Back Projection Algorithm for Line Structured Light Extraction

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***Abstract*—Structure from motion and structure from light are usually regarded separately. To combine both methods, using the same images to retrieve three dimensional information about the environment, both methods must work side by side without interfering each other. This research work describes how laser line patterns can be extracted from images while being robust to scattering media and ambient light.**

I. Introduction

Underwater structures like oil and gas production systems or the foundation of buildings, piers and off-shore wind facilities, have to be regularly inspected to evaluate the state of the structure and to plan future interventions for repair and maintenance. These inspections are currently carried out by remotely operated vehicles (ROVs) or by divers. Inspections of this kind are time-consuming and expensive. On the other hand autonomous underwater vehicles (AUVs) are a growing factor in offshore industry and maritime research. The mission profiles of AUVs are slowly changing from pure bathymetry tasks to inspection tasks. The primary goal here is to reduce the costs of inspection and to inspect underwater structures more often. This poses new challenges, since inspection tasks require a much higher sensor resolution and different modalities than the classical sonar based methods used in bathymetry. Extensive research efforts have been put into the different approaches to utilise high-resolution sensors and mission adaption to sensors on AUVs (e.g. [1], [2], [3], [4], [5]). Within this paper we describe work on a structured light system which aims at giving a high resolution model of the scene while sharing the camera with other applications.

Vision is a sensor modality with a very high spatial resolution for close range underwater inspection but suffers in turbid water conditions. A lot of research was dedicated the last decades with the aim to increase the range and robustness of vision systems in areas with difficult environment conditions [6]. It was found that line structured light systems have very beneficial properties to penetrate water with moderate turbidity and are increasing the maximal working range about three times compared to conventional vision systems [7]. Because of this and its low hardware requirements line structured light systems are often used for underwater 3D reconstruction.

One of the challenges of structured light systems remains the separation of the light pattern from its background in media with high noise level like turbid water [8]. The common solutions for this are the use of optical bandpass filters adjusted to the wave length of the light pattern [9], static background subtraction [9], template matching [10] or maximum value approaches [11]. In contrast to that, this research work is considering the background as additional source of information and uses back projection techniques known from structure from motion [12] to distinguish between the active light pattern and background features. The advantage of this approach is that the camera system can simultaneously be used by the operator, the structured light system and also for estimating the sensor movements without being prone to false positives due to lighting conditions. To the authors knowledge this is the first work using back projection techniques to identify active light pattern in underwater camera images subject to high noise.

The paper is organized as follows: Section II gives a short description of the issues needed to be addressed. Section III illustrates how a laser line pattern detection can be performed in environments with high lightning conditions. Section IV addresses the validation of the detected laser line segments. Section V compares the performance between different laser line peak detection algorithm and shows the result of a sea trial.

II. Problem Statement

Detecting laser line patterns in images can be understood in general as matching known laser line features with image features along epipolar lines described by the fundamental matrix of the line structure light system (projective camera + inverse line camera). Thereby a laser line feature has a very weak descriptor and is only defined by the width of the laser line and its wave length (colour). Furthermore, as long as there cannot be made any assumption on the environment it is not possible to define additional constraints between matches belonging to different epipolar lines nor can be assumed that the laser line features have always the highest pixel value along their epipolar lines (maximum value assumption). Therefore, depending on the environment, there will be most likely multiple matches along each epipolar line. To find the only true match per epipolar line the matches have to be validated with some additional information.

III. Laser Line Extraction

In general the extraction of a laser line projected onto an image plane is straight forward and excellent results can be achieved if the maximum value assumption holds. To support this assumption usually optical bandpass filter are used to suppress environment lighting which fails if the laser sheet

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is penetrating a scattering medium. This can be overcome by the use of template matching approaches like it was shown in [10] or FIR filters proposed in [13]. However if the camera system is shared by several applications and the maximum value assumption no longer holds due to ambient light, the laser line detection gets more complex.

The following section describes the different steps to detect possible laser line features in images even under strong ambient light by using information about the laser line width and system movements. It is assumed that the structured light system is calibrated in such a way that the epipolar lines are identical to image columns. For the calibration process itself the reader is referred to [14].

A. Background Subtraction

Most of the false positives along an epipolar line are because of scene texture illuminated by some unknown external light source. To suppress these (background) signals the ideal case would be to record the scene twice from the same position and at the same time. Thereby one image is taken with laser line projector turned on and the other one with the projector turned off. Obviously, this is not possible and either the time or the position has to be varied. In [9] it is assumed that the scene is static and the structured light system is not moving between two consecutive images. By simply subtracting both images from each other it was shown that the background can successfully be removed.

Unfortunately, this assumptions does not hold if the system is mounted on a free floating vehicle. A slight different in its pose will produce artefacts similar to a laser line after subtraction making the whole detection even more error prone. Furthermore, since 50 percent of the images are taken while the laser line projector is turned off, the resolution of the hole scan also drops by 50 percent in scan direction. To overcome this the following method is proposed.

It is assumed that two consecutive images i_n and i_{n+1} taken at time t_n and t_{n+1} are related by a planar projective transformation. This assumption only holds if all imaged scene points are lying in an arbitrary plane which is usually not the case. Nevertheless, this is a good approximation to transform image i_n into image i_{n+1} while the scene structure is unknown. To remove the background the transformed image $i_{n,t}$ is subtracted from image i_{n+1}. Thereby the laser line is nearly unaltered if the camera movement between both images orthogonal to the laser line was large enough with the result that the laser line is projected onto a slightly different scene location. Because a planar projective transformation is assumed all regions of the image belonging to scene points not following the assumption will produce artefacts which have to be filtered out by the subsequent validation step. Examples for the background removal can be seen in Figure 1.

B. Laser Width Normalization

In the case of no media scattering, Lambertian reflection and a pinhole camera model the width l_p of the projected laser line, intersecting an object at the position x, y, z, can be approximated by a function of the structured light parameters (f = focal length, β = angle between image and laser plane, l_w = physical laser width, d = camera-projector separation) and its position in the image plane y_c.

$$y(z) = d - \tan(90 - \beta)z \tag{1}$$

$$y_c(z) = \frac{yf}{z} = \frac{df}{z} - f\tan(90 - \beta) \tag{2}$$

$$l_p(y_c) = \frac{l_w f}{z} = \frac{f l_w \tan(90 - \beta)}{d} + \frac{l_w y_c}{d} \tag{3}$$

If it can be assumed that the structured light parameters are constant, according to equation 3 the laser line width is changing linearly with its location across the image. Therefore an image of height h can be scaled logarithmically to h_s by equation 5 to normalize the projected laser line width assuming the laser projector is only rotated by the angle β against the image plane and located above the camera. Thereby the logarithm is the result of the integral of equation 5.

$$s(y_c) = \frac{1}{l_p} = \frac{d}{l_w y_c + f l_w \tan(90 - \beta)} \tag{4}$$

$$h_s = \int_{\frac{-h}{2}}^{\frac{h}{2}} s(y_c) dy_c \tag{5}$$

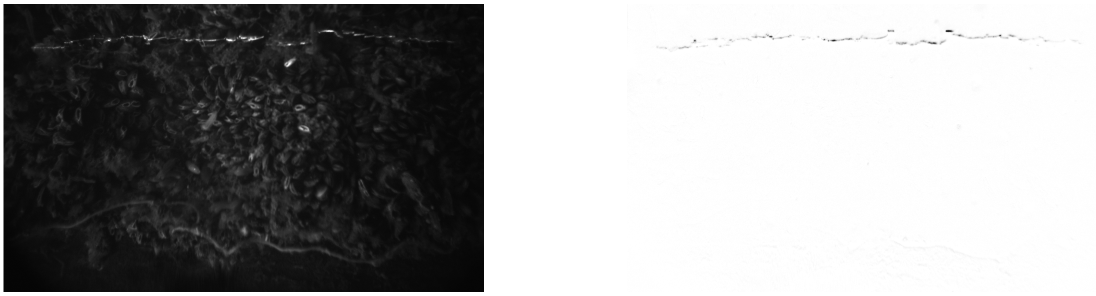
Possible noise like backscattering from the media or non-Lambertian surface are dynamically altering the laser line [13] and have to be taken into account by subsequent steps.

C. Spatial Bandpass Filter

In [10] it was shown that the brightness profile of the backscattered laser sheet can be used as template until a brightness discontinuity is reached to detect the laser line intersection with the scene objects in medias with high turbidity. Thereby the brightness profile can also be interpreted as low frequency and the discontinuity as high frequency signal. Therefore, this method can safely be substituted by a band pass filter with subsequent thresholding. If the bandpass filter is implemented as two moving average filters, this has the benefit of being optimal in reducing random white noise while keeping the sharpest step response which is vital for extracting the exact location of the intersection. Using a FIR filter for laser line peak detection is also suggested in [13]. Here a FIR derivative filter is used whereby its coefficients and order are selected according to the surface optical properties and a previous frequency analysis.

To improve the robustness of the detection the laser line width should be normalized across the image and be used as the center frequency of the passband. This kind of filter is also known as Difference of Gaussian whereby here, the filter kernel is approximated by a box kernel. If the laser line width cannot be normalized integral images can be used to speed up the filtering for different center frequency which is for example also used by the SURF feature descriptor [15].

Possible backscattering from the media and non-Lambertian surface is taken into account by choosing a wider



(a) Original Image

(b) Background Removed (inverted)

Fig. 1. Original image of a heavily overgrown harbour pier with projected laser line and its corresponding image where the background was removed.

passband resulting in a decrease of the signal-to-noise ratio (see figure 7).

Examples for the laser filtering and laser line normalization can be seen in Figure 2.

D. Signal-To-Noise Ratio

The bandpass filter does not completely damp spatial frequencies which are part of its stopband to zero. Therefore, depending on the scene the laser line signal, being the desired signal, is disturbed by some noise. To get a criterion for the quality of the desired signal, we define the noise as the average pixel value in a certain neighbouring area around the currently regarded pixel. The calculation of the signal-to-noise ratio can then be implemented as the division of the filtered image by its averaged (blurred) version. In order to prevent division by zero the minimal noise level is defined as 1. The reason for this definition is that the real nature of noise was not studied and depends on the unknown scene texture. Therefore, a noise estimator was chosen which usually overestimates the true noise.

E. Thresholding

For each pixel, the preprocessed image holds now the ratio between a possible laser line signal and its noise. To finally detect the laser line the image is thresholded at a given signal to noise ratio value. For example for our experiments a value of 3-6dB gave good results. Now, all pixels having a maximum value in a certain environment along their corresponding epipolar line are regarded as laser line candidates. Their subpixel position is then obtained by a Gaussian approximation assuming the laser line profile fits a Gaussian profile [16].

Examples for the detection of laser line candidate can be seen in Figure 3.

IV. Laser Line Candidate Validation

The laser line candidates found by the procedure described in the previous section are possible locations for the real laser line in the image. To validate these candidates a sequence of three consecutive images are used to estimate the movement of the camera and to determine if the candidates either belong to the background or to the projected laser line.

A. Movement Estimation

To estimate the movement of the camera between different views the image content itself can be used which was already shown in [17] and will not be discussed in this work. An open area of research is how feature detectors and descriptors are affected by active light pattern projected onto the scene. In [11] it is proposed to first detect the active light pattern in the image to mask it before the feature detector is applied. However, in our case this is not possible, because in order to apply the background subtraction the feature detection must run first. However, the feature descriptors are encoding the spatial distribution of pixel values around a certain location. Therefore, features can be filtered out which might belong to the laser line light pattern by looking at their descriptors like it is done in the following fur the SURF descriptor.

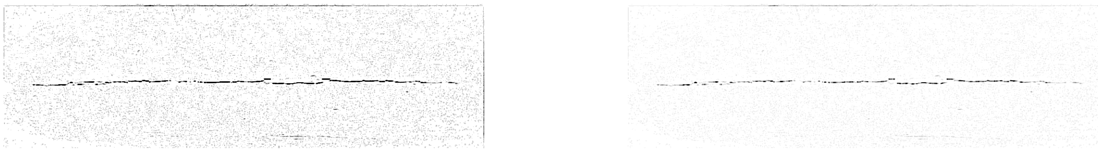
In the case of the SURF feature the spatial distribution is stored as a vector of 64 values. Thereby 4 values each belong to one of 16 regions. For each region the Haar wavelet response in x and y direction and their absolute values are computed [15]. Therefore if the spatial frequency and orientation of the laser line is known, SURF features can directly be filtered out considering those descriptors indicating a strong Haar wavelet response orthogonal to the laser line (see figure 4). This approach assumes that the laser line consists of at least small segments rather than single points.

After SURF features are filtered out which might belong to the laser line pattern the approach suggested in [17] is used to calculate the rotation matrix and translation vector between consecutive views.

B. Laser Line Segmentation and Description

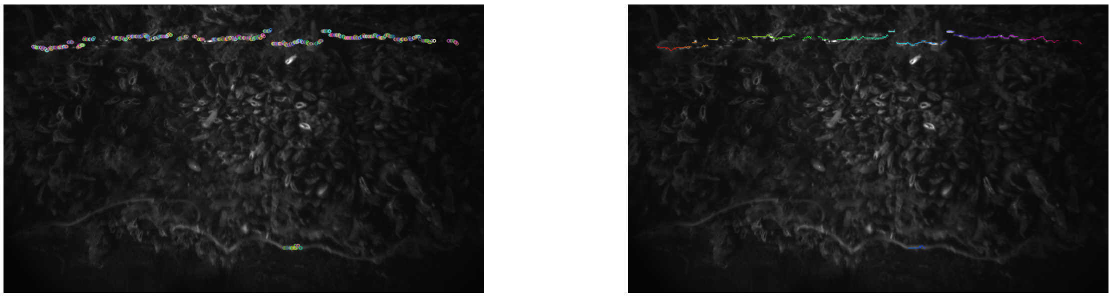
The movement of true laser line candidates is unpredictable unless the scene structure is known. However, the movement of laser line candidates can be estimated if their corresponding image feature belong to the background rather than the laser line pattern.

In order to describe laser line candidates for a subsequent matching the laser line candidates are segmented based on a maximal allowed pixel distance to neighboring laser line candidates. To filter out noise the assumption is made that the scene is smooth enough that segments with less than a certain length are impossible. In our experiments a length of five candidates was used with a maximal allowed pixel distance of five pixels between successive candidates. To describe the



(a) Filtered and Scaled Image (inverted) (b) SNR Image (inverted)

Fig. 2. Bandpass filtered image after the background was removed (figure 1b) and its corresponding signal to noise ratio.



(a) Laser Line Candidates (b) Laser Line Segments

Fig. 3. Detected laser line candidates based on the SNR image 2b and their corresponding laser line segments.

(a) Found key points (b) Key points filtered out.

Fig. 4. Found key points of an image and corresponding key points which are filtered out due to their descriptors.

laser line segment a simple chain code is used. This descriptor is only invariant to translation parallel to the background plane and will result in a poor matching performance if the camera movement violates this constraint. A descriptor which is invariant to rotation, scale and translation is for example described in [18] but comes with the expense of additional computational complexity.

C. Laser Segment Matching

In order to match laser line segments between two consecutive images their descriptors are cross-correlated if the bounding box of the segments are closer than a given maximally allowed distance. The point where the cross correlation has its maximum yields the internal offset between the descriptors. The value itself indicates how good the two segments match.

D. Laser Segment Triangulation and Back-Projection

All image points of laser line segments which are successfully tracked across three images are used pairwise to triangulate the 3D position of the features and are back projected into to the third image. If the back-projected image points do not correspond to the corresponding tracked segment the laser line segment is regarded as valid laser line. Otherwise the segment is rejected as being part of the background.

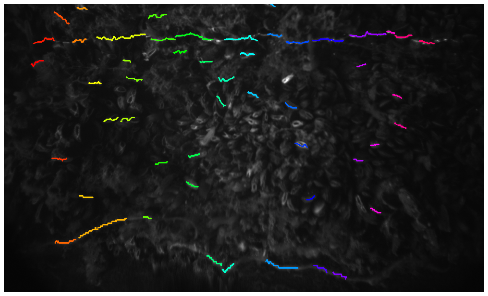
It must be said that this approach puts some constrains onto the environment. If the depth profile of the object relative to the structured light system is changing according to the three projective camera matrices the laser line will wrongly be classified as background.

V. Experiments and Sea Trials

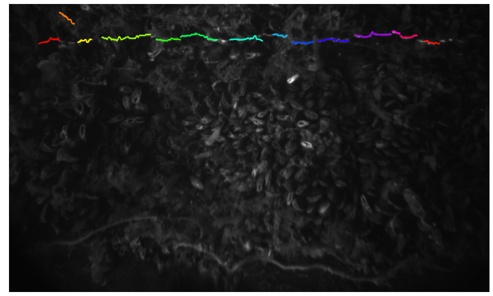
The described method for a detection of the laser line pattern in images subject to high noise was tested in several experiments and used for a sea trial to autonomously inspect a harbour pier in Olpenitz closed to Kiel, Germany.

A. System Description

For the sea trials next to Olpenitz an autonomous underwater vehicle was used, developed in the joint research project CView. The goal of the CView project was to develop an autonomous vehicle able to inspect the aforementioned structures in a cost-efficient manner, by using an autonomous underwater vehicle with a highly integrated inspection unit. The AUV itself is called SeaCat and has been developed by the project partner ATLAS ELEKTRONIK. The inspection unit shown in figure 6a was developed by DFKI in the subproject CSurvey. It is configured as a pan-tilt unit (PTU) and mounted to the nose of the cylindrical SeaCat.

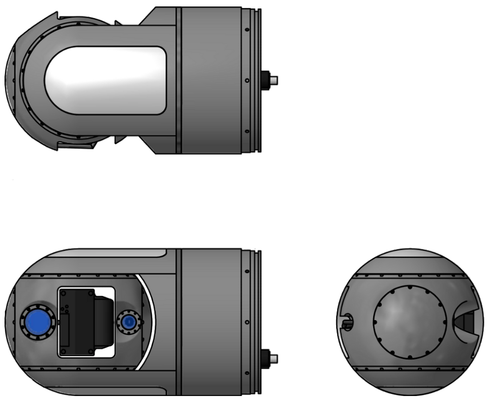


(a) Valid segments after segmentation

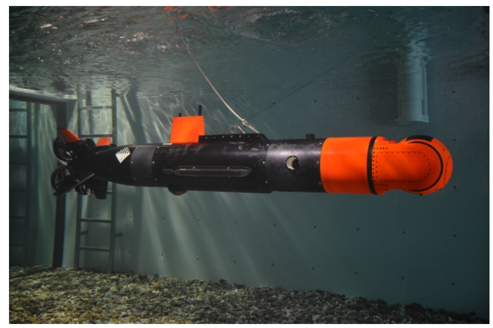


(b) Valid segments after back projection

Fig. 5. Valid laser line segments before and after back projection for images where the background was not removed.



(a) PTU



(b) PTU mounted on SeaCat

Fig. 6. The SeaCat AUV from ATLAS ELEKTRONIK with the CSurvey PTU attached during integration tests inside a test-tank of the DFKI RIC. The pitch axis of the PTU is facing down in this picture.

The primary sensor of the PTU is an optical system using a high-end camera and an one-line structured light projector (535nm, 150mW). The distance and angle of the laser sheet with respect to the camera plane was chosen to ensure a working area of 0.5 - 2.5 meter for the structured light system.

B. Influence of Turbidity

The main sensor of the PTU is an optical sensor and therefore highly affected by water turbidity. To measure the influence of the turbidity on the laser detection algorithm the PTU was mounted on a gantry crane located above a water basin in such a way that it was fully submerged and the structured light system had a distance of 1.4 meter to the next wall used as target.

The turbidity was changed stepwise from 0.2 FTU to 7 FTU by adding clay powder to the water. For each step the signal-to-noise ratio of the detected laser line was measured for different settings of the FIR filter. The results are plotted in figure 7. For a turbidity higher than 7 FTU the signal to noise ratio dropped below 3 dB and a clear laser line detection was no longer possible at the selected distance of 1.4 meters.

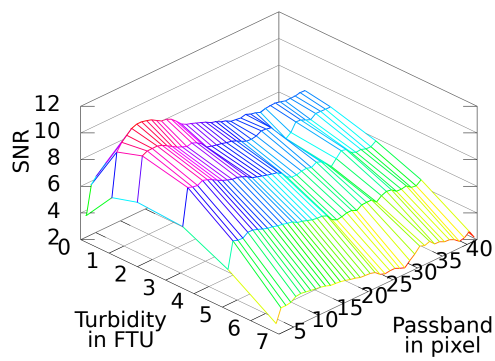
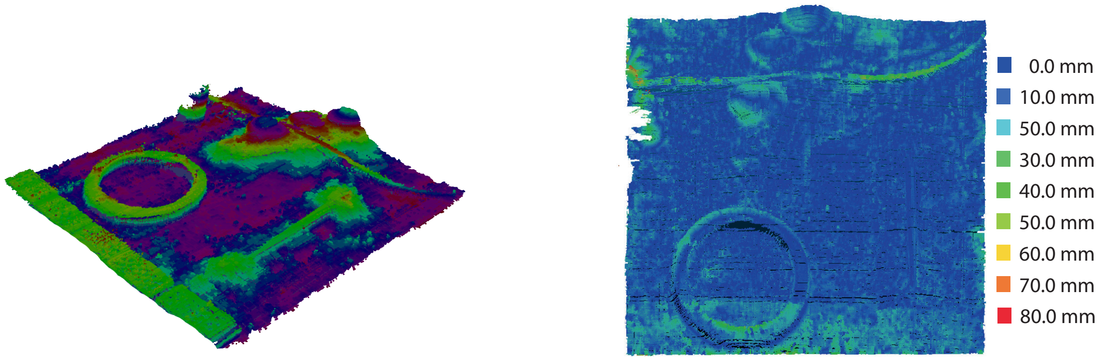


Fig. 7. Signal-to-noise ratio in relation to turbidity and FIR passband frequency.

C. Scan Resolution

In order to measure the accuracy of of the structured light system the PTU was mounted again on a gantry crane in such a way that it was fully submerged and had a distance of two meters to the basin floor. The floor was prepared with gravel and some additional objects. As reference system a Leica 3D laser scanner was used to scan the floor while the basin was not filled with water.

The basin floor was scanned by the structured light system, using the position data of the gantry crane for determining the poses of the single scan lines (see figure 8). Afterwards the fused scan lines were compared with the point cloud measured by the Leica 3D laser scanner whose accuracy is stated with 6 mm for a single measurement. The deviation between both scans is plotted in figure 8b.



(a) 3D Scan (b) Deviation

Fig. 8. Underwater structured light scan and its deviation to a scan taken with a Leica 3D laser scanner.

D. Outdoor experiments

In a harbour next to Olpenitz several tests were conducted with the system described in section V-A. In order, to test the inspection unit the autonomous underwater vehicle was steered along a harbour pier while the PTU was turned sideways and facing the pier. The distance between the pier and the system was kept between one and two meters during all scans.

1) Comparison of laser line detectors: In order to validate the described method for the detection of the laser line in images with high ambient light four different detector methods were tested on a image sequence of the harbour pier. The results are plotted in figure 9. The background subtraction step is considerably improving the detection of the laser line in image sequences with strong ambient light. The validation step via back-projection additionally removes nearly 50 percent of the false positives originating from scene structure violating the plane assumption made during the background subtraction step. Nevertheless, more experiments have to be conducted where the scene structure leads to a sharper distinction between laser line detection with and without back-projection validation step.

Furthermore, the proposed validation via back-projection cannot be regarded as optimal. The reason for this is that the shapes of laser line segments, belonging to background features, are heavily changing across the image due to the laser line width normalization and background removal. This results in wrong point associations between the laser line segments and thereby wrong back projection locations.

2) SURF Features: Projection of a laser light pattern onto scene is changing the image and thereby affecting the detection and matching of image features across image sequences. Therefore, to test the influence of the laser line light pattern on SURF feature detection an image sequence of the harbour pier was analysed regarding the number of features that are affected by the laser line. Thereby, all features whose descriptor area overlaps with the laser line later detected are regarded as affected.

Figure 10 shows the percentage of affected U-SURF features before and after filtering according to section IV-A. In general RANSAC should cope with these kinds of outliers ratios [19] but if the turbidity is high only key points might be found on the laser line which are highly correlated with the scene depth profile leading to a false estimation of the Essential matrix.

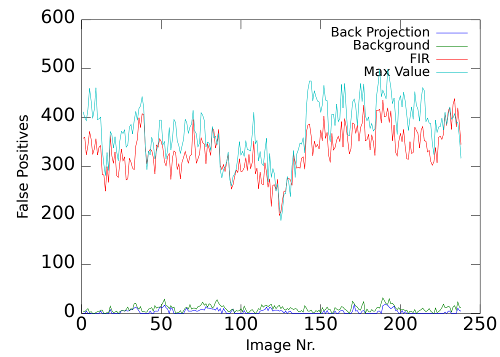


Fig. 9. Comparison of different laser line detectors: Back-Projection = background subtraction + FIR + back-projection; Background = background subtraction + FIR Filter; FIR = FIR Filter; Max Value = Maximum Value

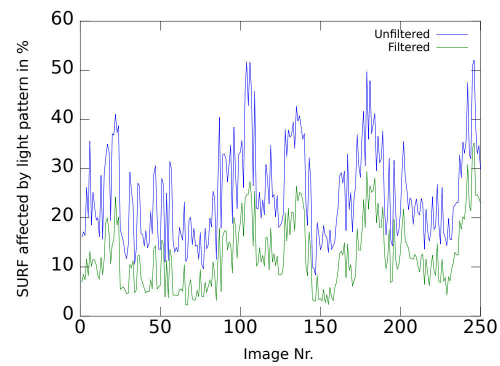


Fig. 10. U-SURF features affected by the laser line pattern during a scan.

3) 3D Scan: Figure 11 shows parts of the 3D scan of the harbour pier. This can be seen as the first step towards automated underwater inspection based on mono vision and structured light rather than a final result. The reason for this is that the structure from motion pipeline is so far not fully integrated into the structured light pipeline and a lot of information are ignored which might support a more accurate 3D reconstruction.

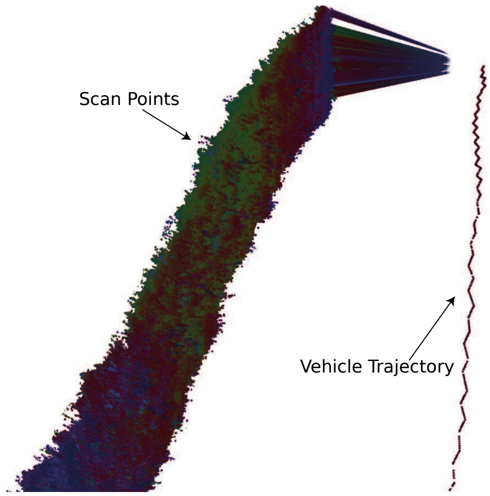


Fig. 11. Structured light scan of the harbour pier.

VI. Conclusion

The proposed detection of the laser line candidates yields better results than the other regarded methods. It is robust to backscattering caused by the media and can deal with high ambient light if the scene is planar. If the scene is non-planar it might produce unacceptably many false positives depending on the lighting conditions.

The proposed validation via back-projection is removing most of the false positives but cannot be regarded as optimal because like described in subsection V-D the shapes of laser line segments, belonging to background features, are heavily changing across the image due to the laser line width normalization and background removal. At this point there is clearly room for optimization like, for example, using the bounding box of the laser line segment as region of interest to find features in the original image which are then used to validate the laser line segment.

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