LOW-COST VESSEL MOTION MONITORING: INERTIAL MEASUREMENT UNIT VALITADION AND CALIBRATION

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Keywords

inertial measurement unit, ship stability, ship dynamics, motion monitoring

Abstract

Vessel motion is influenced by a multitude of factors, including external forces such as waves or wind as well as vessel design and construction. This work presents an initial analysis of the vessel motion based on the

rotational movements roll, pitch and yaw using low-cost, open-source electronics assembled into a 3D printed frame designed and built by the University of St Andrews. The device combines an Inertial Measurement Unit (IMU), with a Global Navigational Satellite Systems (GNSS) and an external battery to operate independent of the vessel.

The results of motion monitoring trials are presented in this work, confirming that the low-cost IMU used is an appropriate device for vessel motion monitoring. This finding represents a significant advancement over more traditional methods of assessing vessel motion and costs approximately 20 times less than other inertial measurement devices.

1 INTRODUCTION

The study of vessel stability and dynamics are key to analysing the ability of vessels to maintain their upright position and performance at sea. From the safety perspective, vessel righting capacity, ship-wave synchronism, parametric rolling and slamming are important parameters. External forces, such as waves or wind, alongside the vessel's inherent motion influence vessel dynamics, together with the design and construction parameters. Vessel motion, principally pitch and roll, influence vessel course or speed changes, depending on the direction, speed, frequency and height of waves. The motion characteristics of a vessel determine its suitability for a given task.

From the safety point of view, Míguez González et al. (2016; 2018), Nielsen et al. (2019; 2020) and Santiago Caamaño et al. (2019) focus their studies on on-board motion monitoring. Nielsen et al. (2019; 2020) developed a ship motion measuring system to determine wave heights that a vessel encounters along its route. Míguez González et al. (2016; 2018) and Santiago Caamaño et al. (2019) studied the motion of fishing vessels, by conducting experiments both in a towing tank with models as well as with a real ships. Roll motion monitoring was used to determine the real-time vertical centre of gravity of the ship. Santiago Caamaño et al. (2022) found a method to calculate the encounter frequency between the ship and the waves, by monitoring heave and pitch. Regarding vessels performance at sea, recent studies are using both vessel position and motion monitoring to study fishing activities. Politis et al. (2012) and Somerton et al. (2017) use vessel motion to study trawl fishing efficiency. Politis correlates stern vertical motions with the movements in the trawl net, while Somerton studies the effects of vessel's roll on the net. The study of vessel motion is also utilised to study sailboat performance. Morris & Williamson (2020) analysed the roll motion of sailing dinghies during tacks with the objective of improving their tacking efficiency for racing purposes. Commercial motion measurement devices can be used for the monitoring of vessel motions but these devices are often expensive. Abankwa et al. (2015) propose the design of an Inertial Measurement Unit (IMU) using a Raspberry Pi board. Galotto-Tebar et al. (2020; 2022) developed an Android based mobile application (App) to record vessel motion during the fishing activity.

This work presents an initial analysis of vessel motion, aiming to determine the stability of the vessel based on the oscillatory movements of roll, pitch and yaw, using a commercially available IMU and a low-cost, open-source device developed by the University of St Andrews which uses a SparkFun OpenLog Artemis board with on-board nine axis IMU together with a GNSS (GPS) receiver to monitor the vessel trajectory.

Prior to vessel monitoring, instrument validation and calibration are necessary. Lamboley, yawing and stability tests were conducted on three different sailing vessels. The Lamboley test induces known oscillations and assesses the response of the IMU in different locations on the vessel. Yawing tests involve both yaw calculations and IMU responses calibrated using GPS heading. Stability tests combine static heel conditions with high angular acceleration motions. All tests included independent measurements to validate orientation from the IMU readings.

2 MATERIAL AND METHODS

The SparkFun OpenLog Artemis has an on-board ICM-20948 IMU, which integrates 3-axis accelerometer, 3-axis magnetometer and 3-axis gyroscope. The accelerometer has a full-scale range of up to ± 16 g, the gyroscope up to ± 2,000 dps, and the magnetometer of up to ± 4,900 µT. All output data resolution is 16-bits. The noise spectral densities of accelerometer and gyroscope are 230 µg/√Hz and 0.015 dps/√Hz respectively, both based on a 10 Hz bandwidth (SparkFun 2024a). The device incorporating the OpenLog has been designed and developed by the Coastal Resources Management Group from the University of St. Andrews

The on-board ICM-20948 has an internal Digital Motion Processor (DMP), which computes the device orientations. The raw sensor data can also be output. When the DMP option is enabled, the raw sensor readings are disabled. If the DMP configuration is disabled, orientations can be computed from the raw sensor readings using sensor fusion algorithms. The GNSS board used, is a SparkFun GPS Breakout – ZOE-M8Q. This unit has a horizontal accuracy of 2.5 m, and a heading precision of 0.3º. All Arduino code to install and configure SparkFun firmware can be found in (SparkFun 2024b).

All trials were conducted at a sampling frequency of 10 Hz to ensure smooth detection of vessel motion, whilst simultaneously capturing both IMU and the GPS data. Three separate IMU / GPS devices were used in every trial. Both configurations, enabling DMP and saving raw sensor data, were employed in parallel in different units. Raw sensor data with the DMP option disabled was used to compute orientation using the AHRS (Attitude and Heading Reference System) filter from MATLAB (2024) software. The AHRS uses an indirect Kalman filter to compute object orientations, utilizing data from accelerometer, gyroscope and magnetometer. The AHRS filter incorporates sensor internal noise data from the three sensors. Sensor internal noises were obtained from a test where IMUs were maintained in a static and stable position. During this test, standard deviation of all sensor readings was computed. In addition, this filter uses the expected magnetic noise in the location and the time of the readings. The DMP filter computes an object's orientation, but does not allow for noise correction related to the sensor or the environment.

Before any validation trial, verification of the IMU's ability to assess the gravitational and magnetic fields surrounding it was conducted. This process is known as spherical calibration. It involves flipping the device in both positive and negative directions along the three axes, x, y and z. By performing these flips slowly and in an environment free of any magnetic interference, it can be assumed that the only acceleration and magnetic fields recorded by the IMU are those attributable to the Earth. A correction factor, comprising gain and bias, was the result of these flips. This methodology was performed in all three IMU units, following the guidelines from Biologging Tools Project (2022).

A series of tests were undertaken to validate the IMU's performance under controlled movements and conditions. The Lamboley test was undertaken to induce known oscillations to the IMUs and served to evaluate various configurations in a same location, as well as to assess the IMU response in different positions inside the vessel. Yawing trials were used to verify the units' GPS in comparison with a smartphone's GPS. This also served to compare yaw data from both IMU configurations with the heading data from the GPS. For stability tests, a heel experiment, a roll test and a pull-down test were carried out. An inclining experiment was used to test the IMU's attitude angles in static conditions, with gravity as the only acceleration. A roll test was useful to determine IMU's capability to detect a vessel's natural roll period, as this has significant implications with respect to the vessels motion at sea. A pull-down test was conducted which exerts a large angular acceleration serving to evaluate the robustness of the calculated orientation.

2.1 Lamboley test

Lamboley test is a common test on sailing dinghies. It is conducted in order to determine the mass distribution within the hull. The test consists on positioning the boat on a pendulum, which oscillates at two different heights. In this case, the test was done in a *patí de vela*, a small wooden sailing catamaran which is 5.60 metres in length. The unit used was the hull number 2944, which displaces 93.70 kg. As Figure 1 shows, this test was done using a pendulum owned by the International Patin Sailing Association (ADIPAV), in the facilities of El Prat Municipal Sailing Centre (Centre Municipal de Vela de El Prat). This test served to compare different IMU configurations. Specifically, IMU #1 and #2 were placed in the centre of the *patí de vela* rotation. IMU #1 had the DMP option enabled, while IMU #2 had this option disabled. In contrast, IMU #3 was placed in the forward bench with DMP configuration disabled. This arrangement, which can be seen in Figure 1 was used to compare different configurations within the same location, as well as the same configuration in different locations.

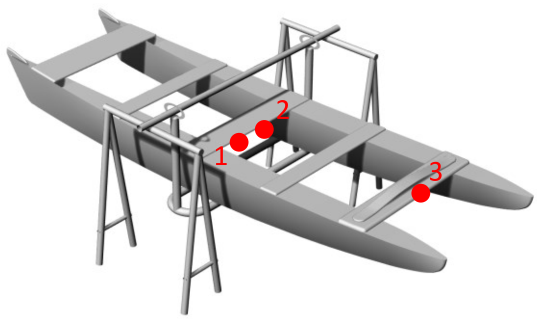

Fig. 1. *Patí de vela* position in the Lamboley test pendulum and IMU placement

An initial pitch motion was given to the *patí de vela*, which was allowed to oscillate freely, completing 10 oscillations. This process was repeated 18 times. Initial pitch angles where 1º and 5º. In addition, IMUs were rotated to simulate different axis oscillations. The IMU's were also rotated 90 º horizontally in pitch oscillations to assess the IMU performance in both the x and y axes. All *patí* movement tests were recorded on video. This video was used to determine the maximum angles of the oscillation.

2.2 Yawing validation

Yawing validation tests were conducted using the "Barcelona" sailboat, owned by the Barcelona School of Nautical Studies (FNB-UPC). The sailboat (Fig. 2) is 12 metres in length and displaces 12 ton. The main objective of this test was to compare the yaw data from the IMU with the heading from GPS measurements. In addition, the IMU's GPS ZOE-M8Q track was compared with a smartphone GPS track recoded at 1 Hz. Yawing validation took place in an area close to the Port of Barcelona, near Marina Vela, the home port of the sailboat. All tests were conducted without sail and the vessel powered by its engine. Wind, wave and current conditions were calm. Thus, it can be assumed that heading and course over ground were the same. During the tests, all three IMUs were placed together, at the saloon main table, on the starboard side. In this test, IMU #1 and #3 had DMP option disabled. Orientations computed from their data were processed using the MATLAB AHRS filter. IMU #2 had DMP option enabled, allowing it to compute orientations without recording raw sensor data. All three IMUs were oriented in the fore-aft direction.

Fig. 2. Barcelona sailboat

Prior the heading test, a 360º turn was made to port and starboard (Fig. 3). The purpose of this test was to estimate the magnetic field corresponding to the sailboat. Thus, it was possible to determine of the magnitude of the magnetic field observed by the IMUs accounted for by the vessel and that related to the Earth.

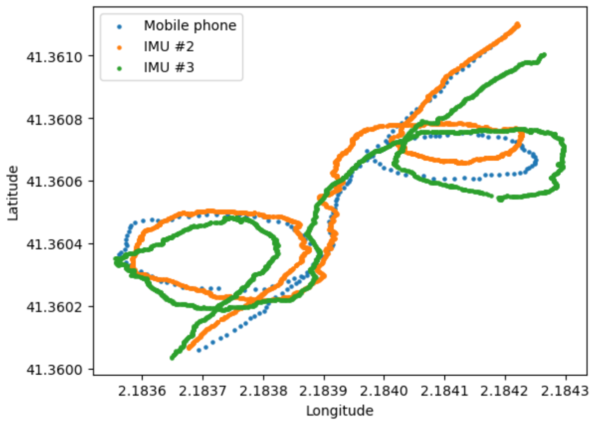

Fig. 3. GPS data showing the two 360º turns prior to the navigation

The yawing validation trial consisted in 1-minute-long segments where the vessel had a straight course, at an average speed of 5 knots. Once the minute was elapsed, course was modified by 15 degrees. Course was computed by using the vessels analogical compass. This process was repeated until all headings were covered, completing a full 360º circle.

2.3 Stability tests

Stability tests were conducted in two different vessels of Class Globe 5.80. Class Globe are offshore racing sailboats 5.80 metres in length and displace 1,145 kg in lightweight condition (Fig. 4). Stability tests were conducted in hulls number 94 and 132. Three different tests were conducted in the facilities of the Royal Maritime Club of Barcelona (Reial Club Marítim de Barcelona), the home port of the two boats used in these tests. Tests were undertaken inside the harbour, in calm conditions and with minimum interference from wind and waves. During the test, IMU #1 and #3 had DMP configuration disabled. Orientations from their data were obtained using the MATLAB AHRS filter. IMU #2 had the DMP option enabled, computing orientations without recording raw sensor data. All three IMU were located in the interior deck, oriented in the fore-aft direction.

Fig. 4. Class Globe 5.80 hull number 94

2.3.1 Inclining test

The inclining test entails inducing different static heels on any type of vessel. To achieve these heel angles, different weights are placed in different locations on vessel's deck. In Class Globe 5.80 inclining tests, six weights ranging 20 and 23 kg were used. Table 1 shows their mass. In both tests, conducted on #94 and #132 hulls, the weights used were the same. During the test, weights were moved sequentially in steps from starboard to port side and vice versa. Figure 5a shows the initial distribution of weights in the test conducted in Class Globe #94, while Figure 5b shows the initial configuration of weights on the test conducted in hull #132. Each weight distribution resulted in a different vessel heel angle, starting and ending at 0º. All three IMUs and two pendulums were located in the interior deck of both sailboats to ensure that there was no wind effect on the movement of the pendulum. In every step of the test, horizontal displacement of both pendulums was measured. Given the known length of each of pendulum, it was possible to calculate every heel angle. Inclining tests were used to check IMU roll angles in static conditions, with the only influencing acceleration being gravity.

Weight	Mass [kg]
#1	22.5
#2	21.4
#3	20.1
#4	22.1
#5	21.2
#6	20.8

Table 1 Masses of weights used in the inclining test

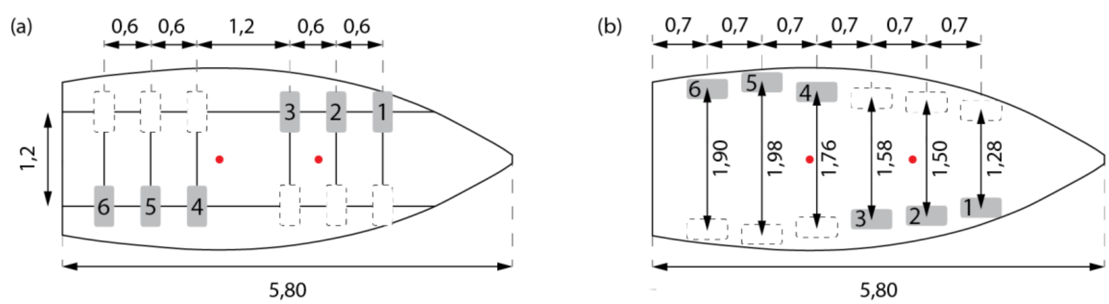

Fig. 5. Initial weight distribution in the inclining test. Distances in [m] (a) Hull #94 and (b) Hull #132

2.3.2 Roll test

The main objective of a roll test is to find the natural roll period of the roll oscillation of a vessel. This period depends on hull form and the position of the centre of gravity. This test consists in inducing a heel angle of 15º and allowing the boat to freely perform damped oscillation (Fig. 6.). The initial roll angle is limited to 15º to ensure all the test remains in the initial stability range, where the transversal metacentric height remains constant. In Class Globe roll tests, the initial oscillation of up to 15º was induced by manually and rhythmically lifting up and depressing the side of the vessel from the side of the dock. A hull mark was made at amidships and at one-eighth part of boat's beam above the waterline. This mark served to indicate the maximum range of movement without exceeding 15º of heel. The trial was conducted in accordance with the procedure of the

Maritime & Coastguard Agency (2014). During the test, a small pendulum was placed on the inner deck of the sailboats. A video recording was used to observe the maximum values of heel. Once boats were left to freely oscillate, five complete oscillations were performed, beginning when boats were rolling freely. Roll oscillation period was visually recorded. During all the test, the mooring was slack, in order to avoid forced decay during oscillations.

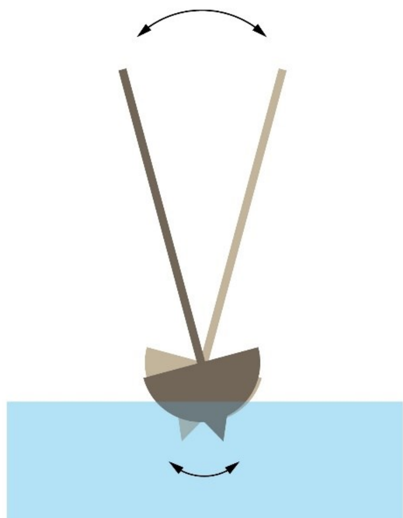

Fig. 6. Roll test conducted in Class Globe 5.80 boats

2.3.3 Pull-down

A pull-down test involves heeling a sailboat up to 90º and leaving it to freely recover its equilibrium position (Fig. 7.). In offshore racing sailboats, the ability to recover from heeling angles of 90º or even more is needed. 90º heel was achieved by using a halyard tensioned from the dock. When boats were left to freely recover their equilibrium position, significant angular acceleration was induced in the IMUs. This makes IMU data filtering more critical, as it is necessary to discern between angular acceleration, gravity and lateral displacement, which can be assumed as negligible in this test. Throughout all pull-down tests, all three IMUs were placed in the interior deck of both sailboats, in accordance with the arrangement in the two previous tests.

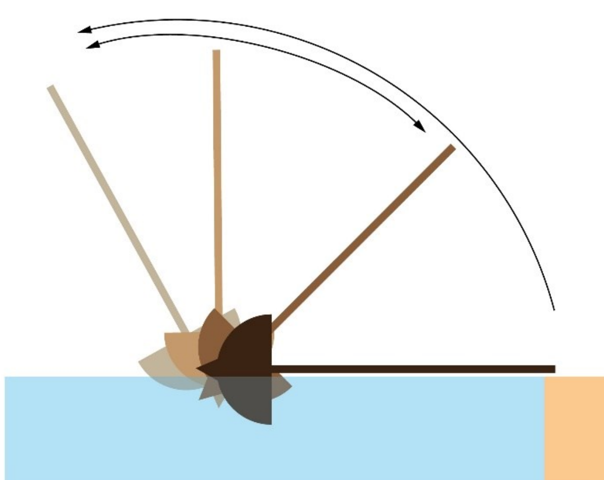

Fig. 7. Pull-down test oscillation

3 RESULTS AND DISCUSSION

The results compare the roll, pitch or yaw values obtained from the DMP filter and from the MATLAB AHRS filter. Raw data from IMU with the DMP option disabled was adjusted using the gain and bias from the spherical calibration done in every unit. All IMU orientation values are compared with reference values which were obtained either through video recordings or through pendulum oscillation measurements. It can be observed that both methods of calculation of the vessel's motions have similar results in all tests. However, the AHRS filter proves to be a more robust system for calculation orientation, given its adaptability to various types of motion.

3.1 Lamboley test

The Lamboley test was used to conduct three comparisons: 1) Comparison of DMP and AHRS configurations in two different IMUs placed at the centre of rotation, 2) Study of the IMU performance in oscillations around both the x and y axes and 3) Evaluation of the AHRS filter in two IMUs, with one positioned in the centre of rotation and the other on the forward bench. Of the two orientation calculation filters, the one employed in two different positions was the AHRS filter as it offers a greater flexibility than the DMP option. Figure 8a shows one of the oscillations conducted with IMUs oriented in the longitudinal axis of the boat, and Figure 8b another oscillation, with IMUs oriented in the transversal axis. In both cases, the initial angle of the oscillation is set at 5º. Maximum values obtained from the video recording of the *pati*'s bow are represented in the figure as black diamonds.

In the pitch trial (Fig. 8a), it can be seen that the IMU's DMP output fits analogical values better than the AHRS filter. IMUs #2 and #3 require three oscillations to converge in amplitude with the DMP values. Probably, the AHRS filter expected a motion with a greater acceleration following the equilibrium position. For roll (Fig. 8b), the AHRS filter aligned with the analogical values. The DMP filtered values did not achieve the expected amplitude. As DMP calculation methods are not published in open access, it is difficult to explain this phenomenon. In this case, the three signals converged after the ninth oscillation.

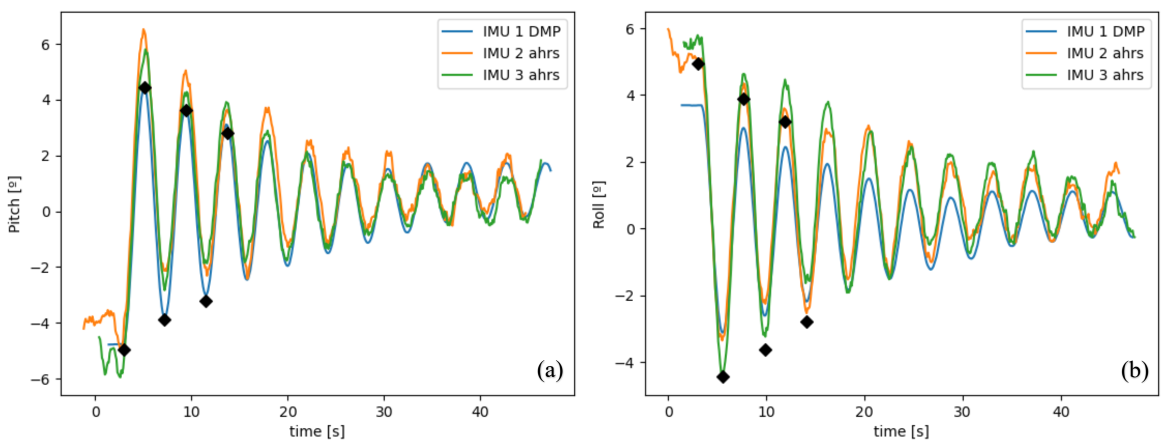

Fig. 8. Pitch and roll recording in Lamboley test.

Both in roll and pitch trials, both the DMP and AHRS filter had consistent results. In the case of the AHRS filter, results were reliable regardless of whether the IMU was located at the centre of rotations or on the forward bench. This fact suggests that the AHRS filter is robust irrespective of the location of the IMU within the vessel. At sea data collection campaigns, determining the IMUs location may not always be feasible. Moreover, the vessels gyradius will vary depending on different weather or loading conditions.

3.2 Yawing validation

The yawing trials involved a comparison between IMU yaw values (using DMP and AHRS filters) and the IMU GPS heading with the heading from a smartphone GPS. During the test, all three IMUs were positioned in the same location, with one of them having DMP enabled, and the other two with the DMP disabled. Results from one IMU of each configuration are presented, as data from the third IMU would be redundant. Both DMP and AHRS filter showed comparable performance in terms of yaw, as well as IMU GPS heading, which accord with smartphone GPS heading. Figure 9 shows 1-minute-long segments where the vessel sailed on a constant heading. The correlation between IMU yaw and IMU GPS heading with smartphone GPS heading all have R^2 values greater than 0.96 (Fig. 10).

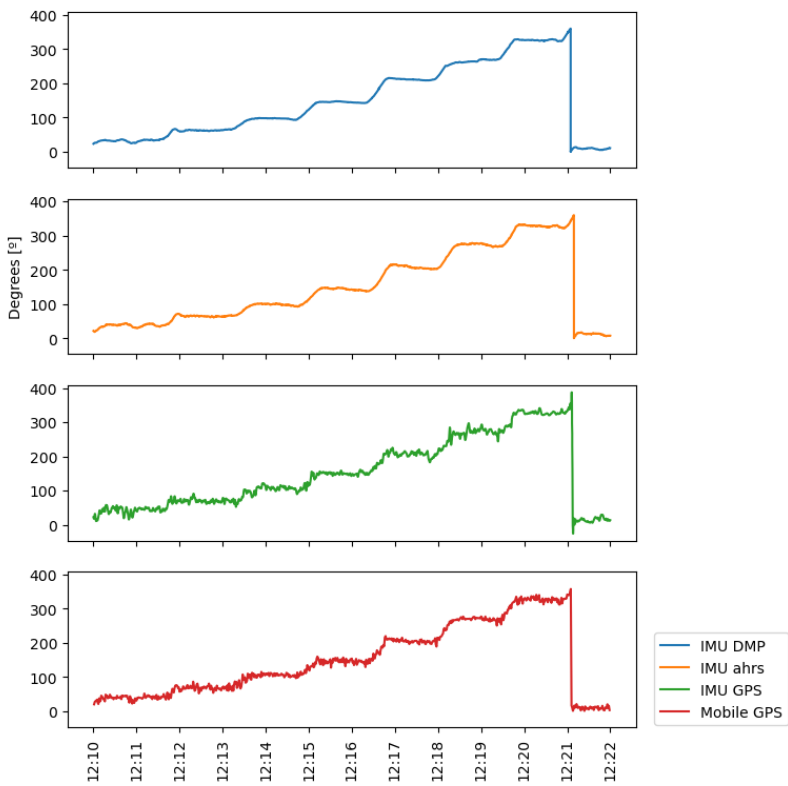

Fig. 9. 1-minute-long segments during yawing validation test.

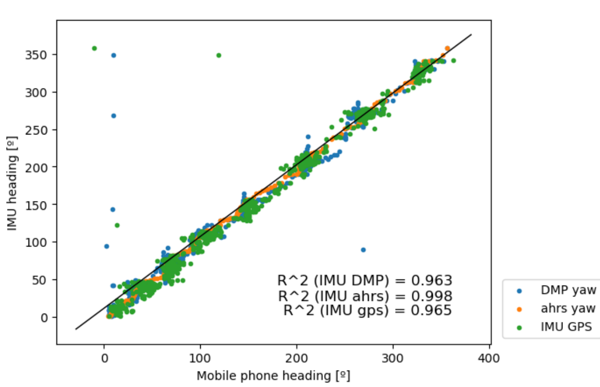

Fig. 10. Correlation between IMU yaw and GPS heading against smartphone GPS heading data.

Figure 11 shows the track recorded during the yawing validation test. Minor differences between IMU values and smartphone tracks can be observed. These differences may be attributed to the different sampling frequencies with IMU data recorded at 10 Hz and smartphone at 1 Hz. In the last segment, it can be seen that the track of one of the IMUs deviates from the smartphone track. This discrepancy can be attributed to the lack of robustness of the GPS Breakout – ZOE-M8Q antenna. This leads to the conclusion that IMU GPS data can be helpful to detect zones of activity, and to locate IMU recorded motions, although the positions may not be as precise as if they were recorded by a commercial GPS.

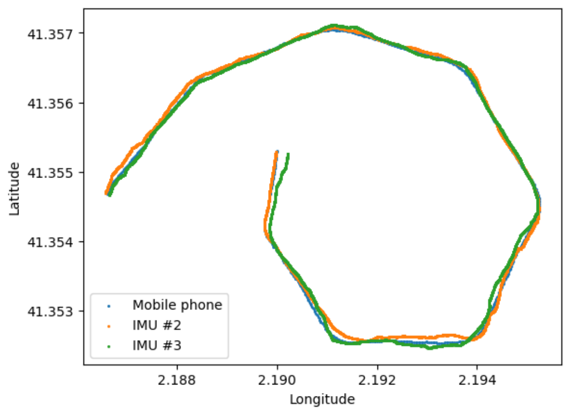

Fig. 11. Yawing validation trial track.

3.3 Stability tests

Stability tests conducted in both of the Class Globe 5.80 units included inclining, roll and pull-down tests. The results of the trials conducted in both vessels were found to be analogous. Therefore, only the results of tests conducted in Class Globe 5.80 hull #132 will be shown. As with the yawing test, all three IMUs were positioned in the same location, with one of them having the DMP enabled, and the other two with the DMP disabled. Results from one IMU for each configuration are presented.

The inclining test involves heel calculation in static conditions. During the orientation calculation, the only acceleration received by the IMUs is the gravity, and gyroscope values should be around 0. Figure 12 illustrates the heel values obtained from the two pendulums installed in the interior deck of both 5.80 boats, along with the heel values from IMU recordings, using the DMP and AHRS filters. With a correlation always greater than an R^2 of 0.97, both methods are considered valid for computing heel values in static conditions (Fig. 13).

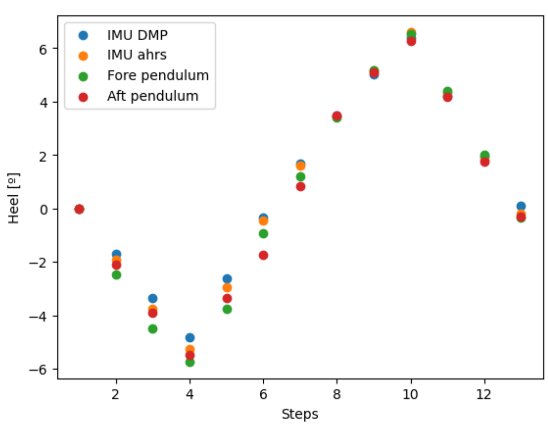

Fig. 12. Heel values from IMU and pendulums during the inclining test.

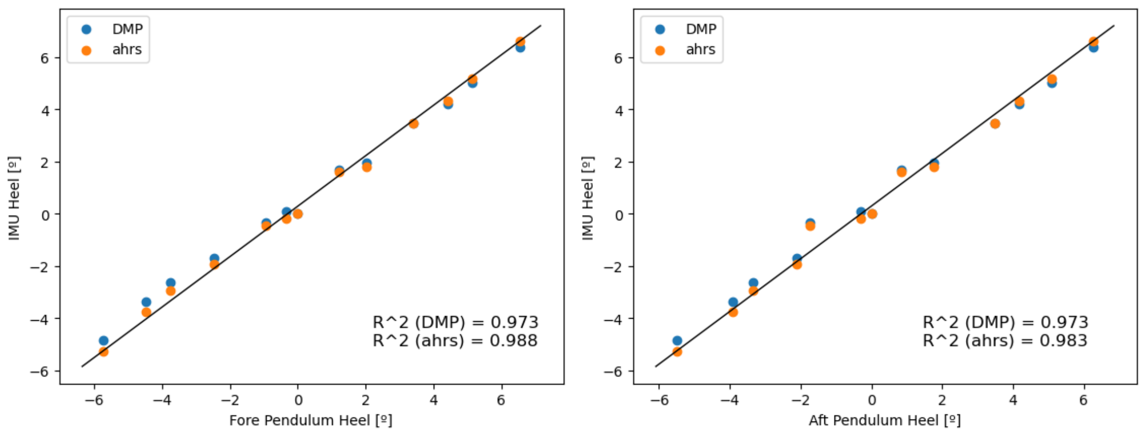

Fig. 13. Correlation between list values from IMU and pendulums during the inclining test.

Figure 14 illustrates roll readings from the roll test conducted in #132 Class Globe 5.80. During the more dynamic part of the test, the AHRS filter generates slightly higher roll amplitudes compared to the DMP. This suggests that, under these conditions, the AHRS filter gives greater significance to sensor readings than to the initial state of the object. In contrast, the DMP appears less responsive in terms of amplitude. It is prioritising the initial state value over accelerations or angular movements. Nevertheless, under these conditions, the differences are negligible, both filters yield nearly identical results.

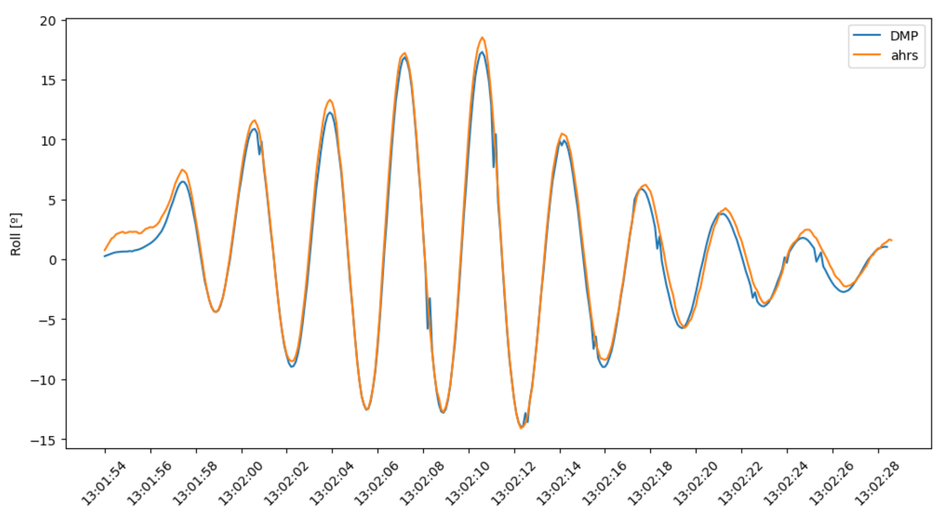

Fig. 14. Roll values during roll test in Class Globe 5.80 #132.

In the roll test, maximum oscillation values, obtained from the video recordings, were analysed. Figures 15 illustrates that the AHRS filter aligns well with the expected maximum values from the video, while the DMP filter is always less responsive in amplitude. Similar to the roll test, the DMP filter appears to assign excessive significance to the initial state orientation. Nevertheless, the computed oscillation periods remain consistent between both filters, as observed in all trials.

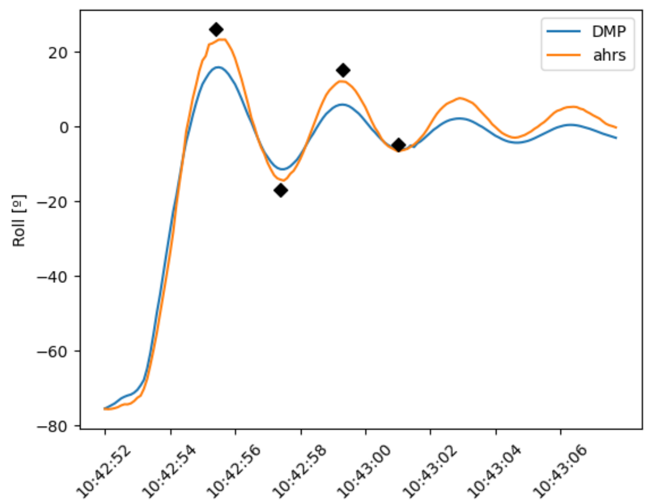

Fig. 15. Roll values during pull-down test in Class Globe 5.80 #132.

4 CONCLUSIONS

The objective of this study was to determine if the low-cost, open source IMUs used in this research are suitable tools for vessel motion monitoring. The results show that the IMU used appears to be an effective tool for monitoring vessel motion. In addition, both calculation methods provide similar precision with respect to observed orientations. Therefore, under the test conditions used, both DMP and AHRS methods of filtering IMU data provide consistent results to compute vessels motion.

However, the results suggest that the DMP filtering method is giving an excessive weight to system stability. Its inaccuracies are related to maintaining the initial state of the vessel. Consequently, this leads to low amplitudes in certain oscillations, particularly those with high angular accelerations. In addition, the IMU firmware prevents the recording of raw sensor data when the DPM filter is enabled. Therefore, the DMP filter is a suitable orientation calculation method in cases were the motion studied is smooth and slow. This situation can be expected in slow vessels, with high metacentric height (GM) values and in favourable weather conditions, especially in terms of wave height.

The AHRS filter offers more flexibility in terms of adjusting its internal coefficients, which affect filter stability. This filter can be adjusted to give a higher weight either to the initial state or the new sensor readings, based on the internal sensor noise. The AHRS filter is more adaptable and is applied post hoc, allowing more flexible filter application. However, in some cases, such as the Lamboley test, pitch results from the AHRS filter were not as accurate as those from the DMP. This leads to the conclusion that the versatility of the AHRS filter does not lead to high precision in all circumstances.

In future trials or monitoring campaigns, the authors would advocate for repetition of the spherical calibration in the location where the IMUs will be placed. This will ensure the correct estimation of magnetic field around the units. If the AHRS filter is used, the magnetometer values are considered in the orientation calculations. In cases in which spherical calibration is not possible, a 360º turn could help to estimate the magnetic disturbance around the IMU. Future trials should also test the IMUs under more adverse conditions. With the exception of the pull-down test conducted on the Class Globe 5.80, all trials had smooth and controlled oscillations. If the objective is to monitor high-speed crafts or planning vessels, IMU performance under high vertical accelerations should be tested beforehand.

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