ means the first and second elements in the vector, ψ_t is the angle of the turret comparing with the reference, $\tilde{\psi}_t = \psi_t - \psi$ is the relative angle between the turret and the heading of the moored vessel. The dynamic model of $\tilde{\psi}_t$ is given by

$$I^t_z\ddot{\tilde{\psi}}_t = -\boldsymbol{g}^t_{mo,3} - D^t_z\dot{\tilde{\psi}}_t, \tag{4}$$

where I^t_z is the mass inertia of moment of the turret and D^t_z is the damping between the vessel and the turret. The restoring forces and moment vector $\boldsymbol{g}^t_{mo}(\boldsymbol{\eta}) \in \mathbb{R}^3$, which the mooring lines exert on the turret, is given by

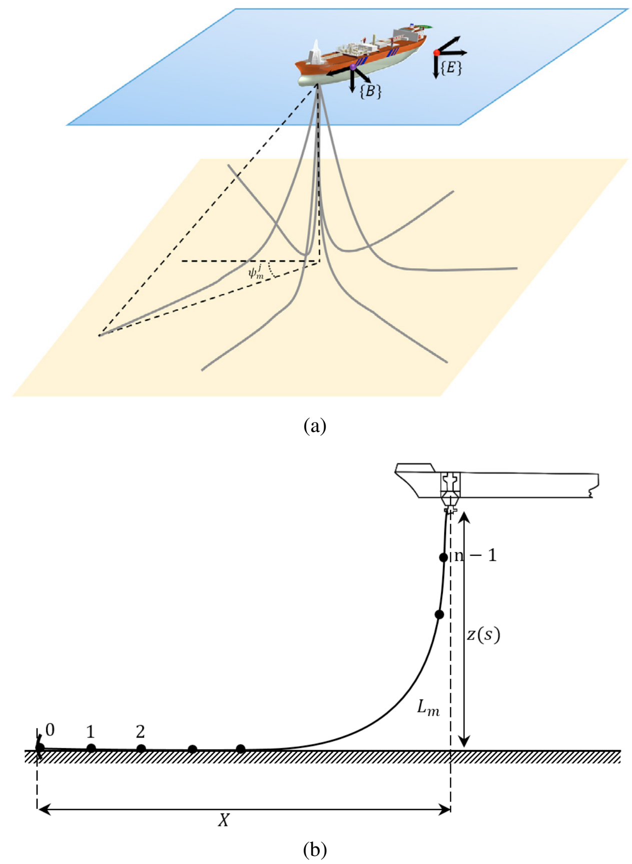

Fig. 1. (a) Reference frames, (b) finite element method (FEM) model of a mooring line.

$$\boldsymbol{g}^t_{mo} = \sum_{i=1}^{M}\begin{bmatrix} \boldsymbol{f}^i_{mo,1:2} \\ \boldsymbol{f}^i_{mo,1:2} \times (\boldsymbol{p}^i_f - \boldsymbol{p}_{COT}) \end{bmatrix}, \tag{5}$$

where $\boldsymbol{f}_{mo} \in \mathbb{R}^3$ is the generalized force at the end of the cable, respectively, in x, y, and z direction. The horizontal position of a fairlead $\boldsymbol{p}^i_f \in \mathbb{R}^2$ are given by

$$\boldsymbol{p}^i_f = \boldsymbol{p}_{COT} + \begin{bmatrix} r_t\cos(\gamma^i_f) \\ r_t\sin(\gamma^i_f) \end{bmatrix}, \quad i = 1, \cdots, M, \tag{6}$$

where $\boldsymbol{p}_{COT} \in \mathbb{R}^2$ is the horizontal position of the COT. For simplification, we consider a situation that the COT overlaps with the center of gravity (COG) of the vessel in this paper, i.e., $\boldsymbol{p}_{COT} = [x, y]^\top$. The horizontal position of the i^{th} fairlead is represented by $\boldsymbol{p}^i_f \in \mathbb{R}^2$, r_t is the radius of the circle where the fairleads locate, and γ^i_f is the angle of the i^{th} fairlead compared to the reference angle.

The FEM model is developed in Aamo and Fossen (2001). With the proof of the existence and uniqueness of the solution, it can be used to simulate the mooring line in the time domain. The unstretched length of the i^{th} cable is L^i. Each of the mooring line is uniformly divided into n segments of length $l^i = L^i/n$, and the weight of all segments concentrate at all the $n+1$ nodes. From the anchor to the fairlead, the nodes are enumerated from 0 to n. The position vector of the k^{th} node along the i^{th} cable in the Earth-fixed coordinate is denoted by $\boldsymbol{r}^i_k \in \mathbb{R}^3$. The positions of the bottom and top end nodes are the anchor and the fairlead, i.e., $\boldsymbol{r}^i_{0,1:2} = \boldsymbol{p}^i_a$ and $\boldsymbol{r}^i_{n,1:2} = \boldsymbol{p}^i_f$. A node is only influenced by its