Lab experiment for Simultaneous Reconstruction of Water Surface and Bottom with a Synchronized Camera Rig

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Abstract: In photo bathymetry, the optical rays are refracted at the air-water interface according to Snell's law, which creates a blur in the images and produces an error in the reconstruction of the topography. Modelling the dynamic, wave-induced water surface would allow correcting the deviation of the rays at this interface and significantly increasing the accuracy of photo bathymetry. In this contribution, we present a technical proposition aiming to simultaneously capture and reconstruct the water surface and the water bottom using a synchronised camera rig. Different scenarios have been set up to allow different approaches to the problem of extracting information about the water surface. In particular, the design and the acquisition plan of this feasibility study are presented, as well as the first results and improvements for future development.

1 Introduction

Photo bathymetry is the use of stereo photogrammetry to reconstruct the underwater topography. It can be a practical and affordable alternative to underwater acoustic systems and bathymetric laser scanning for water bottom mapping, in particular for water bodies with limited depth and low turbidity like inland rivers or coastal areas.

More specifically in aerial photo bathymetry, imaging systems are above water and the situation is then a case of multimedia photogrammetry, as optical rays go through two different media: air and water. Snell's law applies here to describe the effect of refraction of the rays at the water surface. As of today, this issue is the main obstacle to achieving high accuracy photo bathymetry. A 3D model of the water surface is therefore a prerequisite to correct the ray paths, however most existing solutions only approximate the water surface as a static planar surface, while the water surface is a dynamic and wave-induced surface. Regarding that matter, OKAMOTO (1982) has shown that the presence of waves at the water surface causes significant errors.

Existing work regarding the reconstruction of waves includes techniques based on very diverse approaches. Among them, there is the use of surface markers being deployed on an area of interest and their subsequent tracking (CHANDLER et al. 2008), which is not easily implementable in large-scale applications. Other examples use optical properties of the water surface, namely the specular reflection (RUPNIK et al. 2015) or the refraction of the optical rays (MURASE 1992; MORRIS & KUTULAKOS 2011), but most contributions are based on assumptions that are too limiting for our goal. These limitations include previous knowledge of the topography or the mean water height, experiments in very controlled environments or situations not applicable to the specific problem of reconstructing both the water bottom and surface.

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Our method aims to solve the problem of simultaneous reconstruction of the water bottom and surface, and contributes to the development of a solution that would be deployable over inland rivers and coastal areas. This article presents the first steps of our work on this issue and is structured as follows: Section 2 introduces the methodology, Section 3 the results achieved so far, and Section 4 a conclusion and possibilities for future development.

2 Methodology

2.1 Goal and design of experiment

The lab experiment is a data acquisition set-up for simultaneous capture of water surface and water bottom, and its original design is described in Fig. 1. The experiment focuses on (i) determining whether it is possible to (i) capture and (ii) reconstruct the water surface, which are two different issues. Capturing the water surface addresses the search for the optimal configuration that is necessary to obtain the relevant data in terms of equipment, imaging parameters, lighting, positioning, etc., whereas reconstructing the water surface relates to what extent the water surface can be modelled (which parameters can be extracted, which area can be covered …). The second objective is for this setup to be an initial version of a more ambitious experiment: the survey of inland waters using cameras embedded on a squad of Unmanned Aerial Vehicles (UAVs).

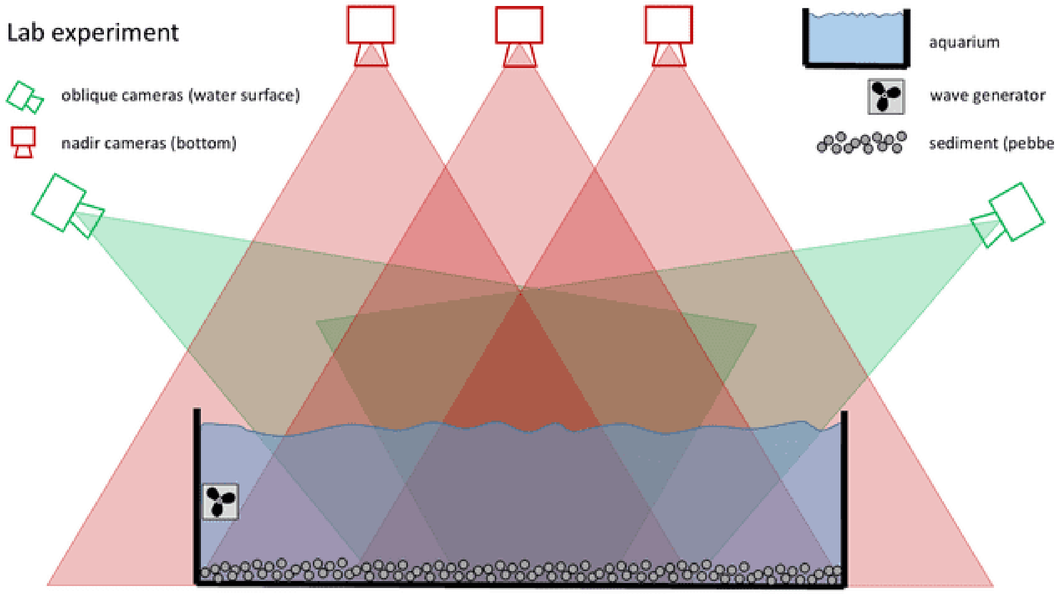

Fig. 1: Data acquisition set-up with multiple static cameras over a water tank. The nadir cameras deliver the bottom via multimedia photogrammetry whereas the oblique cameras are only used for water surface reconstruction

We have borrowed a complete camera rig from IPF Stuttgart to implement this experiment in the measurement lab of TU Wien. This setup is composed of four cameras and lenses, an Arduino Leonardo and the associated cabling. The Arduino serves as a controller and synchronizes the cameras by sending an electrical trigger signal in user-definable intervals via a cabled USB connection. Due to technical constraint, the highest possible frame rate is 1 frame per second and this is the applicable value for all results presented in this article. Two cameras are used to capture the water surface, looking obliquely from the side, and the other two to capture the water bottom, looking nadir from above. An aquarium is filled with water and two layers of stones to obtain a textured topography. Finally, we use an indoor fountain pump to create a dynamic water surface with a regular wave pattern. The set-up and the equipment are presented in Fig. 2.

Fig. 2: Implementation of the experiment in the lab (left) and photo of the water tank, the topography and a dynamic water surface generated by a pump (right)

2.2 Preliminary steps

2.2.1 Calibration and georeferencing

Before carrying out the lab experiment, attention is paid to the calibration and georeferencing. We use Agisoft Metashape (OVER et al. 2021) to estimate the radial distortion, the interior and exterior orientations. Orientation and calibration are then estimated by the bundle-block adjustment.

Ground control points (GCP) are used for the georeferencing in the laboratory local coordinate system. Approximately 80 coded markers were installed and surveyed with sub-cm precision with a total station (Leica TS16). The markers were chosen to allow automatic detection in Metashape. They were put on the scene around the aquarium to serve as GCPs and checkpoints, respectively. Their disposition considered the cameras' field of view and, given the restrictive environment, a distribution along the 3 axis as even as possible. They were measured via angle and distance measurements from six positions. During the processing, we only used the angle measurements and disabled outliers. The coordinates of the points in the laboratory local coordinate system are thus estimated by forward intersection. The maximum standard deviation on a point coordinate is 0.2 mm.

2.2.2 Reference model

Before pouring water into the bucket and starting the acquisition, several pictures of the aquarium and the reference target were taken with a 28 mm focal length Nikon camera to obtain a reference model of the topography. The final model was obtained after applying dense image matching in Metashape.

This model is presented in Fig. 3 and serves as validation.

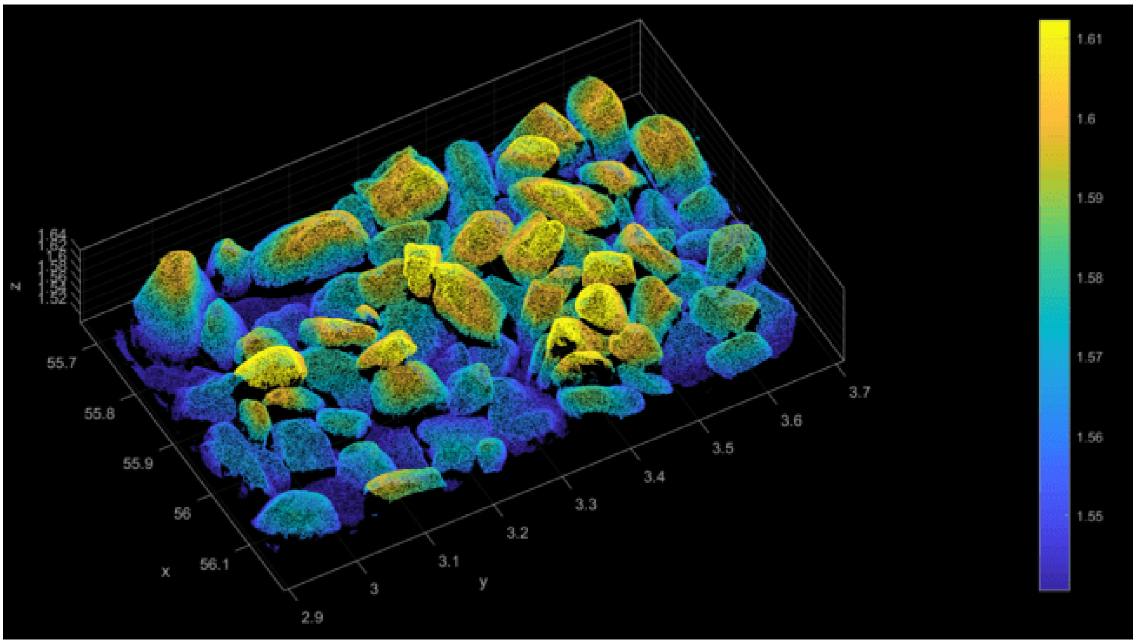

Fig. 3: Reference model of the topography of the water tank used for validation

2.3 Acquisition plan

An extended acquisition plan has been carried out with different scenarios to gather as much data as possible and study the impact of several parameters.

The first scenario is the standard scenario, with two obliquely looking cameras on the side and two nadir looking cameras above the water tank. The oblique cameras are installed on a horizontal bar lifted by two tripods. Three different heights have been tried to vary the amount of specular reflection on the water surface that is visible from the oblique cameras and reduce as much as possible the visibility of the topography from the side. For this configuration, we used additional halogen lamps to add energy and control the directionality of the light. A set of simultaneous photos taken by the four cameras is presented in Fig. 4. The aim of this approach is to find tie points on the water surface by applying a standard Structure-from-Motion approach (SCHÖNBERGER & FRAHM 2016). Another possibility would be to use the specular reflection to retrieve the surface normal vectors.

The other two scenarios consist of using four nadir cameras: organised on a single line, or organised in a squared grid, as presented in Fig. 5. These configurations provide a different approach to the issue of obtaining information from the water surface, by studying the displacement of points underwater due to the refraction at the air-water interface and therefore infer the shape of the water surface, namely 3 coordinates and slope.

In all scenarios, datasets of 60 frames, i.e., 1 minute, have been acquired with a dynamic water surface generated by the pump, and datasets of 20 frames with a flat water surface. We also varied a few camera parameters like exposure time (3 – 9 ms, depending on the lighting), gamma value (1 or 1.6), gain (0 – 10%) and aperture (F/1.8 or F/2).

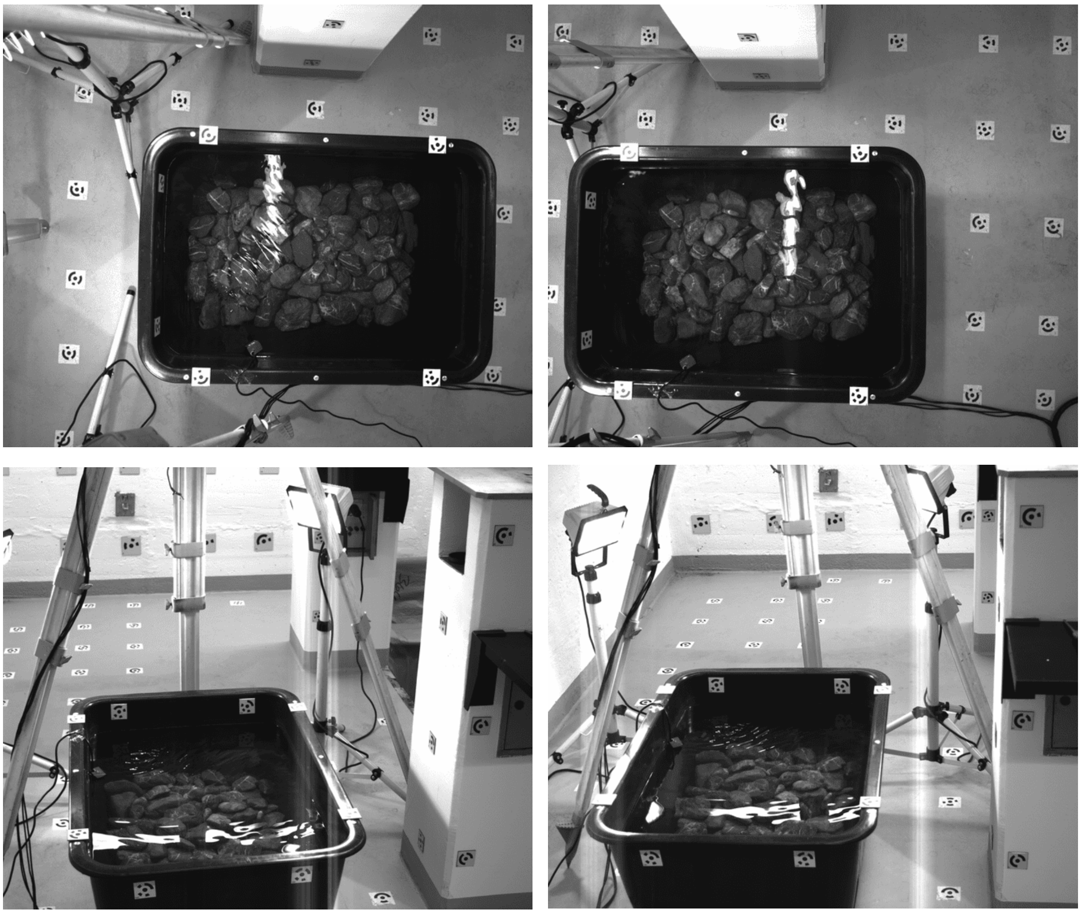

Fig. 4: Example of photos taken simultaneously by two nadir cameras (top) and two obliquely-looking cameras (bottom), in the case of a dynamic water surface and the following parameters: exposure time of 3 ms, gamma value of 1, aperture F/2, gain 0

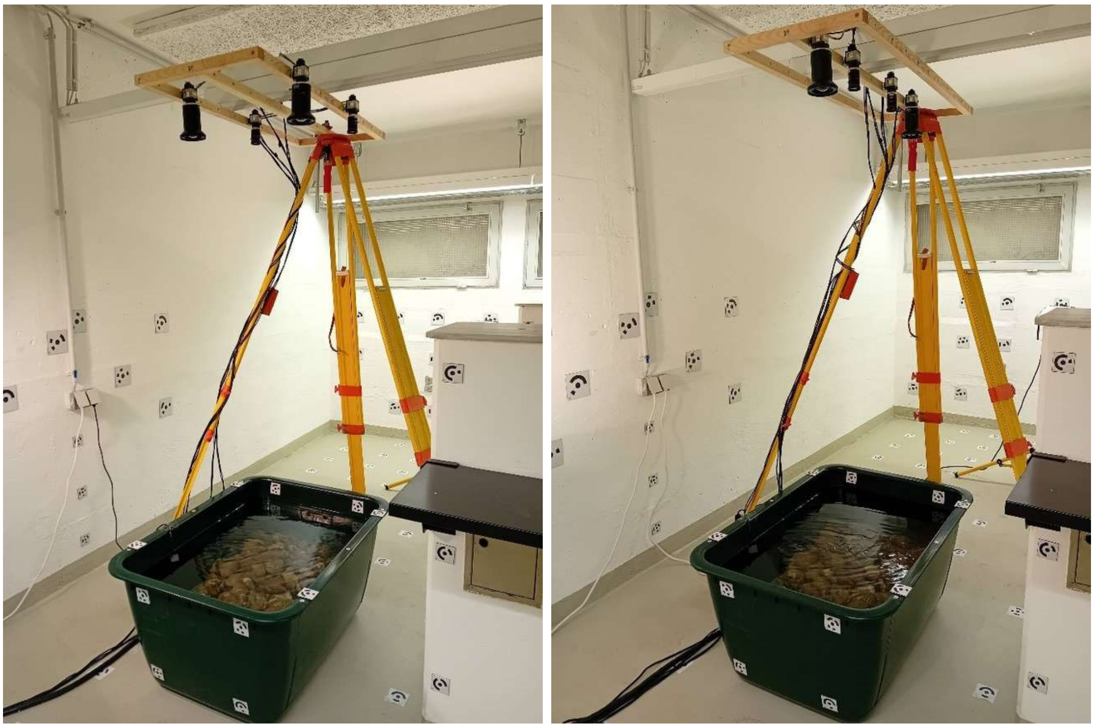

Fig. 5: Implementation of the experiment in the lab (left) and photo of the water tank, the topography and a dynamic water surface generated by a pump (right)

3 Results

3.1 Oblique cameras

A bundle-block adjustment on Metashape was applied to the pairs of images from the obliquely-looking cameras, in different configurations as described in section 2.3 to have a first idea of what could be achievable by this processing technique. The first problem is that the water is too clear as, for all pairs, the tie points in the aquarium area mostly come from the submerged topography rather than from the water surface. In some cases however, very few tie points are identified on the water surface (3 maximum) which allows to separate the topography and the water surface in the dense matching, as we can see on Fig. 6.

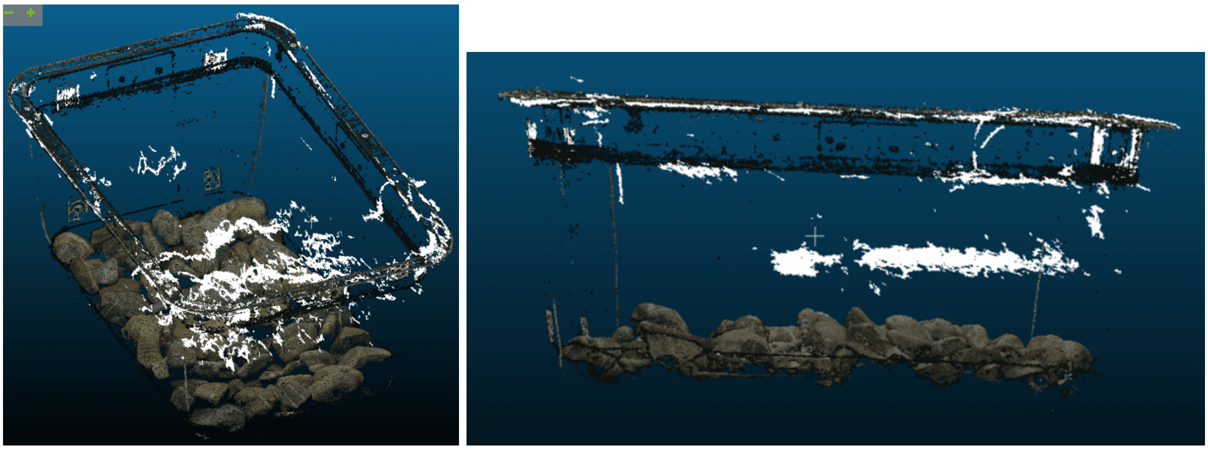

Fig. 6: Overlay of the reference model (textured point cloud) and a point cloud generated from images taken simultaneously from two obliquely-looking cameras (white point cloud)

Fig. 6 shows that the dense point cloud resulting from two oblique images is not complete and does not have many points in general. However, it is interesting to see that we can already distinguish two depths in the water tank: a deeper area which corresponds to the numerous tie points of the topography (due to clear water) and another intermediate depth with very few points which was generated from the 2 tie points on the water surface. We have measured the height between the edge of the water tank and the water surface with a measuring tape: 11cm, and from this point cloud, that same height is estimated at: 10.3cm. Given the accuracy of the measurement (visual estimation using a measuring tape, dense matching applied to only two images, presence of waves), we are satisfied with this result and think it is fair to say we are now able to obtain an estimated value of the mean water height by this technique.

3.2 Nadir cameras

Similarly, a bundle-block adjustment on Metashape was applied to the set of four images from the squared-grid nadir cameras, as described in Section 2.3. Fig. 7 shows that the reconstructed topography does not match the reference model. We measured the displacement of a point of interest: 5.8 mm on the X axis, 7.5 mm on the Y axis and 82.2 mm on the Z axis. This work needs to be deepened but we are hoping to gain information about the water surface by optimizing this approach.

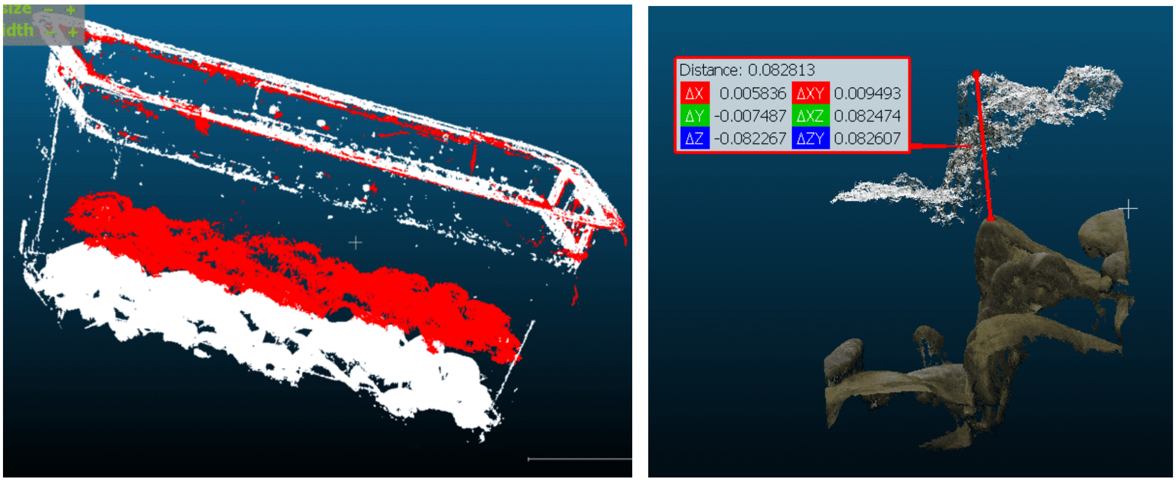

Fig. 7: Overlapping of the reference model of the topography (white) and the model obtained from the images taken simultaneously from four cameras organised in a squared-grid (red)

4 Conclusion and outlook

Our lab experiment provides an opportunity to study the feasibility of capturing and reconstructing the water surface by images only. Several scenarios have been implemented to allow different approaches and processing techniques and, while the outcome is not conclusive so far, preliminary results have shown that it could be possible to gain some information of the water surface, starting with the mean water height. The transparency of the water in the tank is currently an issue and putting opacifiers into it could make the surface more evident in the images and increase the number of tie points resulting from the bundle-block adjustment. This is insofar a feasible approach as natural waters are seldom perfectly clear but show a certain turbidity level. In addition to that, the environment of the laboratory brings some constraints, particularly regarding the lighting and the space, but we strongly believe that intensifying the specular reflection at the dynamic surface could also highlight some features.

Additionally, other ideas can be explored in the future. A first possibility would be to make use of the high reflectance property on the water surface of the wavelengths in the infrared domain. That would solve the problem of the transparency of water and the subsequent issue of capturing the topography instead. This is unfortunately not applicable for us yet due to equipment constraints, i.e., the current cameras are not very sensitive in this domain. Another idea would be to use the dynamic aspect of the water surface by studying the displacement of points at the surface between frames taken at different times, this is called optical flow. Our current setup is only capable of performing at 1 fps, which prevents us from testing optical flow based approaches right now, however this is a possibility for future attempts.

5 Acknowledgements

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