Proceedings of the 6th International Conference on the Application of Physical Modelling in Coastal and Port Engineering and Science (Coastlab16)

Ottawa, Canada, May 10-13, 2016

A NON-INTRUSIVE VIDEO TRACKING METHOD TO MEASURE MOVEMENT OF A MOORED VESSEL IN A PHYSICAL MODEL

JOHAN KIEVIET[1], GEOFFREY TOMS[2], JATIN HARRIBHAI[1]

1 Council for Scientific and Industrial Research, South Africa, jkieviet@csir.co.za, jharribhai@csir.co.za

2 Post Graduate Supervisor (until 2015), University of Stellenbosch, South Africa, geoff.toms@sun.ac.za

ABSTRACT

A new Six Degrees of Freedom (6DOF) motion measurement system for a moored vessel is presented in this manuscript. The system analyses a video image sequence from one remotely located camera. The method estimates the 3D rigid motion for an object of known size by using a 'Pose from Orthography and Scaling with Iterations' (POSIT) algorithm. The object for which the motion is estimated is located on the deck of the vessel and within the camera field of view. Geometric rigid body calculations allow for the calculation of the camera's rotation and translation of an object on the vessel. Further geometric calculations allow for converting camera perspective motions to the 6DOF object motions. The method is validated in a controlled environment as well as evaluated in a dynamic situation by using a small scale physical model set-up.

KEWORDS: Physical, Model, Vessel, 6DOF, POSIT.

1 INTRODUCTION

There are several ports around the world currently experiencing problems with moored vessel motions. Extreme vessel motions are mainly caused by long waves, which can become trapped inside a harbour basin. The extreme motions can cause downtime in port operations and in some instances cause mooring lines to break.

Current vessel motion detection methods used in prototype, range from Differential Global Positioning Systems (D-GPS) to Accelerometers and Gyroscopes. These methods require vessel specific information as input. The implementation of these methods is seen as impractical to implement on every vessel visiting the port and require the physical measurement of some points on the vessel and/or the placement of some kind of measurement device on the vessel. These methods are therefore seen as intrusive in nature.

Recently, optical motion measurements have become the standard for measuring vessel motions in scale models in most Hydraulics Laboratories. These optical motion measurement techniques do not require the placement of motion sensors on a vessel. The markers or targets being tracked by the optical camera equipment, do however, still need to be mounted on the vessel. The installation location of each marker, or target, being tracked in vessel coordinates, is then also needed and used to convert tracked movements to vessel motions.

Following these optical approaches, the work presented herein, aims to show that an image-based method using only a remote camera, which does not require the placement of markers or targets on a vessel, can be used to measure vessel motions. This will significantly reduce installation time and costs when measuring moored vessel motions.

This manuscript will focus on verification testing of this method in a controlled environment as well as physical model testing in a hydraulics laboratory. Verification testing will determine the accuracy of the system. Physical model testing will be done to validate such a non-intrusive image-based vision system for measuring the movements of a vessel when berthed. Physical model work will include a comparison to the Keoship motion capture system used at the CSIR in Stellenbosch, as well as investigating the use thereof in a prototype situation. Following successful verification in the laboratory the system can readily be implemented in the prototype in actual port situations for further trials.

2 PROPOSED NON-INTRUSIVE TRACKING METHOD

The image-based method uses a model based algorithm to give accurate 3D pose of a rigid object which is then translated into vessel motion. Currently, the method saves images into a video sequence of the observed motions to a secure digital (SD) memory card, making only post-processing possible.

The video sequence obtained during a test is input to an algorithm, which calculates the 6DOF motions. The POSIT algorithm used is unlike the typical Coplanar POSIT algorithm which is similar to that presented in (Benetazzo, 2011). The POSIT algorithm makes use of model points in the x, y and z-plane of the model.

Ideally the target object to be tracked will be the superstructure of a vessel for which a wire-frame model will be available to enable object recognition and allow the model features to be tracked. A typical superstructure to be tracked on a vessel is shown in Figure 1.

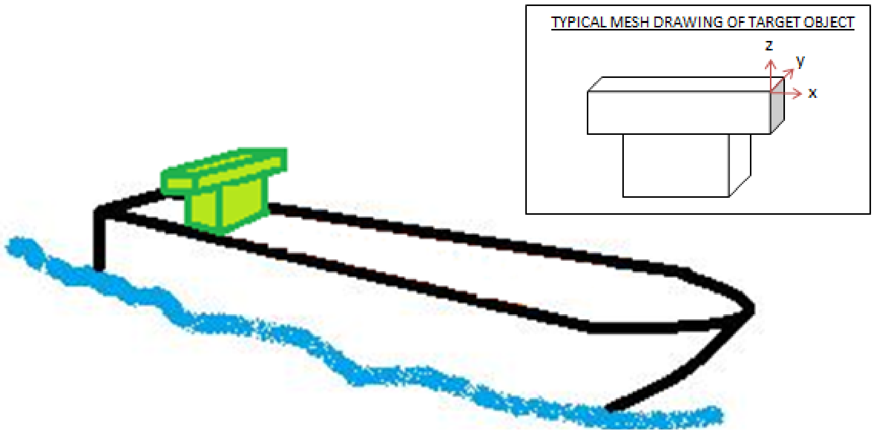


Figure 1. Illustration of typical superstructure (in green) being tracked along with its mesh file as input to the tracking algorithm.

For validation purposes in the physical model the superstructure of the vessel to be tracked will be represented by a three dimensional object (cube) of known dimensions. Image processing will then be used to obtain pixel coordinates of the object corners.

3 CAMERA CALIBRATION

Image processing relies on known camera geometry in order to reconstruct depth when calculating 3D object coordinates from 2D image points. The process used to individually calibrate each camera, made use of a camera calibration toolbox developed by Jean Yves Bouguet (2013) for Matlab. The calibration toolbox is accepted as a recognised camera calibration toolbox for Matlab by the computer vision community and can be easily found on the website of the California Institute of Technology (also known as Caltech).

4 TRACKING ALGORITHM PROCESSING SCRIPTS

The processing involves reading in one image at a time in Matlab and converting each true-colour image to a grayscale intensity image. The process also crops each greyscale image over a predetermined area in an effort to remove the majority of unnecessary information around the object to be tracked. Figure 2, shows such a greyscale image before cropping, with floating vessel in view and tracking objects on the deck.

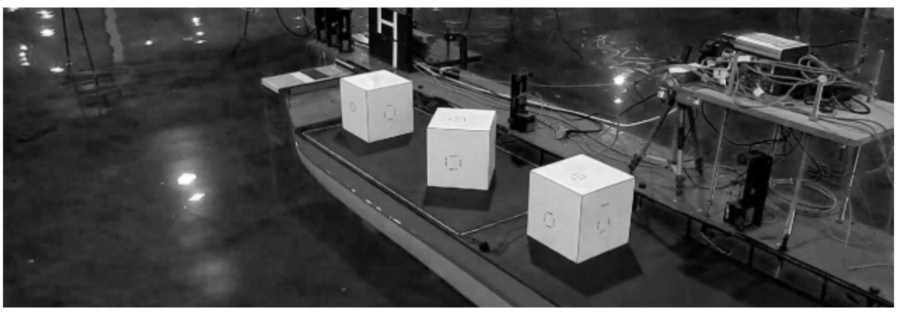


Figure 2. Example image showing water reflections on certain image portions around the cube objects.

Through image processing, each image is converted to a black and white image (binary image) and then eroded and dilated to a point which allows the image (pixel) coordinates of the cube corners to be obtained. An illustration on the cube object after being dilated and eroded with its individual components also separated through image processing is shown in Figure 3. Image coordinates of all the cube corners through time are also determined. Model coordinates, are also used with the intrinsic parameters of the camera as input to the POSIT algorithm. This then results in the pose and orientation of the object from a camera perspective for each image.

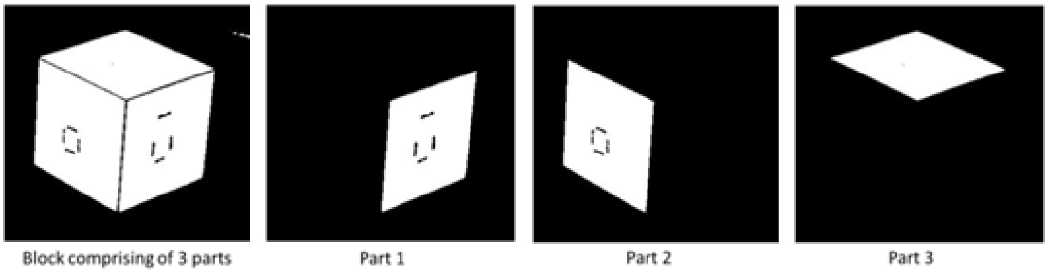


Figure 3. Illustration of connected components being separated.

5 CAMERA TO OBJECT PERSPECTIVE CONVERSION

This part of the analysis converts the camera perspective rotations and translations to scaled rotations and translations around the vessel's centre of gravity (CoG). For an object's rotation, the rotation matrices from a camera perspective are rotated to an object perspective with the rotation of the first frame taken as the zero starting point.

Terblanche and Brink (2014, pers.comm., 26 September) from the Applied Mathematics Department at the University of Stellenbosch, suggested that converting from camera perspective to object perspective, is as simple as multiplying all rotating and translating information with the transpose rotation of the zero position seen from the camera position.

Using this as starting point, and working with examples of known rotation and translation, revealed that the zero point rotation is simply the transpose of the first frame's rotation matrix, multiplied by the rotation matrix of the first frame and can be mathematically written, as shown in Equation (1).

$$\mathrm{R}_0' = \mathrm{R}_0^{\mathrm{T}} \times \mathrm{R}_0 \tag{1}$$

With the rotation of the first frame taken as the zero point, every sequential rotation matrix from an object perspective can be mathematically presented, as in Equation (2) (where 'i' denotes the frame number).

$$R_i' = R_0^T \times R_i \tag{2}$$

Roll, pitch and yaw values (in degrees) from an object perspective are then calculated using Matlab code developed by Corke (2011). The code converts the rotation matrices, R_i' to the respective roll, pitch and yaw rotations in degrees.

For object translations, the difference between each translation matrix 'T' and the zero starting point is calculated and then rotated from a camera perspective to an object perspective. The translation matrices between image frames are simply the difference between sequential translation matrices, as shown in Equation (3).

$$T_i - T_{i-1} \tag{3}$$

Rewriting Equation (3) to be the difference between the first frame taken as the zero starting point and sequential frames it becomes:

$$T_i - T_0 \tag{4}$$

Equation (4) however describes only translation differences seen from the camera perspective. The translation differences are then rotated to be from the object perspective. This is done by multiplying the translation differences with the transpose of the original rotation matrix and the new object perspective rotation matrix (i.e. $\mathrm{R}_i'\mathrm{R}_i^{\mathrm{T}}$). The translation differences from the object perspective can then be mathematically written, as shown in Equation (5).

$$T_i' = R_i' \times R_i^T \times (T_i - T_0) = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} \tag{5}$$

Where x_i, y_i and z_i refer to the surge, sway and yaw around the zero location of the object.

Converting the calculated translations from the object bound coordinate system to the CoG of the vessel; the inverse of Equation Corce (2011) is applied, as shown in Equation (6).

$$x_{COG} = x_i + y_b\psi - z_b\theta$$
$$y_{COG} = y_i - x_b\psi + z_b\varphi$$
$$z_{COG} = z_i + x_b\theta - y_b\varphi \quad (6)$$

Where x, y and z are the vessel motions surge, sway and heave respectively, while x_b, y_b and z_b are the body bound coordinates of object centre on the vessel and the roll, pitch and yaw calculated by Corke (2011) are φ, θ and ψ repectively.

6 STATIC VERIFICATION OF TRACKING ALGORITHM

Comparing results of the proposed non-intrusive method to a specific measurement method will not cover limitations of the measurement device, i.e. the cameras. For determining the accuracy of the system, a few ‘static’ tests were conducted. The clearest way to directly measure displacement is by using a Vernier calliper, which can measure distances at 0.04 mm accuracy. The translation results obtained can then be compared with the distances measured using the Vernier calliper.

The proposed non-intrusive, 3D Object tracking system was tested under controlled conditions to determine the accuracy of the system.

Determining the accuracy differences over a range of distances for all 6DOF motions, required an intricate set-up. For this reason, only the 3D Object (cube) was used separately, and not the complete vessel with objects on the deck. The tracking system was used over a range of distances, ranging from 10 mm to 1500 mm for translation and 15° to 45° for rotation.

For motions in the horizontal plane, a grid with translation and rotation displacements was created using a computer drawing package and printed onto a 600 mm x 2000 mm sheet of paper. Provision was made for surge and sway movements of 10 mm, 50 mm, 150 mm, 500 mm and 1500 mm as well as yaw movements of 15°, 30° and 45°. Figure 4, shows the marked sheet of paper with cube placed on it.

Figure 4. Wooden cube on sheet of paper with marked translations and rotations for surge, sway and yaw accuracy tests.

The set-up for motions in the vertical plane was slightly more intricate. A vertical guide was put in place, onto which the wooden cube was moved up and down to simulate heave motion. The cube was then fixed at pre-marked displacement distances on the vertical guide. Figure 5, illustrates the set-up for heave motions. For pitch and roll motions, a mounting bracket usually used for 3D laser scanning purposes was used. The mounting bracket was adjusted at 15° intervals, accurate to 0.2°. Figure 5, also shows the wooden cube mounted on the bracket to allow simulated pitch and roll motions.

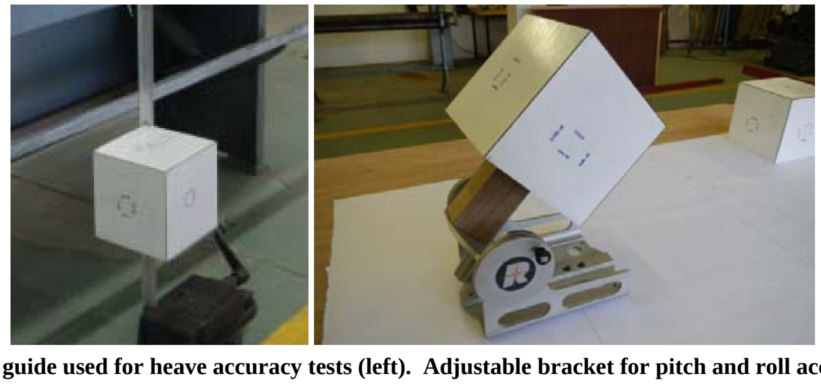


Figure 5. Vertical guide used for heave accuracy tests (left). Adjustable bracket for pitch and roll accuracy tests (right)

Accuracy measurements for all 6DOF motions were done from an oblique view angle. The percentage errors for a range of displacements which ranges from 10 mm to 1500 mm and 15° to 45° were determined. The results obtained are summarised in Table 1 to Table 6 for each individual DOF and graphically presented in Figure 6 and Figure 7.

Table 1. Verification of SURGE motion for 3D object tracking at an oblique angle.

Directly measured displacement		Tracking system measurement	R_{disp} (mm)	% error (%)
10.00 mm	(1)	10.98 mm	0.98	9.80
0.00 mm	(2)	0.19 mm	0.19	-
0.00 mm	(3)	0.03 mm	0.03	-
50.00 mm	(1)	47.55 mm	-2.45	4.90
0.00 mm	(2)	0.31 mm	0.31	-
0.00 mm	(3)	1.94 mm	1.94	-
150.00 mm	(1)	151.43 mm	1.43	0.95
0.00 mm	(2)	1.85 mm	1.85	-
0.00 mm	(3)	0.10 mm	0.1	-
500.00 mm	(1)	498.60 mm	-1.4	0.28
0.00 mm	(2)	3.69 mm	3.69	-
0.00 mm	(3)	3.79 mm	3.79	-
1500.00 mm	(1)	1507.49 mm	7.49	0.50
0.00 mm	(2)	10.28 mm	10.28	-
0.00 mm	(3)	3.17 mm	3.17	-

Note: Surge[1], Heave[2], Sway[3]

Table 2. Verification of SWAY motion for 3D object tracking at an oblique angle.

Directly measured displacement		Tracking system measurement	R_{disp} (mm)	% error (%)
0.00 mm	(1)	10.98 mm	2.66	-
0.00 mm	(2)	0.84 mm	0.84	-
10.00 mm	(3)	2.66 mm	0.98	9.80
0.00 mm	(1)	2.36 mm	2.36	-
0.00 mm	(2)	0.39 mm	0.39	-
50.00 mm	(3)	51.88 mm	1.88	3.76
0.00 mm	(1)	4.27 mm	4.27	-
0.00 mm	(2)	0.45 mm	0.45	-
150.00 mm	(3)	153.85 mm	3.85	2.57
0.00 mm	(1)	1.36 mm	1.36	-
0.00 mm	(2)	4.47 mm	4.47	-
500.00 mm	(3)	502.41 mm	2.41	0.48
0.00 mm	(1)	3.25 mm	3.25	-
0.00 mm	(2)	13.25 mm	13.25	-
1500.00 mm	(3)	1507.49 mm	7.49	0.50

Note: Surge[1], Heave[2], Sway[3]

Table 3. Verification of HEAVE motion for 3D object tracking at an oblique angle.

Directly measured displacement		Tracking system measurement	R_{disp} (mm)	% error (%)
0.00 mm	(1)	3.33 mm	3.33	-
10.00 mm	(2)	15.01 mm	5.01	50.10
0.00 mm	(3)	7.68 mm	7.68	-
0.00 mm	(1)	1.28 mm	1.28	-
50.00 mm	(2)	54.13 mm	4.13	8.26
0.00 mm	(3)	6.01 mm	6.01	-
0.00 mm	(1)	6.98 mm	6.98	-
150.00 mm	(2)	148.45 mm	-1.55	1.03
0.00 mm	(3)	1.44 mm	1.44	-
0.00 mm	(1)	19.95 mm	19.95	-
500.00 mm	(2)	699.71 mm	-0.29	0.04
0.00 mm	(3)	2.79 mm	2.79	-
0.00 mm	(1)	18.06 mm	18.06	-
1500.00 mm	(2)	1503.19 mm	3.19	0.21
0.00 mm	(3)	7.31 mm	7.31	-

Note: Surge[1], Heave[2], Sway[3]

Table 4. Verification of ROLL motion for 3D object tracking at an oblique angle.

Directly measured angle		Tracking system measurement	R_{disp} (°)	% error (%)
15.00°	(1)	14.99°	-0.01	0.07
0.00°	(2)	0.79°	0.79	-
0.00°	(3)	0.63°	0.63	-
30.00°	(1)	29.69°	-0.31	1.03
0.00°	(2)	1.31°	1.31	-
0.00°	(3)	1.77°	1.77	-
45.00°	(1)	44.59°	-0.41	0.91
0.00°	(2)	1.50°	1.50	-
0.00°	(3)	2.62°	2.62	-

Note: Roll[1], Pitch[2], Yaw[3]

Table 5. Verification of PITCH motion for 3D object tracking at an oblique angle.

Directly measured angle		Tracking system measurement	R_{disp} (°)	% error (%)
0.00°	(1)	0.88°	0.88	-
15.00°	(2)	15.45°	0.45	3.00
0.00°	(3)	0.70°	0.7	-
0.00°	(1)	1.68°	1.68	-
30.00°	(2)	30.37°	0.37	1.23
0.00°	(3)	1.03°	1.03	-
0.00°	(1)	2.71°	2.71	-
45.00°	(2)	45.08°	0.08	0.18
0.00°	(3)	1.06°	1.06	-

Note: Roll[1], Pitch[2], Yaw[3]

Table 6. Verification of YAW motion for 3D object tracking at an oblique angle.

Directly measured angle		Tracking system measurement	R_{disp} (°)	% error (%)
0.00°	(1)	0.14°	0.14	-
0.00°	(2)	0.24°	0.24	-
15.00°	(3)	15.06°	0.06	0.40
0.00°	(1)	0.21°	0.21	-
0.00°	(2)	0.29°	0.29	-
30.00°	(3)	30.18°	0.18	0.60
0.00°	(1)	0.29°	0.29	-
0.00°	(2)	0.15°	0.15	-
45.00°	(3)	45.17°	0.17	0.38

Note: Roll[1], Pitch[2], Yaw[3]

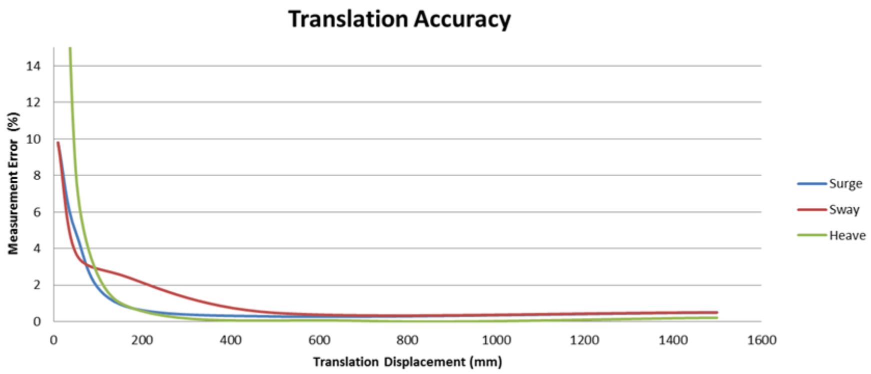


Figure 6. Graphical representation of translation accuracy test results.

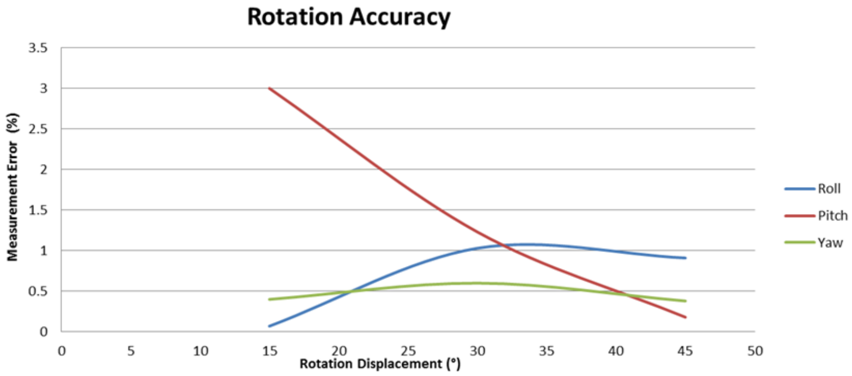


Figure 7. Graphical representation of rotation accuracy test results.

The accuracy results indicate that the 3D tracking system accurately estimates surge and sway for translation. Measurement of heave motion in the vertical plane, is estimated with the least accuracy of all the 6DOF motions. Rotation and pitch motion, which are also in the vertical plane are measured less accurately than roll and yaw. The results also indicate that roll and yaw motions are more accurately measured for small rotations.

The Graphical representations show a drastic decrease in the percentage estimation error when motions are incrementally enlarged. Estimating surge motion for example, improved in accuracy from 9.8% to 0.5% for displacements of 10 mm and 1500 mm respectively.

7 SMALL SCALE PHYSICAL MODEL

The test plan incorporates two different wave heights and periods which are similar to that used for an actual physical model study done at the CSIR (CSIR *et al.*, 2014). Wave heights of 1.5 m and 3.0 m in prototype along with wave periods of 12s and 16s were used. The selection of wave conditions made it possible to establish the viable application limits of each individual method for typical wave conditions used in a vessel motion study. The camera was mounted on a tripod, and placed at an oblique angle to the vessel. Figure 8 shows the vessel with the 3D objects mounted on the deck.

The test plan also includes tests with the same input wave conditions to determine repeatability of the measurement method and correct working of all the equipment used. The Keoship method was set up as the reference for the proposed method to be validated against.

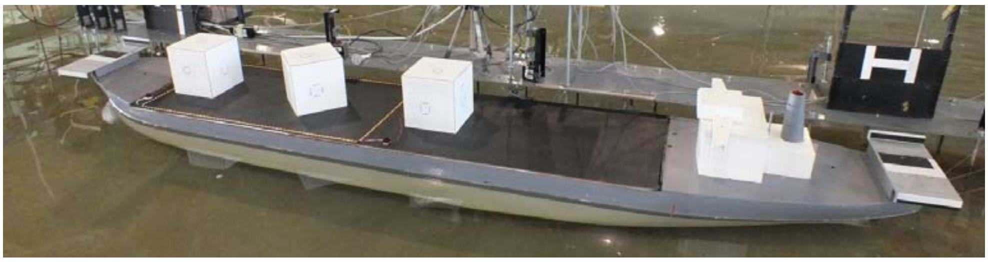
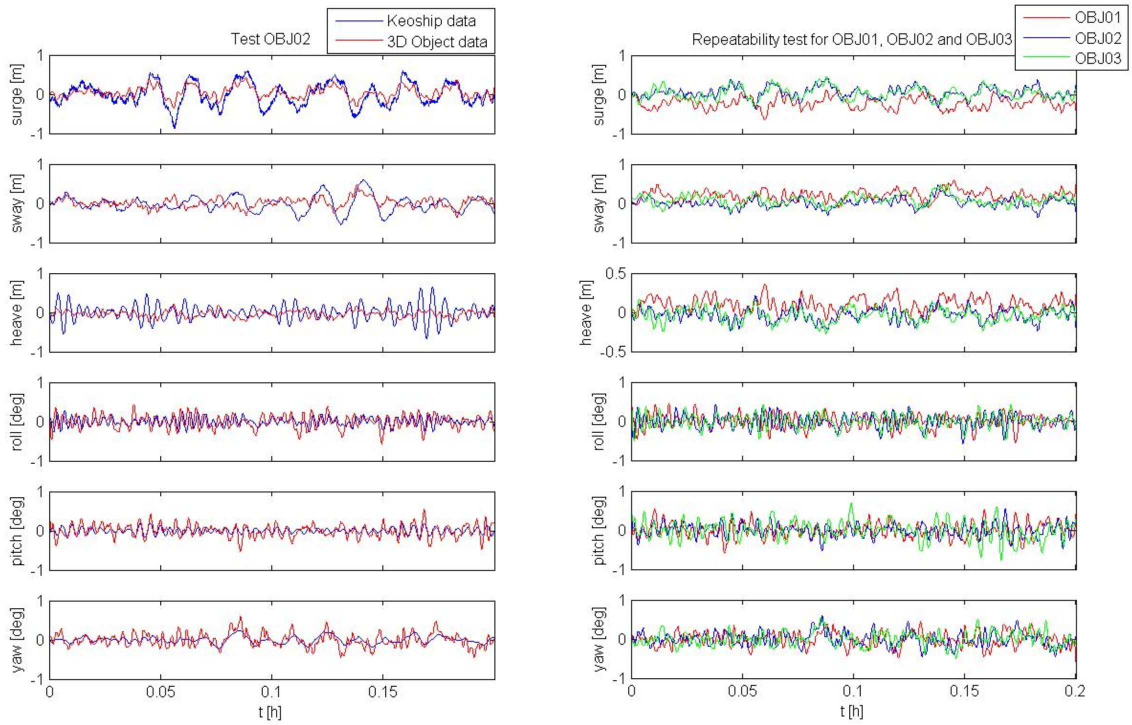


Figure 8. Model vessel with object mounted on the deck.

The physical model results for the proposed non-intrusive 3D Object tracking method showed that there are gain differences between the measured translation amplitudes when comparing to the Keoship system. The gain differences are discussed further in the discussion section.

The root-mean-square error, R_{rms} was used to quantify the difference between the data sets. For comparison with the Keoship system, all data plots are presented in prototype, except for the, R_{rms}values in the tables which are presented in model scale to best quantify the difference. An example of comparison plots between data trends and shape is shown in Figure 9 which illustrates the motion plots for one of the tests. A graphical representation of repeatability measurements are also shown in Figure 9.



Note: In order to visually compare data trends and shape, the amplitudes of the 3D object data were divided by a factor of 5 for all three translations surge, sway and yaw.

Figure 9. Data comparison for one of the tests (left) and graphical representation of repeatability for one condition (right).

8 DISCUSSION OF STATIC VERIFICATION TESTS

The maximum critical significant surge and sway amplitude for an unloading or loading efficiency of 95% is 0.4 m (PIANC, 2012). When applying a conservative rule of thumb, and assuming mooring lines can break at surge or sway motions equal to 1.2 m or larger, it is accepted that the accuracy tests done for translations ranging from 10 mm to 1500 mm, covers motion for normal working conditions at prototype scale.

The maximum significant motion amplitude given in PIANC (2012), is provided to one decimal place. It can be assumed by using this, when analysis of moored container vessel motions is required, an accuracy criterion of 0.1 m is acceptable for surge and sway motions. Figure 10, incorporates the surge and sway results obtained from the accuracy tests as well as the accuracy criterion to help establish the usability of the tracking system developed.

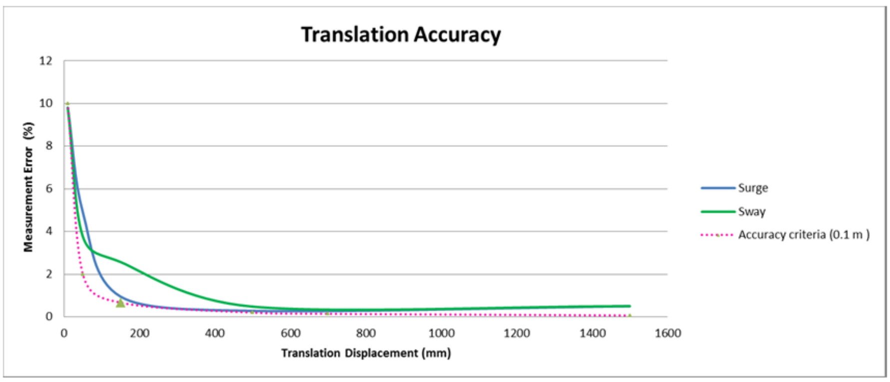


Figure 10. Accuracy criteria incorporated with surge and sway results obtained from the accuracy tests.

The graph indicates that when using the accuracy criterion of 0.1 m the tracking system would be accurate enough to be used when small measurements are of interest (i.e. a physical model study). For a model study however, scaling also has to be considered which for a 1:100 scale model, requires a model accuracy of at least 1 mm to fall within the prototype accuracy criterion of 0.1 m. It is thus possible to state that at the current development stage, the 3D Object tracking system is not accurate enough to be used in physical model studies.

The graph also indicates however, that for prototype motions exceeding 0.6 m (i.e. storm events) the 3D Object tracking system would have an accuracy, close to the maximum allowable criterion of 0.1 m. This makes the system usable at its current development stage when rapid deployment during a storm event is needed in prototype conditions.

In situations where funds and time are available for the deployment of a D-GPS system, it would currently be a better option to utilise a D-GPS system, seeing that it has an accuracy of about 2 cm (CSIR *et al.*, 2013).

9 DISCUSSION OF PHYSICAL MODEL

For surge and sway, when comparing the 3D Object tracking data to the Keoship data, it was found that with an increase in wave height, the root-mean-square error difference becomes larger. For the 16 second wave period tests, the increase in error difference is from a maximum R_{rms} value of 5.76 mm to 16.76 mm. An increase in error difference was also evident for the 12 second wave period tests, changing from a maximum R_{rms} value of 6.58 mm to 10.06 mm.

For heave, the comparison between the 3D Object tracking data and Keoship data show that the tracking algorithm loses track of the smaller frequency heave motions.

For roll, pitch and yaw the 3D Object tracking data compared extremely well to the Keoship data. From comparing data and the root-mean-square error differences, it was possible to see that the rotations are more accurately measured when the rotations are small. A maximum R_{rms} value of 0.23° for motions smaller than 0.5° and a maximum R_{rms} value of 0.29° for motions above 0.5° were calculated. On average, pitch and yaw motions were found to have a R_{rms} value of 0.07° smaller than the R_{rms} values obtained for roll, making the pitch and yaw estimates more accurate.

The resolution for the measurement system is estimated by evaluating the maximum R_{rms} values between repeatability tests. For each repeatability series, the average R_{rms} value calculated for each of the 6DOF motions is taken as a conservative estimate of the resolution for measuring that particular motion. These estimates are presented in Table 7.

Table 7. Estimated resolution accuracy for 3D Object tracking physical model tests.

Motion	Resolution Estimates (in model scale)			
	H_{m0} 1.5m T_p 16s	H_{m0} 3.0m T_p 12s	H_{m0} 1.5m T_p 12s	H_{m0} 3.0m T_p 12s
Surge[mm]	12.07	26.65	9.27	15.77
Sway[mm]	9.35	20.17	13.13	9.97
Heave[mm]	6.93	15.4	9.52	10.20
Roll [°]	0.20	0.33	0.17	0.35
Pitch [°]	0.22	0.31	0.12	0.22
Yaw [°]	0.22	0.32	0.12	0.45

The amplitude gain difference for the translation results is still an unresolved issue. This requires further work to establish why a gain difference is present. This phenomenon is not present with any of the static verification or accuracy tests. The physical model tests, which are dynamic in nature, do however include this phenomenon. It will be important to determine the reason behind this difference before continuing to the next stage of development, which includes refinement of the image processing and tracking algorithms to achieve better accuracies over a range of displacements.

The verification and tracking test results show good data for the current development stage. These verified that the 3D tracking system works and can be developed further.

10 CONCLUSION

The accuracy tests done on the 3D Object tracking system indicates that at the current development stage, the accuracy is unfortunately not good enough to use in a physical model study.

For the physical model tests, the accuracy of the 3D Object tracking system was in the order of 5.76 -16.76 mm for translations and 0.23-0.29° for rotation which is much greater than the allowable accuracy criterion of 1 mm when considering a model scale of 1:100.

At the current development stage, the Keoship system from the CSIR, is still the most accurate for measurements involving physical model tests. The accuracy of the system is 0.1 mm for translations and 0.04° for roll and 0.01° for pitch and yaw (CSIR *et al.*, 2008). The Keoship system is however intrusive and is therefore bound to the physical modelling environment. The verification results indicate that for prototype motions exceeding 0.6 m, the 3D object tracking system, at the current development stage, would have acceptable accuracy close to the allowable accuracy criterion of 0.1 m. When rapid deployment is needed for measurements during a storm event, opting for the non-intrusive method will be an acceptable compromise even though the accuracy of an intrusive D-GPS system is in the order of 2 cm when ultimately deployed. At the current development stage, the system can however only be used as a post processing tool.

11 FUTURE DEVELOMENT

The proposed system should be changed to allow for real time processing. This can be done by running the image point extraction algorithm on the live feed and only saving the points of interest to a text file. The motions could then also be processed and displayed real time by making a few computational improvements and only using one programming platform to do the image processing and 6DOF calculations (currently Matlab and C sharp are used).

The POSIT algorithm that was used, can be compared to other pose estimation algorithms in order to determine if there is another algorithm that can estimate pose more accurately. Refinement of the Matlab algorithm which locates the image coordinates of the object, could also be looked at to enable sub-pixel accuracy.

Focal length which is one of the main input parameters to the POSIT algorithm, was determined using a simple pinhole camera model. It is suggested that a more sophisticated model should be used to determine focal length.

Lens distortion calculated during the camera calibration process is currently not included in the pose estimation process and should be incorporated into the pose estimation algorithm.

In order to avoid lighting effects, which would be a concern for prototype outdoor use, it is suggested that an infrared camera receiver should be used to record image displacements.

It is envisioned that auxiliary vision systems can play a useful role in monitoring maritime operations in the port area, especially while vessels are berthed. With the aid of high resolution camera systems, it will be possible to automatically provide additional visual information as well as give early warning to vessels that experience motions beyond a certain allowable criteria.

From an algorithm development point of view, there are a lot of possibilities. A port could obtain the outer shell dimensions of those ships that frequently visit the port from the respective ship owners (i.e. the outer dimensions of the bridge structure). A database with the 3D mesh information for frequently visiting ships will then be available. The algorithm which currently locates the corner points of a known object could be altered to first find the best possible match to a 3D mesh structure. The relevant image points to the best possible object match on the image could then be used with the current pose estimation algorithm.

A further possible use for the system could be to evaluate under keel clearance for ships entering and exiting a port. The tracking of vessel motions for a ship would be the same as mentioned above. A port operator would then input current tidal conditions and vessel draft information into a GUI. The GUI will then use the real time motions recorded with the parameters provided as input by the port operator and estimate real time under keel clearance.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to a number of people who contributed to the successful completion of the MSc thesis from which this paper originates:

The contribution of the CSIR in Stellenbosch (South Africa), for their efforts and assistance with image processing and training. The CSIR’s hydraulic laboratory staff, Reagan Solomons and Rafick Jappie who assisted with the physical modelling tests, and Gregory Davids who constructed the three dimensional cubes used. Marius Rossouw for his insight in small scale physical modelling.

REFERENCES

Benetazzo, A., 2011. *Accurate measurement of six Degree of Freedom small-scale ship motion through analysis of one camera images*, Ocean Engineering, 38, 16, Pgs1755–1762.

Corke, P.I., 2011. *Homogeneous transform to roll-pitch-yaw angles* [Computer program], [online] .Available: https://code.google.com/p/matlab-toolboxes-robotics-vision/source/browse/matlab/robot/tags/R9.4/tr2rpy.m?r=822 [Accessed 11 September, 2013].

CSIR et al., 2008. *Khalifa Port and Industrial Zone, Physical Modelling of Harbour Agitation and Moored Ship Dynamics*, CSIR, Stellenbosch.

CSIR, Kieviet, J. & Rossouw, M., 2013. *Ship Motion Measurement Exercise for the Port of Ngqura, Navigation and Mooring Safety Study*, CSIR, Stellenbosch.

CSIR, Yoyo, S., Masagela, M., Thesnaar, E., Roux, P., Kieviet, J., 2014. *Pampa De Pongo Iron Ore Project – hysical Model Study of Vessel Motions, CSIR, Stellenbosch*. Report no. CSIR/BE/HIE/ER/2014/0010/B

PIANC, 2012. *Criteria for the (Un)Loading of Container Vessels*. Report no. 115-2012, s.l.: s.n.

Yves Bouguet, J., Last updated 2 December 2013. *Camera Calibration Toolbox for Matlab*. Available: http://www.vision.caltech.edu/bouguetj/calib_doc/htmls/example.html [Accessed September 20, 2014].