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USING STEREO IMAGE RECONSTRUCTION TO SURVEY SCALE MODELS OF RUBBLE-MOUND STRUCTURES

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Abstract

The correction of refraction effects between two media in the stereo reconstruction of a submerged scene is dealt with in this paper. A software package that enables the survey of the armour layer envelope of scale-model rubble-mound breakwaters being made from a stereo pair taken without emptying the wave flume or tank where the model is built is also presented. A slope in a wave flume is employed to assess the quality of the surveys obtained with that package. The first results of this procedure are presented.

1. Introduction

The assessment of the failure probability over a given time span of a rubble-mound structure armour layer is of paramount importance to decide on the most adequate schedule for maintenance and / or repair works on that structure. Melby (1999) presents a formula for the evolution of rubble-mound breakwaters subjected to storms that can be helpful for such a task.

One of the variables in Melby's formula is the dimensionless damage suffered by the breakwater since its construction which is the ratio of eroded area observed in the breakwater profile to the face area of the cube with the volume of the armour elements.

That formula was obtained in several long duration scale-model tests with rock-armoured breakwaters placed on a wave flume. So this damage evolution model is only valid for structures similar to those ones. Should there be the need to use it for structures whose armour layer is not made of rock, for instance tetrapodes or Antifer cubes, it is necessary to adjust the parameters in that equation with new sets of experimental results.

To survey the profile, Melby used a profiler made of eight aluminum profiler arms, laterally spaced at 5 cm, which pivoted about a point on a sliding carriage. A rotating spheroid whose diameter was similar to a typical length of the rocks in the armour layer was located at the end of each profiling arm and followed the surface structure as the carriage passed over the structure, going from the crest to the structure's toe.

Other methods available to assess the breakwater eroded area are reviewed in Vidal et al. (2005) and they include

- counting the displaced armour elements. Then knowing the armour layer porosity and the the side of the cube with the volume of the armour elements one can evaluate the eroded volume;
- measuring the exposed area of the second layer of armour elements. The volume of the elements removed from the first layer can be obtained, assuming that no armour elements are removed from the second layer, once the layer width and a measure of the elements deployment are known.

To evaluate the profile eroded area from the eroded volume it is assumed that the removed volume defined a prism and so only the length of the eroded region has to be known.

In both methods use can be made of photographic techniques, but this may imply emptying the wave flume, a time-consuming task specially when series of tests are to be carried out. These techniques were employed, for instance, by Medina et al. (2003) and by Benedicto et al. (2004).

Laser range finders are an obvious and easy way of surveying the armour layer. However, since common lasers do not propagate in the water, the need for emptying the flume every time a measurement is to be taken emerges again.

This paper aims at describing a surveying technique based on pairs of photographs (also known as stereo images) that is being developed at the Institute for Systems and Robotics and that prevents emptying the flume to get those stereo pairs, speeding up the whole testing procedure.

2. Stereo reconstruction of a submerged scene

The problem to be solved is the reconstruction of a 3D scene with a stereo pair when there is an interface between the scene and the cameras that bend the light rays according to Snell's law.

The main difficulty here is that the known epipolar constraint, which helps reducing the search for a match, is not usable. Unlike conventional wisdom, straight lines underwater do not project as straight lines in the image. Then, for each pixel in one image, possible matches are along a curve which is different for every point on the object. Essentially, this means that most stereo algorithms are unusable. Ferreira et al. (2005) showed that, if the incidence angle is small, the linear part of the Taylor Series expansion, which is equivalent to modifying camera parameters, is precise enough for our purpose. In other words current stereo algorithms can be used, provided the camera orientation parameters are within a certain range.

In fact, the non-linear relation between the light ray emitted from a point above the interface and its refracted ray can be simplified by expanding it in a Taylor series and retaining the first order terms. This approximation leads to a simple rectification processes cancelling most of the distortion introduced by the interface. It can be shown that all light rays converge at a single point $\mathbf{p}_1$, as illustrated in Figure 1.

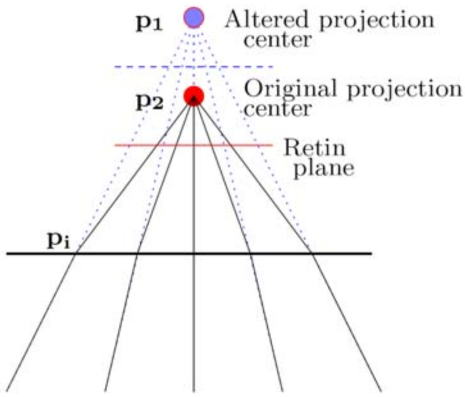

Figure 1. Representation of the path followed by a beam of light when the first order Snell approximation is used.

This fact hints at the possibility of rectifying the image with refraction effects by only changing the extrinsic camera parameters. In other words, by approximating Snell's law, the problem with refraction is transformed into a typical stereo problem without air-water interface. All that remains to be done is to project the original image onto the z=0 plane and to project it back to a virtual camera with projection center at p1.

Depending on the resolution used, baseline, and angle of incidence of the light rays, the epipolar constraint does not occur due to the effect of higher order terms, neglected by the Snell rectification. In case that rectification is not accurate enough, two dimensional search must be done to match the images. In these circumstances, rectification can significantly narrow the band of search around the estimated epipolar line.

Although the matching process gains considerably by assuming the simplification as valid, for greater reconstruction precision the nonlinear terms should not be discarded. After the matching has been done, the true Snell deformation can be taken into account. In other words, the rectification effect must be included on the image coordinates.

3. Developed tools

To survey the envelope of a rubble-mound breakwater scale model, use can be made of scene reconstruction from a stereo pair. The delays associated to emptying the wave flume or tank can be avoided by taking the snapshots with water in the flume or tank and by correcting the obtained stereo pair by using the procedure described before. This means that the characteristics of the devices that got the snapshots, as well as their absolute position in a reference system, have to be known.

First, a setup capable of simultaneous stereo image acquisition is necessary. This might consist of cameras mounted in a fixed configuration and rigged to take simultaneous snapshots, or of a beam splitter mounted on a single camera (Figure 2 shows an example of both). The latter method is preferred due to its easier setup requirements and use. Its major drawback is loss of image resolution since each snapshot has only half the available pixels.

Each time the camera setup changes it needs to be calibrated. These setup changes might result from a conscious alteration of the camera's zoom, focus or relative orientation or be accidental, for instance, depending on the hardware quality, a simple nudge might be enough to change some of these parameters. It is recommended that each session of image acquisition has its own calibration step. This means that for each set of snapshots from the scenery to be reconstructed there is another set of calibrating images obtained from observing a calibrating rig.

Figure 2. Two cameras mounted side by side and an example of a beam splitter.

The software package developed is a complete 3D reconstruction environment using stereo image pairs as input. It consists of three distinct applications implemented in MATLAB™, each with a particular objective:

- **Camera calibration** consists of identifying the parameters describing the projective cameras used and their position and orientation within the observed world;
- **Reconstruction** which consists of identifying depth from two different views of the scenery;
- **Fusion** which merges various separate reconstructions into a single file.

The output of the package consists of a file describing the cloud of reconstructed points. This is a standard file format allowing it to be imported by various CAD and modelling tools, where it may be converted to other formats.

Whatever method is chosen for image acquisition, to run this software it is necessary to have all images in jpeg or tiff format, one image per camera per shot. So if a beam splitter is used it is necessary to separate the left and right images into separate files before using this software.

3.1 Camera calibration

Camera calibration is of utmost importance in any serious precision measurement system using stereo vision. This means that time should be taken to ensure that it is performed correctly with as much reliable data as possible.

The calibration process defines the metric used to measure distances and angles, as well as absolute positions in the world. To accomplish this, several shots of a planar calibration checkered pattern are taken by both cameras. The size of the squares has to be measured with as high precision as possible since everything will be scaled accordingly.

The calibration procedure consists of clicking the four inside corners of the calibration pattern counterclockwise. The first clicked corner specifies the origin of the pattern and the second clicked corner the direction of the X axis. The order of the clicked corners in a pair of left / right images should be exactly the same. Figure 3 shows an example of this procedure applied to a computer generated image of a calibration grid.

When clicking the corners in the images one corner can be picked to define the origin of the world referential. This will calibrate the camera position with respect to it, a very important feature when calibrating for reconstruction of submerged scenes. In this case the calibration rig should be floating on the interface.

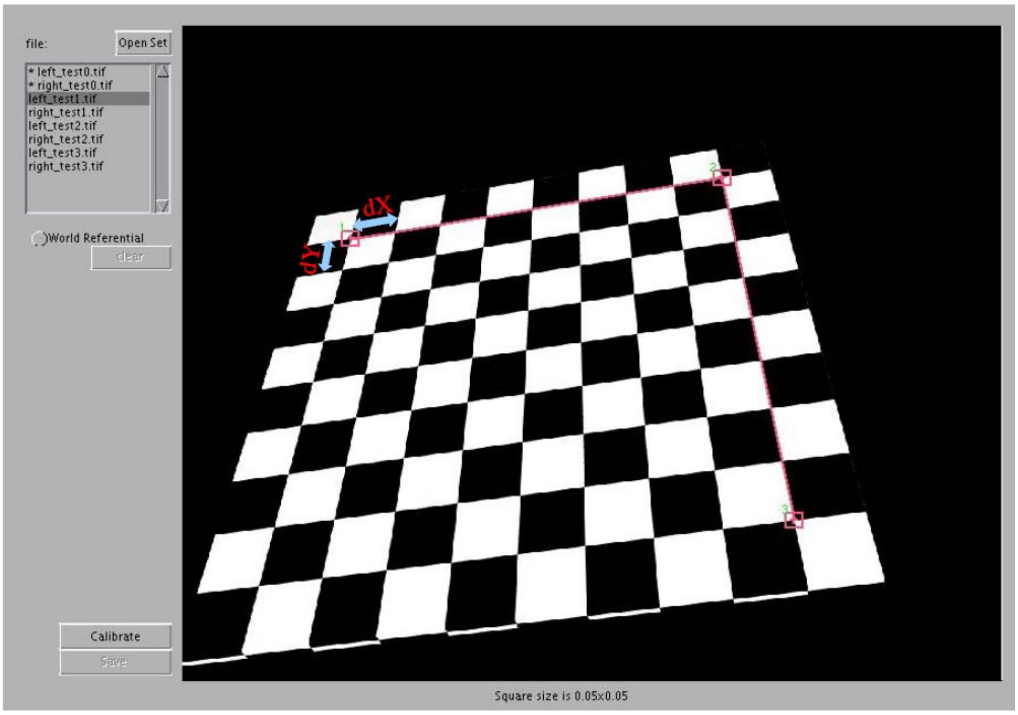

Figure 3. Clicking the inside corners of a calibration grid. The order in which the corners are clicked define the X and Y axis' direction.

The camera parameters that can be calibrated are the aspect ratio, focal length, principal point, skew and several distortions.

3.2 Reconstruction

Once the calibration is complete for a given configuration of the cameras, the scene reconstruction from the stereo pairs obtained with that configuration may begin. For each stereo pair being reconstructed one should include also the corresponding camera parameters and to define what type of reconstruction is desired.

It should be stressed that reconstructions are carried out separately for the above water and for the submerged parts of the scene. After choosing what type of reconstruction is pretended, the images will be rectified according to the camera parameters and will be shown in the left and right image areas of user interface main window, as in Figure 4.

At this point some horizontal clipping may have to be done to discard unwanted areas without information may that may appear due to image rectification, as can be seen in Figure 4. After all clipping is completed, the reconstruction may be performed and disparity maps are obtained. Note that for a below water reconstruction two disparity maps are produced, one for the horizontal displacement and one for the vertical. Figure 5 shows the result of a reconstruction.

Figure 4. Main window of the user interface after loading a stereo pair.

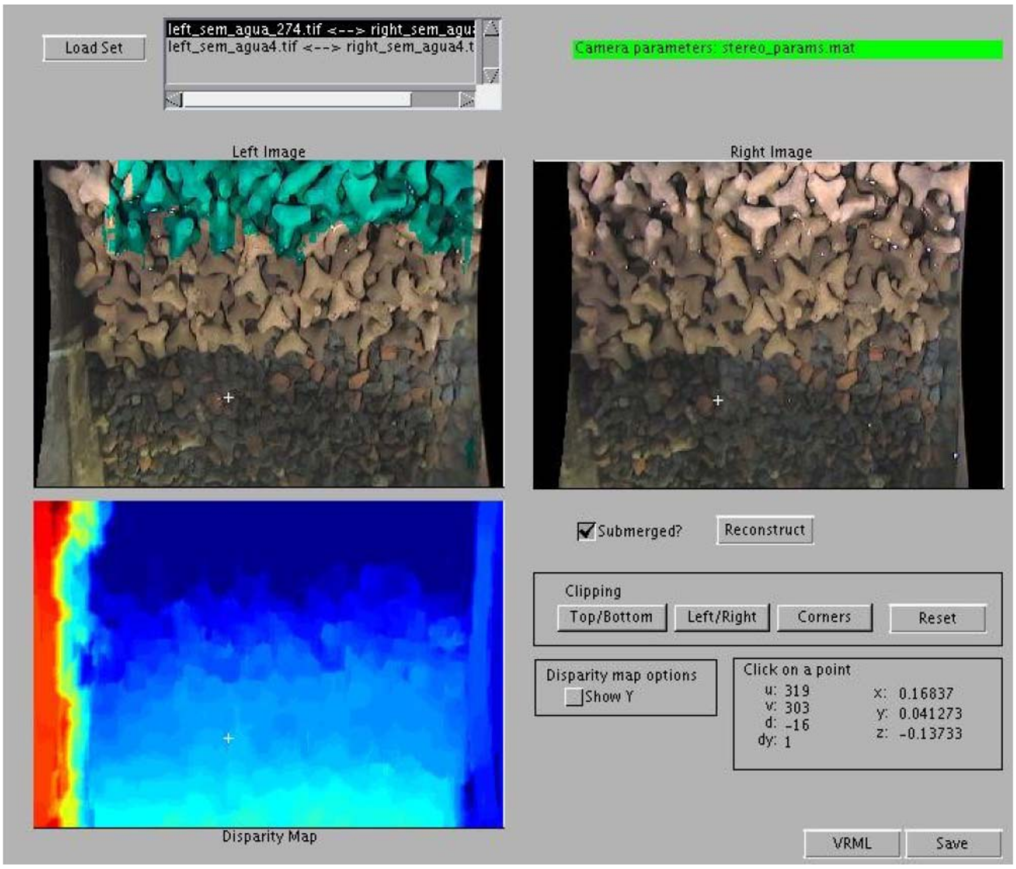

Figure 5. Reconstruction result presented in the user interface.

By inspection of the disparity maps, it is clear that some information is not valid. For instance, on the left and on the right of the scene reconstructed in Figure 5 there is a strip of invalid information. This is due to zones that are not seen by both images of the stereo pair. It is then necessary to remove the corresponding vertical strips.

This procedure can be repeated for as many stereo pairs as needed to cover the whole length of the model being surveyed.

4. Testing the methodology

Ferreira et al. (2005) present the results of the validation of the algorithm to reconstruct a submerged scene. They use a synthetic scene with planes at different depths. Since the images rendered from this scene were completely known, it was possible to measure reconstruction errors. They show that the maximum error can be reduced to as low as 3 cm for a plane located at 1.5 m beneath the interface and the cameras are placed at 1.3 m over the interface with a baseline of 25 cm. Figure 6 illustrates the differences in the 3D reconstructions obtained by correcting the higher order distortion. Without the corrected distortion, the plane is reconstructed as a paraboloid, as can be clearly seen in the top plane. The bottom plane was obtained with the distortion being corrected. Although the planes are placed one above the other for comparisom purposes, they are both on the same depth (1.5 m).

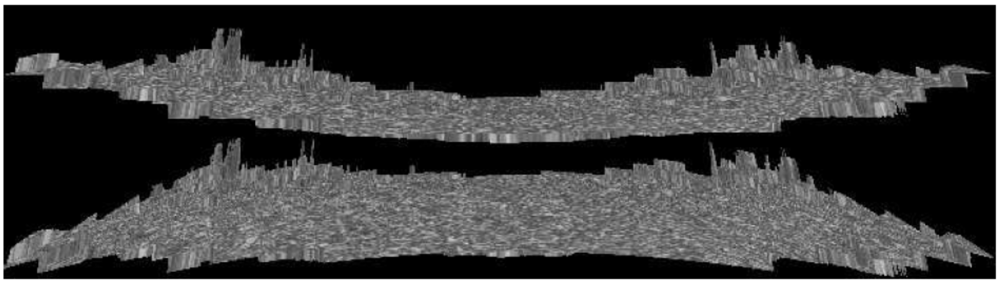

Figure 6. 3D comparison of plane reconstruction with Snell correction applied and without it.

To assess the quality of the surveys produced by the package, a rock slope of 1:2 was built in a wave flume. This slope was surveyed with a rotating laser that took profiles of the slope 1 cm apart along the slope contours. The laser accuracy was 2.5 mm and its resolution 0.3 mm. Figure 7 shows the laser box mounted over the flume as well as the slope being surveyed. Please note on the bottom of the picture a cube placed on the bottom that was meant to help referencing the surveys made both with the laser and from stereo reconstruction.

Figure 8 presents a perspective of the surface defined by Surfer™ based on the points obtained from the slope reconstruction produced from a stereo pair taken with no water in the flume. It can be seen in the picture that the colours employed to represent the several levels do not define strips parallel to the bottom boundary. This means that the stereo pair of the checkered board used to define the axis might have been taken when the board was not completely horizontal.

Figure 7. Laser mounted on the wave flume and rock slope to be surveyed.

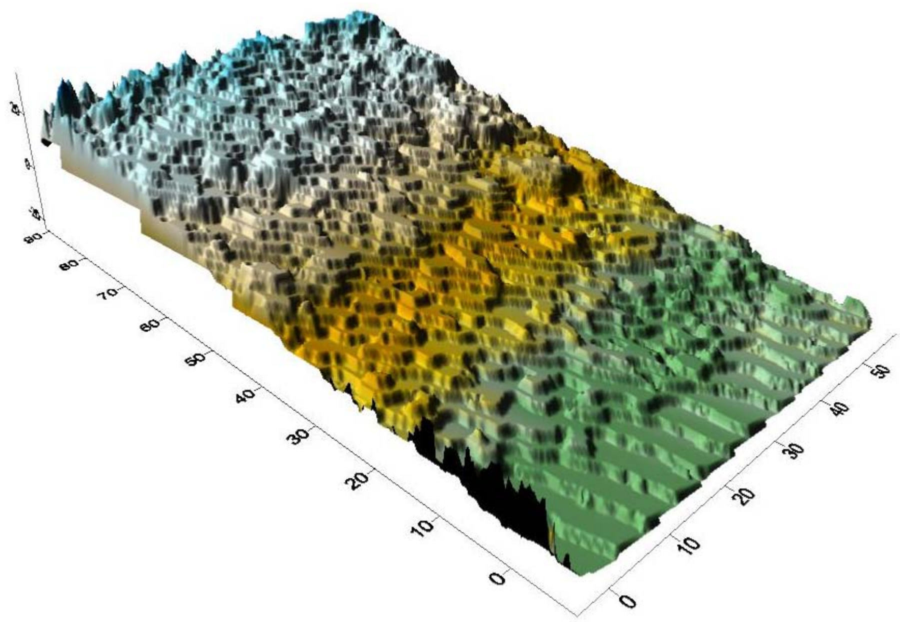

Figure 8. Surface defined by Surfer™ based on the points obtained from the slope reconstruction from a stereo pair taken with no water in the flume.

Figure 9, with the profiles obtained by intersecting with the same vertical plane the surfaces fitted to the points produced by the reconstruction of stereo pairs taken with no water in the flume and with a water depth of 35 cm, shows that the procedure to compensate for the presence of air-water interface gives results quite similar to those obtained by regular reconstruction procedures.

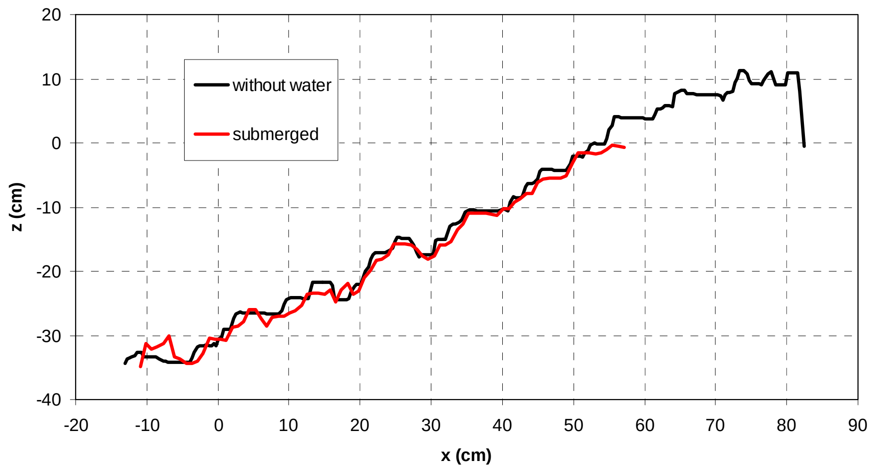

Figure 9. Profiles obtained from reconstructions of stereo pairs taken at a dry and at a submerged rock slope.

The problem with the axis definition may be responsible for the increase of the differences that can be observed in Figure 10 between the profiles taken at the rock slope section that passes through the middle of the cube obtained with the laser and from the stereo reconstruction.

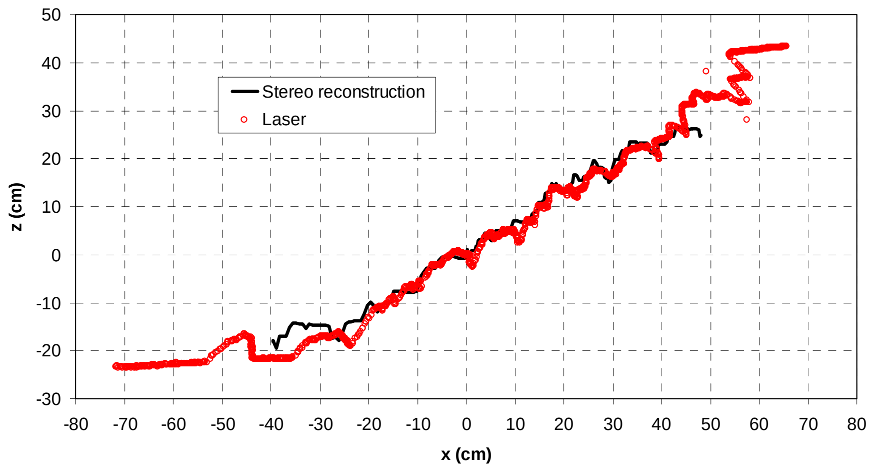

Figure 10. Profiles taken at the rock slope section that passes through the middle of the cube.

5. Conclusions

The procedure of Ferreira et al. (2005) can be useful to get surveys of scale models of rubble-mound breakwaters because the stereo pair needed can be obtained without emptying the flume. This paper reviewed that procedure and presented the software package that implements it. Although the first results of the surveys quality assessment were not conclusive at this stage yet, it must be pointed out the procedure's ability to give results very similar to those that could be obtained by reconstructing a scene from a stereo pair taken with no air-water interface.

Acknowledgments

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References

Benedicto, M. I.; Ramos. M. V.; Losada, M. A. 2004 'Expected damage evolution of a mound breakwater during its useful life', *Coastal Engineering Proceedings of the 29th International Conference*, pp. 3606-3614.

Ferreira, R.; Costeira, J. P.; Santos, J. A. 2005 'Stereo reconstruction of a submerged scene', *2nd Iberian Conference on Pattern Recognition, Estoril, Portugal*.

Medina, J. R.; Garrido, J.; Gómez-Martín, M. E.; Vidal, C. 2003 'Armour damage analysis using neural networks', *Coastal Structures 2003: Proceedings of the conference, August 26-30, 2003, Portland, Oregon*, pp. 236-248.

Melby, J. A. 1999 'Damage progression on rubble-mound breakwaters', Technical Report CHL-99-17, US Army Corps of Engineers - Waterways Experiment Station, Vicksburg.

Vidal, C.; Martín, F. L.; Migoya, L. 2005 'Medida del daño en el manto principal de diques de escollera: comparación entre diferentes metodologias', *VIII Jornadas Españolas de Ingenieria de Costas y Puertos, 17-18 de Mayo de 2005, Sitges, Barcelona*.