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Displacement Measurement System for Small-Scale Vessels Berthed in Physical Models of Port Terminals

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ABSTRACT: This paper presents the development of a displacement measurement system for small-scale physical models of moored ships, aimed at providing data to evaluate displacement amplitudes and determine whether they surpass predetermined operational limits. The system, which combines cameras and inertial sensors, captures six degrees of freedom, allowing measurements of surge, sway, heave, yaw, roll, and pitch. The developed system was initially tested isolating each degree of freedom for analysis, and subsequently applied to a scale model of a port terminal berth, with a bulk carrier vessel docked, subject to wave action. Scale models of port terminals have been extensively validated over numerous years of research and development. To evaluate the system's response, displacement measurements obtained through the developed system were compared with a commercial system widely recognized for measuring rigid body movements, the Qualisys® system. This comparison shows both systems obtained similar results, indicating that the developed system meets its intended purpose. Overall, the system provides a reliable tool for studying the complex behavior of moored vessels and evaluating operational and safety conditions in port terminals.

1 INTRODUCTION

Maritime transport is the primary mode of cargo transportation in international trade. In 2012, approximately 80% of global trade in terms of volume and over 70% in terms of value was transported by sea and distributed among ports and economies worldwide [14]. To meet this huge demand, ships are constantly evolving and becoming larger.

The increase in the volume of goods transportation has driven the size of cargo ships. According to ITF (International Transport Forum) [8], the average capacity of newly constructed container ships ranged from approximately 3,400 Twenty-foot Equivalent Units (TEUs) between 2001 and 2008, to 5,800 TEUs between 2009 and 2013, reaching approximately 8,000 TEUs in 2015.

As the size of vessels have increased, ports have sought wider and deeper nautical spaces. The consequence of this is the displacement of ports, generally towards the sea, where protection from environmental actions is less, or in some cases, non-existent.

The construction of port terminals in unsheltered areas leave vessels vulnerable to environmental actions, especially vessels docked at the pier. To ensure the safety of vessels docked at port terminals, it is essential to study the forces on mooring lines and the displacements of the vessel relative to the pier during cargo handling operations.

Experimental tests using physical models emerge as one of the most important tools in engineering to represent the port nautical environment and its interaction with environmental conditions, allowing for the simulation of scenarios of vessels moored at berths and monitoring their movements when subjected to environmental actions or the passage of other vessels. According to Bernardino et al. [2] physical models are generally small-scale representations of any physical system and its applications in Engineering are widely discussed in the international literature, in references such as [11], [10], [5] and [17]. In the case of port studies, hydraulic physical models, also shortly called scale models, can be used to represent the entire interest area, including topography, bathymetry, docking structures, vessels, and the environmental conditions, such as water level variations, waves, winds, and so on [11].

When the displacements in relation to the pier of moored vessels exceeded certain limits, there are implications for both safety and efficiency of port operations. The excessive movement of moored vessels can stop the loading processes and, in extreme cases, damage the mooring lines, winches, bollards, and fenders. The PIANC (Permanent International Association of Navigational Congresses) [12] has a series of recommendations for vessel displacements. The recommended limits for each displacement vary according to the type of vessel and the type of loading equipment.

In scale models, measurement systems for vessel displacements must be able to accurately measure the six degrees of freedom, which is generally not a simple task due to the small scales of these models. Traditionally, vessel displacement measurements in scale models are performed using potentiometric systems coupled to the vessel or by utilizing accelerometers and gyroscopes [6]. Briggs and Melito [4] present an example of a displacement measurement system using accelerometers and gyroscopes.

According to ITTC (The International Towing Tank Conference) [7], the traditional approach to monitoring vessel displacements in scale models has been replaced by a measurement system that uses video image capture and analysis. Kieviet [9] presents a system that analyzes a sequence of video images of a known three-dimensional object positioned on the vessel's deck. Benetazzo [1] presents a similar system that utilizes a quad grid marker target on the deck, rather than a three-dimensional object.

Currently, this type of displacement measurement has become widely used in hydraulic laboratories due to its non-intrusive measurement technique, avoiding instrument contact with the water and equipment interference with the vessel.

This paper presents the development of a six-degree-of-freedom displacement measurement system for scale models of vessels berthed at port terminals subjected to wave action. The developed system combines measurements by image pattern recognition algorithm with measurements by inertial sensors. The system was tested on a scale model of a port terminal at the Hydraulics Laboratory of the School of Engineering of the University of Sao Paulo (CTH-USP).

2 MATERIAL AND METHODS

2.1 *The displacement measurement system*

The displacement measurement system for small-scale ship models in experimental simulators was developed by the CTH-USP team. The system measures the displacement of vessels in relation to the pier, providing data that allows the evaluation of safety during cargo handling operations. The system can be applied to any scale model of berthed vessels with enough space to position the system structure.

The system contains a set of inertial sensors coupled under a marker target and a camera fixed to the pier. The sensors and the marker target are positioned on the vessel's deck, and the geometric center of this target is the same as the geometric center of the vessel's deck.

Figure 1 shows the inertial sensors and the marker target, assembled in image A (in the same way as when they are installed on the small-scale vessel) and disassembled in image B.

Figure 1. The inertial sensors and the marker target assembled (A) and disassembled (B). Source: Bezerra [3].

The element in Figure 1 (A) has total dimensions of 230 x 100 x 25 mm, which can be adapted depending on the needs of the test. However, it is important to point out that a reduction in these dimensions cannot be exaggerated, since the accuracy of the system would be impaired.

Another element of the measurement system is a camera fixed to the pier, positioned over the marker target. This camera transmits images of the marker target to a computer that processes the images and obtains the displacements. Figure 2 provides an overview of the system.

The measurement uncertainty of the displacement capture system through images depends on the pixel-to-millimeter ratio, which it is defines by the number of divisions the algorithm will use for each millimeter. This measurement uncertainty depends primarily on the number of pixels in the image generated by the camera and the distance between the marker target and the camera.

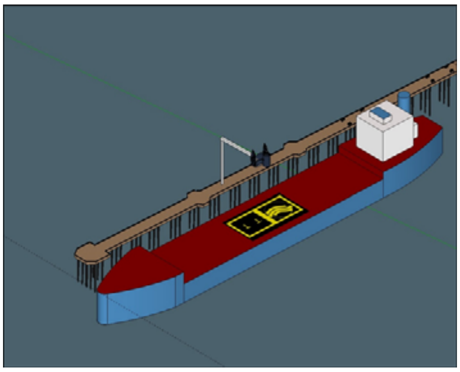

Figure 2. Schematic drawing showing the displacement measurement system which consists of two parts: one fixed to the pier and the other on the vessel. Source: Bezerra [3].

For the case study of this paper, the camera was fixed at 150 mm above the marker target placed on the vessel. This provides a ratio for the system of 0.163 mm/pixels, providing a measurement uncertainty of approximately 0.082 mm to the surge and sway displacements captured using images. The yaw displacements, also captured using images, present a measurement uncertainty of 0.05°.

The heave displacements, unlike other displacements measured by image, are obtained through the image scaling factor of the image pattern recognition algorithm, thus its measurement uncertainty is 0.168 mm with the camera at 150 mm from the marker target. Figure 3 shows the displacement measurement system in a scale model.

Figure 3. Displacement measurement system assembled in a scale model. Source: Bezerra [3].

To complement the camera system, a multi-sensor type IMU (Inertial Measurement Unit) model GY-80 was used to measure other displacements (pitch and roll). This IMU has a gyroscope, an accelerometer, a magnetometer, and a pressure and temperature sensor.

For this work, the measurement of roll and pitch movements was performed using the combined results of the accelerometer and gyroscope present in the IMU. This combination between the two sensors reduces orientation errors (drift) and vibration errors, providing a more accurate measurement of rotational displacements. Figure 4 presents the results obtained from the combination of sensor outputs under the influence of a sinusoidal motion. The use of a sinusoidal motion is a common approach in engineering to test the dynamic response of a system.

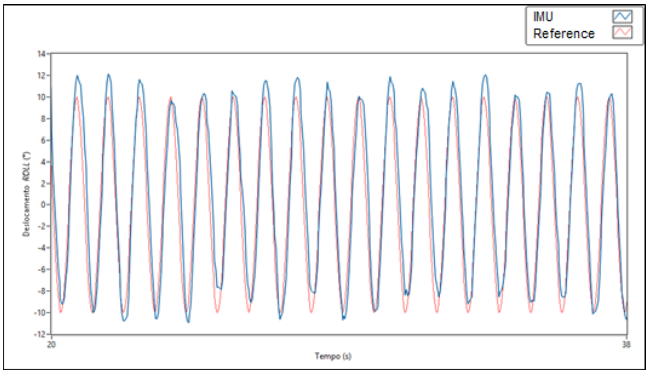

Figure 4. A sinusoidal motion with a frequency of 0.2 Hz and amplitude of 15° is applied to the developed system.

The rotational displacements measured by inertial sensors (roll and pitch) exhibit a measurement uncertainty of 0.5° for amplitudes greater than 2°.

2.2 *Scale model*

After testing the displacement measurement system in the instrumentation laboratory, its performance was evaluated in a scale model of a port terminal. This model represents a specialized iron ore terminal located in a bay in southeastern Brazil. This bay is semi-protected from wave action and the port terminal is connected to the mainland by a conveyor belt used to transport iron ore to moored ships.

The scale model was built in a reduced geometric scale of 1:170, without distortion, according to Froude's similarity criteria. This model can represent tidal currents and their effects on ships, as well as representing regular and irregular waves. The generation of irregular waves is based on the JONSWAP (Joint North Sea Wave Project) parametric spectrum model, used in most engineering projects related to coastal regions for calculating wave spectra.

Figure 5 shows the scale model used to evaluate the developed system.

Figure 5. Three-dimensional scale model with wave generator system located at the CTH-USP. Geometric scale: 1:170. Source: Bezerra [3].

The displacement measurement system was tested in two different wave scenarios: regular and irregular. Table 1 presents the type of wave generated, as well as the significant wave height (Hs) and the peak period (Tp), presenting both prototype values and values measured in the geometric scale of 1:170 model.

Table 1. Scenarios tested in the scale model.

Wave Type	Prototype		Model(1:170)	
	Hs(m)	Tp(s)	Hs(mm)	Tp(s)
Scenerio 1 Regular	2.5	14	14.71	1.08
Scenerio 2 Irregular	1.5	12	8.82	0.92

These scenarios were selected because they are the most representative of the incident waves in the study area.

2.3 *Qualisys® System*

The Qualisys® system has been widely used in various fields, including the measurement of motion in scale models. The system works by capturing motion data through a series of high-resolution digital cameras and reflective markers. The cameras are placed strategically around the object being tracked, and the markers are placed on specific points of the object.

According to Qualisys® [13], the benefits of using optical motion capture for marine applications are that the system does not require wiring for the vessel during the experiment, the position of the vessel is captured by cameras mounted on the side of the basin, avoiding any change in ship movement due to connected wires.

The measurement uncertainty of the Qualisys® system can depend on several factors, including the specific hardware and software configuration used, the calibration process, and the environment in which the system is used. However, Qualisys® reports that their system has a measurement accuracy of less than 0.1 mm and 0.1 degrees [13].

Therefore, as it is a well-established displacement measurement system, the Qualisys® system can be used as an evaluation parameter for the results of the developed system in this work.

3 RESULTS AND DISCUSSION

In this chapter, a comparison of results between the displacement measurement developed system with the Qualisys® system, previously described, is presented. The results were divided into the two simulated wave scenarios, as described in Table 1.

Firstly, the comparison of the measured values was carried out using statistical parameters extracted from the series of measurements of each displacement (section 3.1 for regular waves and section 3.2 for irregular waves). The statistical parameters used were the arithmetic mean (Mean), the root mean square (RMS), the standard deviation and the amplitude.

Then, the results were compared using two inter-comparison methods that assesses the agreement or similarity between measurements obtained by two different systems or instruments (Section 3.3). The inter-comparison methods used were Relative Mean Absolute Error (RMAE) [15] and the coefficient R^2 [16]. These methods are widely used for comparing sensor results.

To facilitate the analysis of the results, all differences greater than 10% were highlighted in red.

3.1 *Moored vessel under regular wave action*

The moored vessel was subjected to a scenario under the action of regular waves, where the regular wave generated in the scale model (1:170) has an amplitude of 14.71 millimeters and a peak period of 1.08 seconds. These values, when scaled up to the prototype, represent regular waves with an amplitude of 2.5 meters and a peak period of 14 seconds.

For visualization of the results under the action of regular waves, Figure 6 shows a comparison of the results obtained by the developed measurement system and the Qualisys® measurement system for the translational displacements (surge, sway, and heave) in a scenario of regular waves. Figure 7, on the other hand, shows the comparison for the rotational displacements (roll, pitch, and yaw) in the same scenario.

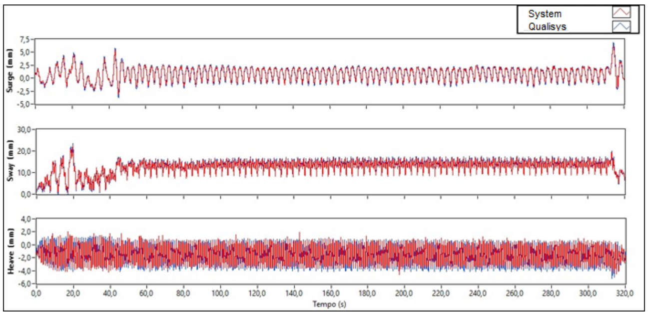

Figure 6. Translation displacements measured by the developed system and Qualisys® system for the moored vessel under the action of regular waves.

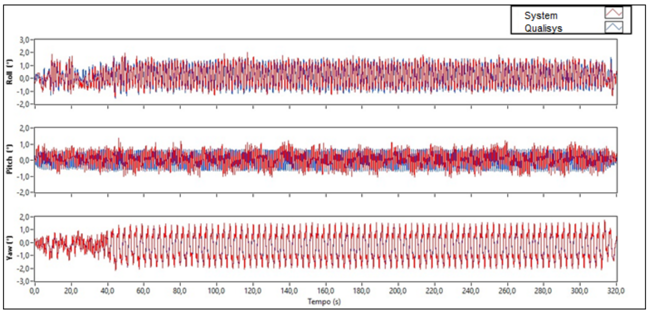

Figure 7. Rotational displacements measured by the developed system and the Qualisys® system for the moored vessel under the action of regular waves.

Table 2 presents the statistical parameters of translational surge displacement measured for each system, as well as the percentage error between the analyses. Table 3 and Table 4 present the same results for translational sway and heave displacements, respectively.

Table 2. Comparison of the statistical parameters of the measurements between the developed system and Qualisys® system for translational surge displacement under the action of regular waves.

Surge (mm)	System	Qualisys®	Difference %
Mean	0.859	0.856	-0.32%
RMS	1.500	1.631	8.01%
Standard Deviation	1.231	1.389	11.38%
Amplitude	9.338	10.612	12.00%

Table 3. Comparison of the statistical parameters of the measurements between the developed system and Qualisys® system for translational sway displacement under the action of regular waves.

Sway (mm)	System	Qualisys®	Difference %
Mean	12.753	13.026	2.10%
RMS	13.133	13.455	2.39%
Standard Deviation	3.141	3.370	6.81%
Amplitude	22.039	23.493	6.19%

Table 4. Comparison of the statistical parameters of the measurements between the developed system and Qualisys® system for translational heave displacement under the action of regular waves.

Heave (mm)	System	Qualisys®	Difference %
Mean	-1.482	-1.596	7.14%
RMS	2.078	2.265	8.25%
Standard Deviation	1.457	1.608	9.35%
Amplitude	6.628	6.644	0.24%

Tables 5, 6 and 7 present the statistical parameters of roll, pitch, and yaw rotational displacements, respectively.

Table 5. Comparison of the statistical parameters of the measurements between the developed system and Qualisys® system for roll rotational displacement under the action of regular waves.

Roll (°)	System	Qualisys®	Difference %
Mean	0.244	0.209	-16.74%
RMS	0.825	0.845	2.33%
Standard Deviation	0.788	0.819	3.69%
Amplitude	3.460	3.307	-4.64%

Table 6. Comparison of the statistical parameters of the measurements between the developed system and Qualisys® system for pitch rotational displacement under the action of regular waves.

Pitch (°)	System	Qualisys®	Difference %
Mean	0.073	-0.066	210.84%
RMS	0.481	0.471	-2.12%
Standard Deviation	0.476	0.472	-0.94%
Amplitude	2.457	1.490	-64.89%

Table 7. Comparison of the statistical parameters of the measurements between the developed system and Qualisys® system for yaw rotational displacement under the action of regular waves.

Yaw (°)	System	Qualisys®	Difference %
Mean	-0.274	-0.272	-0.54%
RMS	1.021	0.996	-2.53%
Standard Deviation	0.984	0.958	-2.69%
Amplitude	3.910	3.636	-7.52%

For the regular waves scenario, the translational displacements (surge, sway and heave) and yaw (rotational displacement measured by camera) present a maximum percentage difference of 12% between the statistical parameters of both measurement systems, demonstrating good agreement in the results.

On the other hand, some comparisons of rotational displacements measured by inertial sensors (roll and pitch) present much larger differences than translational displacements. However, it is important to point out that, for the simulation carried out (Scenario 1), these displacements presented relatively small values, within a range that the developed system is unable to measure adequately, which explains the higher differences obtained in relation to the Qualisys® system.

3.2 *Moored vessel under irregular wave action*

The moored vessel is subjected to a scenario under the action of irregular waves using the JONSWAP wave spectrum with a significant wave height of 8.82 mm and a peak period of 0.92 seconds in scale model values. These values, when scaled to the prototype, represent irregular waves with a significant wave height of 1.5 meters and a peak period of 12 seconds.

For visualization of the results under the action of irregular waves, Figure 8 shows a comparison of the results obtained by the developed measurement system and the Qualisys® measurement system for the translational displacements (surge, sway, and heave) in a scenario of regular waves. Figure 9, on the other hand, shows the comparison for the rotational displacements (roll, pitch, and yaw) in the same scenario.

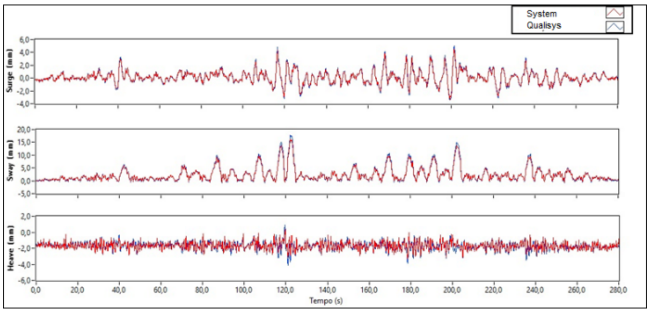

Figure 8. Translation displacements measured by the developed system and Qualisys® system for the moored vessel under the action of irregular waves.

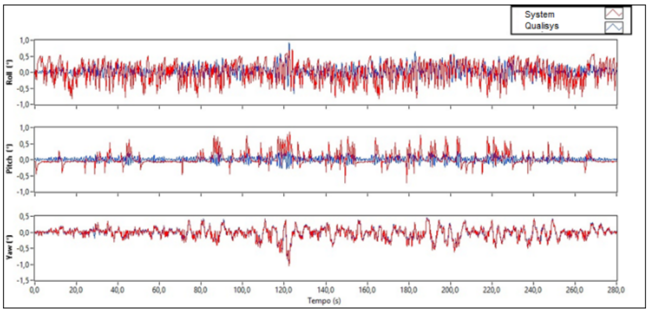

Figure 9. Rotational displacements measured by the developed system and the Qualisys® system for the moored vessel under the action of regular waves.

Table 8 presents the statistical parameters of translational surge displacement measured for each measurement system used, as well as the percentage error between the analyses. Tables 9 and 10 present the same results for translational sway and heave displacements, respectively.

Table 8. Comparison of the statistical parameters of the measurements between the developed system and Qualisys® system for translational surge displacement under the action of irregular waves.

Surge (mm)	System	Qualisys®	Difference %
Mean	0.942	0.946	0.39%
RMS	1.153	1.192	3.27%
Standard Deviation	0.664	0.725	8.40%
Amplitude	3.841	4.196	8.47%

Table 9. Comparison of the statistical parameters of the measurements between the developed system and Qualisys® system for translational sway displacement under the action of irregular waves.

Sway (mm)	System	Qualisys®	Difference %
Mean	1.742	1.751	0.54%
RMS	2.131	2.178	2.17%
Standard Deviation	1.228	1.296	5.22%
Amplitude	6.810	7.492	9.10%

Table 10. Comparison of the statistical parameters of the measurements between the developed system and Qualisys® system for translational heave displacement under the action of irregular waves.

Heave (mm)	System	Qualisys®	Difference %
Mean	-0.685	-0.689	0.55%
RMS	0.842	0.862	2.25%
Standard Deviation	0.491	0.518	5.32%
Amplitude	2.883	2.945	2.09%

Tables 11, 12 and 13 present the statistical parameters of roll, pitch, and yaw rotational displacements, respectively.

Table 11. Comparison of the statistical parameters of the measurements between the developed system and Qualisys® system for roll rotational displacement under the action of irregular waves.

Roll (°)	System	Qualisys®	Difference %
Mean	0.065	0.083	21.46%
RMS	0.324	0.229	-41.45%
Standard Deviation	0.317	0.213	-48.59%
Amplitude	2.192	1.003	-118.56%

Table 12. Comparison of the statistical parameters of the measurements between the developed system and Qualisys® system for pitch rotational displacement under the action of irregular waves.

Pitch (°)	System	Qualisys®	Difference %
Mean	0.012	-0.004	413.15%
RMS	0.210	0.100	-109.68%
Standard Deviation	0.210	0.100	-109.50%
Amplitude	1.385	0.360	-284.18%

Table 13. Comparison of the statistical parameters of the measurements between the developed system and Qualisys® system for yaw rotational displacement under the action of irregular waves.

Yaw (°)	System	Qualisys®	Difference %
Mean	0.027	0.027	2.86%
RMS	0.129	0.136	4.72%
Standard Deviation	0.126	0.133	4.80%
Amplitude	0.801	0.753	-6.27%

As in the scenario of the simulation with regular waves, the percentage differences between the statistical parameters for the displacements in surge, sway, heave and yaw present relatively small values (less than 10%), demonstrating good agreement. But, once again, for the roll and pitch displacements, the percentage differences presented much larger values. In the same way as explained in section 3.1, these differences occurred due to the relatively small values obtained for these displacements in the test carried out (Scenario 2), lying within a range that the developed system is not able to measure properly.

3.3 *Comparison between the results of the two systems*

The comparison between the results of the developed system and the results of the Qualisys® system was carried out using the Relative Mean Absolute Error (RMAE) and the coefficient R^2. Table 14 summarizes the results of these two inter-comparison methods for both regular and irregular waves, considering all measured displacements.

Table 14. Comparison of the results of the translational and rotational displacements of the moored vessel under the action of regular and irregular waves.

	Displacement	RMAE	R^2
Regular Waves	Surge (mm)	0.16	0.980
	Sway (mm)	0.03	0.987
	Heave (mm)	0.26	0.860
	Roll (°)	0.42	0.790
	Pitch (°)	0.76	0.451
	Yaw (°)	0.11	0.987
Irregular Waves	Surge (mm)	0.13	0.956
	Sway (mm)	0.18	0.913
	Heave (mm)	0.28	0.751
	Roll (°)	0.96	0.437
	Pitch (°)	1.82	0.043
	Yaw (°)	0.36	0.824

Analyzing Table 14, it is possible to observe that the pitch displacement presents the worst values for the mathematical methods both in regular and irregular wave scenarios. The roll displacement also shows poor results, with RMAE values close to or above 1. For the other displacements, the developed system shows results close to the measurements made by the Qualisys® system.

4 CONCLUSIONS

This work presents the development of a measurement system for the displacement of moored vessels in physical scale models, which combines image analysis measurements with inertial sensor measurements.

For the displacements in surge and sway, the developed system shows a result closer to Qualisys® data, with RMAE values less than 0.18, a result classified as "Excellent" according to the classification of Walstra et al. [15]. The heave displacements presented RMAE < 0.28 and yaw presented RMAE < 0.36, both results classified as "Good", according to [15]. The quality of the results obtained for these four displacements can also be verified by comparing the statistical parameters of the measurements (items 3.1 and 3.2), which resulted in percentage differences of less than 12%.

The PIANC [12] recommendations for maximum displacements of moored vessel include three main displacements: surge, sway, and yaw. Therefore, when evaluating the recommendations of PIANC in a scale model, the developed system presented excellent results for surge and sway and good results for yaw compared to the Qualisys® system.

The worst results were found for the roll and pitch displacements, with RMAE values close to 1 and percentage differences of statistical parameters with high values, reaching values greater than 400%. These differences found for roll and pitch displacements are justified because the Qualisys® system is capable of measuring displacements with small angular amplitudes, while the developed system is not capable of measuring angles smaller than 2 degrees. This fact can also be observed by comparing the differences obtained in pitch displacement for regular wave conditions (RMAE < 0.76) and irregular wave conditions (RMAE < 1.82). Irregular waves have smaller displacement amplitudes and, consequently, greater comparative difference in relation to regular waves.

It is important to point out that although PIANC [12] does not define operational limits for pitch and roll displacements, the operational practice of most ports tends to consider that small values for these displacements (such as lesser than 2 degree) do not affect cargo handling and do not put at risk the operational safety of the terminal. Therefore, even if the developed system is not able to properly measure small angles, this does not prevent the use of the system for practical Engineering purposes.

In the end, as a suggestion for future research the developed system could benefit from utilizing higher precision sensors to improve the accuracy of measurements for roll and pitch displacements.

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