An optical triangulation method for height measurements on water surfaces

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ABSTRACT:

Optical triangulation methods based on a laser light sheet and a camera are frequently used as a surface measurement technique in a wide range of applications. They allow for the fast and accurate determination of height profiles, based on relatively simple hardware and software configurations. Moreover, they can be implemented very efficiently and are especially suited for measurements on moving objects such as products on an assembly line.

The study presented in the paper describes the adaptation of laser light sheet techniques to the task of water level profile measurements in hydromechanics experimental facilities. The properties of water surfaces necessitate several modifications of optical triangulation techniques to make them applicable: The mirror-like reflection properties of water surfaces form a contradiction to the assumption of diffuse reflection, on which standard light sheet triangulation techniques are based; this problem can be circumvented by using a diffuse reflecting projection plane to capture the mirror-like reflection of the laser line from the water surface. Due to the angle of incidence law, however, water surface tilts caused by waves will usually cause a strong degradation of the quality of the results when using reflected light; this effect can largely be compensated by processing max-store images derived from short image sequences rather than single images.

These extensions of optical triangulation turned out to be crucial for the applicability of the method on water surfaces. Besides the theoretical concept and a sensitivity analysis of the method, a system configuration is outlined, and the results of a number of practical experiments are shown and discussed.

1. INTRODUCTION

Hydromechanical phenomena in rivers are often simulated and studied in laboratory channels or small-scale riverbed models. The quantitative analysis of the effect of flow phenomena or changes in the riverbed on the water level requires techniques to precisely measure the water level. Using standard measuring equipment (water level gauges; ultra sonic devices), only point measurements are possible. The methodology presented in this paper enables the user to measure a whole profile at once. Apart from the advantage of a high spatial resolution, variations of the water level in time (e.g. water level oscillation caused by weirs) can be determined (s. rubber-weir in Figure 1).

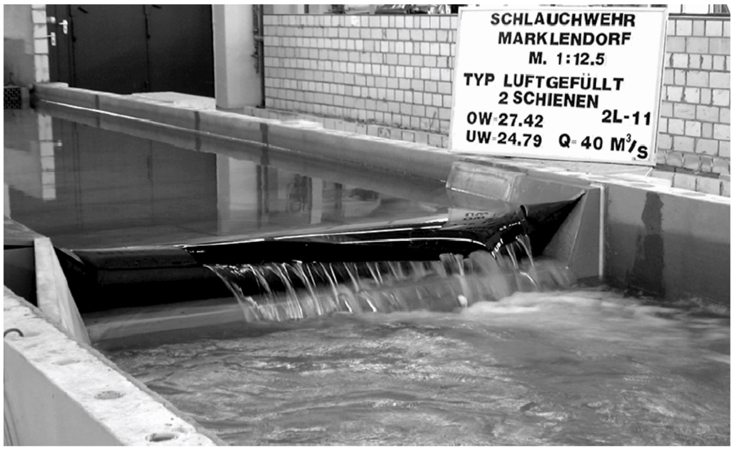

Figure 1: Laboratory channel at BAW, Karlsruhe

This requirement of simultaneous area- or profile-wise measurement is fulfilled by most optical measurement techniques. However, the application of optical measurement techniques to water surface measurements necessitates methods to visualize the water level in images of a camera. Basically, two methods for water surface visualization can be distinguished: Physical visualization, for instance by markers swimming on the water surface, or optical visualization realized by suitable illumination or projected light patterns.

Small particles on a water surface may be imaged by a stereo camera system and used to determine an instantaneous water surface model over a given observation area via their 3-D coordinates interpolated to a regular grid. If stereoscopic image sequences are acquired and processed, the technique may be extended to a 4-D method by tracking particles in time and simultaneously determining 3-D surface models and surface velocity fields (particle tracking velocimetry, Maas et al., 1993). A drawback of physical marking techniques based on adding markers is often formed by the fact that markers pollute the experimental facility. In this sense, the technique can not be considered a non-contact measurement technique.

A widely used optical method object surface height profile measurements is optical triangulation based on the projection of a laser light sheet onto the surface imaged by a camera (Figure 2). The physical properties of water surfaces are, however, in conflict with the requirements of these laser light sheet triangulation techniques: The techniques are based on the projection of a line onto a diffuse reflecting surface, which is imaged by a camera under a parallax, ideally with an angle of 90° between the optical axis of the camera and the laser.

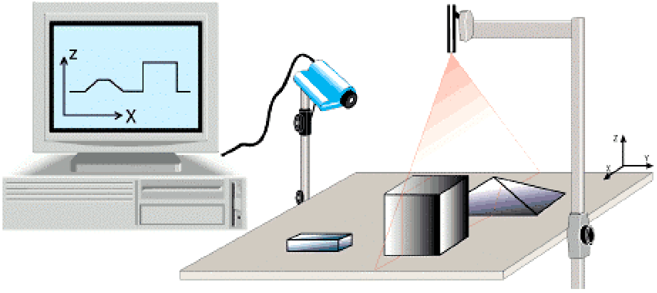

Figure 2: Basic principle of laser light sheet triangulation

The interaction of a laser beam with a water surface is characterized by reflection and refraction. Most of the intensity of the beam will penetrate into the water, with the direction of the beam determined by Snell's Law. The rest of the intensity is reflected according to the angle-of-incidence law. This mirror-like reflection on clean water surfaces can not be used for measurements in a conventional optical triangulation setup.

2. EXTENSION OF THE BASIC LASER LIGHT SHEET TECHNIQUE

In the following, an extension of the laser light sheet technique will be shown, which is especially suited for measurements on surfaces with mirror-like reflection properties. In a second step, the technique will be further extended for measurements on water surfaces with waves.

USE OF A PROJECTION PLANE

To visualize the mirror-like reflection of the laser light sheet from the water surface, the system configuration is extended by a vertical projection plane as shown in Figure 3: The plane is used to capture the reflection, and a camera arranged perpendicularly to the plane can be used to image the reflected and projected line.

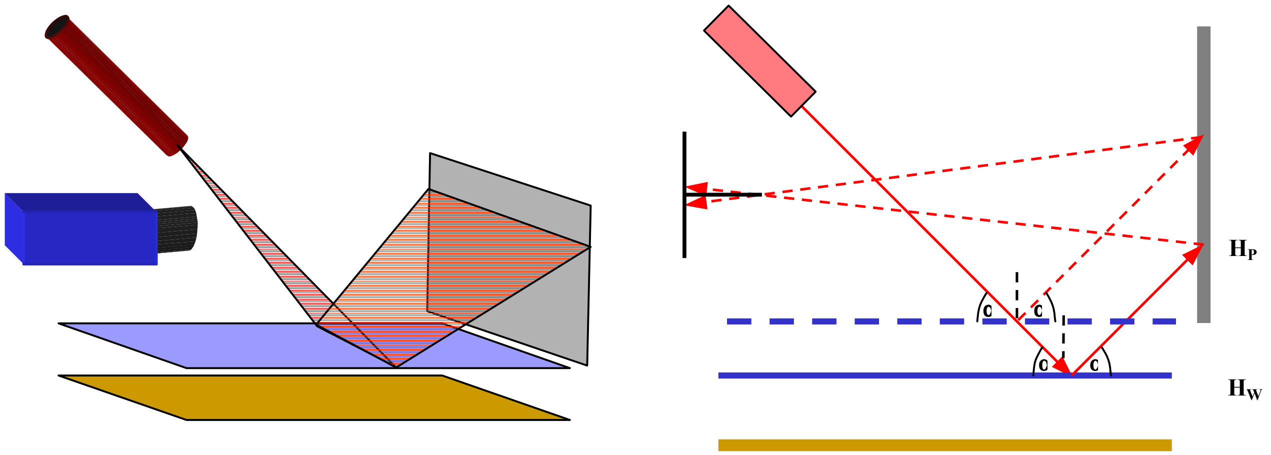

Figure 3: Optical triangulation via a projection plane

As can be derived from Figure 3, the sensitivity of the vertical position of the line on the vertical projection plane to water level changes is

$$\partial H_P / \partial H_W = 2\,.$$

It can be shown that this geometric sensitivity value is independent on the incidence angle α of the laser beam.

The width of the laser line on the projection plane is determined by the divergence of the laser beam, multiplied by a factor $(\sin\alpha \cdot \cos\alpha)^{-1}$ due to the twofold projection onto the water surface and the projection plane. It reaches a minimum at α = 45°. Therefore the incidence angle should be close to 45° in order to avoid a widened projection of the finite width of the laser line, which would reduce the image quality and thus the measurement accuracy.

Using subpixel-accuracy image measurement techniques for determining the vertical position of the line in image space at a pre-defined number of locations across the profile, a high accuracy potential can be achieved: Assuming for instance an image measurement precision of $^1/_{20}$ pixel and a 1300x1000 pixel camera, a relative precision of 1 : 20'000 of the vertical field of view of the camera can be achieved, corresponding to a water level standard deviation of 0.025 mm at an imaged riverbed width of 1.3 meter.

The optimal viewing direction of the camera is perpendicular to the projection plane, with the image scale determined by the width of the observation area on the water surface projected onto the projection plane.

If only a small range of water level changes is expected, the geometric sensitivity of the technique may be further increased by tilting the projection plane backwards as shown in Figure 4.

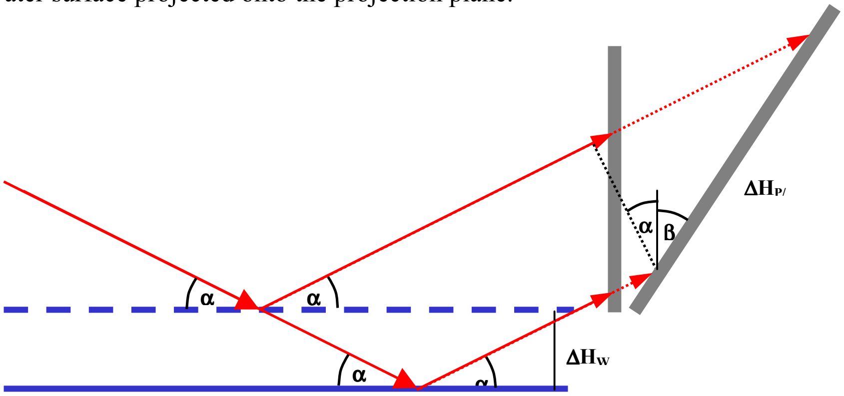

Figure 4: Tilted projection plane

The sensitivity of the methods for water level changes with the projection plane tilted backwards by an angle β can be derived from Figure 4:

$$\partial H_{P/} / \partial H_W = 2 \cdot \cos\alpha / \cos(\alpha + \beta)$$

The achievable gain in height measurement precision by such a tilt will, however, be limited due to the widened image of the laser line and the increased influence of the laser speckle effects on image measurement precision.

ACCUMULATION OVER SHORT IMAGE SEQUENCES

A principle disadvantage of the method as shown before is the fact that the position of the reflected line on the vertical projection plane is not only determined by the water level, but also by the local water surface tilt caused by waves. In the case of the presence of waves on the water surface, the angle-of-incidence law will cause errors in the determined water level heights. As can be seen from Figure 5, this influence is transmitted by a long lever-arm if the projection plane can not be placed very close to the location of reflection. This will generally not be possible if a large range of water levels is to be covered. Therefore, the height errors introduced by surface tilts may even be larger than the amplitude of the waves themselves.

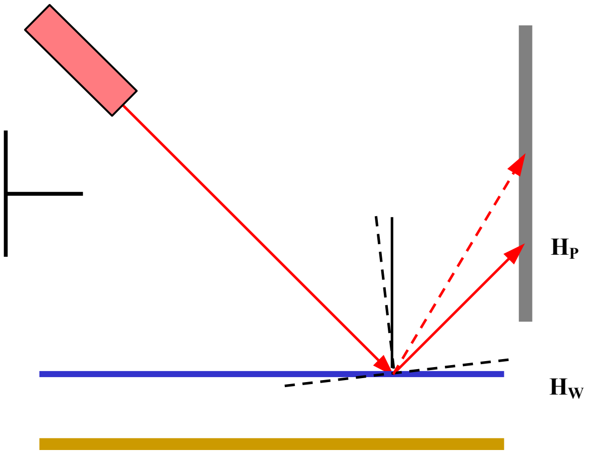

Figure 5: Influence of water surface tilt

This problem might be solved by the projection of multiple light sheets under different angles. In that case, however, the light sheets will only intersect properly at one water level, requiring complex techniques for modeling local water surface patches from measurements at different levels.

A more practical solution is provided by the analysis of short image sequences covering at least one complete wave cycle in time. As an influence of the surface tilt caused by waves, the projected line will move up and down in the image, with the minima and maxima reached at the extreme values of the surface tilts in the direction perpendicular to the line. Assuming spatial and temporal evenness of the wave pattern, a wave-independent position of the line representing the average water level can be found by searching for minima and maxima of the line position and averaging those. A slight asymmetry in the line positions at the extreme tilts with respect to the position at horizontal water level is compensated by the computation of water level differences and the system calibration.

A more efficient method to determine the average line position is the use of a max-store algorithm storing the highest greyvalue of each pixel over the image sequence in an accumulator image. In this accumulator image, the original thin laser line will be widened to a band, with the width of the band depending on the maximum surface tilts. Again assuming spatial and temporal evenness of the wave pattern, the vertical position of the band will be an average over a wave cycle, and the vertical position of the center of the band will be a wave-independent measure for the water level.

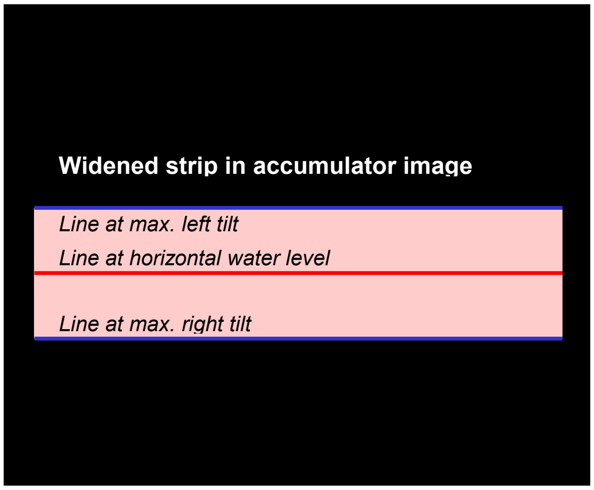

Figure 6: Principle of max-store accumulator image

3. PRACTICAL RESULTS

The extended laser light sheet technique was tested in a series of practical experiments both with horizontal water level and waves. The experimental setup is shown in Figure 7. Note that the camera was tilted downwards in order to image both the line reflected onto the vertical projection plane and the diffuse reflection of the line from the ground of the experimental vessel after refraction; the latter line can also be suitable for measurement purposes, but was not used in the experiments described here.

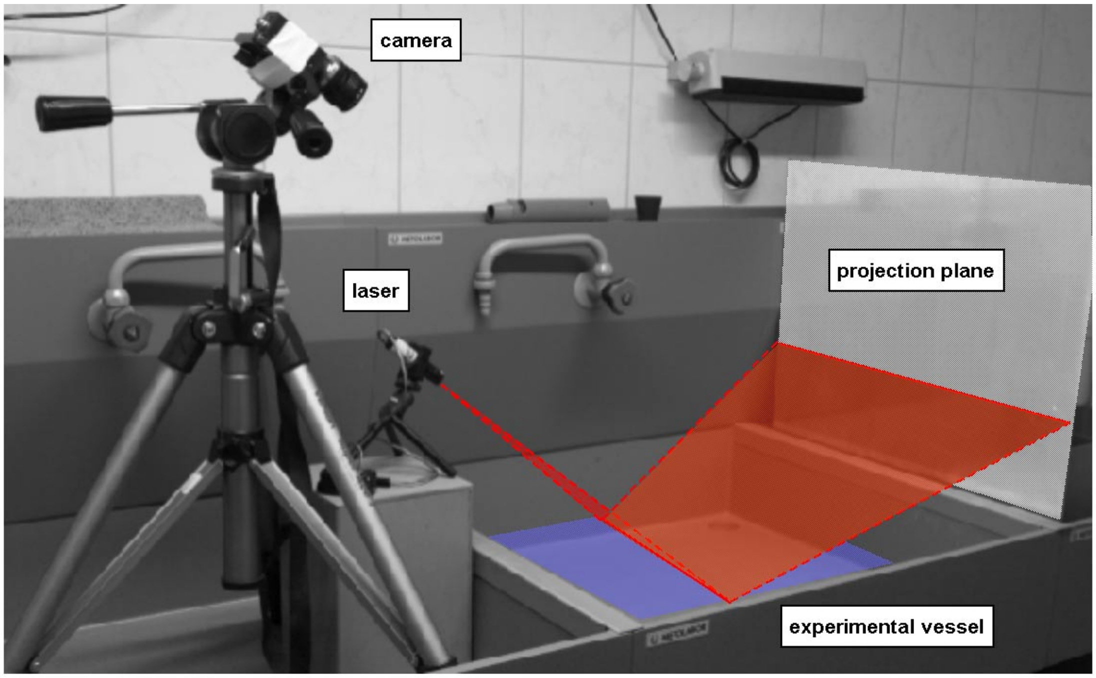

Figure 7: Experimental setup

The laser light sheet was generated by a small diode laser. A Powell lens was used in order to transform the Gaussian intensity distribution along the projection into an almost rectangular intensity profile. The line was imaged by a 15 Hz Sony XCD-X700 black-and-white 1024x768 pixel progressive scan CCD camera, covering a field of view of approximately 70cm x 50 cm and connected to a notebook via IEEE1394. The camera was equipped with a narrow band interference filter designed for the wavelength of the laser.

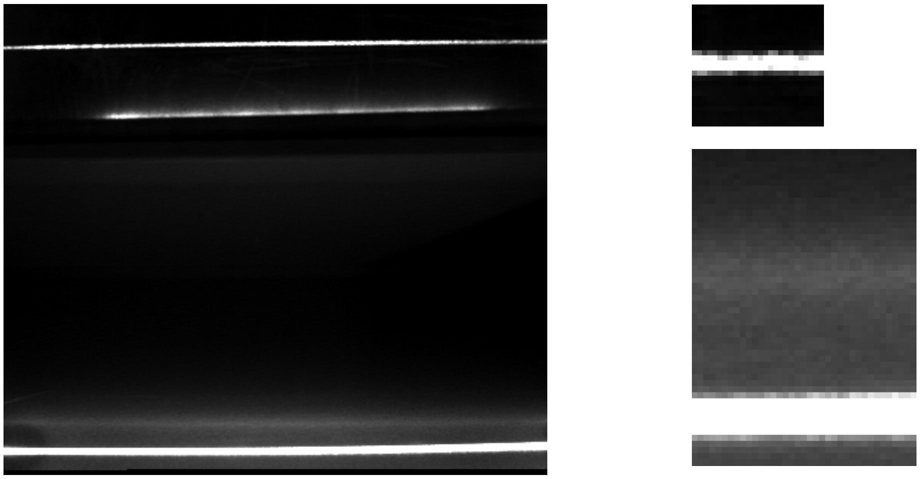

Figure 8: Camera image acquired in setup from Figure 7, zoom on line 1 and line 3

This way, quasi-binary measurement images can be generated. Figure 8 shows an example of an image acquired in an experimental setup as shown in Figure 7. The line in the top (*line 1*) is the mirror-like reflection of the laser line onto the vertical projection plane, which was used for the measurements. *Line 2* was caused by an undesired reflection and does not play a role for measurement purposes. The bottom line (*line 3*) is caused by diffuse a reflection of the refracted line at the bottom of the experimental vessel. If a surface model of the ground is known, this line may also be used for measurement. It can be shown that the geometric sensitivity of water level measurements based on the refracted line of the ground is smaller than the sensitivity of the projection plane method; the position of the line on the ground is also surface tilt dependent – this is an analogy to the basic principle of the 'shape-from-refraction' technique (Jähne, et al., 1994). In the experiments shown in the following, only *line 1* was used.

The vertical position of the line in image space was determined at a preset number of locations along the profile by least squares matching (LSM). Matching was performed with 15x15 pixel patches and restricted to the determination of the vertical shift parameter. Approximate values were obtained by propagating the results through the sequence.

To provide a reference for accuracy assessment, series of images were taken at different water levels in the experimental vessel. The water levels were generated by the addition of a defined amount of water, allowing for a calculation of water level changes by division through the known surface. An addition of 50 milliliters corresponded to a water level change of 0.11 mm.

EXPERIMENT AT PLANE WATER LEVEL

To test the accuracy potential of the method at the absence of waves, a first experiment was conducted on a quiet water surface. The water level was raised in 18 steps, adding 50 milliliter (or 0,11 mm) at each step. After each water addition, an image of the line was acquired after a delay time long enough for the waves to settle. The vertical image coordinate of the line was determined by LSM at 38 positions across the profile for each water level step.

The standard deviation of the image coordinate, determined by LSM and averaged over all 684 measurements, was 0.053 pixel. The average image coordinate change per step was 0,280 pixel. The RMS of the deviations to the average value through the sequence, computed over the 38 positions at 18 steps, was 0.076 pixel and can be considered a meaningful external confirmation for the standard deviation. Translated into object space, this corresponds to a standard deviation of 0.03 mm (0.076/0.280 * 0.11 mm) for the water level height measurement. Taking into consideration the smaller image format, the slightly worse image measurement precision and the tilted camera, this confirms the precision estimates shown before.

EXPERIMENT WITH WAVES

The same experiment was repeated in the same configuration under wave conditions, acquiring images before the water surface had settled after pouring the 50 milliliter water into the vessel.

When processing single images, the standard deviation of image coordinate measurement, obtained from LSM, was 0.030 pixel. The RMS of the deviations to the average image coordinate change at the different water levels, however, escalated to 1,470 pixel (as compared to 0.076 pixel in the comparable experiment with plane water level), translating into 0,56 mm in object space. This corresponds to a loss of a factor 20 in precision.

Figure 9 shows a single image and a max-store accumulator image generated from 50 consecutive images (corresponding to 3.3 seconds at 15 Hz) as described in chapter 2. The tilt of the projected laser line in the single image as well as the larger width of the line in the accumulator image indicate the presence of waves on the water surface.

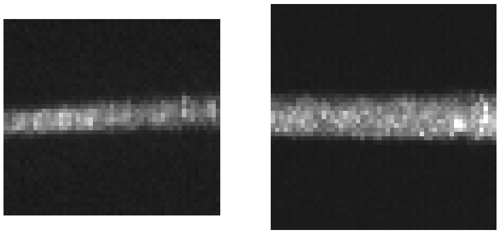

Figure 9: Section of laser line in single image, max-store accumulator over 50 images

When applying LSM to the accumulator images rather than single frames, the RMS of the deviations to the average image coordinate change dropped to 0,250 pixel in image space, equivalent to 0,10 mm in object space.

Thus, as a benefit of the use of the accumulator images rather than single frames, the measurement accuracy under the presence of waves dropped only by a factor of three, rather than by a factor of 20, and a measurement precision of 0.1 mm in object space could be achieved. Although this shows the advantage of the use of accumulator images, these results can not be generalized; further experiments are required to better define the tolerable degree of water surface modulation caused by waves. Moreover, it has to be taken into consideration that the use of accumulator images reduces both the spatial and temporal resolution potential of the basic method.

4. CONCLUSION

Laser light sheet optical triangulation methods can be adapted to measurements on water surfaces. The mirror-like reflection properties of clear water require an extension of the technique. The use of a vertical projection plane forms an elegant method to visualize the reflected light sheet to be imaged by a camera. For measurements at a plane water surface, a very good accuracy potential could be achieved. The results of method may be strongly deteriorated by the presence of waves on the water surfaces. Processing short image sequences rather than single images, these effects could largely be compensated.

Future work will concentrate on the determination of the tolerable degree of surface undulation. More effort will also be put onto the extension of the technique towards multi light sheet or/and multi projection plane techniques allowing for the simultaneous determination of water level and surface tilt in an analogy to photometric stereo techniques (Woodham, 1978).

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