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MEMS-based Inertial Navigation on Dynamically Positioned Ships: Dead Reckoning

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Abstract: Dead reckoning capabilities are vital in ship navigation if position and heading references are unrealizable or lost. In safety critical marine operations such as dynamic positioning, the International Maritime Organization and classification societies require that the vessel possesses dead reckoning capabilities and position reference redundancy. In this paper, we conduct a full-scale experimental validation and comparison of the dead reckoning capabilities using two different high-rate and low-cost micro-electro-mechanical inertial measurement units. The full-scale experimental validation is achieved with two nonlinear observers, aided by gyrocompasses and position reference systems, in a dynamic positioning operation carried out by an offshore vessel in the North Sea. The dead reckoning performance is evaluated after ten minutes without aiding from position reference system measurements.

Keywords: Inertial navigation; Navigation systems, Position estimation, Dead Reckoning; Nonlinear observers; Inertial Measurement Unit; Marine systems

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1. INTRODUCTION

The *dead reckoning* (DR) term is used in the navigation community to describe the process of estimating position relative some departure point by keeping track of the distance covered and direction of travel. The origin of DR as an expression is not known, but one possibility is that it stems from *ded* reckoning, short for deduced reckoning, Misra and Enge (2011, Ch. 1). Inertial navigation systems (INS) are DR based, by deducing position, velocity and attitude (PVA) from previously known states by integration of angular rate measurements and accelerometer readings, once and twice, respectively. Due to errors in the inertial sensor, such as noise and biases, DR is insufficient to maintain accurate estimates over time. To counter INS drift over time, aiding is introduced. Aided INS are often referred to as integrated navigation systems.

INS can be aided by a number of sensors and position reference (PosRef) systems such as radio, laser, hydroacoustic and satellite-based systems. The latter types have the benefit of world-wide coverage, known as Global Navigation Satellite System (GNSS). However, these systems are exposed to both natural degradation and deliberate outages. Natural degradation can be caused by signal distortion from reflection of nearby objects, known as multipath, loss of signal due to sun storms or loss of line of sight to the satellite. Deliberately outages can be because of signal jamming. During loss of reference, good DR capabilities is vital for the INS to provide accurate PVA estimates to the user. Recent works on aided INS using nonlinear observers (NLO), such as Hua (2010), Grip et al. (2013), Bryne et al. (2014; 2015), Grip et al. (2015), and Rogne et al. (2016), have not discussed the DR capabilities using such observer designs. An exception is Fusini et al. (2016), however this result uses visually aided INS to improve the heading estimates and provide velocity aiding, which again is used to improve the DR capabilities. For marine surfaces vessel, particular in dynamic positioning (DP), multiple heading references are available as a result of class requirements, such as DNV GL (2011), leaving the DR capabilities using IMUs and NLOs unanswered for ship navigation.

INS applied in DP is far from novel, as proposed in an industrial context almost 20 years ago (Vickery, 1999). Other similar products were introduced to the market in the years that followed, Faugstadmo and Jacobsen (2003) and Paturel (2004). All these products have been developed with high-end IMUs, based on ring laser gyro (RLG) or fiber optic gyro (FOG) technology. Furthermore, these products have been developed to improve or filter existing PosRef signals before applying them as PosRef measurements in the DP estimator, where the integrated INS solution of Faugstadmo and Jacobsen (2003) is only interfaced with hydroacoustic position reference (HPR) systems. Moreover, some of these INS products are also subjected to export restrictions, limiting the market potential and increasing the cost of installation due to a possibly lengthy approval process before installation.

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Even though the cost of installation is quite high, INS integration in DP has received considerable attention in the industry the last years, Stephens et al. (2008), Carter (2011; 2014), Russell (2012) and Willumsen and Hals (2013). From the latter, it is stated that export restrictions are rarely a problem since "acoustic systems are covered by the same rules". However, this statement does not apply to GNSS technology, which is not subjected to such restrictions. Furthermore, currently there exist numerous MEMS-based IMUs on the market not subjected to export licenses. Such units have a great potential to be used in the maritime and offshore markeds. Therefore, studies on DR capabilities of GNSS aided INS, using high-rate MEMS IMUs, utilized in ship navigation are of great interest.

1.1 Main Contributions

This paper presents an initial study of the DR capabilities in DP obtained using GNSS-aided INS based on high-rate MEMS IMUs. The study is carried out:

- Based on two NLO designs, Mahony et al. (2008) and Rogne et al. (2016), respectively, interconnected with translational motion observers (TMO).
- Employing two types of MEMS IMUs.
- Evaluating the DR capabilities in both position and heading.

For a study on attitude determination using NLOs and high-rate MEMS IMU, Bryne et al. (2016) can be advised.

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 uses four reference 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 as it rotates around the sun, 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

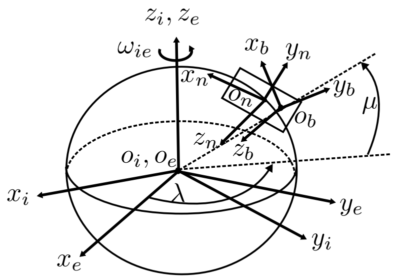

Fig. 1. Definitions of the BODY, NED (tangent), ECEF and ECI reference frames.

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

where μ is the latitude on the Earth and $\boldsymbol{\omega}^\star_{\star\star}$ represents angular velocity. The longitude is denoted λ. Furthermore, 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, and the origin of {b} is located at the vessel's nominal center of gravity. 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

Estimating position when using the tangent frame as the navigation frame, results in implementation of the strapdown equations,

$$\dot{\boldsymbol{p}}^n_{nb} = \boldsymbol{v}^n_{nb}, \tag{2}$$

$$\dot{\boldsymbol{v}}^n_{nb} = -2\boldsymbol{S}(\boldsymbol{\omega}^n_{ie})\boldsymbol{v}^n_{nb} + \boldsymbol{R}^n_b \boldsymbol{f}^b_{ib} + \boldsymbol{g}^n_b, \tag{3}$$

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. $\boldsymbol{R}^n_b \in SO3$ is the rotation matrix. See Bryne et al. (2016) for the rotational kinematic equations used to obtained $\boldsymbol{R}^n_b$. Moreover, $\boldsymbol{f}^b_{ib} = (\boldsymbol{R}^n_b)^\intercal(\boldsymbol{a}^n_{ib} - \boldsymbol{g}^n_b) \in \mathbb{R}^3$ is the specific force decomposed in {b} and where $\boldsymbol{a}^n_{ib}$ is the accelerations decomposed in the tangent frame.

Bryne et al. (2014; 2015) extended the translational motion kinematics further, by including a state of integrated vertical(down) position/heave, i.e,

$$\dot{p}^n_{nb,I} = p^n_{nb,z}, \tag{4}$$

and is motivated by the fact that the mean vertical position of the vessel is zero over time, since the wave-induced motion of the craft in heave oscillates about the mean sea surface. This augmentation of (2)–(3) can be exploited in the INS by incorporating the virtual vertical reference (VVR) of Bryne et al. (2014; 2015; 2016).