Examensarbete

Underwater 3-D imaging with laser triangulation

Examensarbete utfört i bildbehandling av

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vid Linköpings tekniska högskola
av

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Abstract

The objective of this master thesis was to study the performance of an active triangulation system for 3-D imaging in underwater applications. Structured light from a 20 mW laser and a conventional video camera was used to collect data for generation of 3-D images. Different techniques to locate the laser line and transform it into spatial coordinates were developed and evaluated. A field- and a laboratory trial were performed.

From the trials we can conclude that the distance resolution is much higher than the lateral- and longitudinal resolution. The lateral resolution can be improved either by using a high frame rate camera or simply by using a low scanning speed. It is possible to obtain a range resolution of less than a millimeter. The maximum range of vision was 5 meters under water measured on a white target and 3 meters for a black target in clear sea water. These results are however dependent on environmental and system parameters such as laser power, laser beam divergence and water turbidity. A higher laser power would for example increase the maximum range.
1 Introduction

Some underwater operations are today performed by remotely operated vehicles (ROV). To perform tasks at a worksite they need an optical imaging system that is reliable also in high turbidity waters. Underwater viewing is limited due to the physical properties of the viewing medium. One way to improve underwater vision is using a laser triangulation system. The method uses structured light from a laser and a conventional video camera to acquire 3-D images which makes it a low-cost alternative. The structured light is preferably a thin, divergent, laser fan beam. By directing the beam at a target it will appear at different positions in the camera depending on the distance to the object and the angle and separation between camera and laser. Information about the spatial coordinates of the line can be obtained via trigonometric relations. A 3-D image is created by sweeping the laser line over the target.

In this work an algorithm that produces 3-D images by laser triangulation is presented. A field- and a laboratory trial were performed and the results are evaluated. Suggestions of improvements on the triangulation system are presented.

The purpose of this work is to study an underwater active triangulation system to find the maximum range and resolution of the sensor. The influence on the system performance from different system parameters is studied. Examples of system parameters are:

- Laser power
- Camera-laser separation
- Camera settings

1.1 Applications of a 3-D imaging system

The 3-D imaging technique using active triangulation can be applied in both civil and military applications. The advantage compared to passive optical methods such as stereovision systems using two cameras is a longer viewing distance. When compared to acoustical sonar systems, the benefits are high resolution and possibilities for fast data collection due to the high propagation speed of light. Some examples of possible applications are:

- Searching the hull of a ship for foreign objects such as bombs.
- Distance measurement for docking and other applications for underwater vehicles.
- Detection of obstacles under the keel of a ship.
- Damage inspection of the hull of a ship.
- Navigation at a certain height over the bottom for autonomous underwater vehicles.
- Measuring and controlling pipelines and other underwater installations.
- Classification and identification of mines.
- Crime investigations.

Some of the applications are new and some are today performed by special ships or divers. The ships often carry an underwater remotely operated vehicle (ROV). The ROV is normally operated from the ship via cables. There is an increasing interest for autonomous underwater vehicles (AUV:s) which can perform tasks autonomously. These
vehicles will need information from several sensors to be able to act and navigate with high precision and safety. Normal video cameras which are used in underwater applications are sufficient to give identification at short distances. It is however desirable to find better optical sensors which can increase the viewing range and give possibilities for accurate range measurements and 3-D imaging. Here, an imaging system based on active triangulation might be an option [13]. In some applications, where longer ranges are needed, laser and optical systems need to be completed with acoustical sensors such as sonars.
2 Triangulation system

In an active triangulation system, an artificial light source (usually a laser beam) that produces structured light is used. It is important to have a distinct line that is easily detected by the camera. The width of the beam also affects the distance resolution of the system. In our system we use a laser that produces a laser fan-beam (Fig. 2). When a sheet-of-light intersects an object, a bright line of light can be seen. By viewing this line from an angle, the observed distortions in the line can be translated into distance variations (Fig. 1). Scanning the object with the light constructs 3-D information about the shape of the object [2], [4], [6].

The distance to an object can be calculated in different ways. My first approach was using a geometrical relation between system parameters. Some of the parameters were difficult to measure and the distance estimation was not accurate enough. Another approach was simply to calibrate the system to different distances and fit a function with the row pixel position \( u \) as an input parameter, see Fig. 11. In this way, less consideration had to be taken to system parameters. These methodologies will be described in Chapter 4.3.

Before seeking a pixel-distance relation, we need to make a good approximation of the row pixel position that is lit by the light from the beam. The light from the target usually
illuminates more than one camera pixel. It is therefore important to have an algorithm that finds the center of the laser line. This issue will be dealt with in Chapter 4.2.

2.1 Problems and challenges using optical triangulation

Several problems can occur in optical triangulation. During the initial phase of the work the following issues were identified as the most central problems.

The wider a laser line is the more likely is it that the line is divided at an edge of an object. That gives two projections at different distances instead of one. This phenomenon is more common if the object has a sharp edge where the distance suddenly changes or if the laser fan beam is wide. In air there are few particles that can scatter the light. The beam width (Fig. 2) is therefore pretty much the same from one point to another if the laser line has a good quality. On the other hand, in underwater applications there are a lot of scattering particles and the width therefore increases with distance.

Another predicament is that the laser line can be hidden so that the camera can not detect it (Fig. 3). This is because the camera is ‘looking’ from another position than the light source. The problem gets worse when the distance between laser and camera increases. On the other hand, decreasing the distance would make the precision poorer, [2]. Similarly, some parts of the terrain can be hidden for the laser but visible for the camera.

![Fig. 3 Hidden laser spot](image)

The third problem is a result of sudden change in reflectivity of the surface. Using a line detection method that seeks the maximum peak, a small shift in sensor position takes place when the intensity of the reflected beam changes within the line (Fig. 4). If the laser illuminates the border between a black and a white surface the intensity top will be on the edge of the white surface instead of central over the line. In the final 3-D image this will cause a distance error with a notch-like appearance, [10].
Another problem that might arise is that of backscattering light in the water. A high quantity of scattering particles would increase the image noise level. In the field trial performed (see chapter 7) the laser power was not high enough to give backscattering. This issue is therefore not included in the report.

### 2.2 Hardware

The optical imaging system consists of a LASIRIS TEC laser [6] (Fig. 5), a SONY digital video camera recorder (DCR-PC108E/PC109E) equipped with a green wavelength filter (10 nm bandwidth), underwater housings for the camera and the laser and a 6V power supply for the laser. The laser and the camera are mounted with a fix position to a sensor rail (Fig. 7). The sensor rail is attached to a bar which can be rotated (Fig. 6) by a stepper motor controlled by an ESP300 Motion Controller from Newport. The Motion Controller is connected to a PC serial port. The motor rotation is controlled from a user interface written in C++ where simple commands for axis movement, velocity and acceleration are given.
The laser is producing a 20mW structured light beam with 532nm wavelength. It is operational in an environmental temperature from -20ºC to +45ºC. The laser’s thermoelectric cooling device (TEC) keeps the laser diode at 19ºC. It does not turn on until the diode temperature stabilizes around this temperature. This start-up process normally takes less than 10 seconds. If the temperature largely exceeds ambient conditions, the red LED will be lit and the laser will not turn on. It takes 2-3 minutes after the laser is turned on before obtaining a stable output power.

Users can easily focus the TEC laser for a specific range; the procedure is described in the laser instruction manual [7]. We choose a focus distance of four meters. The laser fan beam is fixed to a certain angle of divergence. For our trials, an angle of ten degrees was used. Several different lens versions can be ordered from the supplier, ranging from one degree to 90 degrees. Laser light can cause permanent damage to the eye. The safety distance for our laser is derived in Appendix A.

There are three camera parameters that can be controlled to maximize the accuracy of the system: exposure, focus and zoom. The appropriate settings for the camera will be described more in detail in chapter 7. The camera has the capacity of taking 25 images per second. Processing of the collected images is done with a MATLAB computer program, [7].
Fig. 7 Sensor rail with camera and laser
3 Other types of structured light imaging systems

There are many possible setups for structured light imaging systems, each with different advantages. The laser triangulation technique has been widely used to obtain 3-D information because of its accuracy. In agricultural and food processing industries for example, measurements of true 3-D volume are critical for many processes. One example is grading of oysters. Human grading of oysters is very subjective. Here can a machine vision system make a great difference by determining the exact size of the oyster. The person handling the product in the grading process may also lead to weight loss and contamination, [8].

Laser triangulation is a fast method to obtain 3-D information but usually not complete for surface reconstruction, especially for objects with irregular shapes. A computer vision technique combining laser triangulation and distance transform can be used to improve the 3-D measurement accuracy for objects with irregular shapes, [8].

We now take a look at two different setups of the triangulation system. In Fig. 8 (a) a system similar to ours is shown. The difference is that there are no moving parts. This system can for example be used for online application measuring objects on a conveyor belt. By varying the angle $\beta$, the pixel position-range relation will vary. This angle is normally set between zero and 90 degrees.

Fig. 8 (b) shows a setup described in reference [9]. A group at the department of Computing & Electrical Engineering at the Heriot-Watt University in Edinburgh, United Kingdom, has developed a laser triangulation sensor for underwater use. Scanning is normally performed by using tilt motors, rotating the whole system. Their arrangement uses a laser beam steered by a mirror. This is a much faster method and more suitable for 3-D imaging. In a conventional air-based triangulation system the baseline is constant and is calculated once during calibration regardless of scan angle. In this system, because of refraction effects and the planar air-glass-water interface the effective baseline separation is not constant but varies with scan angle.
The sensor was calibrated in two steps. First the CCD camera was calibrated using Tsai’s noncoplanar method [12] which maps image coordinates to real world coordinates to find the intrinsic parameters (focal length, image center, scale factor and lens distortion) and extrinsic camera properties (the cameras rotation and translation relative to a known world coordinate system). The camera calibration parameters were then used to calibrate the laser plane and to produce values of the disparity angle (angle between laser and baseline) and baseline distance for all possible rotations of the scanner. The real world coordinates were then calculated by geometrical relations between the baseline distance, disparity angle and the tilt angle.

The scanning system was tested for ranges up to 1.2 meters. Tests were done in a tank containing normal water. The standard deviation for range measurement of a flat surface at 1.2 meters was 0.57mm.
4 Image processing

4.1 Creating a 3-D image

The procedure of creating a 3-D image can be divided into a number of steps (Fig. 9). A threshold value is set to define the lowest possible pixel value of a laser line. It can be found by dividing the maximum value of a frame with a constant. The constant is chosen with consideration to background irradiation and noise level. It is important that only parts of the target that are illuminated by the laser line fulfill the threshold condition. A high level of background light will make it more difficult to extract the line from the environment and one must therefore be careful when setting the threshold level.

The frames are read one by one, applying a line detection algorithm (see chapter 4.2) to find the position of the laser line at every row. The row pixel positions can then be transferred into distances by using a predetermined relation between pixel position and world coordinates. This relation is described in chapter 4.3. A calibration gives the parameters for the transformation from pixel to world coordinates. The calibration is performed at given distances in the same medium as the trial is going to be carried out.

When all frames have passed through the algorithm, a complete set of coordinate data is obtained. The 3-D surface is then created using the obtained spatial coordinates.

The last step includes smoothening of the 3-D image. The surface smoothness varies depending on distance and separation between laser and camera. Smoothening is performed by applying a low pass filter over the range data (z). The effect will be an averaging of neighboring pixel values. By filtering several times we can get rid of the majority of the roughness. The need of smoothening depends on what application we are using.
Fig. 10 shows an example of the final image. The color intensity is here proportional to the reflected intensity.

Fig. 11 Triangulation system

A detailed drawing of the system is shown in Fig. 11. The lower part of the figure shows the camera enlarged. The parameter $\alpha$ is the angle between the laser and the $z$-axis and $\beta$ the angle between the camera optical axis and the $z$-axis. The parameter $u$ is the row pixel position in the camera lit by the light from the object and $i$ is a camera parameter determined by the zoom setting.
4.2 Finding the laser line

There are several methods to find the position of the laser line. A well concealed line needs a complex method to be extracted while a bright line without surrounding noise easily can be found. A critical step is to localize the exact position of the center of the line.

4.2.1 Maximum algorithm

If there is no surrounding noise, a simple way to extract the line is searching the maximum value in each row of the image. We denote this as the Maximum algorithm. If the peak has a flat saturated top (the top has more than one pixel with the maximum value) it will be difficult to know which one to choose (see Fig. 12 (b)). This problem occurs when the camera exposure is set too high. A good guess would be that the maximum value is found in the middle between the lowest and the highest indexes of the top.

4.2.2 Center-of-gravity algorithm

One way to localize the beam center is by using the center-of-gravity COG equation [4]

$$pos = \frac{\sum u I(u)}{\sum u I(u)}$$

where $pos$ is the calculated row pixel position for the center of the beam. The index $u$ is the column number and $I(u)$ is the intensity of pixel with column number $u$. Summation is done over a number of columns where the intensity is higher than the threshold value (Fig. 12 a). This method assumes that the noise level is lower than the threshold value. The COG algorithm generally gives a better estimation of the line position than the maximum algorithm.

![Intensity, $I(u)$ vs Column number, $u$](a)

![Intensity, $I(u)$ vs Column number, $u$](b)

(a) Maximum peak (b) Flat intensity peak

Fig. 12. Illustration of the reflected intensity from [4] (a) Maximum intensity found (b) Flat intensity peak

The maximum- and the COG algorithms are compared in chapter 6 and 7.
4.2.3 Obstacles

Localizing the position of the laser line is not always as easy as described above. The center-of-gravity method is very useful in environments where there is no disturbing light or high fluctuation of intensity over the surface. There are however cases when the reflectivity at the surface is so low that surrounding areas give a higher intensity than the laser peak. This is illustrated in Fig. 13 where the left image shows the laser line at a black surface. The bright surrounding areas give higher intensity than the line. A plot of pixel row 300 is shown in Fig. 13 (b) which clearly demonstrates this problem. The laser line is situated at the row pixel position 310 between two white bands. It is the sharp contrast between black and white in combination with the background light that gives rise to the high plateaus.

![Image of laser line at low reflecting surface](a)

![Plot of pixel row 300](b)

Fig. 13 (a) Laser line at low reflecting surface (b) Row pixel values from image row 300

Using one of the previous methods to find the laser line would here lead us to the small peak at the plateau around pixel number 230. That would be a complete mistake and give a great miscalculation.

4.2.4 Correlation method

One way to approach the problem with the hidden peak is to search for a top that is similar in shape instead of looking at intensity. This could be accomplished by using an artificial peak (a triangular shaped correlation kernel). The kernel correlated with the intensity function at every point gives a vector with a maximum at the position where the window shows the highest similarities to the intensity plot. Correlating the whole image with the peak gives a 2-D plot with the highest correlation as bright areas. The operation is applied only in the latitude direction. Correlation is here denoted with \( \circ \) and convolution with \( * \). In the image plane, the correlation \( c(u) \) between two matrices \( f(u) \) and \( g(u) \) can be calculated as (see for example [14])

\[
c(u) = f(u) \circ g(u) = f(-u)^* g(u)
\]  

(2)
In the Fourier domain this corresponds to multiplication between the Fourier transforms of $f$ conjugated and $g$.

$$C(f_u) = F^*(f_u) \cdot G(f_u)$$

(3)

Note that $\Im(f(-u)) = \text{konj} [\Im (f(u))]$. The problem was to find an artificial peak that was similar to all possible peaks but at the same time different from undesired peaks. With a noisy background as in Fig. 13 there are many peaks that look similar to the real one. The correlation method is therefore very uncertain.

The correlation method is very time consuming which also is a drawback. Processing of four frames in Matlab takes about 40 s while the acquisition time for the frames is 4/25 s.

### 4.2.5 Extraction by subtraction

Another approach to extract the concealed line is to remove the disturbing background. Information about the background changes only piece by piece as the sensor rail rotates. This can be used by subtracting one frame from the following. One of the frames needs to be translated a few pixels to make as good fitting to the other as possible. The number of pixels it needs to be adjusted is determined by the angular velocity of the sensor rail. This method requires the objects in each frame to be close in distance or they will move differently each frame. The technique of subtracting images is well suited to simple structures but does not work as well for small details. There is also a risk to lose the line if the object distance changes in a way that the line moves to the same position as in the translated image.

Fig. 14 shows an example of the subtraction method when the background is a black surface. The scanning speed is 2 degrees per second which translates the pixels three steps per frame. Each frame was subtracted by the following fourth frame. A gap of one or two frames would be too little and give a very thin line. Fig. 14 (b) shows the extracted line.

![Fig. 14 (a) Hidden laser line (b) Extracted laser line](image)
If we disregard the bright reflection that did not disappear after subtraction it is a good technique to extract the line. This is however an ideal case. There are no fluctuations in distance which could have affected the filtered image.

One way to decrease background illumination is using a narrow bandwidth filter. The image in Fig. 14 (a) was acquired using a filter with 10nm bandwidth. If the bandwidth is decreased to 1nm we would reduce the background illumination a factor 10. This would make image processing much easier.

4.2.6 Smoothening of image

The filtered line in Fig. 14 (b) is still noisy and that can be a problem when using the line detection algorithm. One way to get rid of the contaminating bright dots is low-pass filtering of the image. This can be done in any direction depending on what convolution kernel is chosen. In practice, the low pass filter is averaging nearby pixels. A disadvantage with smoothening is the loss of information. A 3x3 pixel filter will substitute each pixel with the average of its value and the surrounding eight pixels. As we want to get rid of noise without harming the line peak, a good idea is to choose a convolution kernel that filters in the column direction. An example of a 1x3 pixel kernel is shown in Fig. 15.

![Convolution kernel for smoothening](image)

The difference before and after smoothening can be seen in Fig. 16. In the right image the convolution kernel in Fig. 15 has been applied a number of times.
4.3 Determination of 3-D coordinate from pixel position

The relation between row pixel position $u$ and the distance $z_0$ to the object depends on several parameters. The parameter $i$ is determined by the current zoom setting (Fig. 11). A high zoom (narrow field-of-view, FOV) will increase the distance resolution of the system but it also makes the angle of vision smaller. It is therefore important to choose a zoom that is roughly adjusted to the distance range to be scanned.

4.3.1 Geometrical method

A first approach to find a pixel-distance relation is searching a mathematical expression for the system. One difficulty is how to deal with the refraction at the air-water interface. This can be compensated for by calibration or simply by using Snell's law. We therefore assume that $\alpha (0<\alpha<90^\circ)$ is the refracted laser beam angle in water and $\beta (0<\beta<90^\circ)$ is the angle between the z-axis and the camera optical axis. The row pixel position is denoted as $u$ and $g$ is the distance between laser and camera ($g = e+f$), see Fig. 11. The object is positioned at the distance $z_0$.

\[ d = z_0 \tan \alpha \]  
\[ \frac{g-d}{z_0} = \tan(\beta + \arctan\frac{u}{i}), \gamma>0 \]  
\[ z_0 = \frac{g}{\tan(\beta + \sigma(u) \arctan(\|u/i\|)) + \tan \alpha} \]  

where $\sigma(u)=1$ for $u \geq 0$ and $\sigma(u)=-1$ for $u < 0$. In Fig. 17 some examples of $z_0$ curves from Eq. (6) are plotted for three different values of $i$. The parameter $i$ is adjusted by the camera zoom setting. The constants $g$, $\alpha$ and $\beta$ were given arbitrary values.
As pointed out before, at low $i$ values (low zoom setting) it is possible to view over a wider range of distances than with high zoom. The disadvantage with low zoom is the bad resolution. Each pixel corresponds to a certain distance in real space. If many pixels are used to cover a short distance range, the resolution will be high. As seen in Fig. 17 the derivative of the curves increase at high pixel values so that fewer pixels cover a larger distance range. In other words: resolution decreases as the distance to the object increases.

![Graph showing relation between distance $z$ and row pixel position for three different $i$-values.](image)

**Fig. 17 Relation between distance $z$ and row pixel position for three different $i$-values**

The geometrical method was tried in air but turned out to be very inaccurate. Most of the parameters are difficult to measure e.g. the camera and laser angles. A small angular error gives rise to a high distance error. Another reason is that the arctan function is sensitive to errors when $u$ is close to zero. The uncertainty is therefore high when the line is located in the center of the image. Optimization methods were used to find the most accurate parameter values. It was however difficult to find a good starting point that converged to the optimal value. Instead it found local optima. It is obvious that we need a better method to find the pixel-distance relation.

### 4.3.2 Polynomial fitting

It is not necessary to know the exact camera parameters or laser angle to estimate the distance to an object. A plotting of the pixel position versus the distance for experimental data is shown in Fig. 18. One approximation of this relation is exponential. We can use this by making a LMS (least mean square) fitting of an exponential function and a first degree polynomial function (Eq. (7)). The polynomial is used to increase the accuracy of the fitting. The order of the polynomial was chosen to optimize accuracy without adding unnecessary terms.

$$z_0 = A + Bu + Ce^{Du} \tag{7}$$
where $A$, $B$, $C$, and $D$ are constants. As a polynomial (or exponential) fitting only is valid within the interval of the calibration points, it is important that the calibration is done over the same distances as we believe our scanning targets are positioned.

![Graph showing the experimental values of distance relation to row pixel position](image)

**Fig. 18 Experimental values of distance relation to row pixel position**

### 4.3.3 Compensation for the rotation of the sensor rail

The distance $z_0$ that was calculated in chapter 4.3.1 and 4.3.2 is the vertical distance from the sensor rail to the object. The rail, which is fixed along the $x'$ axis (Fig. 19), will rotate around the center of the coordinate system. If no correction is done here there will be an error that increases as the angle $\phi$ increases. By making a coordinate transformation, the distance can be transferred from the primed coordinate system to the unprimed. A laser spot is positioned at $p'$ (Eq (8)) in the primed coordinate system. The $x'$ component of the vector is found by using a trigonometric relation between the object distance $z_0$, the laser distance $e$ and the laser angle $\alpha$, see Fig. 11.

$$p' = y'\hat{y}' + (e - z_0 \tan(\alpha))\hat{x}' + z_0\hat{z}$$  \hspace{1cm} (8)

![Diagram illustrating the rotated coordinate system](image)

**Fig. 19 Rotated coordinate system**
The transformation matrix from the tilted system to the original is described by Eq. (9).

\[ T = \begin{pmatrix} \cos \varphi & 0 & \sin \varphi \\ 0 & 1 & 0 \\ -\sin \varphi & 0 & \cos \varphi \end{pmatrix} \tag{9} \]

The position of the object in the original coordinate system is then

\[
\begin{pmatrix} x \\ y \\ z \end{pmatrix} = \begin{pmatrix} \cos \varphi & 0 & \sin \varphi \\ 0 & 1 & 0 \\ -\sin \varphi & 0 & \cos \varphi \end{pmatrix} \begin{pmatrix} e - z_0 \tan(\alpha) \\ y \\ z_0 \end{pmatrix} = \begin{pmatrix} \cos \varphi(e - z_0 \tan(\alpha)) + z_0 \sin \varphi \\ y \\ -\sin \varphi(e - z_0 \tan(\alpha)) + z_0 \cos \varphi \end{pmatrix} \tag{10} \]

We still do not know anything about the vertical distance \( y \). One way to find this distance is using a relation between \( y, z, q \) and \( v \) (Fig. 20). At small angles, there will be an approximately linear relation between these parameters:

\[ y = z \frac{v}{q} \tag{11} \]

where \( q \) is a constant. The constant \( q \) is dependent on what zoom we are using. It can be predicted by calibration in the \( y \)-direction. The calibration should be done under water (to be able to perform measurements under water) using a calibration board with a scaled \( y \)-axis. Eq (11) will then provide us with the \( q \)-value.

Theoretically the position can now be determined very well. There are however parameters that can not be measured very accurately. For high accuracy, the distance to the laser \( e \) and the laser angle \( \alpha \) is preferably calibrated.
5 Optical properties of water

When evaluating an underwater optical imaging system, it is necessary to know something about the parameters that influence the propagation of light in water. Overviews of this subject have been presented in several publications, some examples are given in Refs. [5] and [21]. This section will give some selected information from those references.

5.1 Attenuation

The attenuating effects on propagating light can be divided into the two mechanisms: absorption and scattering. Absorption and scattering can be described with the absorption coefficient $a$ and the scattering coefficient $b$. The beam attenuation coefficient $c$ states the fraction of a parallel (collimated) light beam that is either absorbed or scattered, when the light moves through water. The relation between these three parameters is:

$$c = a + b \text{ [m}^{-1}\text{]}$$  \hspace{1cm} (12)

5.1.1 Absorption

Absorption is simply the portion of light that is absorbed by the water volume. For pure water, the absorption is the dominating part of the total attenuation. Scattering effects can however dominate absorption at all visible wavelengths in waters with high particle load. For an optical imaging system, the absorption can often be handled by increasing the power of the illumination source, or increasing the amplification at the receiver.

5.1.2 Scattering

Scattering is when light changes its direction when passing through the water. Scattering is often divided into forward- and backscattering, depending on the angle that the light is turned from its original direction. Scattering can not be handled by increasing the illumination, as that will increase the scattering proportionally to the increase in light returned from the target.

5.2 Attenuation Length

In order to compare images acquired in different water qualities and different distances, the concept attenuation length $AL$ is often used. Attenuation length is the attenuation coefficient $c$ times the physical distance $z$ between the camera and the target.

$$AL = c \cdot z$$  \hspace{1cm} (13)

5.3 Wavelength dependence

As the absorption and scattering is dependent on which wavelength that is used, this is a factor that has to be considered when designing an optical underwater imaging system. From Fig. 21 it can be deduced that it is in the visible band, or near that, that the suitable wavelengths can be found. The total attenuation is lowest for wavelengths between 400 – 500 nm. However, both attenuation and scattering will depend mostly on what type of particles and dissolved substances there are in the water. An example of this is shown in Fig. 22 where the optimal wavelength is somewhere around 575 nm. It is essential to choose a wavelength that is reasonably good for all waters where it will be used. In addition to the water properties, we also have to consider the laser sources available at
different wavelengths. For underwater applications where a maximum range is needed, the Nd:YAG laser with emission at a wavelength of 532 nm is a suitable choice.

Fig. 21 Spectral absorption coefficient of pure water (solid line) and of pure sea water (dotted line) as a function of wavelength. From [21].

Fig. 22 Examples of spectral absorption coefficients for various waters. Waters dominated of phytoplankton are shown in (a), (b) is for waters with high concentration of nonpigmented particles, and (c) is for waters rich of dissolved organic matter [21].
6 Laboratory trial

The laboratory trial was performed in air. Its purpose was to give knowledge about the optical triangulation system and prepare for the field trial. Resolution in the z-direction was measured for three different zooms and two line detection algorithms were compared. Also the separation between camera and laser was alternated to examine how the distance resolution varies. Another important task was to find camera parameters suitable for an underwater environment.

6.1 Resolution

Resolution can be described as the size of the smallest resolvable detail in an image. The resolution in x- and y-direction can therefore be measured with a resolution board with white and black stripes of varying width. The size of the thinnest detectable line determines the resolution. Resolution in z-direction (depth resolution) is more difficult to determine using a similar method. The board would need to have a 3-D structure instead of a 2-D as in the previous case. This is however difficult to accomplish. Instead the distance resolution can be estimated by looking at the standard deviation in the z-coordinate over a flat surface. Scanning a flat surface with our triangulation system, it looks typically as in Fig. 23 where a 20x25cm flat paper sheet is imaged. The color is here proportional to the intensity of each pixel.

The resolution in z-direction of the final 3-D image is dependent on how well the distance $z$ to the object can be determined. One way to increase the resolution is to separate the camera and laser. Measurements were performed for three different separations and compared with two different line detection algorithms. A flat paper sheet was scanned at a distance of two meters. The three camera-laser separations were: 21.5,
31.5 and 41.5 cm. Fig. 24, Fig. 25 and Fig. 26 compare standard deviation in the z-direction with three different zoom settings. In the first figure the field of view is 36° (no zoom), the second 25° and the third has a FOV of 10°. The depth interval in which the line is visible is determined by the FOV but also the laser and camera angle. The laboratory trial was performed using small values of $\alpha$ and $\beta$. Table 1 shows the depth interval in which the line is visible for different FOV from the laboratory trial.

It is clear that a high separation gives better resolution than a low separation. The highest influence on distance resolution, within the tested parameter range, has the choice of line detection algorithm. The COG algorithm gave the most accurate results.

<table>
<thead>
<tr>
<th>FOV</th>
<th>Depth interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>36°</td>
<td>1-8 m</td>
</tr>
<tr>
<td>25°</td>
<td>1.5-5 m</td>
</tr>
<tr>
<td>10°</td>
<td>2-4 m</td>
</tr>
</tbody>
</table>

The best result was a standard deviation of 0.2 mm accomplished with the COG algorithm (Eq. (1)) and 10° FOV at the third separation. A drawback with high camera-laser separation is that the sensor in some applications can become too large.

The lowest field of view (10°) was chosen so that the detectable distance interval was two to four meters. The COG algorithm gave the best result in all comparisons.

Each pixel column in the camera represents a certain distance in real world coordinates. By increasing the camera-laser distance or zooming, the real world coordinates are mapped over a larger amount of row pixel positions in the camera. This explains why the range accuracy increases.
Fig. 24 Standard deviation in z-direction (36° FOV) at 2m distance with two line detection algorithms using three different separations between laser and camera

Fig. 25 Standard deviation in z-direction (25° FOV) at 2m distance with two line detection algorithms using three different separations between laser and camera
The resolution in x-direction (lateral resolution) is determined by the angular velocity of the sensor rail and the width of the beam hitting the target. A thin laser line gives a good resolution but it also requires a low scanning speed. If the rail turns too quickly the camera will not have time to acquire enough images to give good resolution. This will be discussed further in chapter 8.

In air, the resolution in the y-direction is not limited by the width of the line or the angular velocity of the sensor rail. It can therefore pick up variations down to pixel level. In water though, there are scattering particles that blur the line which degrades the resolution in the y-direction.

### 6.2 Exposure setting

A high exposure setting increases the risk of getting a saturated top as was described in chapter 4.2. A low exposure setting will on the other hand give poor visibility at long distances. In an operational system the exposure should be changed depending on viewing distance and other parameters. Optical attenuation filters were used in the laboratory to simulate water attenuation effects and find a proper exposure setting. Table 2 shows the results of this experiment. The variable $T$ is the transmission of the filters, corresponding to the transmission in water, used in the laboratory trial. The transmission $T$ [23] was calculated as

$$T = e^{-2cz}$$  \hspace{1cm} (14)

where $c=0.75$ is the attenuation coefficient in water and $z$ is the distance to the target.
Table 2. Pixel intensity for different exposure settings and target distances.

<table>
<thead>
<tr>
<th>Distance $z$ [m]</th>
<th>T</th>
<th>Exposure [%]</th>
<th>Pixel value, black surface</th>
<th>Pixel value, white surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.22</td>
<td>70</td>
<td>240</td>
<td>255</td>
</tr>
<tr>
<td>2</td>
<td>0.05</td>
<td>70</td>
<td>83</td>
<td>115</td>
</tr>
<tr>
<td>3</td>
<td>0.01</td>
<td>70</td>
<td>0</td>
<td>82</td>
</tr>
<tr>
<td>4</td>
<td>0.0025</td>
<td>70</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0.001</td>
<td>70</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0.22</td>
<td>100</td>
<td>255</td>
<td>255</td>
</tr>
<tr>
<td>2</td>
<td>0.05</td>
<td>100</td>
<td>111</td>
<td>255</td>
</tr>
<tr>
<td>3</td>
<td>0.01</td>
<td>100</td>
<td>0</td>
<td>213</td>
</tr>
<tr>
<td>4</td>
<td>0.0025</td>
<td>100</td>
<td>0</td>
<td>132</td>
</tr>
<tr>
<td>5</td>
<td>0.001</td>
<td>100</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The experimental results show that 70% exposure only gives a maximum distance of three meters on a white surface whereas the maximum distance for 100% exposure is four meters. An appropriate exposure setting is therefore 100%. It might not give as good resolution due to overexposure at short distance but instead we will be able to scan at longer distance.

To illustrate how the exposure setting affects the final result two images were made with two different exposure settings (Fig. 28). In the left image where the exposure is set low, the darkest areas are not visible (for example the pistol butt). At low exposure setting the line is very thin. This gives a higher resolution to the final image. It can be seen that the resolution of the image in Fig. 28 (a) is slightly higher than in Fig. 28 (b). This is more evident looking at small details such as the trigger.
Fig. 28  (a) Low exposure setting (b) High exposure setting
7 Field trial
The field trial was performed at Hästholmen harbor by the lake Vättern in Sweden. The purpose was to test the performance of the optical triangulation system in water. In water, a number of phenomena occur that are not present in air. The light is partly scattered backwards (backward scattering) so that reflected laser energy is registered at more positions than just from the object. Another attenuation aspect is the absorption. In water the absorption is much higher than in air which gives higher requirements on the laser power (see chapter 5). One of the objectives with the field trial was to find the distance resolution of the sensor and how it varies for different camera-laser separations and scanning speeds. The two line detection algorithms were also to be compared. Another important task was to find the maximum working distance for the active triangulation sensor.

7.1 Water quality
The attenuation coefficient $c$ was measured with a c-Beta, beam attenuation transmissometer & backscattering sensor from HobiLabs [19]. The measured value was $c = 0.75 \, /m$ with $0.2 \, /m$ accuracy. The distances used correspond to an attenuation length $AL$ between 1.5 and 3.75. Table 3 shows typical coastal water optical properties for Baltic archipelago waters [20]. Comparing with the field trial we can see that the properties are between clear and average. The scattering coefficient $b$ can be estimated to $b = 0.58$ assuming that also scattering properties are between clear and average.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Clear</th>
<th>Average</th>
<th>Turbid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attenuation coefficient $c$ [m$^{-1}$]</td>
<td>0.5</td>
<td>1</td>
<td>1.6</td>
</tr>
<tr>
<td>Scattering coefficient $b$ [m$^{-1}$]</td>
<td>0.35</td>
<td>0.8</td>
<td>1.3</td>
</tr>
</tbody>
</table>

7.2 Background irradiation
The maximum visible distance under water is limited by backscattering and background irradiation. The background irradiation can be decreased by choosing a wavelength filter matched to the laser wavelength. A drawback is that not all light at this wavelength pass through the filter. During measurements we saw that the fraction of light passing through the filter is about 40%.

If the measurements were taken place at night, when there is no background irradiation, we would probably not need a wavelength filter. The maximum viewing distance would be higher and probably also the range accuracy.

7.3 Method
Three targets were used in the field trial. To measure the resolution in x-, y- and z-direction a black and white resolution board was used. The other target was a dummy used for rescue training (Fig. 29). The targets were suspended in ropes a few decimeters under the water surface. All measurements were done in daylight.
The sensor rail with laser and camera was positioned opposite to the targets, lowered to the same height under the water (Fig. 30). The system was connected to a metallic ladder equipped with wheels so that it could be moved up and down the pier to facilitate the varying of target-camera distance during measurements.
Before the trials a range calibration was performed. A four meter long stick with four distance boards was held in front of the sensor. The boards were positioned so that the line hit all four boards at the same time. Calibration has to be performed every time the camera or laser settings are changed. This was done after every change in camera-laser separation. The three camera-laser separations were: 21.5, 31.5 and 41.5 cm. For every separation the targets were scanned at 4 distances (2, 3, 4 and 5 meters). At each distance two scans were performed: one at low speed (two degrees per second) and one at high speed (six degrees per second). This was done to see the influence from scanning speed on the resolution.

Before the trial, the zoom was set so that the line should be visible at distances from about 1.5 to 8 meters in water. The water would narrow the field of view and an extra marginal was therefore given to ensure that all distances were covered.

The camera focus was at first set to four meters but after the first trial we changed this value to three meters.

The exposure was at first set to 100% in accordance with the laboratory trial (chapter 6.2). Due to high background irradiation however, the pixel intensity became too strong which made the line indistinguishable from the background. We therefore had to lower exposure to about 65%.
7.4 Results

The maximum range to a white surface was five meters. At this distance the board was only detectable with the third camera-laser separation and the resolution was very poor (Table 6). Above five meters, the line could not be seen with any detection algorithm. For a black target the maximum detectable distance was 3 meters.

7.4.1 Resolution

The resolution in x- and y-direction was determined using the part of the resolution board that is striped vertically and horizontally. The thinnest visible line in the intensity plot (Fig. 31 (a)) gives the resolution for the sensor. The sudden change in reflectivity between the black and the white field dislocates the peak with high creases in the z-direction as a result. This phenomenon was described in section 2.1. The blue areas in Fig. 31 (a) correspond to the low reflecting black areas in Fig. 31 (b).

During the field trial, the laser line was wider in the top than in the bottom due to a misalignment in the transmitter optics. More light illuminated therefore the upper part of the board. This is why the lower part of Fig. 31 (a) has lower intensity than the upper part.

![Intensity plot of striped surface](image1.png) ![Resolution board](image2.png)

Fig. 31 (a) Intensity plot of striped surface (b) Resolution board

The resolution was measured at 2.0 and 3.0 meters distance using two different scanning speeds: 2 and 6 degrees/second.

The lateral resolution is limited by the width of the laser line and the scanning speed. The resolution can not exceed the distance of which the line moves from one frame to another. We can regard the lateral resolution in two different ways: limited by the width of the line and limited by the angular velocity of the sensor rail. The second limitation will be addressed in chapter 8. In Table 4 we show how the lateral resolution is related to the distance and scanning speed. Table 5 shows how resolution in the y-direction (longitudinal resolution) depends on scanning speed and distance z. It can be realized
intuitively that longitudinal resolution is not affected by scanning speed. Instead it is very much determined by the width of the line. A thin line will improve the longitudinal resolution.

### Table 4. Resolution in the x-direction

<table>
<thead>
<tr>
<th>Distance $z$ [m]</th>
<th>Lateral resolution [mm], 2 deg./s</th>
<th>Lateral resolution [mm], 6 deg./s</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>4</td>
<td>8-16</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>16</td>
</tr>
</tbody>
</table>

### Table 5. Resolution in the y-direction

<table>
<thead>
<tr>
<th>Distance $z$ [m]</th>
<th>Longitudinal resolution [mm], 2 deg./s</th>
<th>Longitudinal resolution [mm], 6 deg./s</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
<td>32</td>
</tr>
</tbody>
</table>

Resolution in the z-direction (depth resolution) is measured correspondingly to the laboratory trial described in chapter 6. In Table 6 below is the depth resolution, in terms of standard deviation, given for different separations between laser and camera. The target was a flat white and black board. Separation 1, 2 and 3 have the physical distances 21.5, 31.5 and 41.5 cm respectively. The scan is performed with a low speed (2 degrees/second). Table 7 shows standard deviation at high scanning speed (6 degrees/second).

The resolution was compared with respect to the two line detection algorithms Maximum- and Centriod algorithm described in chapter 4. From Table 6 and Table 7 it is obvious that the COG algorithm gives the highest resolution. An example is seen in Fig. 32 where the face of the human-like dummy is imaged. The left image has been created with the Maximum algorithm and the right one with the COG algorithm.
From Table 6 and Table 7 it is evident that a high camera-laser separation grants a high resolution to the final 3-D image. The minimum standard deviation for the 41.5 cm separation, measured on a white surface at 2m distance, was 0.2 mm with the COG algorithm. The pixel resolution at two meters is about 3 mm. That means we can achieve sub-pixel resolution. This is however not the case for the Maximum algorithm. It can be realized intuitively as the Maximum algorithm searches a discrete maximum pixel position while the COG algorithm makes an average over several pixels.
Table 6. Distance resolution for different camera-laser separations using 2º/s scanning speed

<table>
<thead>
<tr>
<th>Distance z [m]</th>
<th>Standard deviation Std [mm] measured on white surface</th>
<th>Standard deviation Std [mm] measured on black surface</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum algorithm</td>
<td>COG algorithm</td>
</tr>
<tr>
<td>Separation 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>0.7</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>0.7</td>
</tr>
<tr>
<td>Separation 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>4.3</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>0.7</td>
</tr>
<tr>
<td>Separation 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>5.4</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>0.6</td>
</tr>
<tr>
<td>4</td>
<td>23</td>
<td>16</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
<td>20</td>
</tr>
</tbody>
</table>

When comparing Table 6 and Table 7 it is seen that the difference in scanning speed does not have a large impact on the distance resolution. Probably the speed has to be much higher to see variations.

Table 7. Distance resolution for different camera-laser separations using 6º/s scanning speed

<table>
<thead>
<tr>
<th>Distance z [m]</th>
<th>Standard deviation Std [mm] measured on white surface</th>
<th>Standard deviation Std [mm] measured on black surface</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum algorithm</td>
<td>COG algorithm</td>
</tr>
<tr>
<td>Separation 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>0.6</td>
</tr>
<tr>
<td>Separation 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>7.6</td>
<td>0.4</td>
</tr>
<tr>
<td>3</td>
<td>8.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Separation 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>7.0</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>5.6</td>
<td>0.8</td>
</tr>
<tr>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The distance resolution decreases rapidly as the target distance increases. Maximum distance measured on a white surface is 5 meters. The resolution was then very poor and sensitive to noise. Assuming that the target color varies between black and white, a guess would be that the system can visualize a target (with reasonable resolution) at distances up to 3 meters under good conditions and using the current laser power and camera equipment.
From the field trial we can conclude that the lateral- and longitudinal resolution is poor compared to the distance resolution. It is possible to improve the lateral resolution either by lowering the scanning speed or using a camera with higher frame rate. This will be discussed further in chapter 8. Longitudinal resolution is improved by decreasing the line width. This could perhaps be accomplished by an adaptable exposure and focus setting.

The Maximum algorithm uses only simple operations. It is therefore much faster than the COG algorithm which operates on one pixel row at the time. The processing time for 12 frames was 0.1 second (8.3ms/frame) with the Maximum algorithm while the COG algorithm needed 1.8 seconds (0.15s/frame). The computer hardware used for the image processing was a PC with a Pentium 4 with 1.3 GHz CPU and the algorithm was developed in Matlab.

### 7.4.2 Contrast

Another way to measure how image quality is changed by an increasing range is to measure the contrast in the image. We define the contrast $C$ as:

$$C = \frac{i_{\text{white}} - i_{\text{black}}}{i_{\text{white}}}$$

where $i_{\text{white}}$ is the pixel intensity where the laser hits a white surface and $i_{\text{black}}$ is the pixel intensity where the laser hits a black surface.

The contrast calculated for different camera-laser separations and distances can be seen in Table 8. We can conclude that the contrast increases with decreasing distance to the object but does not change when varying the laser-camera separation.

<table>
<thead>
<tr>
<th>Distance $z$ [m]</th>
<th>Separation 1</th>
<th>Separation 2</th>
<th>Separation 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.88</td>
<td>0.91</td>
<td>0.91</td>
</tr>
<tr>
<td>3</td>
<td>0.62</td>
<td>0.81</td>
<td>0.79</td>
</tr>
</tbody>
</table>

### 7.5 Comparisons to other field trials

Similar studies of underwater performance with laser triangulation were performed by Tetlow and Allwood [22]. They used a laser stripe system in an open water trial. The camera-laser separation was 0.5m and trials were performed in three different water qualities (Table 9). The laser power used was 5 mW.

<table>
<thead>
<tr>
<th>Volume attenuation coefficient</th>
<th>Approximate contrast limited range for a conventional illuminator</th>
<th>Approximate power limited range for the laser stripe system</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45 m$^{-1}$ (clear fresh water)</td>
<td>14 m</td>
<td>20 m</td>
</tr>
<tr>
<td>0.6 m$^{-1}$ (fresh water)</td>
<td>7 m</td>
<td>9 m</td>
</tr>
<tr>
<td>1.35 m$^{-1}$ (harbour seawater)</td>
<td>3 m</td>
<td>5 m</td>
</tr>
</tbody>
</table>
These results show a higher maximum distance than our field trial even though their laser power is significantly lower. It is however difficult to compare these experiments as the maximum range depends on several parameters, for example background illumination.

Comparable resolution measurements were published in studies by Tetlow and Spours at the Cranfield University of Bedfordshire [23]. Their tests were done in a test tank where the turbidity was increased artificially by the addition of Bentonite, a clay that produces scattering particles. The attenuation coefficient $c$ was 0.55 which is lower than the value in our field trial. A 70cm separation between laser and camera was adopted in the experiments. The laser had a power of 100 mW. Their distance resolution was 1.5 mm at 1 m distance, increasing to 5 mm at 3 m distance (Table 10). For our system, the resolution at 3 m distance was 0.6 mm.

**Table 10. Comparison of distance resolution**

<table>
<thead>
<tr>
<th>Distance z [m]</th>
<th>Distance resolution (Tetlow and Spours) [mm]</th>
<th>Distance resolution (our results) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>0.6</td>
</tr>
</tbody>
</table>
8 Discussion

8.1 System limitations

According to the field trial, objects tend to disappear already at small distances in water. This is due to the water scattering and attenuation effect but also because the laser sheet is diverging. It is of interest to know how high laser power is needed to be able to spot the laser-line at a distance $z$. In Appendix, section B, the maximum range was calculated for different laser powers. According to the calculations, for a 2W laser the maximum viewing range is 6 meters measured on a low reflecting surface and 8 meters using a highly reflecting target. It should be noted that these values are only theoretical and depend on the sensitivity of the camera, the water quality and the beam divergence. Increasing the laser power will also increase the backscattering. The maximum range will therefore have a limit that depends on the quantity of scattering particles in the water.

One aspect of the system limitations is the sensitivity of the digital video camera. The conventional video camera that we used in the field trial is designed for imaging in air and under good illumination conditions. The sensitivity might therefore not be optimized to the small intensities we are trying to detect. It could perhaps be advantageous to use a CCD with higher sensitivity and a larger camera aperture.

As pointed out before, background illumination could be reduced by using a wavelength filter with smaller bandwidth. The filter used in the field trial has a bandwidth of 10nm. A filter with 1nm bandwidth would reduce the background illumination ten times. This would make the image processing easier and more time efficient.

8.2 Alternative laser sources

To reach higher distances in water we need a laser sheet with higher power density. One way is simply to increase the laser power. There are several high power lasers available on the market.

One example is Snake Creek Lasers [15] which produces small solid-state lasers. The MiniGreen Laser SCL-CW-532-9.0MM-050/100 is one of the highest density lasers ($\text{mW/cm}^3$) available on the market (Fig. 33). The laser is capable of up to 100mW power output at 532nm wavelength.

Optronic laboratories [16] has a commercially available laser that gives up to 1W power output. It is a diode pumped solid state (DPSS) laser with 532nm wavelength. An example of a high power laser is “elite 532” from Photonic Solutions Plc [17]. It produces up to 5W of highly stable power at a wavelength of 532nm.
Other ways to increase the laser power density is using several laser sources or using pencil beams instead of a homogeneous fan beam. The laser line will be replaced by dots. A drawback is that the longitudinal resolution will be limited by the distance between these dots.

### 8.3 Shifted zoom and focus for higher resolution

From the field trial we saw that the maximum viewing range was about three meters for a black surface. By optimizing the system to this distance, both the zoom and the focus can be set to improve the resolution. Using a zoom that covers only distances between for example two and four meters would make the sensor more sensitive to changes in any direction and maximize the performance of the system. More details could be revealed and maybe also the maximum viewing distance.

The camera setting used in the field trial gave a pixel resolution shown in Fig. 34. The dashed line shows how the pixel resolution varies when the camera zoom is set to 10° FOV (as used in the lab trial) when compared to 25° FOV. There is a rather high difference in pixel resolution depending on the zoom used. The solid line in Fig. 34 covers distances from 1.5 to 4 meters while the dashed line covers distance between 2-4 meters. It is evident that the pixel resolution deteriorates much faster for low zoom than for high zoom.
Before the field trial, the focus was set to three meters in air. Water has higher refraction index than air which makes the focal distance slightly higher in water. Focus was set to three meters before the field trial but should be set somewhat lower to give a good focus at three meters under water.

8.4 Lateral resolution as a function of scanning speed

The results from chapter 7.4.1 show how scanning speed and target distance affect the lateral resolution. At very low scanning speeds only the width of the line and distance $z$ affects lateral resolution but at higher scanning speeds the angular velocity is limiting factor. The physical distance between two frames increases with increasing distance to the object. This gap between line projections can be considered as the lowest possible resolution in the x-direction $R_x$. It can be calculated as:

$$R_x = \omega \Delta t z$$

where $\omega$ is the angular velocity, $\Delta t$ the time span between two frames and $z$ the distance to the object. The camera used in the field trial produces 25 frames per second. Table 11 shows resolution examples for different distances and angular velocities. The scanning speeds $\omega=2^\circ/s$ and $\omega=6^\circ/s$ are the values used in the field trial.

Table 11. Estimated resolution for different distances and scanning velocities

<table>
<thead>
<tr>
<th>Distance $z$ [m]</th>
<th>Lateral resolution [mm], $\omega=2^\circ/s$</th>
<th>Lateral resolution [mm], $\omega=6^\circ/s$</th>
<th>Lateral resolution [mm], $\omega=10^\circ/s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.8</td>
<td>8.4</td>
<td>14</td>
</tr>
<tr>
<td>3</td>
<td>4.2</td>
<td>12.6</td>
<td>20.9</td>
</tr>
<tr>
<td>4</td>
<td>5.6</td>
<td>16.8</td>
<td>27.9</td>
</tr>
</tbody>
</table>
To be able to scan an object more rapidly we would need much higher frame rate. Assuming that we require a 3-D imaging system that produces 10 images per second with a resolution of 5mm at two meters distance and the scanning angle 28.6 degrees (this corresponds to 1.0x0.2m scanning area at 2m distance), we would need a scanning rate of 2000 images/second. In this case we would need a slow motion camera. A problem that would arise is the processing of 2000 images per second. This is not possible with the tested algorithms and conventional computers without tailored signal processing hardware. The minimum processing time for one frame was 8.3ms (see chapter 7.4). With a high frame rate the camera also needs more light to produce good images. This could be done by increasing the laser power.

An option to the rotating sensor rail is a rigid system with the rail fix at one angle, and scanning the bottom as the vehicle moves forward (Fig. 35). Assuming that we require a lateral resolution of 1cm and a minimum vessel speed v of 1m/s, the minimum frame rate will be 100 frames/s. The frame processing time has to be less than 10ms which is possible with the Maximum algorithm using the same hardware as in the field trial.
9 Suggestions to future work

During this thesis work there was not time enough for more than one field trial. We were limited to test only the influence of laser-camera separation and the target distance on the system performance. As mentioned in previous chapters there are several system parameters that could be optimized to improve the system resolution and maximum range. In future trials the following issues could be investigated:

- A high laser power increases backscattering in water. How much higher maximum range is possible with higher laser power?
- What is the system performance with reduced background illumination? Tests could be performed at night or using a more narrow bandwidth filter in front of the camera. With less background illumination we can increase the camera exposure setting without loosing information about the line position. This might increase the maximum range of vision.
- The camera exposure and focus setting could be tuned manually or automatically to achieve a better resolution to the final 3-D image.
10 Conclusions

A laser triangulation system to allow an underwater vehicle to scan an area and create 3-D images has been tested and evaluated. The experimental setup uses a laser fan beam and a conventional video camera. Different methods to find the center of the laser line and techniques to transfer pixel coordinates into spatial coordinates were tested. The performance of the system was tested in a number of laboratory trials and a field trial where scanning speed and separation between camera and laser were varied.

The COG algorithm which locates the laser line position gave the best accuracy to the 3-D image. A drawback was the long processing time. In environments with high background irradiation the line was successfully extracted by an image-subtraction algorithm.

A polynomial fitting method was found to give an accurate relation between pixel positions and spatial coordinates.

Camera parameters were optimized to increase the resolution of the sensor. A zoom setting adapted to the current scanning distance enhances the resolution in all spatial directions. The camera exposure is preferably set low in environments with high background irradiation for the laser line to appear.

In the underwater experiments, the best resolutions in the x-, y- and z-directions were 4mm, 16mm and 0.6mm respectively. This was achieved with the COG algorithm using a camera-laser separation of 0.41m at 2m distance from the target. Distance- and longitudinal resolution were found to have no dependence of the scanning speed. Lateral resolution (in x-direction) decreased with increasing scanning speed.

The maximum range measured on a white surface was 5 meters under water. For a black surface this distance was 3 meters.

In future triangulation systems the laser power should be increased to reach higher distances in water. There are lasers available on the market with powers up to 5W. Another option is to use pencil beams where the energy is better conserved than in an ordinary fan beam. The lateral resolution can be significantly increased by the use of a high frame rate camera.

The work has shown that a structured light imaging system can be used to give underwater 3-D images with high resolution. For some applications this might be an option to other 3-D imaging systems such as laser systems using modulated or pulsed light. The choice of technology depends on the requirement on resolution, scanning speed as well as available budget and requirements on the physical size of the system.
11 References


Appendix A

Laser safety

Laser Safety Classification
The CDRH (center for devices and radiological health) classifies lasers into several different categories depending on output power, wavelength and fan angle. Structured lighting products mainly fall into the following three categories:

Class 2- “Caution”
- Visible laser light less than 1.0mW-
  Considered eye-safe, normal exposure to this type of beam will not cause permanent damage to the eye. When exposed to this level of laser light, the blinking reflex of the human eye is fast enough to avoid any damage. Class 2 safety rating is considered eye-safe.

Class 3a- “Danger”
- Visible laser light between 1.0 and 5.0mW-
  Considered eye-safe with caution, but may present a greater hazard if viewed using collecting optics. Some groups of Class 3 lasers have a DANGER label and are capable of exceeding permissible exposure levels for the eye in 0.25 sec and still pose a low risk of injury.

Class 3b –“Danger”
- Visible laser light between 5.0 and 500 mW-
- Invisible laser light less than 500 mW-
  High-power visible lasers and infrared lasers are considered dangerous to the retina if exposed. This includes looking directly into a reflection from a specular (mirror-like) surface. Class 3b lasers will not produce a hazardous diffuse reflection. At higher levels of the class, these lasers can be skin hazards.

Safety precautions
Our laser is producing a 20mW beam with a 532nm wavelength. The light is spread out in a homogeneous line with the angle $\theta=10^\circ$ (Fig. 1). According to the laser safety classification, the laser is to be considered as a Class 3b laser.

The useful path of a beam is the distance after which all the light should be terminated by a diffusely reflecting material of appropriate reflectivity and thermal properties or by absorbers. Open laser beam paths should also be located above or below eye level. The beam path from a Class 3b laser should be as short as possible, have a minimum number of directional changes and avoid crossing walkways.
Mirrors, lenses and beam splitters should be rigidly mounted and should be subject to only controlled movements while the laser is emitting. Reflecting surfaces that appear to be diffuse may actually reflect a considerable part of the radiation beam, especially in the infrared spectral range.

Eye protection which is designed to provide adequate protection against specific laser wavelengths should be used in all hazard areas where Class 3b lasers are in use. [3]

The maximum permissible exposure (MPE) can be calculated from equations found in table 6 in Ref. [3]. The MPE value is given by Eq. 17. The calculated MPE for different exposure times \( t \) is shown in Table 12.

\[
MPE = 18 \cdot t^{0.75} \cdot C_6 J \cdot m^{-2}
\]  

(17)

**Table 12. MPE for direct and indirect exposure [W/m²]**

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>Direct exposure (( C_6=1 ))</th>
<th>Indirect exposure (( C_6=\alpha/\alpha_{\text{min}} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>25</td>
<td>3000</td>
</tr>
<tr>
<td>1</td>
<td>18</td>
<td>2100</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>1800</td>
</tr>
<tr>
<td>5</td>
<td>12</td>
<td>1400</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>1200</td>
</tr>
</tbody>
</table>

Assuming that the beam width is 1mm we can calculate the minimum distance of exposure using the values in the table above. The exposed area at a distance \( L \) from the laser is equal to

\[
A = \frac{L \cdot \pi \cdot 10^{-3}}{18}
\]  

(18)

The laser power per square meter is then calculated by dividing the laser power with \( A \).

\[
\frac{P_{\text{laser}}}{A} = \frac{18}{L \cdot \pi \cdot 10^{-3}} \cdot 20 \cdot 10^{-3}
\]  

(19)

For the indirect exposure we assume that the reflected light is diffuse and homogeneously spread out over a half-sphere. The power per square meter is then

\[
\frac{P_{\text{refl}}}{A_{\text{half-sphere}}} = \frac{20 \cdot 10^{-3}}{2 \cdot \pi \cdot r^2}
\]  

(20)

The calculated minimum distances to the laser is shown in Table 13. The distances have been calculated with the condition to have irradiation levels below the MPE according to Table 12.
Table 13. Minimum distances for exposure.

<table>
<thead>
<tr>
<th>Time of exposure</th>
<th>Direct exposure [m]</th>
<th>Indirect exposure [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25s</td>
<td>4.5</td>
<td>1.1</td>
</tr>
<tr>
<td>1s</td>
<td>6.4</td>
<td>1.3</td>
</tr>
<tr>
<td>2s</td>
<td>7.6</td>
<td>1.5</td>
</tr>
<tr>
<td>5s</td>
<td>9.5</td>
<td>1.6</td>
</tr>
<tr>
<td>10s</td>
<td>11.5</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Appendix B

Increased laser power for high viewing range

The irradiance $E_1$ (Fig. 37) of the light propagating towards the target is because of the divergence of the beam decreasing proportional to $z^{-1}$. The water scattering and attenuation also has to be taken into account. The equations (21)-(27) were proposed by Mclean [18] and give the scattered $E_{sc}$ and unscattered irradiance $E_{unsc}$. The scattered irradiance at a distance $z$ is given by

$$E_{sc}(r,z) = \phi_{sc}(z) \frac{1}{2\pi \sigma_{sc}^2} \exp(-\frac{r^2}{2\sigma_{sc}^2})$$  \hspace{1cm} (21)

where

$$\phi_{sc}(z) = \phi_0 [1 - \exp(-bz)] \frac{\exp(-az)}{1 + a2c_w \sigma_{\tau}^2 / \mu_{\tau}}$$  \hspace{1cm} (22)

is the scattered power at distance $z$. $\phi_0$ is the laser power output, $a$ the absorption coefficient, $b$ the scattering coefficient and $c_w$ the attenuation coefficient (see chapter 5). The radial distance from the optical axis is denoted as $r$ and $\sigma_{sc}^2$ (Eq. 23) is the variance for radial displacement. The variables $\mu_{\tau}$ (Eq. 24) and $\sigma_{\tau}$ (Eq. 25) are the mean and standard deviations for multipath time $\tau$ for conservative scattering.

$$\sigma_{sc}^2 = \sigma_{\tau}^2 = \frac{4}{3} c_w  \frac{1}{1 + a2c_w \sigma_{\tau}^2 / \mu_{\tau}}$$  \hspace{1cm} (23)
\( \frac{\mu_r}{z/c_w} = \frac{1}{4} b z \langle \Theta^2 \rangle - \frac{1}{24} (b z)^2 \langle \Theta^2 \rangle^2 + ... \) (24)

\( \frac{\sigma_r^2}{(z/c_w)^2} = \frac{1}{12} b z \langle \Theta^4 \rangle - \frac{1}{24} (b z)^2 \langle \Theta^2 \rangle^2 + ... \) (25)

where \( \langle \Theta^2 \rangle \) and \( \langle \Theta^4 \rangle \) are constants obtain from field trials performed in similar waters.

The unscattered irradiance is

\[ E_{unsc}(r, z) = \phi_{unsc}(z) \frac{1}{2\pi \sigma_{unsc}^2} \exp\left(-\frac{r^2}{2\sigma_{unsc}^2}\right) \] (26)

where

\[ \phi_{unsc}(z) = \phi_0 \exp(-b z) \exp(-az). \] (27)

\( \sigma_{unsc}^2 \) is the variance for radial displacement. The irradiance \( E_1 \) is proportional to \( z^{-1} \) and \( E_{sc} + E_{unsc} \).

\[ E_1 \propto z^{-1}(E_{sc} + E_{unsc}) \] (28)

Because of the diffuse reflection, the light reflected from the target will spread out spherically from the object with the irradiance \( E_2 \) (Fig. 37) proportional to \( z^{-2} \) and the attenuation function. The attenuation function is negatively exponential with a slope depending on the absorption coefficient \( a \). The reflection on the object gives an extra loss in irradiance. For a white surface we approximate the reflectivity \( \rho \) to 0.8.

\[ E_2 \propto \rho z^{-2} \exp(-az) E_1 = \rho z^{-3} (E_{sc} + E_{unsc}) \exp(-az) \] (29)

To simplify the problem we look at only the center of the line \( (r = 0) \) which terminates the last part of the irradiance expression. This simplification is motivated because we are interested in the irradiance from the center of the line.

We can assume that pixel intensity \( I \), illuminated by a point on the line, is proportional to the irradiance \( E_2 \) (Eq. (29)). This assumption is reasonable at least when \( I \) is not close to zero or close to 255 and when the camera exposure is constant.

\[ I = \alpha E_2 \] (30)

where \( \alpha \) is a constant.
According to the assumption above, the intensity $I$ was measured for the distance $z=3$ m. At this distance, the pixel intensity is not too high or too low and can be assumed to be proportional to the irradiance. The background intensity should be subtracted from the total intensity because the calculations do not include light from more than one point on the centre of the line. It is however difficult to get an accurate value of the background intensity. At low intensities we can not assume linearity between irradiance and pixel values. Background intensity can therefore only be estimated by looking at intensity at a surrounding surface that is not illuminated. The obtained intensity from a white laser illuminated surface for $z=3$ m was $I=70$. From the formula above, the constant $\alpha$ was calculated to

$$\alpha=6.0e+3.$$ 

$\alpha$ is influenced by the camera exposure setting and will therefore vary depending on background light. A high exposure setting would make it possible to see objects with lower intensity but it would also increase backscattered light and background irradiation. Increasing the laser power will also increase the backscattering. The maximum range will therefore have a limit that depends on the quantity of scattering particles in the water.

The lowest detectable intensity for a laser line varies depending on which line detection algorithm we use. In Fig. 38 the maximum detectable distance to the target has been plotted against pixel intensity for different laser powers. The surface in Fig. 38 (a) is white with a high reflectivity whereas Fig. 38 (b) shows intensity from a black surface. It should be noted that these values are only theoretical and depend on the sensitivity of the camera, the water quality and the beam divergence.
Fig. 38 Pixel intensity plotted against distance to target for different laser power sources. (a) target is a black surface. (b) target is a white surface.
If our theoretical calculations can be trusted one can from Fig. 38 see that a limiting distance is about 6 meters using a 2W laser fan beam. Any higher distance would give too low intensity after reflection on a black surface.
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