The Ngongotaha river UDPS experiment: low-cost Underwater Dynamic Stereo Photogrammetry

Y.H. Chan, M. Nguyen
IVS Lab
The Department of Computer Science
The University of Auckland
Auckland, New Zealand

A. Gastelum, S. Yang
IVS Lab
The Department of Computer Science
The University of Auckland
Auckland, New Zealand

R. Gong, N. Liu
IVS Lab
The Department of Computer Science
The University of Auckland
Auckland, New Zealand

P. Delmas, G. Gimel'farb
IVS Lab
The Department of Computer Science
The University of Auckland
Auckland, New Zealand
p.delmas@auckland.ac.nz

S. Bertin, H. Friedrich
Department of Civil and Environmental Engineering
The University of Auckland
Auckland, New Zealand
h.friedrich@auckland.ac.nz

ABSTRACT

We propose to integrate the newest developments in stereo-matching theory, affordable parallel processing capabilities (using GPU e.g. PC gaming/graphic card) and statistical surface analysis to implement and test an in-situ Underwater Dynamic Stereo Photogrammetry (UDSP) system for civil engineering applications. The proposed UDPS system aims to provide underwater Digital Elevation Models (DEM), for applications such as a two-dimensional discrete matrix of data underwater elevations. Experiments on river bed stereophotogrammetry in the Ngongotaha Stream near Rotorua using consumer grade stereo cameras including GoPro and Fujifilm W3 are used in through-water and underwater calibration and stereo measurements of 32 pebbles on the river bed. Pebbles are measured and identified. Initial results highlight the need for specialised equipment for through-water and underwater photogrammetry experiments to limit blurring effects caused by the water-plastic-air interfaces. Despite poor optical quality of the images obtained, we were able to correlate pebble sizes from calibrated stereo depth maps and actual measurement.

Categories and Subject Descriptors

I.2.10 [**Artificial Intelligence**]: Vision and Scene Understanding—*3D/stereo scene analysis*

Keywords

Stereo-photogrammetry, Underwater, Calibration

IVCNZ '12 November 26 - 28 2012, Dunedin, New Zealand

1. INTRODUCTION

Not so long ago, producing 3D descriptions of the environment was reserved to a few wealthy companies and users. With the advent of affordable and ubiquitous imaging and communication devices the society has reached an unsurpassed level of geomorphological description of the world in which we live. Still, there is no readily **affordable and deployable** underwater technologies which could provide the required level of detailed information. While 3D mapping of the ocean floor can be obtained relatively straight forward – and is now visible on Google maps for selected iconic locations [11] using a unique camera design [13] – it does not provide spatial (both in resolution and accuracy) or temporal 3D details necessary for closer range applications necessary for the study of dynamic processes such as sediment transport or the assessment of freshwater and marine life resources. Still, recent advances in technologies allowed retrieval of underwater 3D information of deep wreck sites [3]. Some success have been met regarding shallow underwater measurements of animal-fluid interaction [10].

Similarly, stereo-vision has seen a resurgence of interest and applications in everyday life with the advent of well performing low-priced camera technologies [1] and new calibration, alignment and image matching algorithms [7, 5]. Still there is a lack of readily available systems able to obtain dynamic 3D data for underwater applications. Possible applications for such Underwater Dynamic Stereo Photogrammetry (UDSP) systems range from fresh and salt water resources management [4], underwater erosion [2], underwater archaeological sites mapping [9], to marine biology and ecology applications [12, 14].

The research presented here aims at integrating the newest developments in stereo-matching theory, affordable parallel processing capabilities (using GPU e.g. PC gaming/graphics card) and statistical surface analysis to implement and test an in-situ UDSP system for civil engineering applications. Using off-the-shelf optical imaging and latest advances in computer vision, the proposed in-situ UDPS system aims to provide underwater Digital Elevation Models (DEM), for applications such as a two-dimensional discrete matrix of data underwater elevations.

We present here an economical and small-scale UDSP system used to readily acquire and process dynamic 3D data obtained during a one-day experiment on measurement of pebble sizes in the Ngongotaha Stream near Rotorua, New Zealand (see Figure 1). Section 2 provides a full description of our experimental setup leading to through-water and underwater stereophotogrammetry. Section 3 provides details of our specific camera calibration procedures. Section 4 introduces our stereo-matching algorithm and briefly describes the GPU acceleration which allows for real-time processing. Section 5 shows 3D images of gravel-bed-surface structures and gives preliminary results of our through- and underwater 3D measurements of pebbles stones compared with manual calliper measurement. Section 6 provides our current directions of progress and future achievements.

Figure 1: Satellite image of the experiment location.

2. EXPERIMENT SETUP

The experiment took place around a small section of the Ngongotaha Stream. We identified a flat area of the river bed approximately 5 meters away from the shore as our experiment location. The river depth was measured by a tape measure to be approximately 19 cm at the experiment location.

We used one Fujifilm FinePix REAL 3D W3 camera[1] (hereafter referred to as the *W3* camera) and two GoPro Hero cameras with the 3D HERO System[2] waterproof stereo housing (hereafter referred to as the *Hero* cameras). These cameras were selected because they offer low-cost consumer-grade stereo systems that are highly portable. Due to the experiment location being in the middle of the river (see Figure 2), we have decided against using USB cameras with a laptop computer to avoid potential damage to equipment, and selected only cameras that record on removable storage such as SD cards.

The W3 is a consumer grade "point and shoot" stereo camera with a resolution (per camera) of 10 megapixels. The system is also capable of recording stereo video at HD resolution and video frame rate. The baseline separation between the left and right camera is 75 mm. This camera can be set to manual operation and allows adjustment of parameters such as zoom, focus, exposure, aperture, ISO speeds, etc. Typical of modern digital cameras, this camera provides high quality images with low lens distortion and accurate colour reproduction at a reasonable cost. We selected this camera due to it's portability and high quality stereo images it provide.

The Hero cameras combines two standard GoPro Hero cameras in a compact waterproof housing. The two cameras are rigidly mounted inside the housing and is synchronized electronically via a dedicated cable connection. This system is capable of recording synchronized stereo video at HD resolutions and video frame rate. The cameras are also capable of capturing still photographs at resolution up to 5 megapixels. The baseline separation between the left and right camera is 33 mm. As this camera is designed for sporting use, it is not possible to manually adjust settings such as exposure, aperture, focus, or white balance. We selected this system for our experiment as it currently provides a low cost (less than $400 USD) method to obtain underwater stereo images without the need for custom engineering.

Our intent is to obtain stereophogrammetric measurements of the riverbed with cameras above the water surface viewing the target underwater (hereafter referred to as *through-water* measurements) and with cameras in the water viewing the target underwater (hereafter referred to as *underwater* measurements). For comparison, we can also obtain images in the traditional case of cameras in air viewing target in air (hereafter referred to as *in air* measurements). As our W3 camera is not equipped with a waterproof housing, it is limited to in air and through-water measurements; the Hero cameras with the waterproof housing can obtain all three types of measurements.

To reduce distortion and water surface reflecting and refracting light due to water surface fluctuations, we utilized a 1 m long perspex skimmer device. The skimmer has adjustable supports and it was set to sit lightly on the water surface so that the waves are flattened without causing significant disturbance to the water flow. In the river environment, extra care was required to ensure the top surface of the skimmer is free of water, as waves and ripples may breach the side walls of the skimmer. See Figure 2 for a photograph and diagram of the experiment setup.

In our experiment, we did not use a tripod to stabilize the cameras due to the possibility of water damage to the equipment. In normal sunlight conditions in the outdoors, the shutter speed is sufficiently fast to avoid most blurring from handling of the cameras.

For measurement of river bed pebbles, we selected 32 pebbles of various sizes from around the experiment area. These were measured, then placed manually on the river bed for measurement by stereophotogrammetry.

3. CALIBRATION AND IMAGE ACQUISITION

In order to determine the distortion effects of the river water, we calibrated both camera systems on location in the configuration they were used to obtain measurements. Specifically, the Fujifilm W3 was calibrated in the through-water configuration viewing the submerged target through the skimmer; the GoPro Hero cameras were calibrated through-water viewing the target through the skimmer, and under-

[1] `http://www.fujifilm.com/products/3d/camera/finepix_real3dw3/`
[2] `http://gopro.com/hd-hero-accessories/3d-hero-system/`

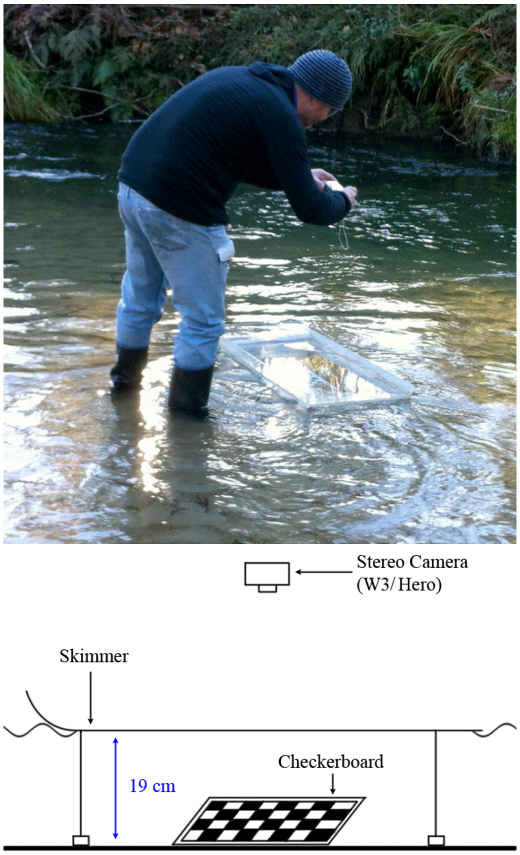

Figure 2: Above: Experiment setup on location. Below: Diagram of experiment setup.

water with the skimmer removed.

We used Zhang's method [15] to calibrate the cameras. Part of the goals of this experiment is to determine whether the pinhole camera model with radial distortion used by Zhang's method can be applied with the addition of the water-air interface and still obtain usable measurements for stereophotogrammetry.

A laminated checkerboard was secured to a glass board using rocks and submerged underwater. The lamination is of matte type and is non-reflective to reduce effects of sun glare. The checkerboard is placed at the location where the pebbles will be photographed – beneath the skimmer. Due to water pressure, the checkerboard remains flat on the glass surface provided it was not moved by water currents. This provides a low-cost method to create a suitable underwater calibration target for use with Zhang's calibration method. We attempt to ensure the checkerboard is free of sand and debris, and no air bubble lie beneath the skimmer.

Multiple images are taken with the checkerboard centred in the field of view. This is similar to how we will obtain the actual riverbed images where the object lies within the centre of the field of view. The checkerboard does not fill the entire field of view due to the distance to the target and the relatively wide field of view of the Hero cameras. The W3 was set at a constant zoom level such that the checkerboard fills approximately the same area in the image as the GoPro Hero. Figure 4 provides an example of the calibration target

Figure 3: The 32 pebbles selected for this experiment.

from each camera configuration used.

In many cases, we observed that the images we obtain is far from ideal. For example, many images have lighting variations due to water currents and ripples; the camera may sometimes focus on the perspex skimmer instead of the river bed; positioning of the experimenter may cast shadows or reflections; motion blur from hand shaking when operating in the unsteady river bed. Thus throughout calibration and image acquisition, many more images are taken than necessary and undesirable images with artefacts or distortions are examined and removed.

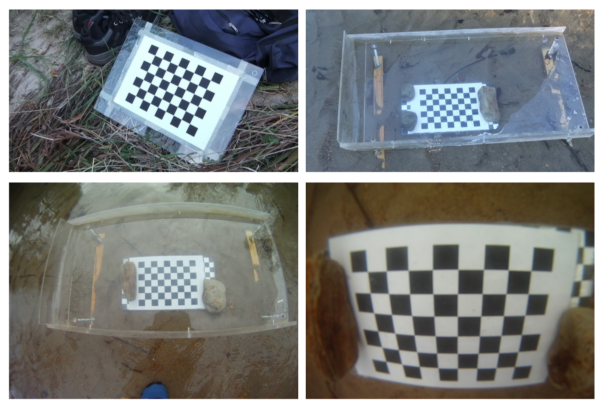

Figure 4: Example calibration image from Fujifilm W3 in air (above left), through-water (above right), GoPro Hero through-water (below left) and underwater (below right).

3.1 Fujifilm W3

The Fujifilm W3 was calibrated in air and through-water. The camera is set to automatic focus to ensure a sharp image. Care was taken to photograph all images of the checkerboard at a consistent distance, and the same distance was used for data acquisition. The small change in focus should not have a large effect on the calibration values. The W3 was approximately 30 cm above the river surface in the through-water scenario.

The camera was set to 1/100 s exposure time and F/3.5 aperture, which is sufficient to obtain a sharp image with good brightness. Table 1 summarizes the camera parameters obtained from calibration in air and above water. Estimations of higher order radial distortion showed large uncertainties both in air and above water, and thus κ_2 and above is removed from the model. This is likely due to the W3 having high quality lens that is mostly free from visible distortion. The values of the focal length and first order radial distortion κ_1 increased when measured through the air-water interface. None the less, the calibration accuracy remains high with the average pixel error between estimated and measured corners of the checkerboard at less than 0.4 pixels in a full resolution of 3584×2016 pixels.

Parameter	value in air	value through-water
f (1 mm pixel)	4234 mm	4405 mm
κ_1	-0.0873	-0.1507

Table 1: Camera parameters of W3 camera from calibration.

3.2 GoPro Hero

The same checkerboard and procedure as the W3 is used for the GoPro Hero. The Hero cameras were used for through-water and underwater stereo experiments.

Due to the difficulties of operating the Hero stereo system through the water-proof casing, we instead set the camera system to continuously take time-lapse photos with an interval of 3 seconds. By pausing at a desired pose for at least 5 seconds, we ensure at least one image is taken when the camera is stationary. Extra images that are not needed were manually identified and removed in post-processing.

The Hero cameras does not provide any way to alter image capture parameters, thus cameras were set to automatic exposure, white-balance, a fixed aperture and fixed focus. The cameras were approximately 30 cm above the river surface for through-water, and at the water surface for underwater acquisition.

Table 2 summarizes the camera parameters for through-water and underwater calibration for the Hero cameras. Similar to the W3, we again observe an increase in focal length, indicating that submerging in water causes a zoom-in effect. The distortion model used both first and second order radial distortion, and they have similar values through- and underwater. The range of uncertainty is larger than the change in values. In fact, we experienced significant uncertainties in accurately detecting checkerboard corners in the underwater images (see Section 3.2.1) and resorted to manually determining the location of the corners using a zoomed in image to an accuracy of approximately 0.1 pixel.

Parameter	value through-water	value underwater
f (1 mm pixel)	1203 mm	1412 mm
κ_1	-0.2764	-0.2699
κ_2	0.0703	0.0684

Table 2: Camera parameters of Hero cameras from calibration.

3.2.1 Underwater Blurring

During the analysis of images taken by the Hero cameras under water, severe blurring of the images was observed. From visual inspection of the images, the centre of the images are less blurry than the peripherals, but still visiably blurred compared to images taken in air or above water. We decide to investigate the cause of this problem in a controlled manner.

The first possible cause we investigated was the short distance between the camera and the objects. It was suspected that close distances may be outside the camera's focus range, causing the blur. Images of a checkerboard were taken at various distances, ranged from 500 mm to 100 mm. The result image had a similar amount of blurring as though taken while using the skimmer, even at extremely short distance. We concluded that the blurring was not caused by the short distance between the camera and the object.

Next we simulated the river environment by filling up a sink with water to approximately the same depth as the river. We then placed a checkerboard at the bottom of a sink and took images from both without water and submerged below water (see Figure 5). The result showed that when the camera was below water, the image is blurred similarly to those taken in the actual river, and when the camera was slightly above water, no such blur was observed. In this test, we also eliminated the possibility of blurring from camera shake by placing the cameras on static supports.

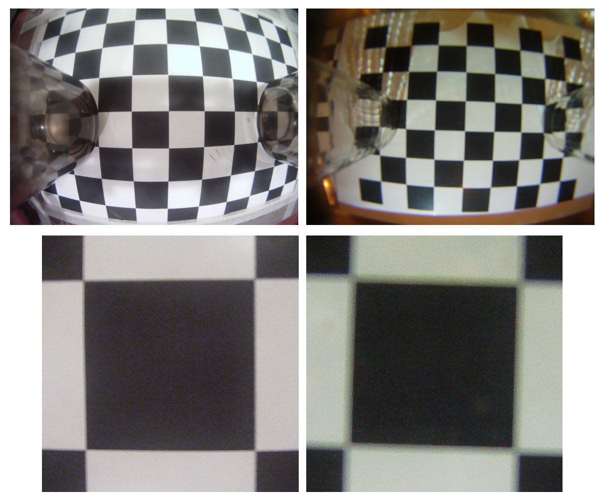

Figure 5: Above: View of the checkerboard without water (left) and submerged in water (right). Below: Magnified view of a central square.

From these tests, we conclude that close distance and hand shaking was not the main cause of the blur. We suspect that the blurring effect is because of the casing used to waterproof the cameras causing additional refraction of light. The casing are made of low-grade plastic, and has a domed shaped lens cover positioned directly in front of the camera lenses. The low quality of the plastic cover lenses and the dome shape, combined with the large difference in the refractive indexes of water and plastic caused the light to refract, resulting the blur observed. This problem could be addressed in the future by using a housing with higher quality glass and a flat viewport for angles less than 60°.

4. STEREO MEASUREMENT

In this section we demonstrate the potential of stereo photogrammetry techniques for underwater measurement of river bed pebble sizes.

The 32 pebbles we selected were placed on the riverbed underwater in a group with minimal overlap in the same location as the checkerboard (now removed, see Figure 6 (right)).

Figure 6: Pebble size measurement using digital caliper (left) and through water image of pebbles (right).

Using the same camera configurations and acquisition techniques as calibration, we took images of the pebbles through-water with the W3 and Hero cameras, and underwater with the Hero cameras. The images were then undistorted and formed into rectified stereo pairs using the technique of Fusilleo et al. [6].

Using our CUDA parallel computation implementation of the 1D (scan-line-wise) Belief Propagation (BP) algorithm [8] on a laptop equipped with the Nvidia GTX460M graphics processing unit, we were able to generate about 25 depth maps within an hour at the site of the experiment. This fast on-site processing capability helps mitigate the large amount of data collected to deal with image problems (as detailed in Section 3).

Given the known size of the calibration target, the camera parameters from calibration can relate the stereo reconstruction to actual length units through stereo triangulation. We then manually identified the extent of each pebble in the depth map and computed the length of two axis (long and intermediate axis) on the same plane as the image. The third axis (short axis) along the viewing direction was approximated as $2\Delta d$ where Δd is the range of depth measured from stereo reconstruction for the pebble. We compare this size measurement of select pebbles against those measured using a digital calliper in the next section.

Automatic identification, segmentation and measurement of pebbles from depth images of such quality is not possible. Instead, we manually determined the pixel position of the ends of each axis in the image.

5. EXPERIMENTAL RESULT

Due to water and lighting effects, many images suffer from poor quality stereo reconstruction, as Figure 7 demonstrates. In some images the autofocus of the W3 targeted the perspex skimmer instead of the pebbles beneath. In other images the light reflection on the water surface and the skimmer is different in the left and right image. Much of the lighting effects did not affect the accuracy of calibration made a large impact in stereo reconstruction. Flowing sand and debris in the river also invalidated a number of images. In the underwater images from the Hero cameras, the main cause of problem is the blurring of the images as described in Section 3.2.1. We note that it is generally very difficult to predict the quality of stereo matching from visual inspection of the input images. Despite the general poor quality of the reconstructed depth maps, some images return good quality results, e.g. the lower right part of the W3 image, and these areas allow us to measure some of the pebbles. The three axis of each pebble is then compared with the measurement taken from a digital calliper.

Out of the 32 pebbles placed we only observe 6 pebbles correctly reconstructed with clear visibility in depth maps from both cameras with all three axis measurable. Table 3 and Table 4 summarises stereo measurement accuracy of the 6 measurable pebbles in through-water using W3, and underwater using Hero.

Unfortunately due to the relatively large distance of acquisition compared to the baseline distance of the Hero cameras, the through-water configuration lacks any reasonable depth resolution and we discarded them in this comparison of pebble sizes – only data from the W3 images were used for through-water comparison.

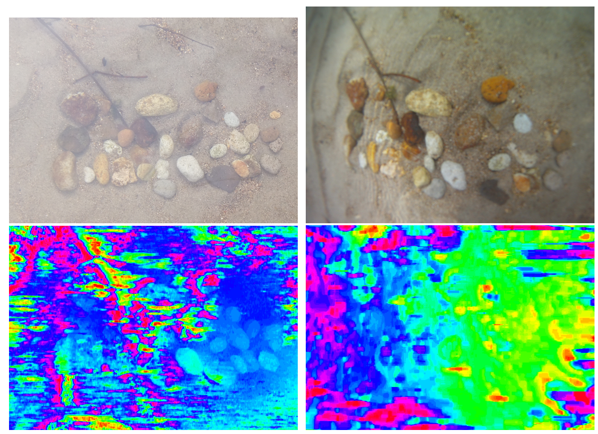

Figure 7: Images (above) and depth map (below) of stereo reconstruction from W3 above water (left) and Hero under water (right).

Pebble	Long axis error (mm) (% axis)	
	W3 through-water	Hero underwater
A	6 (11%)	4 (7%)
B	4 (8%)	6 (13%)
C	7 (22%)	3 (9%)
D	9 (20%)	7 (15%)
E	5 (12%)	1 (2%)
F	7 (31%)	6 (26%)

Table 3: Pebble long axis measurement accuracy for different cameras compared to calliper measurement.

We observe that measurement of the long axis (parallel to the image plane) generally achieves reasonable accuracy, having a error of approximately 15% of the axis length. Both W3 and Hero cameras achieved similar accuracy – the W3 have a higher image resolution, however the Hero was able to be placed closer to the pebbles when underwater. A large portion of this error can be attributed to the difficulty in determining the ends of the axis as some pebbles are rotated and the true end of the axis obscured.

The measurement of the short axis (along the view direction) achieves much poorer accuracy, with errors approaching a full axis length in some cases. Several factors contribute

Pebble	Short axis error (mm) (% axis)	
	W3 through-water	Hero underwater
A	14 (83%)	19 (113%)
B	8 (56%)	15 (106%)
C	9 (75%)	8 (67%)
D	13 (57%)	21 (92%)
E	7 (58%)	9 (74%)
F	11 (164%)	14 (209%)

Table 4: Pebble short axis measurement accuracy for different cameras compared to calliper measurement.

to this: the crude assumption that the pebbles are symmetric by computing the depth to be $2\Delta d$; high amount of noise present in the depth maps; and low depth resolution of the Hero cameras even at close range.

The manual selection of measurement points and often only a single available measurement weakens the confidence of these results.

6. CONCLUSIONS

We performed and described here an attempt at producing depth elevation maps of pebble-like stones in the Ngongotaha river using our low-cost Underwater Dynamic Stereo Photogrammetry system. Under challenging conditions (adverse weather and cold water temperature) we deployed our equipments, calibrated our cameras and acquired large amount of data (both through and under water) within two hours.

The Fujifilm W3 camera achieved through-water higher accuracy and resolution than the Hero camera underwater thanks to its larger baseline, higher image resolution, sensor and optics quality.

Real environment conditions such as limited time for experiment, changeable illumination conditions, irregular river velocity generated difficulty in camera control. A need for real-time feedback reflects the need for fast acquisition system and on-site processing thus validating our software and hardware approach. We managed to correlate obtained photogrammetric measurements of the pebbles stones with minimal manual measurements of a set of pebbles stones chosen as our benchmark. Next battery of tests will require additional equipments such as underwater housing for Fujifilm W3 and Achromat Wide Conversion Lens for the Gopro cameras. We will also generate benchmark pebble stones surface measurement using in-house laser scanner to compare with our set of experimental measurements.

7. REFERENCES

[1] R. Basri, D. Jacobs, and I. Kemelmacher. Photometric stereo with general, unknown lighting. *International Journal of Computer Vision*, 72(3):239–257, 2007.

[2] J. Butler, S. Lane, J. Chandler, and E. Porfiri. Through-water close range digital photogrammetry in flume and field environments. *Photogrammetric Record, 17(99), 419-439.*, 17(99):419–439, 2002.

[3] P. Chapman, K. Bale, and P. Drap. We all live in a virtual submarine. *IEEE Computer Graphics and Applications*, 68(7):745–751, 2010.

[4] A. Chong and P. Stratford. Underwater digital stereo-observation technique for red hydrocoral study. *Photogrammetric Engineering and Remote Sensing*, 68(7):745–751, 2002.

[5] P. Delmas, G. Gimel'farb, A. Shorin, and J. Morris. Robust least-squares image matching in the presence of outliers. In *Proc. 12th Int. Conf. Computer Analysis of Images and Patterns (CAIP 2007) - Lecture Notes in Computer Science*, pages 776–783. IAPR, August 2007.

[6] A. Fusiello, E. Trucco, and A. Verri. A compact algorithm for rectification of stereo pairs. *Machine Vision and Applications*, 12(1):16–22, 2000.

[7] G. Gimel'farb. Probabilistic regularisation and symmetry in binocular dynamic programming stereo. *Pattern Recognition Letters*, 23(4):431–442, 2002.

[8] R. Gong. Belief propagation based stereo matching with due account of visibility conditions, 2011.

[9] M. Kampel, C. Liska, and S. Tosovic. Adaptive 3d reconstruction of archaeological pottery. In *Proc. 3DIM01 Conf.*, pages 42–51, 2001.

[10] K. Katija and J. Dabiri. In situ field measurements of aquatic animal-fluid interactions using a self-contained underwater velocimetry apparatus (scuva). *Limnology and Oceanography: Methods*, 6(APR):162–171, 2008.

[11] pcmag.com. Google unveils underwater street view for maps. online, September 2012.

[12] M. Shortis, E. Harvey, and D. Abdo. A review of underwater stereo-image measurement for marine biology and ecology applications. *Oceanography and Marine Biology*, 2009.

[13] C. S. Survey. A game-changing scientific study of coral reefs. online, September 2012.

[14] S. Windsor, S. Norris, S. Cameron, G. Mallinson, and J. Montgomery. The flow fields involved in hydrodynamic imaging by blind mexican cave fish (astyanax fasciatus). part i: Open water and heading towards a wall. *Journal of Experimental Biology*, 213:3819–3831, 2010.

[15] Z. Zhang. Flexible camera calibration by viewing a plane from unknown orientations. In *Computer Vision, 1999. The Proceedings of the Seventh IEEE International Conference on*, volume 1, pages 666 –673 vol.1, 1999.