A SIMPLIFIED OPTICAL TRIANGULATION METHOD FOR HEIGHT MEASUREMENTS ON INSTATIONARY WATER SURFACES

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ABSTRACT

The determination of water level heights is an important task in experimental hydromechanics. The Institute of Photogrammetry and Remote Sensing (IPF) at Technische Universität Dresden developed a system, which allows the user to measure the water surface in every surface situation profile wise with a high rate and contactless. The actual system marks the maximum of design and development. As always, this is accompanied by a high complexity of algorithms and cost for hardware. But the highest level of accuracy and performance is not always required. For some applications it is not necessary to acquire measurements of every surface situation. If only horizontal surface level variations are needed, the system can be drastically simplified.

This article presents the basic principle, potential and limitations of this simplified method. Besides the geometrical and mathematical model, the procedure of the system calibration will be described in deep. The results of practical tests show the applicability of the chosen method.

1. MOTIVATION

The determination of water level heights is an important task in experimental hydromechanics (Figure 1). The need for a contactless measuring system led one major research institute, the Federal Waterways Engineering and Research Institute (BAW), to the initialisation of a project to develop a system to fulfil all necessary aspects. The Institute of Photogrammetry and Remote Sensing (IPF) at Technische Universität Dresden was chosen as cooperation partner to develop and implement a method to measure water-surface profiles via photogrammetric methods. The basic measuring principle was outlined in (MAAS et al., 2003) and based on optical triangulation with a projection laser light sheet and a video camera. On the first view, this traditional photogrammetric method for surface measurement is not suitable for water surfaces, because of the necessity of diffuse-reflective textured surfaces. The mirroring properties of fluid surfaces are prejudicial to define direct its surface, but an adoption of optical triangulation enables to meet the requirements.

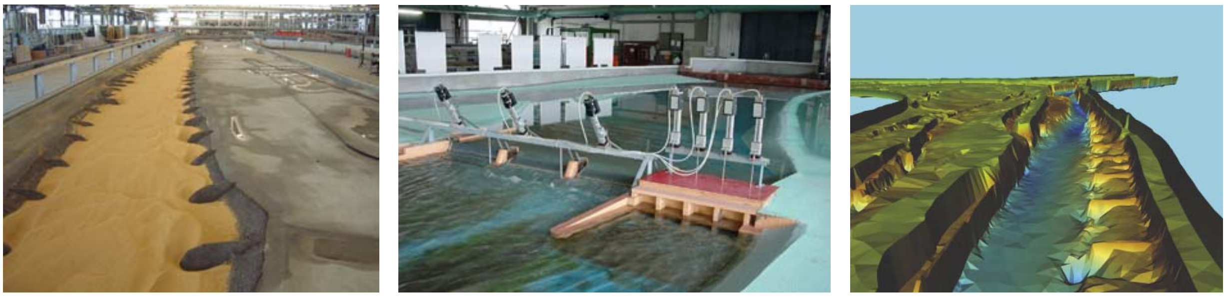


Figure 1 : Test bed of a river model, measurement devices (non contact less), generated 3D model (source BAW)

2. MEASURING PRINCIPLE

The reflection and transmission properties of fluids do not allow the observation of an analysable laser line on the surface. This can be done in an indirect way. The intersection line on the object surface can be visualised by projection of the reflected laser light sheet onto a plane, which is orientated vertically to the surface (see Figure 2a).

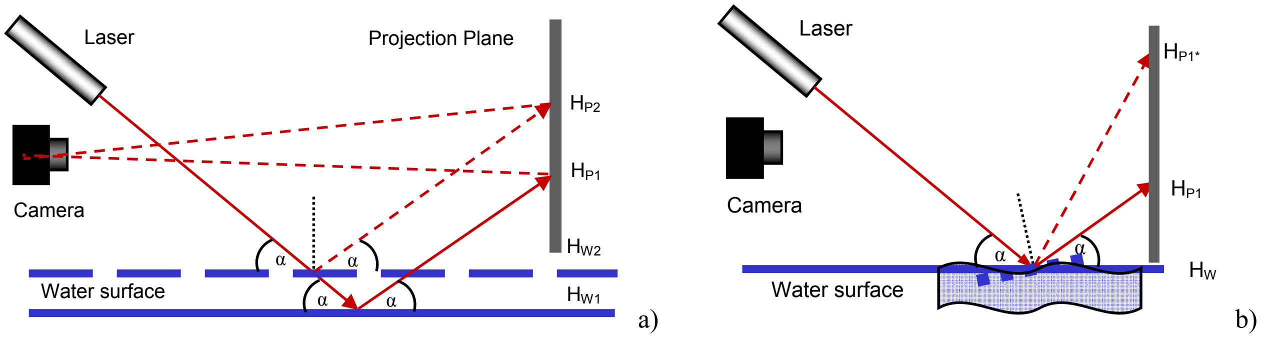


Figure 2: a) Optical triangulation using a vertical projection plane b) Effect of water movement on height measurement

The resulting laser line can be observed by a camera. Therewith a measurement of the water level change is possible. The calibration is rather simple and can be performed by measuring the laser line variances of two different water level heights. (MAAS et al., 2003) confirmed the applicability of the basic principle and the high accuracy potential of the technique. By using a digital video camera with 1024 × 768 pixel sensor and a recorded 70cm wide profile, an accuracy of 0.03mm was achieved for the determination of variances in water level (MAAS et al., 2003).

A limitation of practical applications of this method is the requirement of a quiet water surface. If this is not taken into account, water-level induced effects cannot be separated from slope-induced effects (see Figure 2b). The constraint is fulfilled only in a few cases in experimental researches, especially when analysing high dynamical phenomena.

Therefore it is necessary to modify the basic configuration of the system. This can be done by observing the projected laser line in accumulated image sequences rather than in a single image. Processing maxstore images obtained from short image sequences can reduce the errors resulting from water surface tilts in single images up to a factor of six. This strategy can only compensate small regular waves (MULSOW et al., 2005). Experiments showed, that the precision of the water level measurement is still three times worse as on quiet surfaces (MAAS et al. 2003).

A consequent solution to the discussed wave problem can be achieved by the integration of a second projection plane into the architecture of the system. This allows a rigorous geometrical solution for the surface determination (see Figure 3).

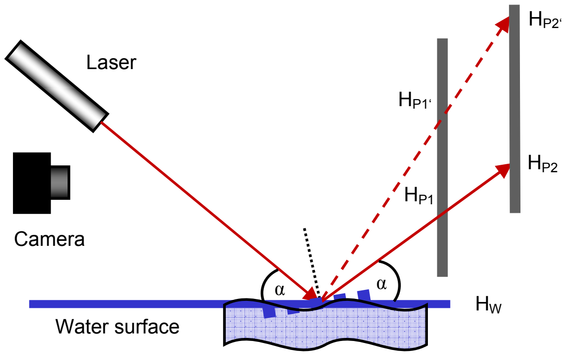


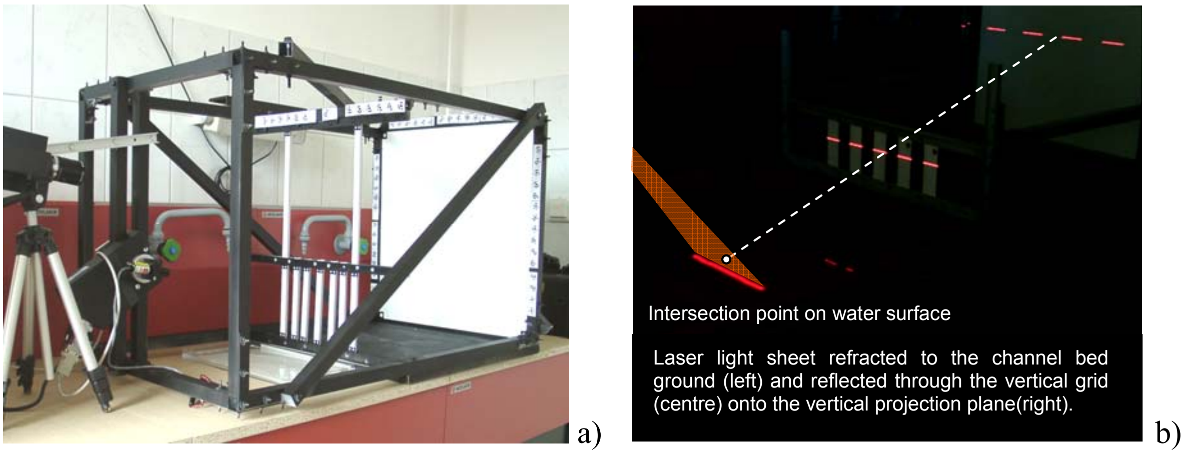
Figure 3: System with two projection planes

Now a complete reconstruction of the reflected laser light sheet can be performed. The thus modulated reflected laser sheet can be used for the calculation of the fluid profile by intersecting it with the projected laser layer. Besides the elevation values, the normal vector of the fluid surface in their actual profile points can be derived from the measured values simultaneously.

Unlike the one-plane laser light sheet projection system, the calibration of such a configuration is rather complex. The calibration parameters in an adequate model should describe the spatial relationships among the several system elements and a reference plane (air-fluid level in initial position).

3. ACTUAL SYSTEM LAYOUT

The actual system consists of several components (see Figure 4a). The main parts are a Firewire camera, a line-laser on a step motor and the projection planes. All parts are hold together by a rugged aluminium frame. The used camera is a Sony XC700 Firewire camera with a band pass filter. A homogeneous laser light sheet is generated by a 35 mW diode with a Powell lens.
As shown in Figure 4a, the front projection plane is designed as a vertical grid. This construction allows parts of the reflected laser light sheet pass through the front plane in an unaffected manner and are mapped on the second plane behind. The rest of the laser light sheet is caught by the frontal grid parts. The laser line elements are observed by a camera. Afterwards, the line elements are transformed into the object space. The corresponding end points are defining a vector. This vector can be intersected with the light sheet, which is coming from the laser directly. The resulting intersecting point coordinates describe the 3-D position of the corresponding water surface point.



Intersection point on water surface

Laser light sheet refracted to the channel bed ground (left) and reflected through the vertical grid (centre) onto the vertical projection plane(right).

Figure 4: a) Actual experimental system layout b) Measuring principle

As an additional component, a stepping motor, on which the laser light unit is fixed, was integrated into the system. This type of combination allows variable settings of the incidence angle of the laser light sheet. This way a sequential measurement of several parallel profiles is possible and requires no position change of the measurement unit (see Figure 5a).
Based on this system, a mathematical model was created and a calibration procedure was implemented. The model describes all movement and projections in the system. A number of parameters defines the true motor rotation axis, the orientation of the laser plane with respect to a certain incidence angle of the motor, the systems reference to a still water surface, etc.

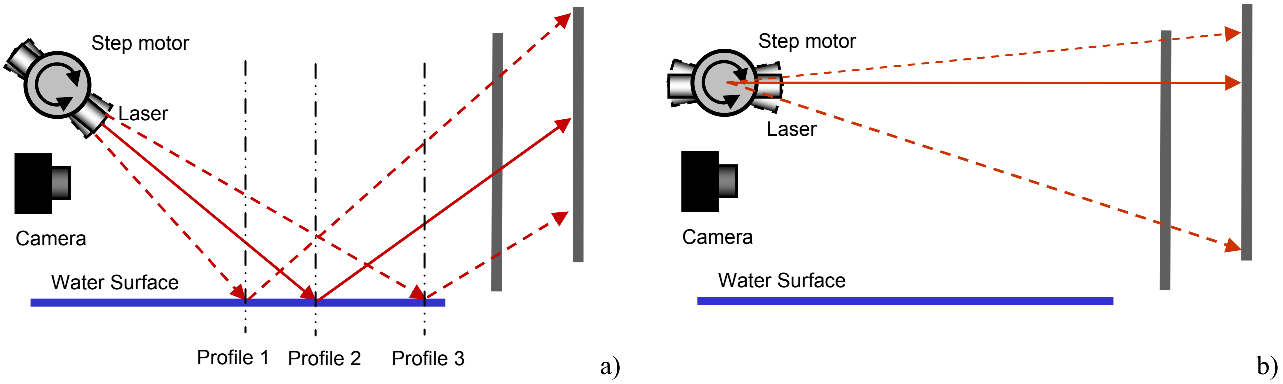


Figure 5: a) System with step motor b) Data acquisition for Calibration - direct projection with different rotation angles

The implemented calibration procedure is rather complex. Image sequences of different incidence angles of the laser sheet on the projection planes are taken as a basis for the determination of the calibration parameters.

During experiments, a measurement accuracy of 0.3 mm was achieved (MULSOW et al., 2006). These results show that the precision of the water level measurement is still three times worse as the single plane system. On the other hand, now it is possible to measure on any conditioned liquid surfaces.

4. SYMPLIFIED SYSTEM

As mentioned before the modelling and calibration of the actual system is complex. Also the inclusion of the step motor increases the hardware costs. The required stability of all components, especially the relative positioning of the projection planes, decreases the variability of the system. For some applications it is not necessary to acquire measurements of every surface situation. If only horizontal surface level variations are needed, the system can be drastically simplified. These new layout lacks the step motor and waives the rigorous geometrical determination of the surface. Now the calibration is more orientated on the single plane system. The defined water level change in a vessel and the observed variations of the laser lines are taken as input for the calibration. Measuring is performed on quit water surface.

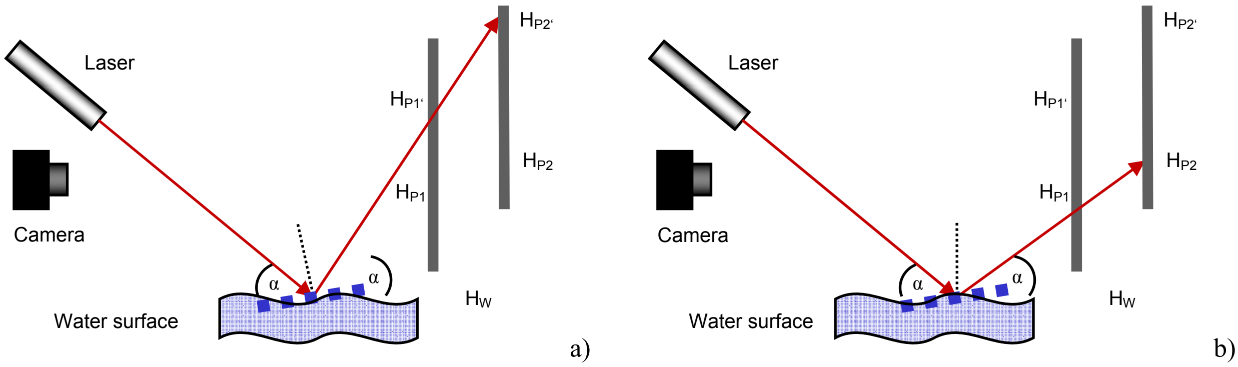


Figure 6: a) "Invalid" measurement b) "Valid" measurement

The computed proportion between the variations of water level and laser lines on one projection plane allows the determination of surface variations during the actual experiment. To separate water-level induced effects (Figure 6b) from slope-induced effects (Figure 6a) the mathematical proportions of the laser line heights on both projection planes can be analyzed (see also 4.1). Therefore a detection of measurements of water surface points with a strict vertical normal vector in longitudinal direction of the fluid surface is possible (see Figure 6).

However, this technique can only detect incorrect measurements induced by longitudinal waves (relative to the projection planes). But, lateral waves cause also incorrect height determinations. To detect these affected measurements the image material taken during calibration procedure can be further analyzed. By connecting the corresponding endpoints of at least two measurements a profile line can be defined, where valid laser line end point measurement should positioned (see Figure 7). Quantum of the effects from lateral waves on the classification should be one dimension smaller than from longitudinal waves.

The accuracy of such a system should be in the range of the single plane system. Reliability performance of classification of the measurement values ("valid" and "invalid") is depend on detection and measurement accuracy of laser lines on the rear projection plane.

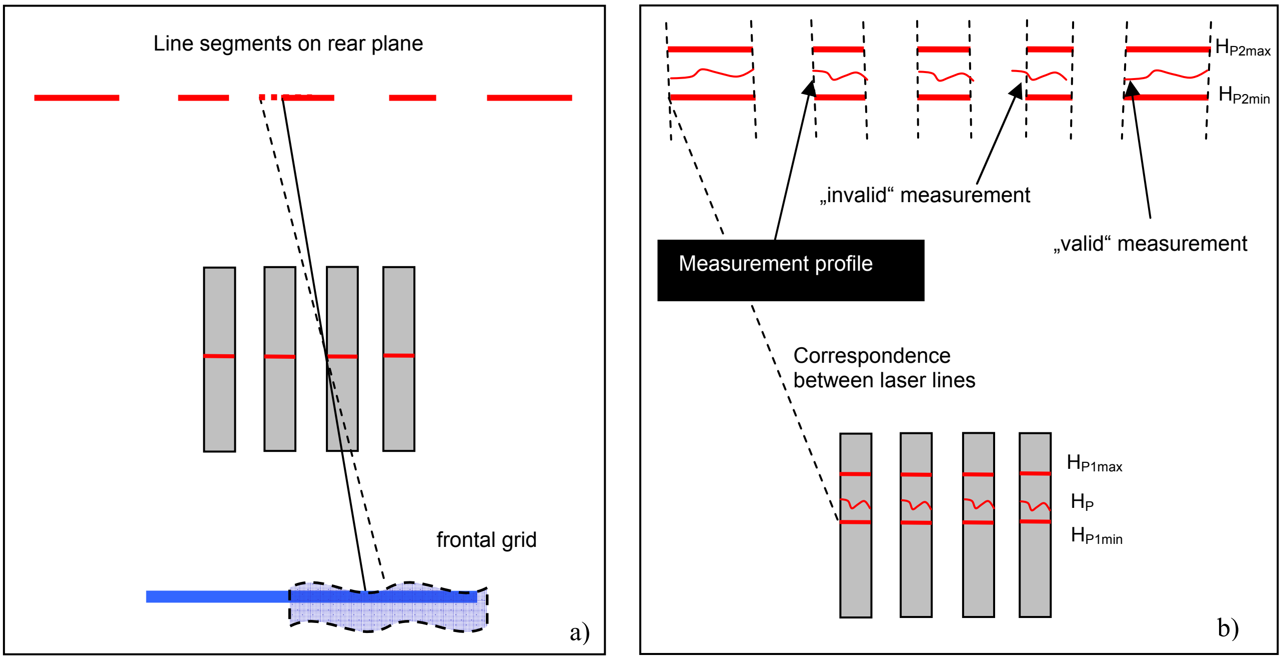


Figure 7: a) Effects caused by lateral waves viewed from front. The edge of the frontal grid element is hit by different elements of reflected laser light sheet when surface normal is strict or not vertical. This causes a lateral shift of the laser segment on the rear plane and thus can be detected as seen on b). Here are the laser line segments of the calibration images are superimposed. They are forming profile lines, where valid line measurements should be.

4.1 Calibration

The calibration is similar to the procedure of the single plane system (MAAS et al. 2003). Image sequences are acquired of two defined extreme water levels while water surface is quite. The defined level change can be realized by addition of a specified amount of water in a vessel, whose dimension is known with an adequate precision.

The image analysis comprises a processing of the image sequences to two single images, line detection and line measurement. To compensate the speckle of the laser and effects of small waves (actually a water surface is never absolutely quit) the image sequences of each level step are accumulated to a single image via maxstore-algorithm (see also (MAAS et al. 2003)). The usage of a band filter on the camera the images are quasi binary and the laser segments can be easily detected by scanning the image rows for peaks. Over a simple connectivity algorithm the lines can be segmented. The subpixel measurement of the laser line is performed by a centroid operator in lateral and by the moment-preservation algorithm in longitudinal direction with an accuracy of 0.1 - 0.2 pixel. In the following step the measured line-endpoints are corrected from distortion effects caused by camera and optics. Afterwards, the image coordinates are delivered to the calibration parameter calculation.

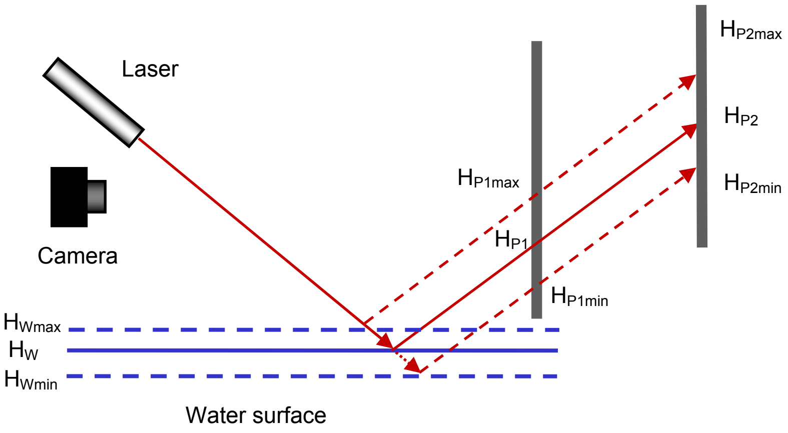


Figure 7: Calibration geometry and procedure

The linear interpolation function for the derivation of a certain water level from the image coordinate of a line end point can be defined by the following equation (MAAS et al.,2003):

$$H_W = H_{W\min} + (H_P - H_{P\min}) \cdot \frac{H_{W\max} - H_{W\min}}{H_{P\max} - H_{P\min}} \qquad \text{(eq. 1)}$$

To differ between “valid” and “invalid” measurements the proportion between the measured image-coordinates can be used. A “valid” measurement is existent if the following equation is fulfilled:

$$\frac{H_{P1\max} - H_{P1\min}}{H_{P2\max} - H_{P2\min}} = \frac{H_{P1} - H_{P1\min}}{H_{P2} - H_{P2\min}} \qquad \text{(eq. 2)}$$

4.2 Measurement

After the calculation of all necessary parameters the actual water profile measurement can be performed with the acquisition of images. In this stage of the system the calculation of the water level changes is post processed. An online processing software is planned but not yet implemented. Image processing is quit simple. Along the profile lines, which where defined in the calibration process, grey value peaks are detected and measured. The width of the search profile can be varied by several pixels and is depend of the image quality and the degree of waviness of water. The raw rectified image coordinates of laser line endpoints are analyzed by the formulas above (eq.1 and eq.2) and are transformed into water profile heights.

4.3 Theoretical Accuracy Analysis

The accuracy potential of this system configuration can be estimated from the geometric conditions in the system and should be equal to the single plane system. (MAAS et al., 2003) estimate a relative precision of 1:20,000 of the vertical filed of the camera, which corresponds to a standard deviation of 0.025 mm for an observed water level change at a 1.3 m wide profile (assuming a typical image measurement precision for line profiles of $^{1}/_{20}$ Pixel). This estimation is based on the measurement of a straight laser line in the images. But a straight line can only be observed when water is still and not during the actual measurement of a dynamic surface, where only the end point

of a laser segment can be used for the height calculation. Therefore a decrease of accuracy of a factor (at least) 10 is most presumable. An accuracy of 0.25 mm can be estimated.
Beside the accuracy, the performance of discrimination between measurements on strict horizontal water surface elements and not horizontal elements is crucial. The estimation of this parameter can be derived from Figure 8.

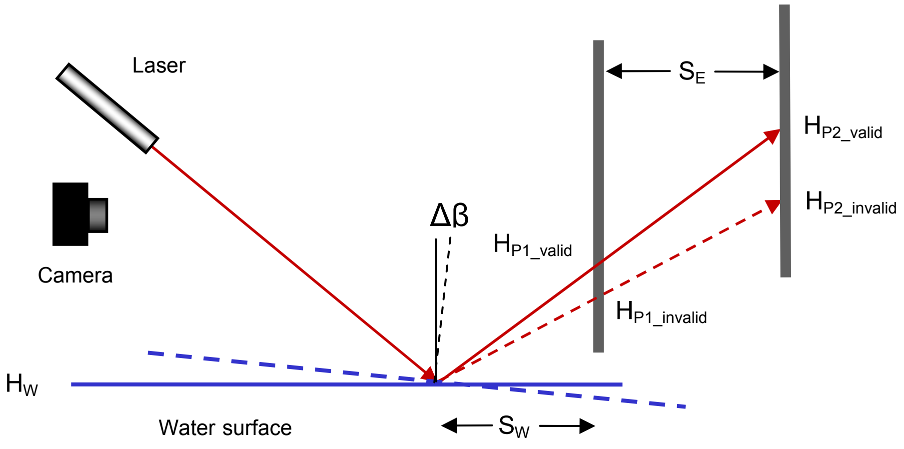


Figure 8: Geometric conditions in the system

The sensitivity of the system, which means the rate of laser line shift to a water level change, can be derived from Figure 2 [MAAS et al.,2003]:

$$\frac{\partial H_P}{\partial H_W} = 2 \qquad \text{(eq. 3)}$$

A tilt of the measured water element effects a specific laser line shift on the frontal grid and the rear plane. The magnitude of the line shift on the rear plane as the deciding parameter for the classification is depend on the distance of the rear plane to the intersection line of the laser and the water surface (S_W + S_E) and the tilt angle (Δβ). With an incidence angle of 45°, which is an optimum for the measurement, the vertical shift can be estimated with equation 4.

$$\Delta H_{P2} = \sqrt{2} \cdot \tan(2 \cdot \Delta\beta) \cdot (S_W + S_E) \qquad \text{(eq. 4)}$$

Assuming a distance (S_W + S_E) from 1 m and a Δβ of 0.1° a shift of 5 mm can be suspected. On the other hand, this vertical tilt effects a line shift on the frontal grid of 0.05 mm, when a distance S_W of 0.1 m was supposed. In this case the sensitivity of the classification is 100 times better than the height measurement itself, which speaks for the potential of the method.

5. RESULTS

Some tests where carried out to verify the accuracy and reliability of this approach. To verify the accuracy potential of the water level height measurement, the water level in a basin was raised in five defined steps. For each step, a measurement was carried out in the same manner like the calibration. The results where compared with the reference level changes. At still water, a standard deviation of $^1/_{18}$ Pixel in image space could be achieved, which means a standard deviation of 0.014 mm. In the experiment a water profile of 0.6 m was captured. The performance is comparable

to the results in (MAAS et al., 2003). The direct verification of the classification performance is not possible without a defined non planar mirroring surface. However, this system parameter can be estimated by analysing the accuracy of water level variation measurement on the rear plane, which is an indicator of the classification potential. In the same mentioned experiment a standard deviation of $^{1}/_{13}$ Pixel in the image space could be achieved, which means a standard deviation of 0.028 mm. With the help of equation 4, the sensitivity of this system layout can be estimated with 1 mgon for the tilt of water surface. The distance between the rear plane and the water profile was 0.6 m. When considering the estimated sensitivity, a tilt of 1 mgon would effect a vertical shift of 5 µm on the frontal grid ($S_W = 0.1$ m), which is far below the accuracy of height measurement.
Beside the maximum potential of this method, the accuracy of a measurement under application conditions (wavy water) is the most interesting parameter for a potential user. At this moment this can only be estimated from the standard deviation of a profile point measurement of a laser line. In an accumulated image of the calibration dataset the standard deviation of a profile point was 0.1 – 0.2 pixel on the frontal grid and the rear plane. When analyzing a single image, a standard deviation of 0.2 – 0.3 pixel could be achieved. Comparing these results with the calibration, a decrease of factor 5 can be determined. This fact can be transferred into a height measurement accuracy decline from 0.014 to 0.06 mm. The same shift can be applied to the classification performance.

6. CONCLUSION

The paper presents several layout possibilities of the adaptation of laser light triangulation methods for the determination of water level changes. A strict solution for the measurement task in respect of all possible influences by the water surface was shown. But this method requires a lot of hardware and a high amount of software implementation. For some tasks in experimental hydromechanics it is not necessary to capture the water level during each surface situation. When only measurements of temporally horizontal surface elements are needed, the system can be drastically simplified. This comprises the elimination of hardware components and the simplification of algorithms. The results show, that the accuracy is in the same range like the single-plane system and better than the original system. A true evaluation of performance of the classification of measurements is a task for the future. The presented simple measurement system can be easily implemented and a real time version should be ready soon. The temporal resolution is only limited by the frame rate of the camera due to the simple algorithms for image measurement, height calculation and classification.

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