A Low-Cost Inertial Measurement Unit for Ship Motion Estimation

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***Abstract*—This paper presents the development of an Inertial Measurement Unit (IMU) tailored for maritime applications. Leveraging cost-effective MEMS sensors, the IMU integrates a 3-axis accelerometer and a 3-axis gyroscope. Utilizing a Kalman filter for roll, pitch, and yaw estimation, and an algorithm based on the Fast Fourier Transform (FFT) for heave, sway, and surge estimation, the proposed IMU enables comprehensive motion analysis for ships. The proposed system efficiently manages all required data processing, and does not relies on the ship's infrastructure highlighting the feasibility of utilizing low-cost MEMS sensors and embedded systems for accurate and reliable motion estimation in maritime environments. The accuracy of the proposed system is experimentally determined by using a high-accuracy IMU as reference.**

***Index Terms*—Accelerometer, gyroscope, heave, IMU, inertial measurement unit, pitch, roll, surge, sway, yaw**

I. Introduction

INERTIAL sensors have a rich history in maritime applications, with their utilization dating back to the early 20th century. Initially employed for navigation and control purposes, these sensors have played a pivotal role in enhancing the safety and efficiency of maritime operations. Their integration within ships' systems has evolved significantly, revolutionizing the field of marine technology and paving the way for advanced applications in modern shipping.

The contemporary maritime industry faces a pressing need to minimize its environmental impact and optimize operational efficiency [1]. The measurement of a ship's energy footprint has emerged as a critical metric in this endeavor. Understanding and quantifying the energy consumption of vessels allows for the implementation of targeted strategies to reduce fuel consumption, minimize emissions, and enhance overall sustainability. By leveraging data from onboard sensors, comprehensive insights into the energy usage patterns of ships can be obtained, facilitating the implementation of eco-friendly practices and regulatory compliance.

In the context of energy optimization, the measurement of both rotational (roll, pitch, yaw) and translational (sway, surge, heave) displacements of a ship plays a crucial role [2], [3]. These parameters serve as key indicators of the vessel's dynamic behavior and performance characteristics. Analyzing the rotational movements offers insights into the ship's stability, maneuverability, and response to external forces, while assessing the translational displacements provides valuable information on the ship's acceleration, velocity, and overall trajectory. By monitoring these dynamic parameters, maritime operators can fine-tune propulsion systems, adjust navigation routes, and optimize operational practices, ultimately leading to a reduction in energy consumption and environmental impact.

The utilization of low-cost MEMS sensors presents a compelling advantage in this context. By leveraging affordable 3-axis accelerometers and gyroscopes that do not rely on the ship's infrastructure, the developed IMU system enables cost-effective yet accurate data collection and analysis. This approach not only reduces the overall implementation costs but also enhances the accessibility and affordability of advanced monitoring and control systems for a wider range of shipping applications, promoting widespread adoption and scalability within the maritime industry.

High-accuracy commercial IMUs are readily available and are capable of providing precise estimations of rotational motion such as roll, pitch, and yaw. However, when it comes to translational motion estimation the offerings are more limited. The products available are generally targeted towards the industrial marine sector. These devices tend to be quite expensive and often rely on the ship's infrastructure to function, which can pose a challenge for smaller vessels.

The proposed system integrates a low-cost, MEMS 3-axis accelerometer and a 3-axis gyroscope, enabling real-time estimation of the ship's roll, pitch, yaw, sway, surge, and heave motions. Leveraging the popular Kalman filter technique for rotational displacement calculations and an algorithm based on the Fast Fourier Transform (FFT) for translational motion estimation, the system ensures precise and efficient motion estimation. The proposed IMU executes all the estimation calculation onboard and does not rely on the ship's infrastructure. The estimation results are evaluated using a high-accuracy IMU as refreence.

II. The Proposed System

In this Section, the hardware design of the proposed IMU is presented and analyzed. A top-level system architecture is presented in Figure 1, while in Figure 2 the data processing flow is presented. In the rest of this section, the hardware design of the proposed system as well as the motion estimation algorithms are described in detail.

A. Hardware Design and Sensors Calibration

The proposed system integrates the Bosch Sensortec BMI088 sensor which embeds a three-axis accelerometer and

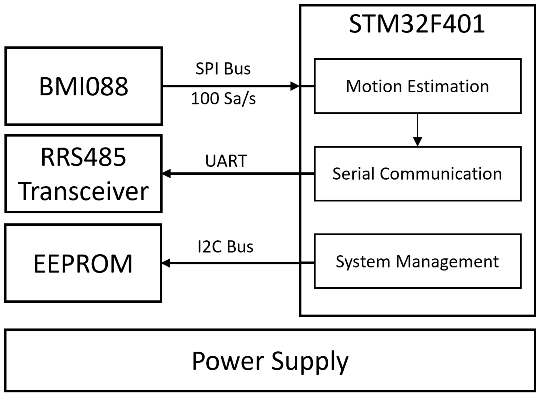


Fig. 1: Top-level system architecture of the proposed IMU.

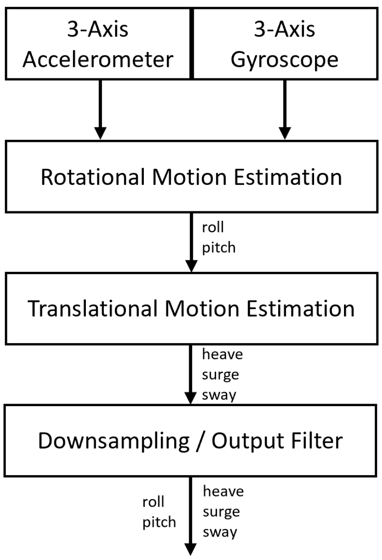


Fig. 2: Data processing flow of the proposed IMU.

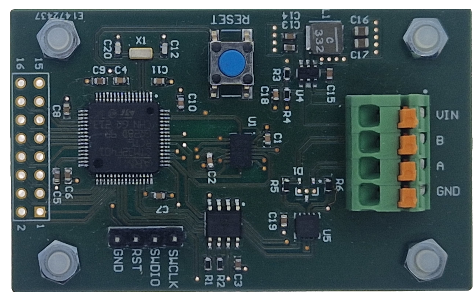
a three-axis gyroscope on a single chip. It provides high-resolution measurements (16-bit) while maintaining very low measurement noise and reduced scale manufacturing imperfections (such as non-linearities, cross-axis sensitivity, etc.) compared to other sensors in this price range. Some performance characteristics of the BMI088 sensor are presented in Table I.

The sensor data is read by a 32-bit microcontroller (ST Microelectronics STM32F401). The microprocessor also handles the processing of data and the estimation of motion parameters. The choice of this microcontroller was influenced by its large RAM and Flash memories, as well as its floating-point unit which allows for real-time data processing.

The system is supplemented by a power supply, an EEPROM memory for storing some basic settings, and a transceiver for the RS485 communication protocol. The RS485 protocol was chosen for the communication between the IMU and the other systems of the ship as it is a standard industrial protocol widely used in the marine industry. The designed

Accelerometer	
Measurement Range	±3g-±24g
Sensitivity	1365LSB/g - 10920LSB/g
Sensitivity Temperature Drift	0.002%/K
Zero-g Offset	±20mg
Zero-g Offset Temperature Drift	< 0.2mg/K
Output Data Rate	12.5Hz - 1600Hz
Bandwidth range	5H-280Hz
Nonlinearity	0.5%FS
Output Noise Density (X,Y)	160 $\mu g/\sqrt{Hz}$
Output Noise Density (Z)	190 $\mu g/\sqrt{Hz}$
Cross Axis Sensitivity	0.5%
Alignment Error	0.5 degrees
Gyroscope	
Measurement Range	±125dps - ±2000dps
Sensitivity	16.384LSB/dps - 262.144LSB/dps
Sensitivity Temperature Drift	±0.03%/K
Zero-g Offset	±1dps
Zero-g Offset Temperature Drift	< 0.015dps/K
Output Data Rate	100Hz - 2000Hz
Bandwidth range	12H-523Hz
Nonlinearity	0.005%FS
Output Noise (BW=47Hz)	0.1 dps
Cross Axis Sensitivity	1%

TABLE I: Measurement Characteristics of BMI088 Accelerometer and Gyroscope.



(a)

(b)

Fig. 3: The PCB (a) and the complete system in its enclosure (b) of the designed IMU.

printed circuit board (PCB) along with the complete IMU including its enclosure are shown in Figure 3.

To get accurate results, the two sensors (accelerometer and gyroscope) must be calibrated. To this end we use MAG.I.C.AL. methodology [4] along with the axis alignment algorithm of [5] and an external magnetic field sensor. This setup allows accurate compensation for all linear time-invariant distortions such as scale-factor, cross-coupling, and offset of the two sensors.

B. Rotational Motion Estimation

The estimation of the ship's translational motion requires knowledge of its rotational motion for aligning the reference axes of the measurements with the ship's reference axes. Thus, we begin by estimating the roll, pitch, and yaw from the measurements of the accelerometer and the gyroscope. To this end, we used a Kalman Filter based algorithm following the existing literature [6].

Initially, the algorithm calculates the pitch and roll angles using exclusively the measurements of the gyroscope. Let the gyroscope measurement at time k,

$$\omega_k = \left[\omega_x^k,\ \omega_y^k,\ \omega_z^k\right]^T. \tag{1}$$

Furthermore, we suppose that at time $k-1$, the roll (φ_{k-1}) and pitch (θ_{k-1}) angles are known. The variation of the two angles from time $k-1$ to time k can be calculated using just the gyroscope's measurements as follows:

$$\begin{aligned} \delta\varphi_k &= \omega_x^k + \sin(\varphi_{k-1})\tan(\theta_{k-1})\omega_y^k \\ &\quad + \cos(\varphi_{k-1})\tan(\theta_{k-1})\omega_z^k \\ \delta\theta_k &= \cos(\theta_{k-1})\omega_y^k - \sin(\varphi_{k-1})\omega_z^k \end{aligned} \tag{2}$$

Additionally, it is assumed that the estimates of φ and θ also include a constant error $b\varphi$ and $b\theta$ respectively. Then, the evolution of the two angles over time can be expressed as:

$$\begin{aligned} \begin{bmatrix} \varphi_k \\ b\varphi_k \\ \theta_k \\ b\theta_k \end{bmatrix} &= \begin{bmatrix} 1 & -dt & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & -dt \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \varphi_{k-1} \\ b\varphi_{k-1} \\ \theta_{k-1} \\ b\theta_{k-1} \end{bmatrix} \\ &\quad + \begin{bmatrix} dt & 0 \\ 0 & 0 \\ 0 & dt \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta\varphi_k & \delta\theta_k \end{bmatrix} \end{aligned} \tag{3}$$

Subsequently, the algorithm computes the pitch and roll angles using solely the measurements of the accelerometer. Let the accelerometer measurement at time k,

$$f_k = \left[f_x^k,\ f_y^k,\ f_z^k\right]^T. \tag{4}$$

Then it follows:

$$\begin{aligned} \varphi_k^a &= \arctan\left(\frac{f_y^k}{\sqrt{\left(f_x^k\right)^2 + \left(f_z^k\right)^2}}\right) \\ \theta_k^a &= \arctan\left(\frac{-f_x^k}{\sqrt{\left(f_y^k\right)^2 + \left(f_z^k\right)^2}}\right) \end{aligned} \tag{5}$$

The estimation of the rotational motion through (5) is more accurate than that obtained using the gyroscope measurements and (3). This is because (5) depends solely on the accelerometer error at time k, whereas using (3), the error of each gyroscope measurement accumulates.

This fact is utilized within a Kalman filter, with equation (3) used to update the state vector and (5) introduced into the filter as a measurement.

C. Translational Motion Estimation

The estimation of the translational motion is based on the methodology proposed in [7]. The proposed methodology introduces a model which adapts to different sea states without the need for vessel-specific parameters. The research demonstrates the successful application of this method in simulations and experimental setups, validating its effectiveness in accurately estimating heave motion using readily available accelerometer data. In this section the methodology of [7] is briefly described; for more information the reader is encouraged to refer to the original manuscript.

The authors of [7], focus on the estimation of the vertical movement of a vessel (heave) through the use of accelerometer data. The proposed methodology begins by modeling the heave motion as a sum of periodic components, each representing a different mode of motion. Mathematically, this heave motion, $z(t)$, is expressed as

$$z(t) = \sum_{j=1}^{Nm} A_j \cos(\omega_j t + \phi_j) + v(t) \tag{6}$$

where A_j, ω_j, and ϕ_j are the amplitude, frequency, and phase of the j^{th} mode, respectively, and $v(t)$ includes slower varying effects like tidal changes.

The identification of significant modes of motion is achieved using Fast Fourier Transform (FFT) on accelerometer data. This process determines the frequency (ω_j) and phase (ϕ_j) of each wave component. The amplitude and phase spectrum of the position ($A(\omega)$ and $\phi(\omega)$ respectively) are derived from the amplitude and phase spectrum of the acceleration, $A''(\omega)$ and $\phi''(\omega)$, as follows

$$A(\omega) = \frac{A''(\omega)}{\omega^2} \text{ and } \phi(\omega) = \phi''(\omega) - \pi \tag{7}$$

where $\omega > 0$.

For observer design, each identified mode is treated as the time-domain solution of an undamped oscillator

$$z_j(t) = A_j \cos(\omega_j t + \phi_j), \quad j = 1, \ldots, N_m. \tag{8}$$

The ordinary differential equation of each mode is written as

$$\ddot{z}_j + \omega_j^2 z_j = 0. \tag{9}$$

The accelerometer's measurement is modeled as

$$a_{z,\text{imu}} = \sum_{j=1}^{N_m} \ddot{z}_j - \cos(\phi)\cos(\theta)g + b_z + \xi_z \tag{10}$$

where g is the Earth's gravitational field, b_z represents the accelerometers' bias and ξ_z represent the sensor's noise. Using (9) and (10), the authors formulate a discrete state-space observer which is realized using an Extended Kalman Filter (EKF).

III. Performance Evaluation

To evaluate the performance of the proposed IMU we used Xsens MTi-630, a high performance, factory calibrated IMU as reference. The sensors of Xsens MTi-630 are calibrated and checked to meet their specifications for offset, axis alignment, non-linearity, scale factor and G-sensitivity over a wide range of temperatures.

We mounted the developed IMU and the Xsens MTi-630 on a rigid board as shown in Figure 4.

Fig. 4: Designed IMU along with reference IMU (Xsens MTi-630) mounted on a rigid board.

We used the synchronization input of Xsens MTi-630 to synchronize the sampling of the two sensors. Several measurements of both IMUs at different orientations were captured. The rotational and translational motion estimation error of the designed IMU are presented in Table II.

Roll Estimation Error	0.91° RMS (static) 1.33° RMS (dynamic)
Pitch Estimation Error	0.97° RMS (static) 1.42° RMS (dynamic)
Heave Estimation Error	12%
Sway Estimation Error	12%
Surge Estimation Error	12%

TABLE II: Measurement error of the proposed IMU.

IV. Conclusion

This paper has successfully presented the development of a low-cost IMU specifically designed for maritime applications. The integration of cost-effective MEMS sensors with a 3-axis accelerometer and a 3-axis gyroscope into the IMU illustrates a significant advancement in maritime technology. Utilizing a Kalman filter for precise roll, pitch, and yaw estimation, and an FFT-based algorithm for heave, sway, and surge estimation, this IMU offers comprehensive motion analysis for ships.

The innovative approach of the proposed system lies in its ability to perform all required data processing independently, without relying on the ship's infrastructure. This independence not only demonstrates the feasibility of using low-cost MEMS sensors in maritime environments but also underscores the potential for wider adoption due to its affordability and efficiency.

Experimental results, benchmarked against a high-accuracy IMU, validate the accuracy and reliability of our proposed system. The demonstrated precision in motion estimation positions this IMU as a promising tool for enhancing the safety, efficiency, and environmental sustainability of maritime operations.

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