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A Tension-based Position Estimation Solution of a A Tension-based Position Estimation Solution of a Moored Structure and its Uncertain Anchor Moored Structure and its Uncertain Anchor Positions Moored Structure and its Uncertain Anchor e and its $\mathbf c$
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 $\frac{1}{2}$ and $\frac{1}{2}$ are 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 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
mapping algorithm to m provide an additional position reference system with uncertain anchor positions. It is especially costprovide 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
as a sensor network of the 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. scheme and a state-space model are proposed, and an extended Kalman filter (EKF) is employed to estimate the uncertain anchor position. estimate the uncertain and a state-space model are proposed and and and an extended Kalman filter (EKF) is extended Kalman fil Abstract: Thruster-assisted position mooring (TAPM) is an attractive stationkeeping solution for longprovide a additional provide a additional position reference system and provide a supervisors. It is especially contained the system with uncertainty contained the system of the system of the system of the system of the sy

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

1. INTRODUCTION 1. INTRODUCTION 1. INTRODUCTION

Since oil exploration moves towards deeper waters, thrustersince on exploration moves towards deeper waters, unuster-
assisted position mooring (TAPM) has become an attractive assisted position mooting (TAFM) has become an attractive
stationkeeping solution for long-term operation (Skjetne et al., 2014). With the increasing attention to safety and new techno-
logical importance, pouly huit $TADM_0$ to the continued logical innovations, newly built TAPMs tend to be equipped logical inflovations, hewry built TAFMs 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 breaksystematic autonomy, as wen as detect ratigue and line break-
age (May et al., 2008). Aamo and Fossen (1999) theoretically age (way et al., 2006). Aanto and rossen (1999) theoretically
addresses a robust dynamic mooring tension control scheme. 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 may potentially be used to estimate the current profile (Ren and Skjetne, 2016). may potentially be used to estimate the current profile (Ren and Skjetne, 2016). Skjetne, 2016). Skjetne, 2016). 1. INTRODUCTION scheme to locate the position of the moored vessel with known
state/adoct state/adoct stationkeeping solution for long-term operation (Skjetne et al.,
2014) With the increasing ettention to sefety and new technol with tension cens, which gives availability of tension mea-The experimental verifications are conducted in Nguyen et al.
 (2011) and E at al. (2015) . Eugharmore, tangian maggiusmanta

It has been reported by the main class societies that one anchor It has been reported by the main class societies that one anchor It has been reported by the main class societies that one anchor It has been reported by the main class societies that one anchor
is lost per 100 ships each year (Gard News, 2011). The risk is lost per 100 sinps each year (Gard News, 2011). The 11sk
of losing anchors and chains is tremendous when considering or iosing 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 and anchors are considered as wrecks. According to the INO
convention, shipowners has the financial responsibility to the convention, sinpowners has the miancial responsibility to the
wreck removal (Ratcovich, 2008). Therefore, techniques which can quickly locate and remove the lost anchors are valuable. can quickly locate and remove the lost anchors are valuable. It has been reported by the main class societies that one anchor can quickly locate and remove the lost anchors are valuable. the service life in more than 20 years. The broken chains
and apphora are considered as wrocks. According to the IMO wreck removal (Ratcovich, 2008). Therefore, techniques which
aan quickly looste and remove the lost anghors are veluable.

Collaborative position location is a localization technique. Nodes in a sensor network can determine their locations collaboratively. It can be also signified into deterministic and probability oratively. It can be classified into deterministic and probabilis-
tie methods. Approaches besed on the maximum likelihood tic methods. Approaches based on the maximum likelihood, such as the second-order cone programing (SOCP) and semi-
definite programming (SDP) are widely emplied determinis definite programming (SDP), are widely-applied determinis-
tie optimization beged opproaches (Neddefradeb Shirozi et el. tic optimization-based approaches (Naddafzadeh-Shirazi et al., 2014; Tseng, 2007). Ren et al. (2015) applies a tension-based tic 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 scriente to locate the position of the moored vesser with known
anchor positions. The anchors are then regarded as landmarks. anchor positions. The anchors are then regarded as familiarks.
However, the application of the algorithm is limited by the precise knowledge of the positions of the anchors. The above-
montioned methods are not rebust appuch since a moored mentioned methods are not robust enough, since a moored inentioned methods are not robust enough, since a moored
structure can only move in a limited region much smaller structure can only move in a infinited region much smaller
than the footprints of the mooring lines. Hence, the anchor positions may not be distinguishable. Simultaneous localization positions may not be distinguishable. Simultaneous localization 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 robotics to locate the robot with uncertain landmarks and no robotics to focate the robot with different randmarks and no
access to position reference (posref) through a joint estimation access to position reference (poster) unough a joint estimation
of pose and landmarks (Gustafsson, 2010). Normally, extended or pose and randmarks (Gustafsson, 2010). Normany, extended
Kalman filter (EKF), particle filter, and FastSLAM are the most popular approaches (Durrant-Whyte and Bailey, 2006). popular approaches (Durrant-Whyte and Bailey, 2006). popular approaches (Barrant Whyte and Baney, 2000). However, the application of the algorithm is limited by the positions may not be distinguishable. Simultaneous localization Kalinan 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 This paper adapts the map alted localization technique to the
TAPM system. The key application is to locate the vessel with
tension measurements. In addition, a simplified model is used tension measurements. In addition, a simplified model is used tension measurements. In addition, a simplified model is used tension measurements. In addition, a simplified model is used
to track the uncertain anchor positions for any vessels equipped to track the uncertain anchor positions for any vessers equipped
with tension cells. With precise localization and short operation with tension cens. With precise localization and short operation period, the costs to remove the lost anchors will be reduced. TAPM system. The key application is to locate the vessel with period, the costs to remove the lost anchors will be reduced.

1.1 Terminology 1.1 Terminology 1.1 Terminology 1.1 Terminology

In this paper, an *anchor* and an *anchor node* are two different terms with unlike meanings. We define them as follows: 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 each a coble or obein which is used to prevent the creft from drifting a cable or chain which is used to prevent the craft from drifting a cable of chain which is used to prevent the craft from drifting
due to environmental loads (Oxford Advanced Learner's Dictionary, n.d.). due to environmental loads (Oxford Advanced Learner's Dic-

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

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

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

$$
M\dot{\nu} = -D\nu + R(\psi)^{\dagger} b + \tau_m + \tau_c \tag{1c}
$$

$$
\dot{\xi} = A_w \xi + E_w w_w, \tag{1d}
$$

$$
\eta_w = C_w \xi, \tag{1e}
$$

where $\eta = [x \ y \ \psi]$ consists of LF position and heading orientation of the vessel relative to the NED frame, $\nu = [u \, v \, r]^{\top}$ represents the vector of transverse and angular velocities decomposed in the body-fixed reference, $\mathbf{R}(\psi) \in \mathbb{R}^{3 \times 3}$ denotes the rotation matrix between the body-fixed frame and the NED frame (see Fig. 1(a)), $E_b \in \mathbb{R}^{3 \times 3}$ is a diagonal scaling matrix, $M \in \mathbb{R}^{3 \times 3}$ is the generalized system inertia matrix including zero frequency added mass components, $D \in \mathbb{R}^{3 \times 3}$ denotes the linear damping matrix, $\mathbf{b} \in \mathbb{R}^3$ is a slowly varying bias vector in the NED frame, $\tau_c \in \mathbb{R}^3$ represents the thruster-induced loads, and $\tau_m \in \mathbb{R}^3$ is the mooring loads. $\xi = [\xi_1, \xi_2, \xi_3, \xi_4, \xi_5, \xi_6]^\top \in$ \mathbb{R}^6 , $\eta_w \in \mathbb{R}^3$ is the WF motion vector, $w_w \in \mathbb{R}^3$ is a zeromean Gaussian white noise vector, $A_w \in \mathbb{R}^{6 \times 6}$, $C_w \in \mathbb{R}^{3 \times 6}$, and $E_w \in \mathbb{R}^{6 \times 3}$ 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 horizontalplane spread mooring model is formulated as

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

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

$$
g_{mo} = \begin{bmatrix} g_{mo,1:2}^t \\ D_z^t \tilde{\psi}_t \end{bmatrix},\tag{3}
$$

where g_{mo}^t 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

$$
I_z^t \ddot{\tilde{\psi}}_t = -\boldsymbol{g}_{mo,3}^t - D_z^t \dot{\tilde{\psi}}_t, \tag{4}
$$

where I_z^t is the mass inertia of moment of the turret and D_z^t is the damping between the vessel and the turret. The restoring forces

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

and moment vector $g_{m\rho}^t(\eta) \in \mathbb{R}^3$, which the mooring lines exert on the turret, is given by

$$
g_{mo}^t = \sum_{i=1}^M \left[\frac{f_{mo,1:2}^i}{f_{mo,1:2}^i \times (p_f^i - p_{COT})} \right],
$$
 (5)

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

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

where $p_{COT} \in \mathbb{R}^2$ 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., $p_{COT} = [x, y]^\top$. The horizontal position of the *i*th fairlead is represented by $p_f^i \in \mathbb{R}^2$, r_t is the radius of the circle where the fairleads locate, and γ_f^i 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 $r_k^i \in \mathbb{R}^3$. The positions of the bottom and top end nodes are the anchor and the fairlead, i.e., $\mathbf{r}_{0,1:2}^i = \mathbf{p}_a^i$ and $\mathbf{r}_{n,1:2}^i = \mathbf{p}_f^i$. A node is only influenced by its

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