An Optical Triangulation Method for Height Measurements on Instationary Water Surfaces

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Zusammenfassung: *Eine Methode zur optischen Triangulation für die Bestimmung von Oberflächenprofilen von Flüssigkeiten*. Die Bestimmung von Oberflächenprofilen von Flüssigkeiten ist eine Grundaufgabe in der experimentellen Hydromechanik. Die spiegelnden Eigenschaften von Flüssigkeitsoberflächen verhindern jedoch die Anwendung herkömmlicher Oberflächemessverfahren. In der Oberflächenmesstechnik weit verbreitet sind optische Triangulationsverfahren, welche auf der Projektion einer Laserlichtschicht auf ein Objekt und der Beobachtung der resultierenden Laserlinie basieren. Diese Systeme erlauben eine schnelle sowie genaue Erfassung von Oberflächengeometrien mit einem relativ geringen Hard- und Software-Aufwand.

Die Möglichkeit der Adaption des Grundprinzips innerhalb eines Messsystems für die Bestimmung von Wasseroberflächen sollten in einem Projekt am Institut für Photogrammetrie und Fernerkundung (IPF) der TU Dresden untersucht werden. Als Projektpartner fungierte die Bundesanstalt für Wasserbau (BAW), einem potentiellen Anwender derartiger Systeme. Als zusätzliche Anforderung wurde die Erfassung von dynamischen Veränderungen der Objektoberfläche benannt, da das zu entwickelnde System von der BAW zur Messung von bewegten Wasseroberflächen eingesetzt werden soll.

Als Messprinzip wurde eine Weiterentwicklung der optischen Triangulation unter Ausnutzung der Reflektionseigenschaften von Flüssigkeitsoberflächen angewandt. Dabei wird eine Laserlichtschicht auf eine Flüssigkeitsoberfläche gerichtet und nach der Reflektion an der Oberfläche auf zwei hinter einander angeordnete senkrechte Ebenen projiziert. Die projizierten Laserlinien werden durch eine Kamera beobachtet und anschließend detektiert. Die erkannten Linien können subpixelgenau in den Aufnahmen gemessen und die Werte dann durch ein am Institut entwi-

Summary: Optical triangulation methods based on a laser light sheet and digital camera are used as a surface measurement technique in a wide range of applications. They allow a fast and accurate determination of surface profiles, while consisting of relatively simple hardware and software configurations. The definition and analysis of surface profiles on reflective materials plays an important roll in experimental hydromechanics. The Institute of Photogrammetry and Remote Sensing (IPF) at Dresden University of Technology, in cooperation with the Federal Waterways Engineering and Research Institute (BAW), initialised a project to develop and implement a method to measure water-surface profiles based on laser light sheet projection. As the developed system will be installed and used in a laboratory to capture moving water surfaces, a registration and recording of dynamic phenomena is requested additionally.

The study presented in the paper describes a further development of the optical triangulation based on laser light by using reflection properties of mirror-like surfaces. For this task, a laser sheet is projected onto the water surface and reflected onto a set of two vertical planes, which are arranged parallel behind each other. The resulting laser lines are observed by a camera and measured by subpixel operators. Water surface level and gradient can be derived from these lines by using a mathematical model, which was developed at IPF. The integration of a step motor to vary the incidence angle of the laser plane allows on the one hand the efficient calibration of the whole system and on the other hand the sequential measurement of different surface profiles from one system position. In this configuration, the temporal dynamic of the surface variation is just limited by the frame rate.

The article presents the basic principle, potential and limitations of the method. Besides the

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ckeltes mathematisches Modell in Oberflächenhöhen und -neigungen überführt werden. Die Integration eines Schrittmotors zur variablen Einstellung der Laserebenenneigung ermöglicht zum einem die effiziente Kalibrierung des Gesamtsystems und zum anderen die sequentielle Messung von mehreren Profilen bei gleich bleibender Position des Messsystems. Die erfassbare zeitliche Dynamik der Oberflächenänderung ist dabei nur durch die Aufnahmerate der Kamera begrenzt.

Der Beitrag stellt das Grundprinzip der Messmethode, die geometrische Modellierung sowie einen darauf basierenden Ansatz zur strengen Kalibrierung des Systems vor.

geometrical and mathematical model, the procedure of a strict system calibration is outlined, and the results of a practical test are shown and discussed.

1 Introduction

The application of scaled physical models is an often used method to solve complex problems in connection with project planning in river engineering (ATV-DVWK 2003, Block 1936). Due to the improved computer technique, hydromechanics phenomena can be simulated and analysed theoretically in mathematical models nowadays. Beside these theoretical approaches, practical experiments on modelled systems like water channels (see Fig. 1) are still necessary (Godding et al. 2003). One of the most important measurand to define hydromechanics phenomena in a model is the vertical position of the water level. Its determination is usually done by punctual water gauge measurements. Different methods such as monitoring the vertical motion of a floater or ultrasonic height measurements in cylinders, which are connected with the channel bed via conduits, can be used.

These methods are limited concerning their temporal and spatial resolution and may affect the hydromechanic behaviour of the model (Mulsow et al. 2005). Because of the inadequacies of present methods a system is needed to measure water levels area-wide, contactless and with both high temporal and spatial resolution. A high degree of automation is a further requirement to such system. For this reason, photogrammetry, as a provider for non-contact measurement solutions, was chosen for this application. In cooperation between the Institute of Photogrammetry and Remote Sensing (IPF) Dresden and the Federal Waterways Engineering and Research Institute (BAW) a project was initialised to develop and build up a system which is capable to fulfil all aspects above.

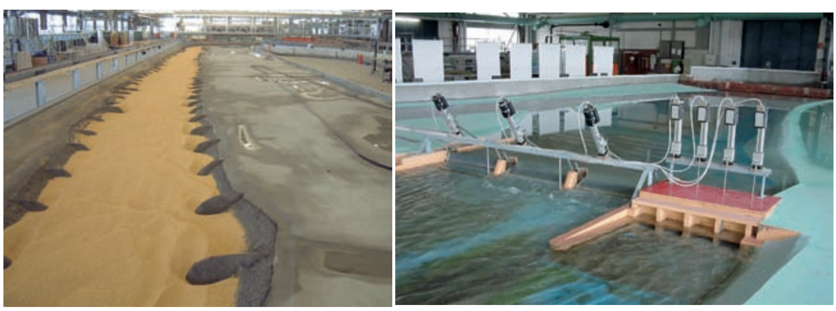

Fig. 1: Laboratory channels (Source BAW).

2 Measuring Principle

The estimation of water surfaces cannot be realized with traditional photogrammetric methods for surface measurement, because these methods assume diffuse-reflective textured surfaces. At first view, the mirroring properties of fluid surfaces are prejudicial to define direct its surface by optical triangulation based on laser light, but an adoption of this approach gives the solution for the discussed measurement task (MAAS et al. 2003).

According to the traditional acquisition of surfaces of objects via laser light sheet in combination with one or more cameras, the IPF developed a system which projects a laser light sheet onto the fluid surface. Because of the reflection and transmission properties of fluids, no analysable laser line can be observed on the surface. To visualise the intersection line on the object surface, the laser light sheet has to be reflected and projected in an indirect way onto a plane which is orientated vertically to the surface (see Fig. 2).

A camera can observe the resulting laser line. Therewith a measurement of the water level change is possible. (MAAS et al. 2003) confirmed the applicability of the basic principle and the high accuracy potential of the technique. For the determination of variances in water level by using a digital video camera with 1024 × 768 pixel sensor and a recorded 70 cm wide profile an accuracy of 0.03 mm was achieved (MAAS et al. 2003).

However, the technique requires a quiet water surface. If this is not taken into account, water-level induced effects cannot be separated from slope-induced effects (see Fig. 3). The abovementioned constraint is fulfilled only in a few cases in experimental researches.

Consequently, it is necessary to modify the basic configuration of the system. If the projected laser line will be observed in accumulated image sequences rather than in a single image, it is possible to compensate small and regular waves (MULSOW et al. 2005). Processing maxstore images obtained from short image sequences may reduce the errors resulting from water surface tilts in single images by a factor of six. Nevertheless, the precision of the water level measurement is still three times worse as compared to measurements 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

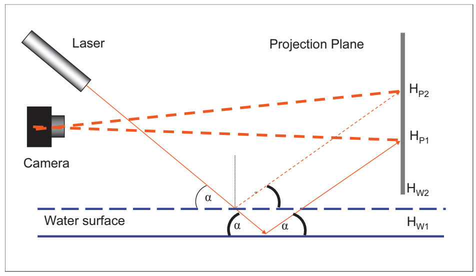

Fig. 2: Optical triangulation using a vertical projection plane.

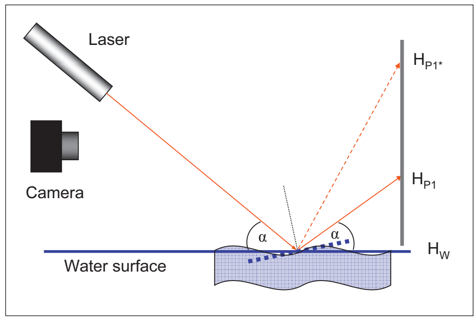

Fig. 3: Effect of water movement on height measurement.

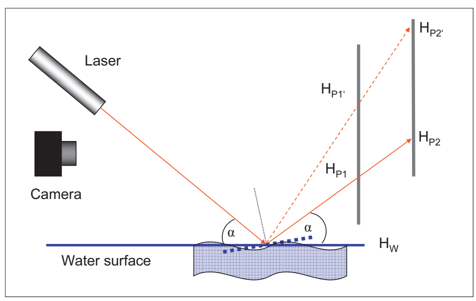

Fig. 4: System with two projection planes.

the surface determination (see Fig. 4). 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.

The basic requirements are the priori knowledge about the spatial relationships among the several system elements themselves (projection area and laser light layer) and the reference area (air-fluid level in initial position).

Fig. 5: Experimental system layout.

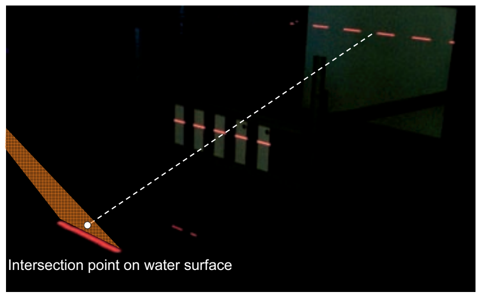

Fig. 6: Laser light sheet refracted to the channel bed ground (left) and reflected through the vertical grid (centre) onto the vertical projection plane (right).

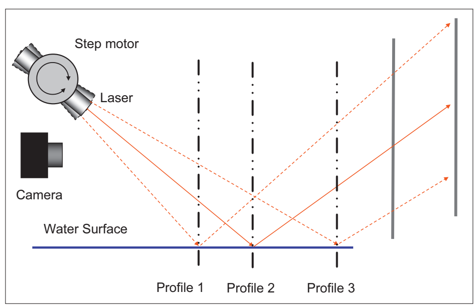

Fig. 7: System with step motor.

3 System Architecture

As shown in Fig. 5, the front projection plane is designed as a vertical grid. Some sections of the laser light sheet are caught by the grid parts, the remaining sections pass through the front plane in an unaffected manner and are mapped on the second plane behind. This system design turned out to be superior to using semi-transparent material for the first projection plane, as this would be accompanied by an undesired widening of the laser light sheet.

Thus, a complete projection of the laser light sheet onto both planes was abandoned, which means that a full reconstruction of the whole profile is not possible. Instead, the profile is represented by the intersection points of the joint vector between the corresponding end points of the respective laser light lines and the projected laser light sheet (see Fig. 6).

The number of profile points is two times the number of gaps in the front projection plane.

Furthermore, this discretisation facilitates the subsequent 3D reconstruction. In the case of the line-wise analysis, it would be necessary to intersect a deformed plane with the projected laser light plane, which would be a rather complex and singularity-prone procedure. Using the end points of line segments on both planes, the task is reduced to the intersection of a vector with the laser light sheet.

The point displacement of the discretisation of the fluid profiles depends on the width and distance of the front plane fields. These parameters should be chosen in a way that an overlay of projections on the rear projection plane as a consequence of lateral water level changes is impossible.

A Firewire camera Sony XC700 performs the image acquisition. A homogenous laser light sheet is generated by a 35 mW diode-laser with a Powell lens (dihedral angle of 45°).

To warrant a high rigidity of the system, the component mounting frame was designed in a robust manner. To focus attention on the stability of the projection planes as well as their relative arrangement, it became necessary to assume that the projection areas are planes in mathematical sense and the position and orientation are known. Firmly fixed circular targets with given coordinates allow the transmission of the line observations into the 3D space.

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 Fig. 7).

4 Modeling and Calibration

Unlike one-plane laser light sheet projection systems, the calibration of such a configuration is rather complex and requires additional parameters, as mentions above. This includes the determination of the true motor rotation axis, the orientation of the laser plane with respect to a certain incidence angle of the motor and the systems reference to a still water surface. The mathematical model is not based on a set of observed equations rather on a system of constraint equations. The model describes the variable projection of the laser light sheet on to the planes with a set of 14 parameters (see Tab. 1):

Input values are the 3D coordinates of the end points of the laser light lines. These are calculated from their image coordinates, the 3D coordinates in the frame system as well as the image coordinates of the circular targets via perspective transformation.

Tab. 1: Parameters.

Parameter	Description
A_i, B_i, C_i, D_i	parameters of plane i (i = 1 ... n)
φ_i	rotation angle of the motor
V_X, V_Y, V_Z	Direction of the motor rotating axis
R_X, R_Y, R_Z	Origin of the motor rotating axis
N_X, N_Y, N_Z	Normal direction of the reference plane for the rotation angle ($\varphi = 0$)
A_W, B_W, C_W, D_W	Parameters of quiet water surface

This approach breaks down the main problem into single aspects. All end points, which result from the projection of the light sheet in one stepper motor position, represent a plane *i*:

$$0 = A_i \cdot x + B_i \cdot y + C_i \cdot z - D \quad (1)$$

With the following formula

$$0 = A_i^2 + B_i^2 + C_i^2 - 1 \quad (2)$$

as a constraint to prevent over-parameterisation.

All planes are rotated around the step motor axis by a rotation angle φ_i. At first the change of the normal vector of the plane is modelled as a function of the motor axis orientation (V_X, V_Y, V_Z), the reference normal vector (N_X, N_Y, N_Z) and φ_i:

$$A_i = V_X \cdot (1 - \cos\varphi_i) \cdot K + N_X \cdot \cos\varphi_i + (V_Y \cdot N_Z - V_Z \cdot N_Y) \cdot \sin\varphi_i$$

$$B_i = V_Y \cdot (1 - \cos\varphi_i) \cdot K + N_Y \cdot \cos\varphi_i + (V_Z \cdot N_X - V_X \cdot N_Z) \cdot \sin\varphi_i$$

$$C_i = V_Z \cdot (1 - \cos\varphi_i) \cdot K + N_Z \cdot \cos\varphi_i + (V_X \cdot N_Y - V_Y \cdot N_X) \cdot \sin\varphi_i$$

$$\text{with} \quad K = N_X \cdot V_X + N_Y \cdot V_Y + N_Z \cdot V_Z \quad (3)$$

To prevent over-parameterisation the following constraints have been included:

$$1 = N_X^2 + N_Y^2 + N_Z^2 \quad \text{and}$$
$$1 = V_X^2 + V_Y^2 + V_Z^2 \quad (4)$$

The origin of the motor rotation axis is mathematical described by the expression:

$$0 = B_i \cdot R_Y + C_i \cdot R_Z - D_i \quad \text{with} \quad R_X = 0 \qquad (5)$$

The eccentricity of the laser light sheet with respect to the motor rotation axis can be neglected, as the eccentricity of the actual setup is much lower than the expected accuracy of the whole system.

The parameters of the quiet water surface are not included in the model, because the geometrical system layout does not allow the proper estimation of their parameter values. The parameters are calculated separately in a post process. The estimation is based on measurements on quiet water on a certain height, which is used as the reference level.

The implemented approach lacks a separate handling of each observation. Instead, groups of observations within each constraint equation are used as input data set. Consequently, loading and testing for single observation is difficult.

Based on this model a calibration procedure was implemented. Image sequences of different incidence angles of the laser sheet on the projection planes are taken as basis for the calibration. The resulting line segments on the vertical grid and the rear plane as being projected directly, thus without reflection from the waters surface can be analysed automatically from these images. An angular rotation sensor can determine the motor position at a precision of 0.001°. The reference between the image and the incidence angle is realised by numbering the images. The detected laser line end points can be transformed into the 3D frame system with a precision of 0.2 mm on the vertical grid and 0.3 mm on the rear plane.

The mathematical estimation of the calibration parameters is implemented as least-squares adjustment in the Gauss-Markov-model.

5 Measurement

The complete analysis procedure takes place in a fully automatic way in an integrated software package. The system calibration starts with the detection and subpixel measurement of the frame targets. Afterwards the whole measurement range is scanned sequentially. This means that both direct as well as indirect projections will be captured. Determining the maxstore (storage of the maximum gray value of an image assembly) for every image speckle effects of the laser can be reduced. In the images, the laser lines can be detected via a modified Hough-Transformation. Subsequently, the appropriate laser ends are determined with subpixel accuracy and corresponding laser ends of the front and the rear plane are connected for every image. After this, the calibration parameters can be calculated with the help of the approach as described in chapter 4. The total time for the calibration process, including stepper motor motion, is about one minute.

The actual water surface height profile measurement can be started after the calibration of the system. The procedure follows similar principles as the calibration (see Fig. 8).

The measurement range covered during the calibration is taken as a basis for the actual realtime surface measurement. Thus, the image analysis task can be reduced to the detection, measurement and tracking of the laser line end points with subpixel accuracy operators. Subsequently, the 3D coordinates of the according water surface profile points can be calculated by spatial intersection of the vector between the corresponding laser ends on the two planes with the laser light sheet. Fig. 9 shows two examples.

6 Theoretical Accuracy Analysis

The accuracy of a determined 3D point coordinate on the water surface is affected by many factors. An estimation for the accuracy can be calculated from the system parameters and the input quantities:

- Accuracy of image space measurements: < 0.2 pixels;
- Accuracy translated in to the object space, depending on the resolution of the camera

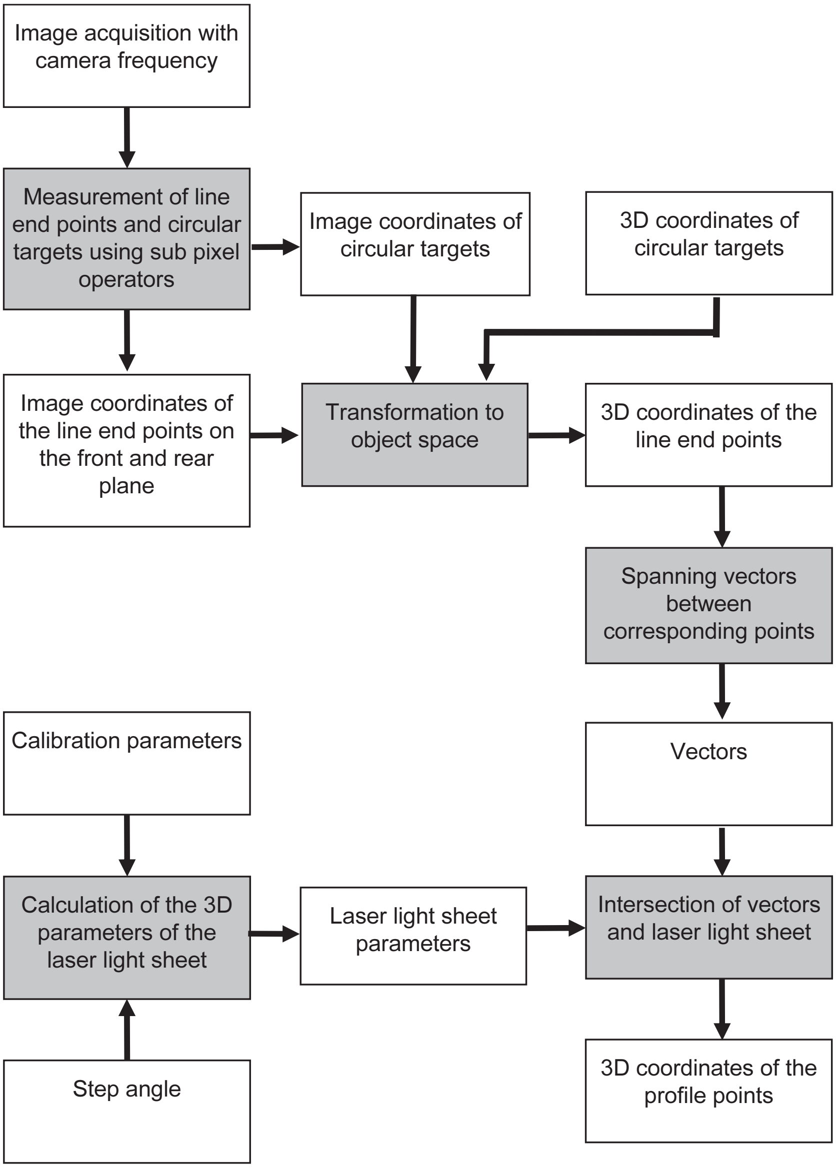

Fig. 8: Measurement workflow.

and the mapped area: < 0.2 mm in on the vertical front grid (X- and Z Direction) and < 0.3 mm on the rear plane.

- Accuracy of the circular target positions representing the projection plane geometry (3D): 0.05 mm (negligible).
- 3D accuracy of the line end points after transformation (see also chapter 4 and 5): 0.3 mm (vertical front grid) to 0.5 mm (rear plane).
- Accuracy of the laser light sheet parameters (calculated from the calibration parameters and the incidence angle): 0.1 % resulting in a false estimated laser projection line on the planes of 0.5 mm.

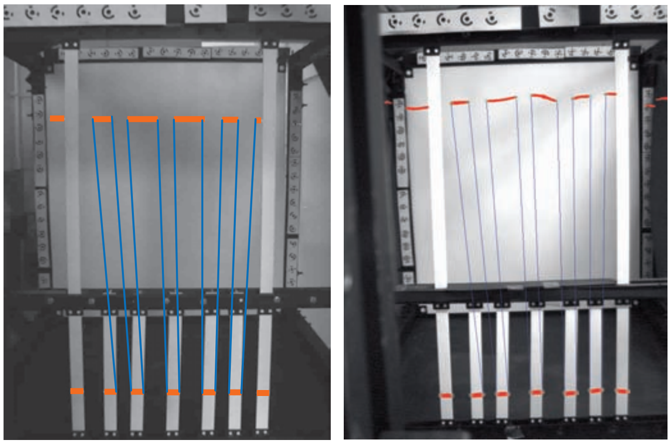

Fig. 9: Corresponding laser ends (left: quiet surface; right: dynamic surface).

- Accuracy of a vector (between corresponding line end points), calculated from a constant term and a linear factor (see also Fig. 10):

$$\sigma_V = \sigma_R \cdot s_2 + \sigma_{LP} \qquad (6)$$

σ_R ... accuracy of direction
σ_{LP} ... accuracy of line end point (3D)
s_2 ... distance between a point on water and vertical grid.

- Estimated accuracy of a direction between the front grid and the rear plane:

$$\sigma_R = \frac{\sigma_{LP\_front} + \sigma_{LP\_rear}}{s} \qquad (7)$$

The accuracy of a water surface profile point obtained as intersection point between a vector and the laser light sheet can now be estimated:

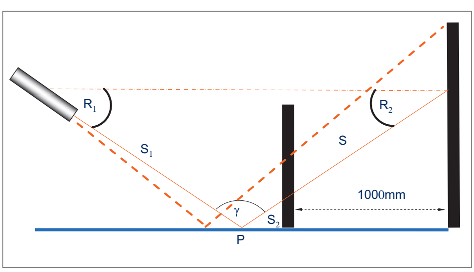

Fig. 10: Geometrical conditions in the system.

$$\sigma_P = \frac{1}{\sin\gamma} \cdot \sqrt{s_1^2 + s_2^2} \cdot \frac{\sigma_{LP\_front} + \sigma_{LP\_rear}}{s} + \sigma_{LP\_front} \qquad (8)$$

When inserting the parameters of the actual system with

γ ... $90 - 120°$
s_1 ... 300–250 mm
s_2 ... 100–150 mm
s ... 1200 mm
σ_{LP_front} ... 0.3 mm
σ_{LP_rear} ... 0.5 mm

an absolute precision of 0.5–0.6 mm for a point on the water surface can be estimated. The relative precision (precision of a measured level change) is much better, because the last term of (8) can be omitted and several system parameters are correlated. Therefore, a measurement accuracy of 0.3 mm can be estimated. It must be pointed out, that the accuracy is not constant over the whole measuring range. Formula (8) shows that the distance between the intersection line on the water and the vertical grid is a deciding parameter for the measurement accuracy. This parameter value changes with to the incidence angle of the laser light sheet and with water level height. The parameter s_2 has to be as small as possible as well as the parameter s_1. The distance between the laser and the water surface is defined from the beam width of the laser lens and the aimed measuring width.

Another important aspect is the distance between the vertical grid and the rear plane. This parameter should be as wide as possible, because of lever arm effect on the spanned vector. This claim is limited by the system requirement of a most possible size.

7 Results

To determine the practical accuracy of the system the water level in a test basin was sequentially risen by adding exactly 100 ml per step resulting in a level change of 3.20 mm. The measurement was carried out on quiet water level. Tab. 2 shows the results of one experiment.

A relative accuracy of water level difference was achieved by about 0.20 mm in all steps and is thus below the results of the one plane system (0.1–0.2 mm) shown in (MAAS et al. 2003). The strict solution of the surface problem goes along with loss of accuracy. Further experiments are planed and will be carried out to analyse and describe the effect of moving water surface on accuracy and potential of this method.

Tab. 2: Test results (example).

Angle [°]	Point 1 [mm]	Point 2 [mm]	Point 3 [mm]	Point 4 [mm]
71,96	3,18	3,15	3,15	3,48
72,42	3,30	3,05	3,24	3,15
73,03	3,35	2,89	3,11	3,30
73,56	3,34	2,92	3,20	3,24
73,98	3,24	2,95	3,17	3,06
74,44	3,07	3,30	3,09	3,10
Mean	3,25	3,04	3,16	3,22

In this experiment the water surface was scanned in two different levels which are presented by six profiles. Each angle value stands for a certain profile. The height differences in each profile point are listed in the table above. When comparing the results with the reference value of 3.20 mm, a mean deviation of 0.12 mm can be calculated.

8 Conclusion

The presented system shows an adaptation to the general principal of the optical triangulation on mirroring surfaces. A modification in system set-up and analysis was necessary. First results proved the principal capability of this approach to measure air-liquid surfaces. But limitations of this solution were obviously and will require further improvement of the analysing strategy and the system's setup. The strict solution to define moving water surfaces is realised and verified in one system.

As this approach is strictly depending on surface reflection, any disturbance on the water like swimming materials or water turbulences will cause measurement errors.

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