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Attitude and Heave Estimation for Ships using MEMS-based Inertial Measurements

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Abstract: We conduct full-scale experimental validation and comparison of three different nonlinear attitude observers, two of them with inherent heave estimation, in two different operational scenarios encountered by an offshore vessel in the North Sea. Two different micro-electro-mechanical inertial measurement units are the primary sensors for driving the nonlinear observers, which are aided by gyrocompasses and position reference systems. The results are compared with data from well-proven industry standard vertical reference units.

Keywords: Inertial navigation; Attitude estimation; Nonlinear observers; Inertial Measurement Unit; Marine systems

1. INTRODUCTION

Attitude information is of importance for navigating a ship, in particular in dynamic positioning (DP) operations. Knowledge of the ship's heading is essential in order to guide the vessel correctly, and inertial measurement technology has become the de facto standard for estimating the heading of a ship. Since the first operational gyrocompass was installed by Anschutz in 1907, and the following ballistic compass by Sperry three years later, the gyrocompass based on gimbal inertial sensor technology and physical self-alignment, has been established as the main source of heading information on ships and free floaters. For positioning, roll and pitch information is also vital in order to transform the position measurements, global or relative, from the measurements' point to a point of interest somewhere on the ship. This is known as lever arm compensation. Knowledge of the vessel's roll and pitch angles are also needed to operate ballast systems. During both ballasting and lever arm compensation of position reference (PosRef) system measurements on a ship, a VRU is typically utilized, Ingram et al. (1996). This is a compact and cost-effective solution, typically using micro-electro-mechanical systems (MEMS) based strapdown inertial navigation systems (INS), providing roll, pitch and heave estimates. The heave estimates are also of interest in heave compensation of cranes or drill floors during drilling operation in waves, in heave displacement control of high-speed surface effect ships and for on-board decision support systems such as weather and sea state prediction.

The increasing availability and quality of cost-effective MEMS inertial measurements units (IMU) the last decade have also spurred the research on attitude estimation using nonlinear observer (NLO) theory, based on MEMS inertial technology, such as Mahony et al. (2008), Hua (2010), Grip et al. (2012a) and Batista et al. (2012a; 2012b). The NLO of Grip et al. (2012a), based on Mahony et al. (2008), has been extended to make use of the translational motion obtained in a PosRef-aided INS to improve the attitude observer's estimates, based on the theory of Grip et al. (2012b). Examples of such results are Grip et al. (2013; 2015) where a three degree of freedom position measurement is assumed available. Furthermore, in Bryne et al. (2014, 2015) the results of Grip et al. (2013) have been tailored for marine surface navigation by replacing the need of vertical global navigation satellite system (GNSS) or hydro acoustic measurement components with a virtual vertical reference (VVR) measurement to stabilize the vertical axes of the INS. In Rogne et al. (2015), the attitude observers of Hua et al. (2014) and Grip et al. (2013) were compared to test fault tolerance w.r.t. heading and position reference errors. NLOs have the benefit of explicit stability properties making the observer robust to sensor noise and large initialization errors since no linearization is needed in the attitude estimation, as compared with estimators based on the extended Kalman filter (EKF), Groves (2013) or the multiplicative extended Kalman filter (MEKF), Markley (2003).

Examples of heave estimation based on MEMS inertial sensors using both linear and nonlinear methods are presented in Godhavn (1998), Küchler et al. (2011), Richter et al. (2014), Bryne et al. (2014; 2015). Godhavn (1998) and Richter et al. (2014) are based on linear bandpass filtering, while Bryne et al. (2014; 2015) is applying NLOs to estimate heave.

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1.1 Main Contribution

The main contributions of this paper are on full-scale verification of different NLOs for attitude estimation for ships, using two low-cost MEMS IMUs. The verification consist of:

- Applying three NLOs; Mahony et al. (2008), Bryne et al. (2014) and Rogne et al. (2016) for ship attitude estimation.
- Applying the NLOs and IMUs during two operation conditions: DP and turning maneuvers.
- Evaluation of heave estimation performance using a virtual vertical reference (VVR) signal, Bryne et al. (2014; 2015).

The results are obtained by comparing the estimation result to well-proven sensor systems providing roll, pitch and heave measurements for marine surface vessels.

2. PRELIMINARIES

2.1 Notation

The Euclidean vector norm is denoted $\|\cdot\|_2$. The $n \times n$ identity matrix is denoted $\boldsymbol{I}_n$, while the transpose of a vector or a matrix is denoted with $(\cdot)^\intercal$. Coordinate frames are denoted with $\{\cdot\}$. $\boldsymbol{S}(\cdot) \in SS(3)$ represents the skew symmetric matrix such that $\boldsymbol{S}(\boldsymbol{z}_1)\boldsymbol{z}_2 = \boldsymbol{z}_1 \times \boldsymbol{z}_2$ for two vectors $\boldsymbol{z}_1, \boldsymbol{z}_2 \in \mathbb{R}^3$. In addition, $\boldsymbol{z}^a_{bc} \in \mathbb{R}^3$ denotes a vector $\boldsymbol{z}$, to frame $\{c\}$, relative $\{b\}$, decomposed in $\{a\}$. Moreover, $\otimes$ denotes the Hamiltonian quaternion product. Saturation is represented by $\mathrm{sat}_\star$, where the subscript indicates the saturation limit.

The rotation matrix describes the rotation between two given frames $\{a\}$ and $\{b\}$ and is denoted $\boldsymbol{R}^b_a \in SO(3)$. Similar to the rotation matrix, the rotation between $\{a\}$ and $\{b\}$ may be represented using the unit quaternion $\boldsymbol{q}^b_a = (s, \boldsymbol{r}^\intercal)^\intercal$ where $s \in \mathbb{R}^1$ is the real part of the quaternion and $\boldsymbol{r} \in \mathbb{R}^3$ is the vector part. Roll, pitch and yaw are denoted ϕ, θ and ψ, respectively.

2.2 Coordinate Reference Frames

This paper employs four coordinate frames; The Earth Centered Inertial (ECI) frame, the Earth Centered Earth Fixed (ECEF) frame, a tangent frame equivalent of a Earth-fixed North-East-Down (NED) frame, and the BODY reference frame, denoted $\{i\}$, $\{e\}$, $\{n\}$ and $\{b\}$, respectively (see Fig. 1). ECI is an assumed inertial frame following the Earth, where the x-axis points towards vernal equinox, the z-axis is pointing along the Earth's rotational axis and the y-axis completes the right hand frame. Regarding the ECEF, the x-axis points towards the zero meridian, the z-axis points along the Earth's rotational axis, while the y-axis completes the right hand frame. The Earth's rotation rate $\omega_{ie} = 7292115 \cdot 10^{-11}$ rad/s is given by the WGS-84 datum. It is further decomposed in the ECEF and NED frame as

$$\boldsymbol{\omega}^e_{ie} = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \omega_{ie}, \quad \boldsymbol{\omega}^n_{ie} = \begin{pmatrix} \cos(\mu) \\ 0 \\ -\sin(\mu) \end{pmatrix} \omega_{ie}, \tag{1}$$

where μ is the latitude on the Earth and $\boldsymbol{\omega}^\star_{\star\star}$ represents angular velocity. The longitude is denoted λ. Furthermore,

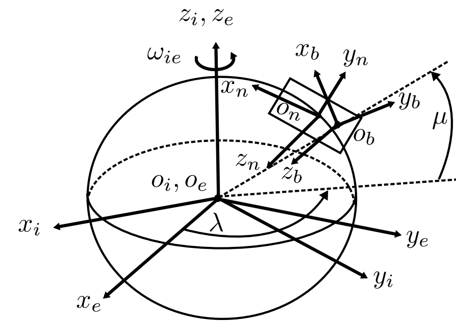

Fig. 1. Definitions of the BODY, NED (tangent), ECEF and ECI reference frames.

the navigation frame is a local Earth-fixed tangent frame, {n}, where the x-axis points towards north, the y-axis points towards east, and the z-axis points downwards. The BODY frame is fixed to the vessel. The origin of {b} is located at the nominal center of gravity of the vessel. The x-axis is directed from aft to fore, the y-axis is directed to starboard and the z-axis points downwards.

2.3 Kinematic Strapdown Equations

The attitude representation most comprehensible for the user is the attitude between the BODY and the NED or tangent frame. This is also the most intuitive representation for control and lever arm compensation purposes. Using a rotation matrix representation, the attitude kinematics in this paper is given as

$$\dot{\boldsymbol{R}}^n_b = \boldsymbol{R}^n_b \boldsymbol{S}(\boldsymbol{\omega}^b_{ib}) - \boldsymbol{S}(\boldsymbol{\omega}^n_{in})\boldsymbol{R}^n_b, \tag{2}$$

or equivalently,

$$\dot{\boldsymbol{q}}^n_b = \frac{1}{2}\boldsymbol{q}^n_b \otimes \begin{pmatrix} 0 \\ \boldsymbol{\omega}^b_{ib} \end{pmatrix} - \frac{1}{2}\begin{pmatrix} 0 \\ \boldsymbol{\omega}^n_{in} \end{pmatrix} \otimes \boldsymbol{q}^n_b, \tag{3}$$

using the unit quaternion attitude representation. $\boldsymbol{\omega}^b_{ib}$ is the angular rate of the navigating object relative the inertial frame, while $\boldsymbol{\omega}^n_{in}$ is the angular velocity of navigation frame relative the inertial frame where,

$$\boldsymbol{\omega}^n_{in} = \boldsymbol{\omega}^n_{ie} + \boldsymbol{\omega}^n_{en} = \boldsymbol{\omega}^n_{ie}, \tag{4}$$

since a tangent frame representation of the strapdown equations are chosen, resulting in $\boldsymbol{\omega}^n_{en} = \boldsymbol{0}_{3\times1}$. Furthermore, from Fossen (2011), Eq. (2.56) and reference therein, the rotation matrix $\boldsymbol{R}(\boldsymbol{q}^n_b) := \boldsymbol{R}^n_b$ is obtained from $\boldsymbol{q}^n_b$ using

$$\boldsymbol{R}(\boldsymbol{q}^n_b) = \boldsymbol{I}_3 + 2s\boldsymbol{S}(\boldsymbol{r}) + 2\boldsymbol{S}(\boldsymbol{r}). \tag{5}$$

When using the tangent frame as the navigation frame, the rotational and translational motion is related with

$$\dot{\boldsymbol{p}}^n_{nb} = \boldsymbol{v}^n_{nb}, \tag{6}$$

$$\dot{\boldsymbol{v}}^n_{nb} = -2\boldsymbol{S}(\boldsymbol{\omega}^n_{ie})\boldsymbol{v}^n_{nb} + \boldsymbol{R}^n_b \boldsymbol{f}^b_{ib} + \boldsymbol{g}^n_b, \tag{7}$$

where $\boldsymbol{p}^n_{nb} \in \mathbb{R}^3$ is the position, relative a defined origin of the tangent frame, $\boldsymbol{p}^n_{nb}(0) := \boldsymbol{0}_{3\times1}$ based on $\mu(0)$ and $\lambda(0)$. Furthermore, $\boldsymbol{v}^n_{nb} \in \mathbb{R}^3$ is the linear velocity. It follows that $\boldsymbol{g}^n_b(\mu, \lambda) \in \mathbb{R}^3$ is the local gravity vector which may be obtained using a gravity model based on the vessel's latitude and longitude. $\boldsymbol{f}^b_{ib} = (\boldsymbol{R}^n_b)^\intercal(\boldsymbol{a}^n_{ib} - \boldsymbol{g}^n_b) \in \mathbb{R}^3$ is the specific force decomposed in {b}, where $\boldsymbol{a}^n_{ib}$ is the accelerations decomposed in the tangent frame, measured by the IMU. Moreover, (6)–(7) can further be extended for marine surface craft with the auxiliary variable $p^n_{nb,I}$. The augmentation, first applied in Bryne et al. (2014), is