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INERTIAL MEASUREMENT UNIT TO DETERMINE MOORED VESSELS MOVEMENTS

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ABSTRACT

Inertial Measurement Units (IMU) are usually employed to determine the dynamic positioning of vessels during navigation. However, this paper proposes a novel application of a self-made IMU to estimate the angular movements (roll, pitch and yaw) of a moored vessel. This IMU is equipped with three orthogonal gyroscopes and accelerometers capable of measure three of the six degrees of freedom of a floating body.

The vessels dynamic behavior characterization inside the port has a major importance not only in the design of mooring and anchoring systems, but also in the optimization of operations. The oscillations of moored vessels and their interactions with anchoring systems are usually described using physical scale or numerical models. However, the study of moored ships under real conditions is less frequent. The proposed technique has been validated in laboratory conditions and successfully used in two different projects with field campaigns developed in the Outer and Inner Port of A Coruña (Spain).

KEWORDS: Port operability, field campaign, IMU, mooring.

1 INTRODUCTION

The main objective of this paper is to present the results of two different projects with field campaigns developed in the Outer and Inner Port of A Coruña (Spain). Since 2013, A Coruña Port Authority has shown special interest in the monitoring and control of the ship motions, mooring analysis and their relation with the marine conditions during loading or unloading thereof. Moreover, comparison of the results with the PIANC and Spanish ROM Recommendations were done analyzing new thresholds for harbor operations, also as part of the planned traffic translation from the Inner to the Outer Port in 2016-2018.

The first field campaign was developed in the Outer Port of Punta Langosteira, located 20 km away from the city of A Coruña in extreme conditions (Figure 1, left). Main breakwater 3.35 km length was designed with Hs[m] = 15.2, Tp [s] =18.0, T[years] =140, opened officially in 2012. Western breakwater will be finished in 2016. First field campaign was developed measuring the behavior of an antipollution vessel (Urania Mella), with 72 meters length and 3.300 DWT, moored during two and a half months (December 2012 to February 2013). Innovation procedure for monitoring motions was made with a self-made inertial measurement unit (IMU, Figure 2, left), a 3-axis accelerometer and gyroscope capable of measure three of the six degree of freedom of a floating body, and complementary visual imaging techniques.

IMU was carefully calibrated in different laboratory and field tests with precision up to 0.1º (see Rodríguez et al., 2015), with two cameras located at both ends of the vessel (Figure 2, right). Results are in in agreement with the literature (Rosa-Santos et al., 2014, among others). As a complement to develop harbour improvement factors, tensions were measured at mooring lines with 3 load cells at both head line, an aft line and a fore spring line. Hydrodynamic campaign was also done in collaboration with consultancies Aquática Ingeniería Civil and Siport21, installing an external buoy, 2 AWACS and pressure gauges to detect long waves influence (for more details see Trejo et al, 2014).

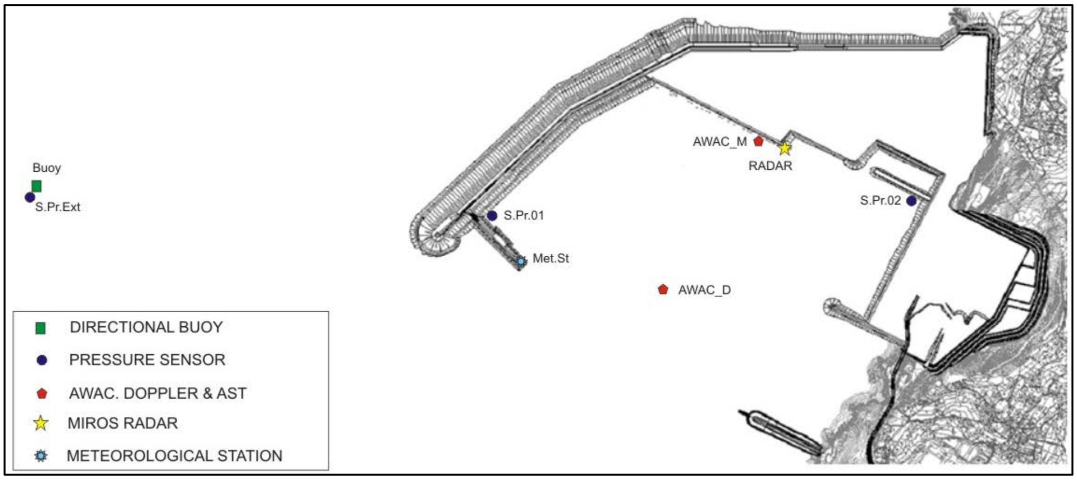

Figure 1. Left: Outer Port in Punta Langosteira. Hydrodynamic campaign and location of Urania Mella (AWAC_M point).

The second field campaign was carried out in the Inner Port of A Coruña, located inside the city, with important cargo operations potentially dangerous (LPG and LNG tankers, oil tankers and general cargo ships). IMU unit, cameras and load cells were also applied in this project, measuring those ships during fall 2015 with a mean stay of 1.5 days. The objective in this second project was to detect during extreme events the ship motions and mooring tensions, comparing them with operational limits.

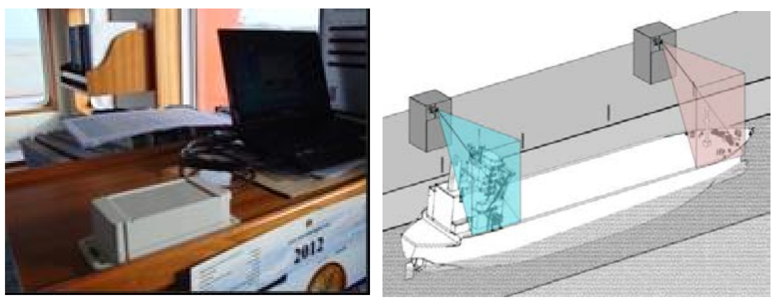

Figure 2. Left: IMU inside the vessel. Right: Location of the cameras at both ends of the vessel.

2 METHODOLOGY

This section presents the theoretical background of the application of IMU units in port operability. Then, the description of the IMU device is presented.

2.1 Theoretical background

The development of the ocean industry and the increasing size of vessels, which can only be accommodated in a few harbours with sufficient water depth, the need arose to moor ships in more exposed areas. The characterisation of the dynamic behaviour of the vessels inside the port is necessary to establish limiting operation conditions, quantify the availability of the terminals, evaluate berthing methodologies and equipment, analyse impact on operations of meteorological conditions, reduce the downtime of the terminals and establish recommended mooring arrangements.

These aspects are a key challenge for researchers attempting to describe mathematically the dynamic behaviour of moored vessels. In the first works of this area, waves were modeled as a summation of impulsive sources (Finkelstein, 1957). A different approach to the problem was proposed assuming that a vessel is able to make any arbitrary motion with six degrees of freedom, floating on the sea, which is considered as an incompressible, homogeneous and irrotational fluid.

Cummins (Cummins, 1962) considered the behaviour of the fluid and the ship in the time-domain, considering impulses in the components of motion. This resulted in a boundary value problem, which was separated into two parts; an instantaneous effect (during the duration of the impulses) and a memory effect (after the impulses extinguished).

The motions of the ship in the six degrees of freedom are obtained by integrating the equation of motion in time as follows:

$$\vec{F}(t) = (M + A)\ddot{\vec{X}}(t) + B\dot{\vec{X}}(t) + \int_{-\infty}^{t} K(t-\tau)\dot{\vec{X}}(\tau)\,d\tau + C\vec{X}(t) \tag{1}$$

Where $\vec{F}$ represent the external forces, including wave exciting forces, current forces, wind forces and mooring forces. M is the inertia matrix. A, B and C are the matrixes for the added mass, linearized viscous damping and hydrostatic restoring respectively. K contains the impulse response functions. The added mass coefficients and impulse response functions can be determined directly with the time-domain boundary-integral model following (Beck and Liapis, 1987).

Most of these mechanisms are well, known. However, the effect of the mooring system itself on the behaviour of a moored ship is not easy to estimate (Rosa-Santos, et al., 2014). The fundamental purpose of a mooring is to maintain the floating vessel in a constant unvarying mean position in order for it to perform its intended function. However, as a result of dynamic effects, this can only be approximately attained (de Kat and Paulling, 2001).

In general, the magnitude of the loads to be absorbed by the mooring system are the lower, the more freedom of movement is permitted to the vessel. On the other hand, reducing the amplitude of the moored ships' motions is crucial to increase the loading and unloading operations efficiency, to minimize port operational costs, as well as to reduce security and environmental risks, especially when dealing with dangerous cargoes (Malheiros, et al., 2013).

Nowadays a variety of mooring arrangements are in operation, and the appropriate system for a particular mooring depends on water depth, weather conditions, ship size and the allowable motions of the moored ship (Rosa-Santos, et al., 2014). The mooring lines have properties of elasticity, mass and hydrodynamic drag that can affect the dynamic response of the vessel to waves and wind. Additionally, the driving mechanisms in harbour hydrodynamics are complex and include interactions of mechanisms such as currents, wind and tidal forces, harbour infrastructures or freshwater discharge.

Furthermore, phenomena such as harbour oscillations due to resonance phenomena, can affect dramatically the harbour functioning. These oscillations are related with offshore long-period waves entering through the harbour entrance from the sea (Uzaki et al., 2010; Sammartino et al., 2014).

A different approach, have appeared with the advance of computers, allowing the implementation of numerical models in computer simulations. Therefore, six degrees of freedom computational models have been used to calculate the motions of the moored ship and forces in mooring lines for more than 20 years (Van der Molen, et al., 2003). Nowadays, there are commercial products which are available to perform these simulations.

Finally, in complementary research works, these techniques are also used to perform hydrodynamic characterisation of different harbours (Grifoll, et al., 2009; López, et al., 2012), and, in works such as (Van der Ven, 2012), to study the response of moored vessels.

In this work, IMU (Inertial Measurement Unit) is proposed to study the oscillations of a moored vessel. The IMU is the main component of inertial navigation systems used in aircraft, spacecraft, watercraft, and guided missiles among others (Ayub, et al., 2012). It allows to track the position and orientation of a moving body object relative to a known starting point. Its main disadvantage is that it requires to be used in combination with absolute positioning systems to rule out long term errors in positioning (Woodman, 2007). A low-cost implementation of an IMU device, without using GPS or external references, and taking into account the particulars of the motions of interest, will be described in the next section.

2.2 Description of the Inertial Measurement Unit (IMU)

Ship orientation can be modified by three angular motions, which constitute the focus of this work (Figure 3). Pitch, is the rotation of a vessel about its transverse (side-to-side) axis. Roll, is the rotation of a vessel about its longitudinal (front/back) axis and it is related to transverse stability. Yaw, is the rotation of a vessel about its vertical axis.

To measure these motions, the built IMU unit integrates data of three different sensors:

First, three orthogonal gyroscopes have been used to measure the angular velocity of the body. Gyroscopes suffer from noise component, called bias, which is the average output from the gyroscope when the body is not undergoing any rotation. This error can be ruled out measuring the long term average signal obtained without any rotation and subtracting it from the output (Woodman, 2007). One of the biggest problems of using gyroscopes in IMU units is that they have tendency to drift, not returning to zero when the system went back to its original position. As a result, gyroscope data is reliable only on the short term, as it starts to drift on the long term.

The IMU device used in this work is also equipped with three accelerometers. Accelerometers measure the acceleration of the moving object relative to itself. The most important source of error from accelerometers is also the bias constant error (Woodman, 2007). Accelerometers are very sensible to disturbances due to small forces acting on the body. In general, the accelerometer data is reliable only on the long term.

Finally, the proposed device was equipped with three orthogonal magnetometers. The magnetometers measure the strength and direction of the local magnetic field, allowing the north direction to be found. Magnetometers are not accurate enough to replace gyroscopes or accelerometers and they are affected by local disturbances in the earth's magnetic field caused by nearby magnetic objects.

Integration of different sensor devices to obtain a robust IMU unit have been studied in works such as (Gebre-Egziabher, et al., 2004). In general, the gyros are used as the primary source of orientation information, and other measurements are used as a feedback to the system to dissipate the errors. Therefore, two corrections will be applied. First, the magnetometers will be used to correct the heading of the vessel, i.e. the rotation on the *Z* axis, and then the accelerometers will be used to correct the orientation of the *Z* axis, which, in the frame reference of the earth, coincides with the orientation of the gravity vector.

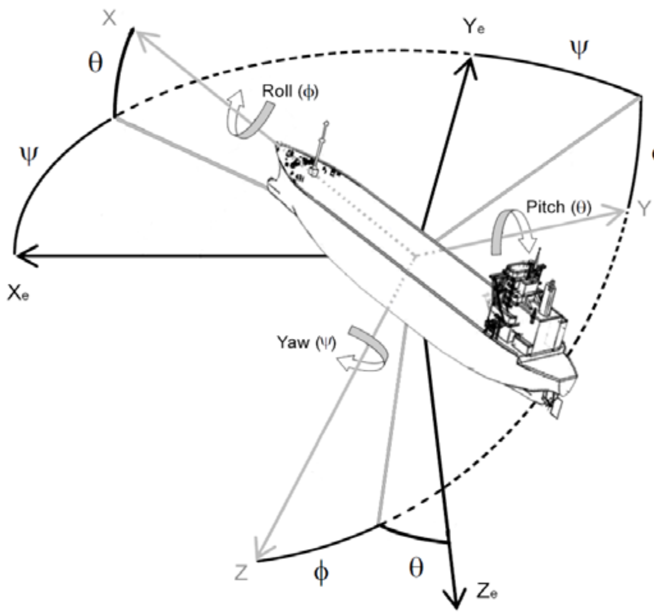

Figure 3. Orientation of a moored vessel. Angles and the Earth axis X_e, Y_e and Z_e are shown in black. Ship axis and their projection into Earth reference planes are marked in grey. The ship has three rotation modes relative to ship axis *X*, *Y* and *Z*; called roll, pitch and yaw respectively, originating the rotation angles ϕ, θ and ψ respectively.

2.3 IMU validation in laboratory tests

In order to measure and compare the accuracy of the system, several experiments were conducted in a 25x0.8x0.6 m wave-current flume located in the Center of Technological Innovations in Construction and Civil Engineering (CITEEC) of the University of A Coruña. In these experiments, a two hulls scale ship model was used to test the accuracy of the system with waves of different heights and amplitudes. The experimental layout used in these experiments is shown in Figure 4.

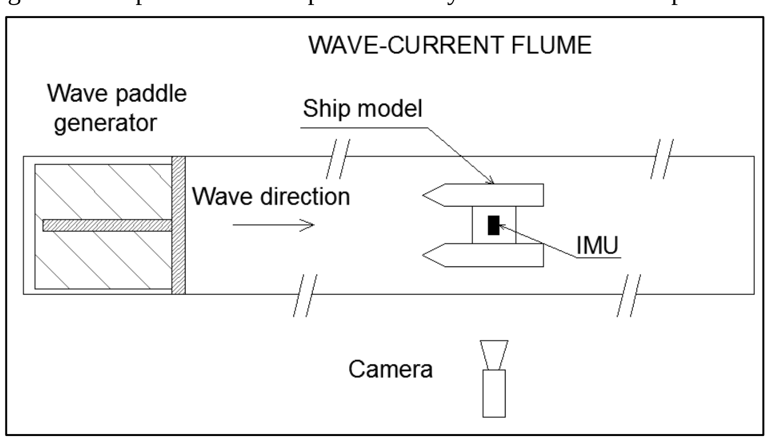

Figure 4. Experimental setup in the wave-current flume of CITEEC.

In the first of the conducted experiments, the correction of the long term drifting is analysed. To this end, a 7 hour test was conducted, starting and finishing in a resting (no waves) condition. A wave frequency of 0.8 Hz and a wave height of 8cm were used in the rest of the experiment. Different tests were conducted measuring the pitch of the model and rotating the units to align different axis of the IMU units with the longitudinal axis of the hull. The results obtained in each of these tests were almost identical.

To analyse the obtained data from the tests, in the first place, the average resting values at the beginning and the end of the experiment were compared, detecting a deviation of 0.0015 degrees. This result probes that there is no significant zero drift in the units.

Additionally, a peak analysis was performed, disregarding the first minutes of the experiment to ensure that the oscillation of the ship has reached a stable behaviour. The maximum and minimum peaks of oscillation were fitted using a linear regression technique. The slope of the regression models were -1.8e-7 and -2.7e-7 respectively for a sampling frequency of 5Hz. This result shows that there is no significant drift in the measured oscillation peaks.

A second set of experiments was conducted in the wave-current flume of the CITEEC to compare the proposed technique with a Computer Vision system. The use of Computer Vision to analyse the displacements of a vessel was validated in ship models in works such as (Malheiros, et al., 2009). Therefore, the conducted experiments were recorded with a video camera and a pattern of visual targets was placed in the hull of the model. To measure the pitch of the model, these visual targets were tracked using a block matching technique (Rodriguez, et al., 2015). The experimental assembly used in these experiments is shown in Figure 5.

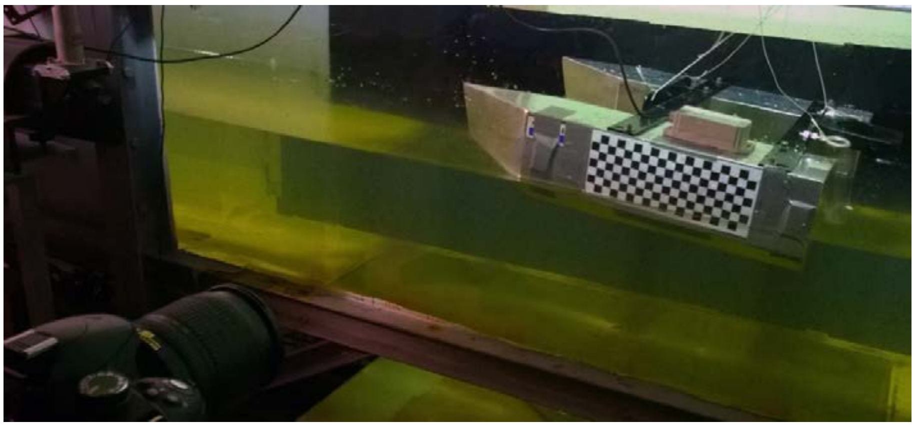

Figure 5. Experimental assembly used in the comparative assays.

Obtained results using a wave height of 18 cm and wave frequency of 0.7Hz are shown in Figure 6. Similar results were obtained with 0.5Hz.

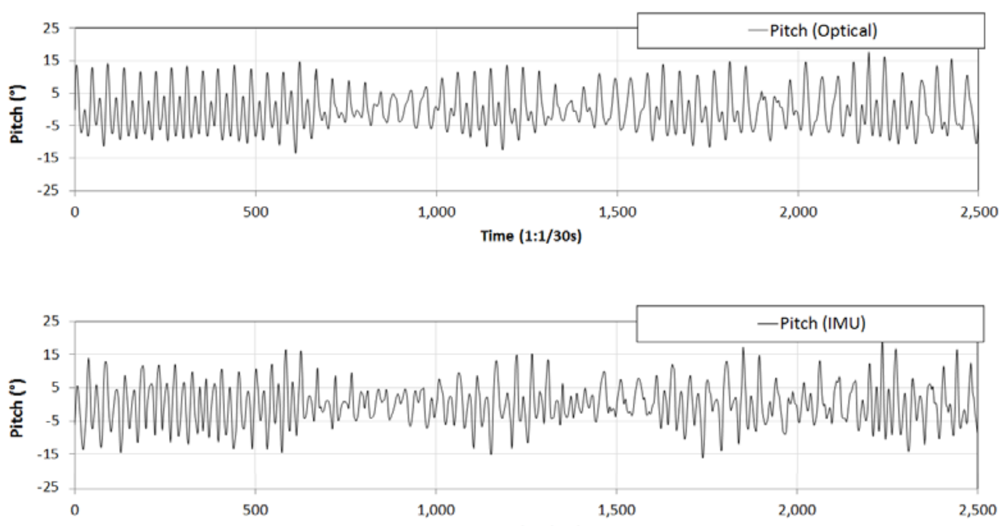

Figure 6. Pitch measurements with the Computer Vision system and the proposed technique for a wave frequency of 0.7 Hz.

Examining the previous results, it can be seen that the output of the two systems is very similar. Although the camera and the IMU unit were not completely synchronized, a correlation analysis revealed a strong correlation in the significant pitch obtained with both systems. Therefore, this experiment results in Pearson values of 0.89 for 0.7Hz wave frequency test and 0.96 for 0.5Hz, with p-values < 0.05.

2.4 Data analysis procedure

Described technique allow monitoring the angular motions of moored vessels uninterruptedly during their stay in port. The time domain analysis of the motion series was based on a zero crossing technique having as reference the ship initial position. Therefore, for each specific oscillation mode, peak-to-peak motion amplitudes are the differences between the maximum and minimum positions of the ship's center of gravity between two successive down-crossing zeros (which define a ship oscillation, PIANC 1995). Data were split in blocks of 20 minutes and then a statistical analysis was performed to compare the maximum and significant values of each movement.

The significant value of motions was chosen with the purpose of being compared with wave parameters (Hs: significant wave height, Tp: peak period). Furthermore, for each monitored vessel, maximum and mean significant values of each angular motion during their stay in port were obtained. This mean significant value is calculated as the average of all significant values obtained for each block of 20 minutes.

3 RESULTS

Once validated the utility of the IMU to study the dynamic behavior of moored vessels in laboratory tests, two different field campaigns were carried out in Outer and Inner ports of A Coruña.

The first project was developed in the Outer Port of A Coruña in order to validate IMU device in a real scenario. A field campaign was performed to measure the dynamic behavior of the ship *Urania Mella*, an antipollution vessel of 72 m length, 15 m beam, a gross tonnage of 1,676 tons and deadweight tonnage of 3,180 tons. The mooring location of the *Urania Mella* (red shape, not scaled in Figure 7: vessel length = 72 m, berthing line length = 900 m) and the characteristics of the Outer Port of *A Coruña*, in *Punta Langosteira* are shown in Figure 7.

Figure 7. Outer Port of Punta Langosteira, in A Coruña, and mooring location of the Urania Mella during the field campaign.

The dynamic behavior of the vessel was measured uninterruptedly for nearly three months in the winter season (December 2012 to February 2013). Figure 8 shows maximum and significant values of roll angular movement.

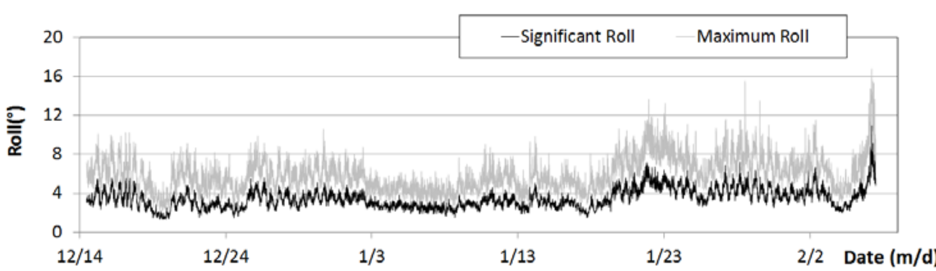

Figure 8. Significant and maximum roll measured with the IMU.

Additionally, during the measurement period, a hydrodynamic campaign was developed and mooring tensions were quantified. A strong linear relation of the angular movements with wave height measured inside the port has been detected (Figure 9). In addition, a light linear relation with wave height in the open ocean has been observed. Obtained results are statistically significant using Pearson equation (p-value < 0.05) and are shown in Table 1.

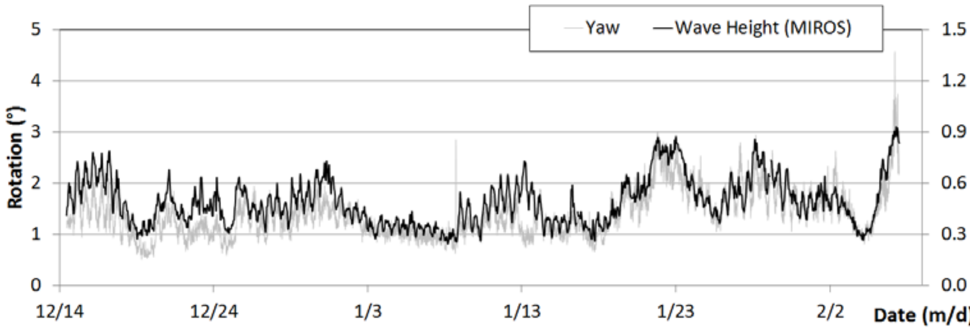

Figure 9. Evolution of Hs with MIROS radar compared with significant yaw measured with the IMU.

Table 1. Pearson correlation of angular movements with wave height and mooring tensions.

	Wave Height Ocean	Wave Height Port
Roll	0.64	0.79
Pitch	0.62	0.72
Yaw	0.68	0.83

During the field campaign, tensions in three mooring lines were measured (head line, stern line and spring). Mooring load registration showed three different mooring arrangements (boxes 1, 2 and 3 in Figure 10). High pretensions in lines were associated with relevant rope tensions and low motions (Figure 10, box 1). Lower pretensions lead to higher ship motions and lower line loads (Figure 10, box 2). Layouts with almost no initial pretension are related to the largest vessel motions, and the mooring lines experience peaks of tension with higher values due to the strong pull when the rope reach its end (Figure 10, box 3).

Taking into account that not all mooring lines were monitored, the results give a partial description of the mooring arrangement, limiting the analysis and obtaining firm conclusions.

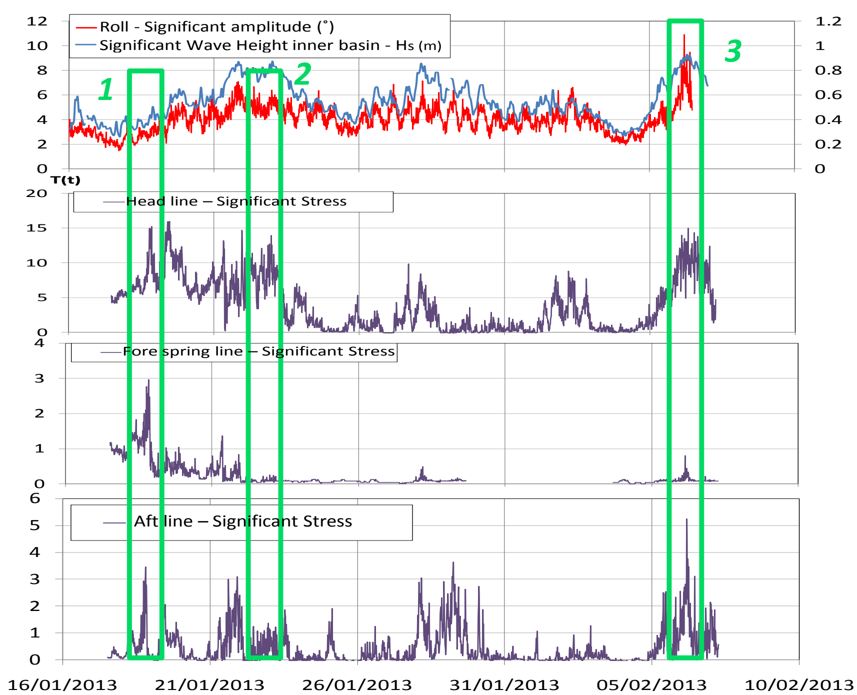

Figure 10. Significant roll, significant wave height and mooring tensions comparison in the Outer Port.

A second project is being carried out in the Inner Port of A Coruña, which is allowing to determine new port operability thresholds comparing with current recommendations. The dynamic behavior of seven vessels has been monitored during their operation time. Roll movement presented the highest amplitudes of the angular motions, in most of the analyzed vessels. Figure 11 shows significant amplitudes of angular movements of a representative ship.

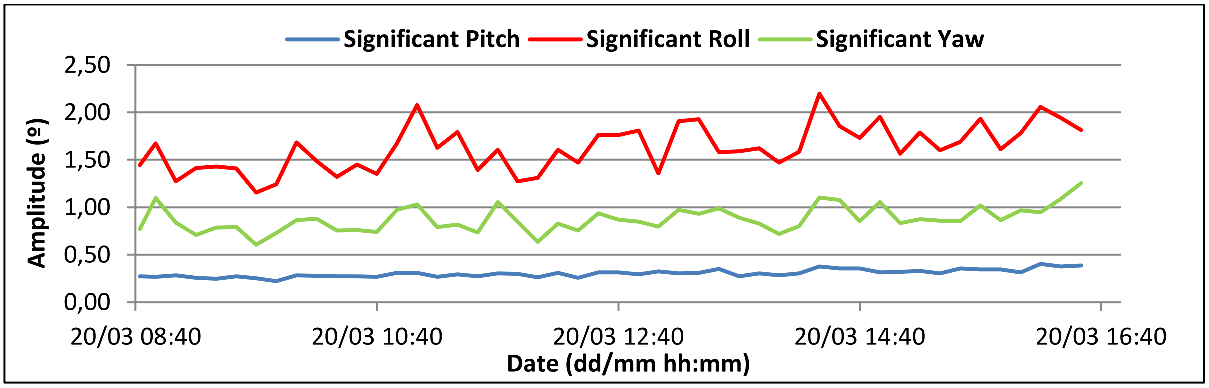

Figure 11. Significant pitch, roll and yaw movements of Esky general cargo vessel.

It is remarkable, the amplitudes of roll and yaw movements measured during cargo operations in two of the analysed vessels, *Matthew* and *Scali del Teatro* LPG tankers moored in the 2nd jetty of the Inner Port (Figure 12), exceeded PIANC and Spanish ROM Recommendations standards. The obtained results are showed in Figure 13, where PIANC and Spanish ROM thresholds, maximum and significant values of roll angular movement are represented. Blue boxes in Figure 15 represent cargo operation interruptions due to an electric storm.

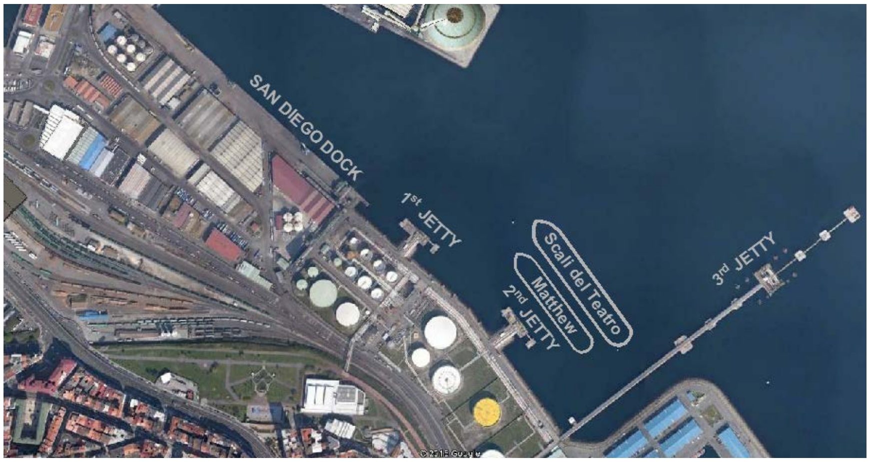

Figure 12. Mooring location of the Matthew and Scali del Teatro during the field campaign.

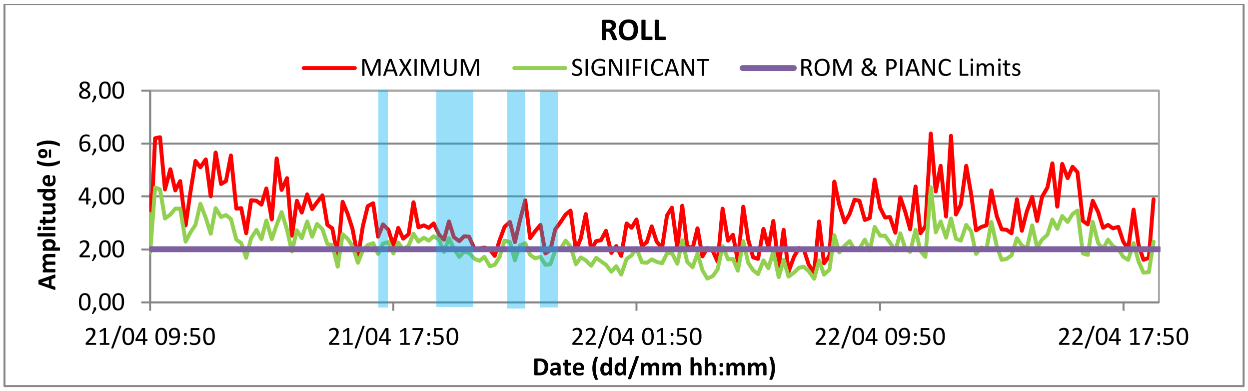

Figure 13. Maximum and significant values of roll angular movement of Matthew.

It should be note that not only maximum and significant peak values of roll and yaw exceeded the operational limits, but also the mean significant value (see chapter 2.4) of these movements during the analyzed period (Table 2).

Table 2. Maximum and Mean Significant values during cargo operation of Matthew and Scali del Teatro LPG tankers.

	Maximum (º)		**Mean Significant (º)**		**PIANC & ROM Limits (º)**	
	Matthew	Scali del Teatro	Matthew	Scali del Teatro	Matthew	Scali del Teatro
Pitch	0.58	0.76	0.16	0.38	2.0	2.0
Roll	6.38	7.36	2.14	2.84	2.0	2.0
Yaw	4.52	6.15	0.99	3.70	2.0	2.0

Surge and heave displacements were also monitored in all analyzed vessels, using a visual imaging technique (see Trejo et al., 2014). Nevertheless, these results were not available at the moment this paper was written. This information will allow to identify if the registered values of surge, heave, roll and yaw are similar under the same conditions. It may be possible that downtimes for these type of ships are more influenced by displacements (mainly surge) rather than by angular motions.

As PIANC and Spanish ROM are useful guidelines, their motion limiting criteria represent generic values applicable to facilities all over the world and exceptions are possible. Currently, the number of monitored vessels is being increased in order to identify specific operational thresholds for these facilities. In addition, since December 2015 a hydrodynamic campaign is being developed with the aim of determining relations between wave parameters and the dynamic behaviour of moored vessels.

In order to complete the obtained information, tensions were measured in two mooring lines of analyzed vessels with load cells (head line and stern line). No excessive tensions were registered at any monitored ships. Roll and yaw movements show a light linear relation with measured tensions. Figure 14 shows evolution of significant tension compared with significant roll movement of a representative vessel.

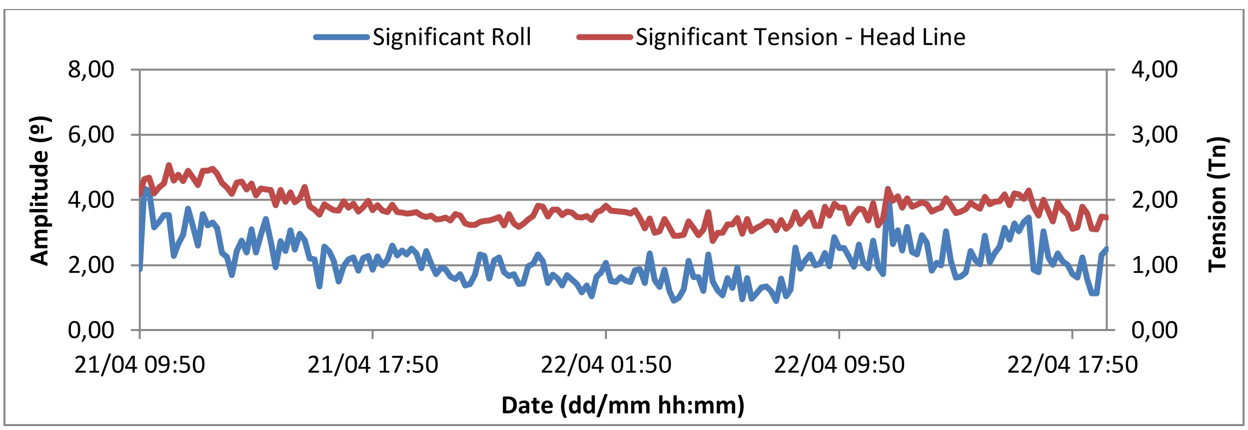

Figure 14. Evolution of significant tension compared with significant roll movement of Matthew LPG vessel.

4 CONCLUSIONS

The main conclusion obtained with this study is that a self-made Inertial Measurement Unit (IMU) allows to characterize the behaviour of moored ships inside ports in field campaigns, in order to establish limiting operation conditions and quantify the availability of the terminals. This device is able to measure the angular movements of moored vessels. Laboratory test were performed initially to validate and calibrate the instrumentation. Later, it was applied to two real projects in the Port of A Coruña (Spain).

In the first project of this work, the IMU has been tested in the *Urania Mella*, moored in the Outer Port of A Coruña, in order to analyze its dynamic response. During the field campaign, roll, pitch and yaw have been characterized and compared with wave heights and loads in the mooring lines. Obtained results showed that wave height was the most determinant factor in the dynamic behavior of *Urania Mella*, and also interesting correlations have been found with the partial monitoring of the mooring arrangement (only three mooring lines were analyzed).

In the second project, developed in the Inner Port, seven different vessels were analysed. Some of the monitored ships had higher angular movements than the maximum values established for loading and unloading operations by the PIANC and

Spanish ROM Recommendations. However, these operations were carried out without any problem. Although the obtained results suggest that angular movement thresholds stablished by the recommendations should be revised, it is necessary more in-depth studies to analyze not only angular movements but also displacements in order to determine the limiting criteria applicable to these facilities.

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REFERENCES

Ayub, S., Bahraminisaab, A. and Honary, B., 2012, A sensor fusion method for smart phone orientation estimation. *Proceedings of the 13th Annual Post Graduate Symposium on the Convergence of Telecommunications, Networking and Broadcasting*, Liverpool, UK.

Beck, R. and Liapis, S., 1987, Transient motions of floating bodies at zero forward speed, *Journal of Ship Research*, 31.

Cummins, W.E. (1962) The impulse response function and ship motions. *Symposium on Ship Theory*. Hamburg, Germany.

de Kat, J.O. and Paulling, J.R., 2001, Prediction of Extreme Motions and Capsizing of Ships and Offshore Marine Vehicles. *OMAE 2001-20th Conference on Offshore Mechanics and Arctic Engineering*, Rio de Janeiro, Brazil.

Finkelstein, A.B., 1957, The initial value problem for transient water waves, *Communications on Pure and Applied Mathematics*, 10, 511-522.

Gebre-Egziabher, D., Hayward, R.C. and Powell, J.D., 2004, Design of multi-sensor attitude determination systems, *Aerospace and Electronic Systems, IEEE Transactions on*, 40, 627-649.

Grifoll, M., Fontán, A., Ferrer, L., Mader, J., González, M., Espino, M., 2009, 3D hydrodynamic characterisation of a meso-tidal harbour: The case of Bilbao (northern Spain), *Coastal Engineering*, 56, 907-918.

López, M., Iglesias, G. and Kobayashi, N., 2012, Long period oscillations and tidal level in the Port of Ferrol, *Applied Ocean Research*, 38, 126-134.

Malheiros, P., Rosa-Santos, P., Moreira, A.P., Taveira-Pinto, F., 2009, Robust And Real-Time Motion Capture Of Rigid Bodies Based On Stereoscopic Vision, *International Conference on Integrity, Reliability and Failure*, Porto, Portugal, S0215_P0429.

Malheiros, P., Rosa-Santos, P., Gonçalves, J., Costa, P., Moreira, A.P., Veloso-Gomes, F., Taveira-Pinto, F., 2013, Real-Time Tracking System for a Moored Oil Tanker: A Kalman Filter Approach. *Advances in Sustainable and Competitive Manufacturing Systems*. Springer, pp. 749-760, ISBN 978-3-319-00557-7.

Permanent International Association of Navigation Congresses (PIANC) 1995. Criteria for movements of moored ships in harbours, a practical guide. *Report of theWG24 of the Permanent Technical Committee II, Supplement to Bulletin N°88*. PIANC, Brussels, Belgium.

Rodríguez, A., Rabuñal, JR., Peña, E., Costa, F., Figuero, A., 2015, Inertial measurement of moored vessel dynamics in the Outer Port of A Coruña. *Journal of Ship Research* (under review).

Rosa-Santos, P., Taveira-Pinto, F. Veloso-Gomes, F., 2014. Experimental evaluation of the tension mooring effect on the response of moored ships, *Coastal Engineering*, 85, 60-71.

Sammartino, S., Sánchez Garrido, J.C., Delgado, J., Naranjo, C., Criado Aldeanueva, F., García Lafuente, J., 2014, Experimental and numerical characterization of harbor oscillations in the port of Málaga, Spain, *Ocean Engineering*, 88, 110-119.

Trejo, I., Pérez, JD., Guerra, A., Iribarren, JR., Gómez, J., Sopelana, J., Peña, E. 2014. Onsite Measurement of Moored Ships Behaviour (RTK GPS), Waves and Long Waves in the Outer Port of A Coruña (Spain). *Proceedings. of PIANC World Congress*, San Francisco, USA

Uzaki, K.-i., Matsunagab, N., Nishiic, Y., Ikehatad. Y., 2010, Cause and countermeasure of long-period oscillations of moored ships and the quantification of surge and heave amplitudes, *Ocean Engineering*, 37, 155-163.

Van der Molen, W., Ligteringen, H., van der Lem, J.C., de Waal, J.C.M., 2003 Behavior of a moored LNG ship in swell waves, J*ournal of Waterway, Port, Coastal, and Ocean Engineering*, 129, 15-21.

Van der Ven, P., 2012, *The use of numerical models to determine the response of moored vessels to waves in a complex harbour geometry*, Delft University of Technology.

Woodman, O.J., 2007, *An introduction to inertial navigation*. University of Cambridge Computer Laboratory, ISSN 1476-2968.