Application of an off-the-shelf Fiber Optic Gyroscope based Inertial Measurement Unit for Attitude and Heading Estimation

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***Abstract*—The ability to estimate attitude (pitch, roll) and heading (yaw) in reference to the North-East-Down frame is of great importance for localization applications. Determining true north proves to be especially challenging. This paper presents a fast and simple north-seeking method by utilizing earth's rotation measured by a three-axis Inertial Measurement Unit (IMU) based on Fiber Optic Gyroscopes (FOG) and Micro-Electro-Mechanical Systems (MEMS) accelerometers. Assuming a non-moving IMU, its measured accelerations and angular velocities are solely evoked by earth's gravitation and angular speed. To increase accuracy, a static multi-position calibration scheme is introduced. Sensor bias is estimated under the assumption that the magnitude of accelerometer and gyroscope data equals earth's gravitation and angular speed. Precision and accuracy of the gyrocompass is experimentally evaluated and prove to be a promising alternative in comparison to expensive commercially available Attitude and Heading Reference Systems (AHRS).**

***Keywords*—Gyrocompass, North Seeker, North Finder, Fiber Optic Gyroscope, Heading Estimation.**

I. INTRODUCTION

It is desired to exploit robotic assistance in ever more versatile surroundings. Localization and navigation through those challenging environments is one of the basic core modules. Besides position estimation, it is also vital to estimate the platform's attitude and heading.

A. Problem Statement

The orientation of an object in space is described by three angles, which is usually given relative to the navigation-frame. This frame is also called North-East-Down-frame since its axes are aligned to the cardinal directions and earth's gravity vector. Attitude and heading estimation boils down to finding a rotation R_b^n from the body-frame (b) to the navigation-frame (n), illustrated in Fig. 1. By exploiting the local gravity vector g_e static attitude estimation can easily be achieved with low-cost MEMS accelerometers. Heading estimation, meaning to find true north turns out to be the challenging part. Over the years several approaches have been developed:

The exploitation of earth's magnetic field is the most obvious, but it is error-prone due to disturbances. Also, GPS turns out to be a simple and reliable tool as long as signal is available. Mechanical north-seeking gyrocompasses are still used and have proven high accuracy, but turn out to be disadvantageous concerning their size, weight, mechanical complexity and costs. Hence, great efforts are made on finding alternative north seeking approaches.

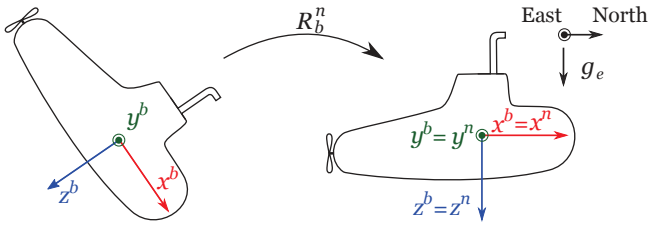

Fig. 1. Visualization of R_b^n: Rotation from body-frame (b) to navigation-frame (n).

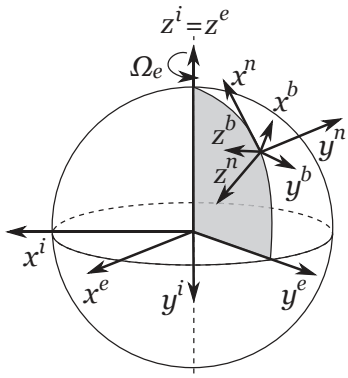

Fig. 2. Overview of frames: inertial-frame (i), earth-frame (e), navigation-frame (n) and body-frame (b).

By definition, the North-South-Axis is aligned with earth's rotation axis. Commercially available attitude and heading reference systems based on FOGs already prove the successful exploitation of earth's rotation. Those systems are characterized by high weights, large dimensions and exorbitant prices. For a more widespread application in GPS-denied environments such as underwater and indoor scenarios, more cost-efficient, smaller and lighter systems are required.

B. Proposed Solution

This paper outlines how a lowcost off-the-shelf IMU consisting of a triaxial fiber optic gyroscope and accelerometer can be utilized for heading estimation. The major contributions are as follows:

- To boost the accuracy, a generic calibration routine is introduced. A complex calibration set-up is not needed. The procedure exploits the multi-position scheme of [1] and [2]. Sensor bias is estimated under the assumption

that the magnitude of accelerometer and gyroscope data equal earth's gravitation and angular speed.
- Extensive experimental investigation is carried out to understand what level of accuracy and precision can be expected from off-the-shelf FOGs.
- Attitude and heading ground truth is generated by bearing landmarks with know coordinates.

C. Related Work

Working principles of FOGs are explained in [3]. First north seekers were equipped with just one sensitive axis making the whole set-up quite complicated. The FOG is strapped on a turntable and a set of measurements with various orientations of the sensitive axis is carried out in either a static [4] or dynamic scheme [5]. The employment of a three-axis FOG equipped with a three-axis accelerometer simplifies the whole setup. This way the earth's rotation and gravity vector can be completely captured with one single pose of the device.

An overview of the frames is given in Fig. 2. Given that the IMU is fixed to the earth-frame (e), its measurements of the accelerometers and gyroscopes are solely evoked by earth's gravity and angular speed. A concise description of determining the attitude of the body-frame in reference to the navigation-frame is suggested by [6]:

$$\hat{z}_n^b = -\frac{a_{ib}^b}{\left\|a_{ib}^b\right\|}, \tag{1}$$

$$y_n^b = \hat{z}_n^b \times \frac{\omega_{ib}^b}{\left\|\omega_{ib}^b\right\|}, \tag{2}$$

$$\hat{x}_n^b = \hat{y}_n^b \times \hat{z}_n^b. \tag{3}$$

The measurements are given in notation from [7]. The superscript indicates the body-frame as frame of reference. The subscripts denote a acceleration/ velocity of the body-frame relative to the inertial-frame. The results of Eq. 1 and Eq. 3 are unit vectors. For the sake of clarity normalization to $\hat{y}_n^b$ has not been squeezed into Eq. 2. The rotation matrix, linking the body- and navigation-frame is given by: $R_n^b = [\hat{x}_n^b, \hat{y}_n^b, \hat{z}_n^b]$.

The IMU has been calibrated by the manufacturer and outputs gyroscope and accelerometer measurements, which are already compensated for bias offset, absolute scale factor, scale factor linearity, axis misalignment and their dependency towards temperature changes. The bias offset is changing over the device's lifetime and is therefore becoming one of the biggest contributors to erroneous data. Fortunately, it is also one of the easiest to remove. Therefore, a frequently used IMU measurement model [8] is considered. It assumes two types of sensor errors, namely a sensor bias and an additive noise term:

$$\tilde{a}_{ib}^b = a_{ib}^b + b_a + \eta_a, \tag{4}$$

$$\tilde{\omega}_{ib}^b = \omega_{ib}^b + b_w + \eta_w. \tag{5}$$

where $\tilde{a}_{ib}^b$ denotes the measurement of the accelerometer, which consists of the true acceleration a_{ib}^b, the accelerometer-bias b_a and zero-mean Gaussian sensor noise η_a. Similar equation holds true for the measurement model of the gyroscope. Note that above mentioned model is quite simple and optimistic. It does not consider temperature changes, scale factors and non-orthogonality of the sensors. For more advanced calibration models refer to [9]. Nevertheless, the measurement model turns out to be suitable for precalibrated IMUs.

A straightforward calibration is suggested by [6]. Unfortunately, additional infrastructure is required to adjust specific sensor orientations. A robust and easy-to-implement calibration without the need for external equipment is demonstrated in [2]. The procedure is based on a multi-position scheme.

II. CALIBRATION

Eq. 4 and Eq. 5 form the core of the calibration. Assuming a static sensor setup, $\left\|a_{ib}^b\right\|$ equals the magnitude of the local gravity vector g_e. Likewise, $\left\|\omega_{ib}^b\right\|$ equals the earth's rotational speed Ω_e. Both values can be retrieved from literature. The noise terms of the IMU measurement models are neglected since signal averaging is applied. The cost functions for estimating the sensor biases can be described as follows:

$$\underset{b_a}{\operatorname{argmin}} \sum \frac{1}{2}(\left\|\tilde{a}_{ib}^b - b_a\right\| - g_e)^2, \tag{6}$$

$$\underset{b_w}{\operatorname{argmin}} \sum \frac{1}{2}(\left\|\tilde{\omega}_{ib}^b - b_w\right\| - \Omega_e)^2 \tag{7}$$

The estimation of the accelerometer bias is done according to [2]. This paper transfers this idea to the estimation of the gyroscope bias. With this prerequisite, the gyroscope bias can be determined in the same way.

III. EXPERIMENTAL RESULTS

Experiments were carried out with the KVH 1750 IMU at a sampling frequency of 1000 Hz. To evaluate the performance of the measurement system, its accuracy and precision were experimentally investigated.

A. Precision

Precision characterizes the closeness of a set of measurements. The repeatability of measurements is influenced by measurement noise. To quantify the impact of measurement noise, the signal to noise ratio (SNR) was experimentally determined by recording sensor data of a non-moving IMU for one hour:

$$a_{\text{SNR}} = \frac{\left\|\sigma_{a_{ib}^b}\right\|}{\left\|\mu_{a_{ib}^b}\right\|} = 0.6\%, \quad \omega_{\text{SNR}} = \frac{\left\|\sigma_{\omega_{ib}^b}\right\|}{\left\|\mu_{\omega_{ib}^b}\right\|} = 342.6\%. \tag{8}$$

The standard deviation is denoted with σ and the mean value with μ. The measurement of earth's angular velocity is heavily influenced by noise. Its SNR vividly demonstrates that the heading estimation works poorly for just a single IMU measurement. The influence of the averaging time was empirically investigated. Fig. 3 visualizes the angular deviation with respect to the averaging time. For ongoing investigations an averaging time of 30 seconds has been identified as a promising compromise. It has to be acknowledged, that bias calibration has no effect on precision. Nevertheless, accuracy can benefit from a meaningful calibration.

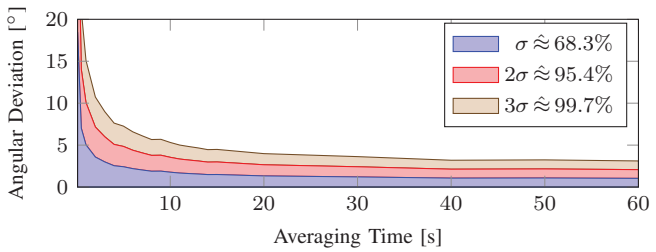

Fig. 3. Angular deviation with respect to averaging time.

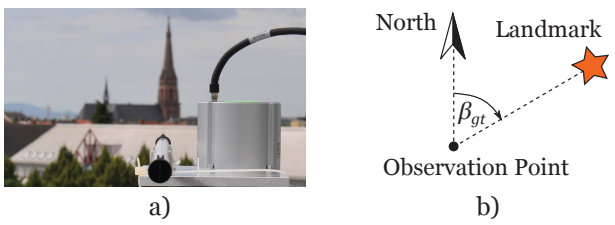

Fig. 4. Establishing ground truth: a) Bearing tube with rigidly attached IMU pointing at landmark: Church spire. b) Ground truth heading β_{gt} given by coordinates of the observation point and landmark.

B. Accuracy

Accuracy describes the closeness of measurements to the true value of the measurand. In order to evaluate the heading estimation, a meaningful ground truth needs to be established. Using a magnetic compass as ground-truths is not a feasible option due to the aforementioned error-proneness to disturbances. Application of a commercially available AHRS is the preferred setup. However, such a system was not available. An alternative ground truth is shown in Fig. 4. The gyrocompass was aligned via a bearing tube to a known landmark. The heading angle β_{gt}, can be easily obtained by the coordinates of the observation point and the selected landmark. To minimize bearing errors, landmarks in great distance have been chosen.

The landmark orientation given in bearing tube frame (t) needs to be transformed in the navigation frame (n):

$$p_t^n = R_b^n R_t^b p_t^t, \tag{9}$$

where $p_t^t = (1, 0, 0)^T$ stands for a unit vector aligned to the bearing tube. R_b^n is the result of the attitude and heading estimation. R_t^b is determined by the mechanical design. With given ground truth only the heading angle β can be verified, which is extracted by:

$$\beta = \text{atan2}(p_{t,y}^n, p_{t,x}^n). \tag{10}$$

It has to be mentioned that this ground truth may not be perfect. It is assumed that the angle between bearing tube and IMU can not be determined with high accuracy. That is why the heading angles β and β_{gt} are not directly compared. Rather the delta angles between two bearings are considered. This way, the hard-to-quantify misalignment angle drops out of the equation. For evaluation, 14 landmarks have been selected. Every single landmark bearing has been taken three times to mitigate outliers during the measurement campaign. Comparison with ground truth data revealed an average deviation angle of $2.47°$. This deviation could be reduced to $2.11°$ by considering bias calibration. Also, it has been proven, that calibration has an even bigger influence on sensors with not up-to-date calibration parameters. Tab. I compares those results to a commercially available subsea gyrocompass and attitude sensor. Although the heading accuracy of commercially available AHRS can not be outperformed, our system delivers promising accuracy and precision at settling times of just 30 seconds combined with a small, light and cost-efficient design.

TABLE I
COMPARISON OF AHRS (E.G. OCTANS NANO FROM IXBLUE [10]) AND HEADING ESTIMATION BASED ON AN OFF-THE-SHELF FOG (1750 IMU FROM KVH [11]).

	AHRS	off-the-shelf FOG
Heading accuracy (@lat = 49°):	0.76°	2.11°
Settling time (ready to nav):	<300s	30s
Weight:	9.5 kg	0.7 kg

IV. CONCLUSION

It has been demonstrated that an off-the-shelf IMU consisting of a three-axis FOG and three-axis MEMS accelerometer can be successfully employed for true north finding. Contrary to other routines, our calibration does not require a specific set-up. The IMU simply needs to be rotated in multiple arbitrary orientations. Carried out experiments showed that high precision can be achieved with short settling times such as 30 seconds. The accuracy has a deviation of $2.47°$, which can be reduced to $2.11°$ by contributed calibration. The outcome of our work is also a promising foundation for more sophisticated calibration models making even less accurate FOGs applicable for attitude estimation.

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