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Towards Underwater Biomass Estimation using Plenoptic Technology

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Summary

This research faces a completely new issue where it is investigated if plenoptic camera technology can provide decent depth results of objects underwater. The plenoptic camera technology has been developed as a tool meant for 3D monitoring in stable and still environments. But could the technology also potentially be used in an ocean fish farm measuring the biomass of several hundred thousand Atlantic Salmon?

Biomass estimation is something that is longed-for by the aquaculture industry, especially the fish breeding industry. It would increase profits, help production planning and potentially decrease the vulnerable phase of a breeding fish's life, which is in the saltwater due to lice.

This is a fundamental study with the overall goal of biomass estimation in mind. The objective of this research is to use plenoptic camera technology to produce a good depthmap of underwater objects, where the setup, the calibration process and the verification of depth points are the main focus areas.

This report will present the basic theory behind plenoptic camera technology along with information on the camera used throughout this research - the Raytrix R42 color camera. The idea of underwater biomass estimation using plenoptic technology is discussed and experiments on obtaining a good camera calibration and underwater results are presented.

Sammendrag

Denne studien tar for seg et helt nytt problem hvor det undersøkes om plenoptisk kamera teknologi kan gi gode 3D-bilder av objekter under vann. Plenoptisk kamerateknologi har blitt utviklet som et verktøy ment for 3D-overvåkning i stabile og rolige forhold. Kan denne teknologien også potensielt bli brukt i en oppdrettsmerde for å måle biomassen av flere hundre tusen laks?

Biomasseestimering er noe som er sterkt ønsket av oppdrettsnæringen, og da spesielt fiskeoppdrettsnæringen. Det vil kunne gi økt profitt, hjelpe produskjonsplanlegging, og potensielt minske den mest utsatte delen av en oppdrettsfisks liv, som er i saltvann på grunn av lus.

Dette er en fundamental studie hvor det er tatt i betraktning at det endelige målet er biomasseestimering. Hovedmålet med studien er å bruke plenoptisk kamerateknologi til produsere et bra dybdebilde av objekter under vann, hvor kalibreringsprosessen og verifikasjon av dybdepunkt er fokusområde.

Denne rapporten vil presentere grunnleggende teori om plenoptisk teknologi, samt gi informasjon om kameraet brukt gjennom hele studien - Raytrix R42 fargekamera. Ideen bak biomasseestimering under vann er diskutert, og flere eksperimenter er presentert.

Acknowledgements

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I would also like to thank SEALAB OCEAN GROUP for the collaboration. They have provided all equipment needed, provided help for image taking and let us students use their test facility. They have also let us join field testing several times on Hitra.

At last, I would like to thank Marine Harvest for allowing us to use one of their ocean fish farms on Hitra for testing.

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Abbrevations

MLA	=	Micro lens array
FPS	=	Frames per second
DOF	=	Depth-of-field
FOV	=	Field-of-view
POV	=	Point-of-view
TCP	=	Total covering plane
DCP	=	Double covering plane

Contents

Chapter 1

Introduction

1.1 Motivation

The aquaculture industry has grown dramatically over the last decades, and is the fastest growing, animal-based food-producing sector. Great development in breeding technology, system design and feed technology in the second half of the twentieth century has made an expansion of viable aquaculture across species and in volume. For this growth to continue, the aquaculture industry makes demand for new innovative technology for making the production more profitable while minimizing risks of affecting the marine environment and biological diversity.[3]

One of the challenges for the aquaculture industry is biomass estimation. Especially for the salmon breeding companies it is difficult to estimate the volume of fish, as each farm can contain up to 200,000 fish, and even larger farms are planned for the future. With each fish normally weighing between 3-5 kg, or 4-6 kg, depending on the production, the resulting differences in total biomass can be huge. As today's practice is to estimate the biomass of an entire fish farm and sell the fish before emptying the farm, this can result in large estimation errors and thereby huge losses. As Norway is the world's leading producer of Atlantic Salmon and the second largest seafood exporter in the world, a better estimate of the biomass in a fish farm would be beneficial to the Norwegian aquaculture industry.[3] If biomass estimation could be achieved by a single camera placed in a farm, it would serve almost as pure profit for the industry.

But, developing new technology for volume estimation has its challenges. Underwater imaging is in itself a challenge. The lightning conditions are not optimal, there are particles in the water, other fish in the background and light scattering issues. Volume measurement also requires 3D information. Using plenoptical camera technology would most likely be simpler than the use of a stereo camera system. This because the correspondence issue is minimized and the camera extracts both horizontal and vertical information, which improves the reliability of the depth measurements. Using two cameras instead of one often leads to difficulties with calibration and ambiguities about correspondence often present formidable computational challenges. In addition, stereo cameras cannot offer depth estimates for contours parallel to the parallax axis.[4] The best plenoptic camera technology in the current market is provided by Raytrix, a German company.[5] The Raytrix R42 provides high resolution images with both depth information and standard color images. The camera is made for industrial purposes in stable environments and is currently the absolute best plenoptic camera in air. Because of its outstanding specifications and results in air, it is now longed-for investigating if this technology could also perform underwater in more unstable environments.

The main purpose of this research is fundamental work to see if plenoptic camera technology can provide decent depth results in underwater environments. The report will therefore investigate the plenoptic camera technology, and also present the Raytrix R42 color camera used throughout this research. Experiments will be done both in air and water, where the main focus is to achieve a good camera calibration for attaining as good depth results as possible. At last, the camera will be tested in a salmon fish farm to see if the depth results can be further used for biomass estimation.

1.2 Report Outline

First, Chapter 2 will investigate the plenoptic camera technology, while Chapter 3 will give an overview of the exact camera used throughout this research. Next, Chapter 4 will introduce the two-year long process of attaining a grown salmon, and also investigate the underwater environment of a fish farm. In Chapter 5, different experiments are presented, with the goal of figuring out how to attain the best depthmaps using a test fish in a closed test facility. The results from each test are also discussed, before the conclusion in Chapter 6 describes to what degree this research gives any clear indication on whether plenoptic technology can be used for biomass estimation in aquaculture environments.

The complete setup and full results for the experiments presented in Chapter 5 can be found in Chapter 7.

Chapter 2

Plenoptic Camera Technology

Plenoptic cameras are made by placing a micro lens array between the main lens and the image sensor in a camera. This micro lens array transforms a standard camera into a single lens 3D camera, and allows for capturing 3D information from a scene in a single shot with a single lens. While a traditional camera only records the light intensity emanating from a scene, the plenoptic camera also captures the direction of which the light rays are traveling in space. The concept of plenoptic cameras appeared as a topic already in 1908, but due to the lack of computing power and production of the advanced micro lens arrays, the production and use of such cameras has just recently become feasible. The depth estimation in a plenoptic camera is similar to a stereo camera system as they are both based on disparities, but plenoptic cameras has some additional features. Plenoptic cameras can change the focus area of an image after it has been taken. They can also change the point-of-view and the perceived depth-of-field.[5]

For better understanding of the plenoptic camera, an introduction to a standard optical camera is first given, where important definitions and concepts are explained. These concepts are then used in the much more advanced introduction of the plenoptic camera.

2.1 Standard Optical Camera

This section gives a short introduction to some relevant concepts of a general optical system. Figure 2.1 shows such a system.

An optical camera must consist of a main lens and an image sensor. The image sensor is what captures the incoming light projected from the main lens. The main lens can have many forms where each form gives different features. This will be discussed later. In Figure 2.1 an object is projected onto the image sensor. It is seen that the light rays crosses perfectly on the image sensor. This specifies that the object is in focus and will appear clear on the image. Objects further away or closer to the camera will not get their light rays crossed perfectly at the image sensor and will therefore appear blurry on the image. Figure 2.1 also defines the object space as the space in front of the main lens, and the image space as the space behind the main lens.

When analyzing images or projections behind the main lens it is normal to place the center of the coordinate system at the center of the image sensor as

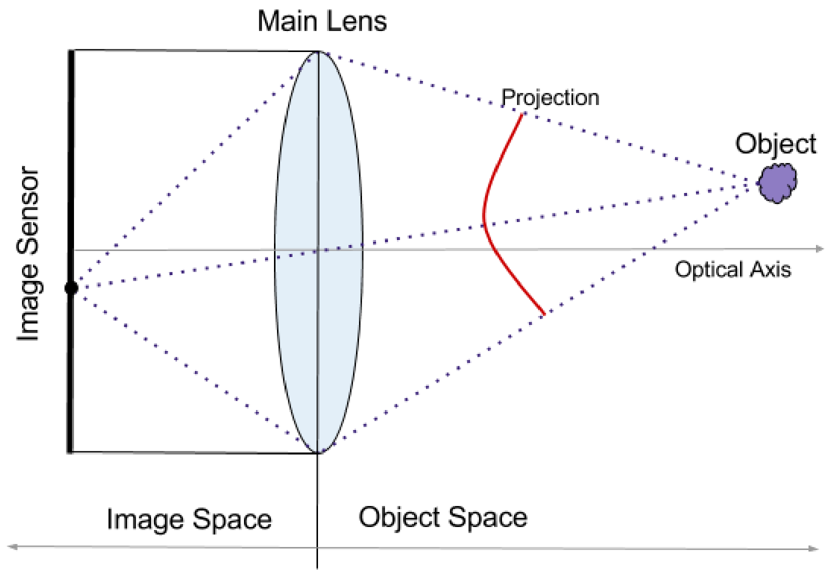


Figure 2.1: Simple setup of a standard optical camera.

opposed to the center of the main lens.

Before analyzing the properties of a camera with mathematical equations, some definitions of a cameras properties must be explained. Some of these properties are internal to the specific camera while others can be adjusted.

2.1.1 Focal Length

An important internal property of a camera is its *focal length*. The focal length is determined by the main lens and is known to the camera. The focal length is a measure of how strongly the lens bends light and is measured as the distance from the center of the lens to which parallel rays towards the lens crosses, as shown in Figure 2.2.[6]

The focal length in air can be calculated using the thin lens equation,

$$\frac{1}{f} = \frac{1}{a} + \frac{1}{b} \tag{2.1}$$

where a is the distance from the center of the lens to an object in object space, and b is the distance from the center of the lens to the light ray crossing from the object at distance a. The thin lens[1] equation is only valid for rays close to the optical axis and does not apply to thick lenses[2].

[1]Thin lens: a lens with a thickness (distance along the optical axis between the two surfaces of the lens) that is negligible compared to the radii of curvature of the lens surfaces. The thin lens approximation ignores optical effects due to the thickness of lenses and simplifies ray tracing calculations.[7]

[2]Thick lens: a lens which has a non-negligible thickness.[6]

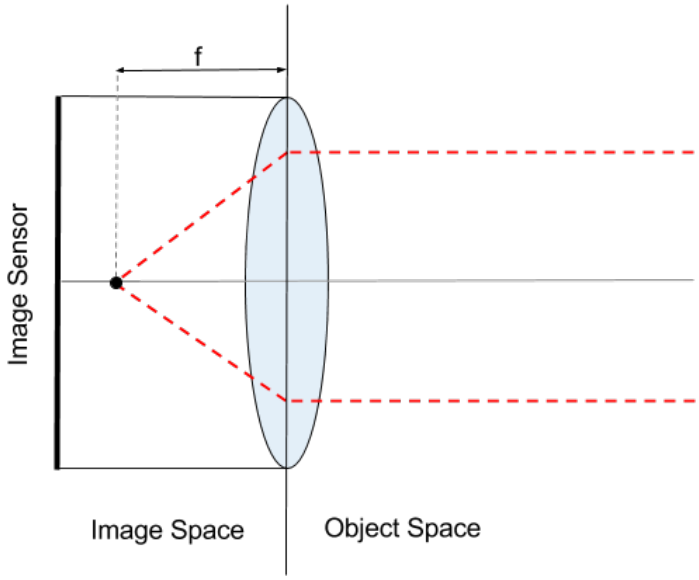


Figure 2.2: Explanation of a cameras focal length.

For thick lenses in air the Lensmaker's equation is more precise for calculating the focal length.

$$\frac{1}{f} = (n-1)\left(\frac{1}{R_1} - \frac{1}{R_2} + \frac{(n-1)d}{nR_1R_2}\right) \tag{2.2}$$

In the Lensmaker's equation f is the focal length, n is the refractive index of the lens material, R_1 is the radius curvature of the lens surface closest to the light source, R_2 is the radius curvature of the lens surface farthest from the light source and d is the thickness of the lens.[8]

Another useful property calculated by the focal length is the magnification. For thin lenses the magnification M can be calculated by:

$$M = \frac{f}{f-a} \tag{2.3}$$

where f is the focal length and a is the distance from the lens to the object.

2.1.2 Depth-of-Field and Aperture

Working with images, *depth-of-field* (DOF) is an important factor as it defines how much of the scene that will appear sharp on the image. Depth-of-field is defined as the distance between the nearest and the farthest point in object space that is acceptably sharp on the image. Figure 2.3 shows an example of DOF and an object beyond that depth range whose light ray crossing is not acceptably close to the image plane.

Dealing with imaging, a large depth-of-field is often needed. One way of increasing the DOF in object space is to decrease the size of the *aperture*. The aperture is the opening diameter of the camera lens, and works much as the pupil in the human eye. The aperture along with the focal length determines where in image space the rays from an object is focused. A wide aperture gives a sharp

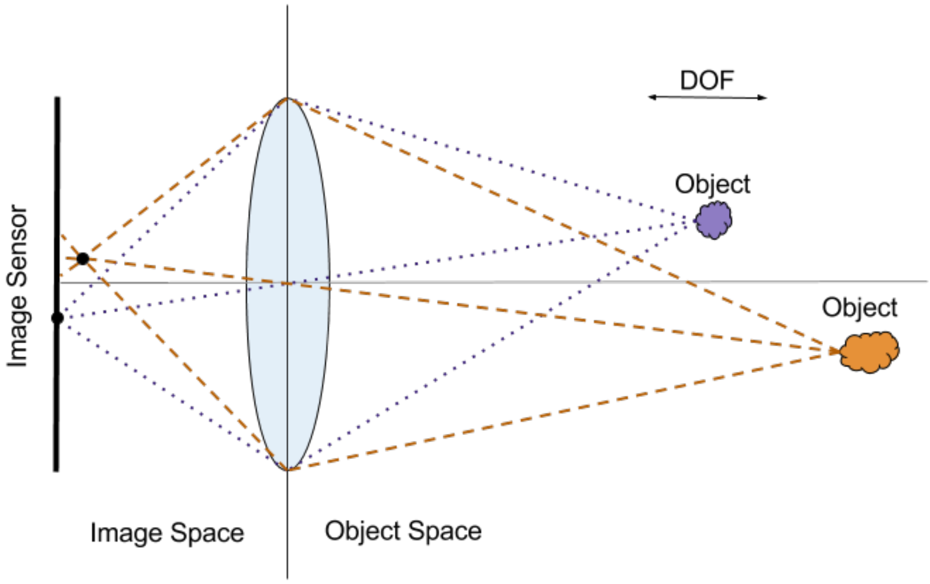


Figure 2.3: Depth-of-field in optics.

image for objects located at a specific distance.[1] By decreasing the aperture, the projection rays diverge more slowly away from the optimal focal plane. By comparing Figure 2.3 to Figure 2.4, it is seen that the rays are closer at the image plane with narrower aperture, resulting in a larger depth-of-field. The aperture also determines how much light reaches the image plane, therefore, decreasing the aperture gives a darker image. When choosing the aperture to be infinitely small, depth-of-field will be infinitely large, and it it will create the pinhole model where the focal length can be ignored. For a small aperture, a slower shutter is needed, as that gives time for more light to reach the image plane. From Figure 2.5 it is clear to see the connection between the aperture and depth-of-field.

Another common relationship in optics is the relationship between aperture and focal length. This is called the f-number, and is given by:

$$N = \frac{f}{D} \tag{2.4}$$

where N is the f-number, f is the focal length and D is the effective aperture.

2.1.3 Effective Resolution

An important property in imaging is the *effective resolution*. As shown in Figure 2.6, the objects at distance a from the lens is not completely in focus at the image sensor. Light emitting from point X_0 maps to a range s on the image sensor about the optical axis. It is seen that the light from point X_1 also maps to a range s since this point is at the same distance a from the camera as point X_0. $|s|$ can therefore be regarded as the effective pixel size for the object plane at distance a from the lens.

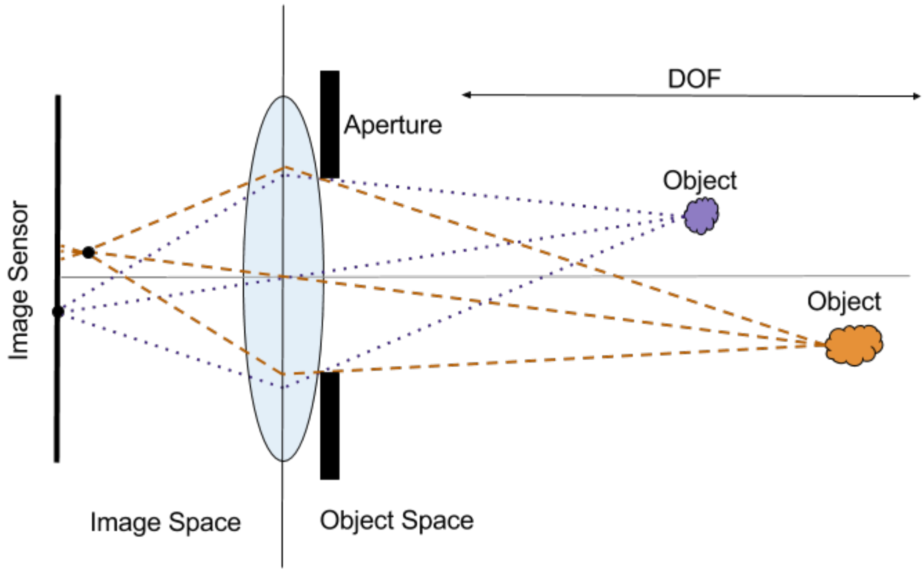


Figure 2.4: Depth-of-field when decreasing the aperture.

(a) Large aperture with fast shutter.

(b) Small aperture with slow shutter.

Figure 2.5: Example of large and small aperture[1].

The effective resolution R_e is defined as:

$$R_e = \frac{D_I}{max[|s|, s_0]} \tag{2.5}$$

where D_I is the extent of the image sensor and $s_0 = max[p, s_\lambda]$ is the minimal size of a projected point that can be resolved with the image sensor where p is the side length of a pixel.

In addition, the total resolution is defined as:

$$R_t = \frac{D_I}{p} \tag{2.6}$$

And thereby, the effective resolution ratio (ERR) is defined as:

$$ERR = \frac{R_e}{R_t} = \frac{p}{max[|s|, s_0]} \tag{2.7}$$

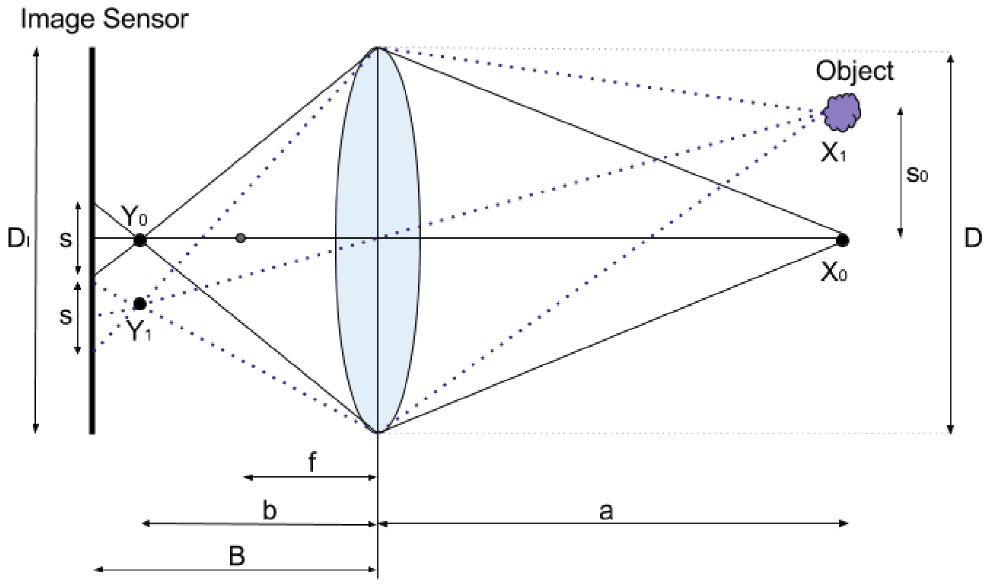


Figure 2.6: Effective resolution in optical camera.

By using the method of similar triangles, the relation between s and a can be found from Figure 2.6 as:

$$s = D\left(B\left(\frac{1}{f} - \frac{1}{a}\right) - 1\right) \tag{2.8}$$

where D is the aperture, f is the focal length, B is the distance between the main lens and the image sensor and a is the distance from the main lens to the object in object space. The effective resolution ratio for a single lens can thus be written as a function of the object distance a as:

$$ERR = \frac{p}{max\left[\left|D\left(B\left(\frac{1}{f} - \frac{1}{a}\right)\right)\right|, s_0\right]} \tag{2.9}$$

Figure 2.7 shows an example plot of the ERR, where B, D, f and p are fixed. Point X_0 is projected to point Y_0, such that X_0 is the position of optimal focus.[5][9]

Depth-of-field is often chosen as the area where the blur is smaller than or equal to the size of a pixel. For a typical camera, the main lens aperture D will be much larger that the pixel aperture p, such that the pixel to lens aperture ratio $P = \frac{p}{D} \ll 1$. By approximating $P \simeq 0$ it follows that, for a standard camera, when scaling the image down to half its size, the effective pixel size is increased by factor 2 and $ERR = \frac{1}{2}$. This in turn doubles the DOF. This shows that by simply scaling the image of a typical camera down, the camera's DOF can be extended at the cost of its lateral resolution.[5]

This section should give a good basic understanding for standard optical systems, and will help for understanding the following section introducing the plenoptic camera system.

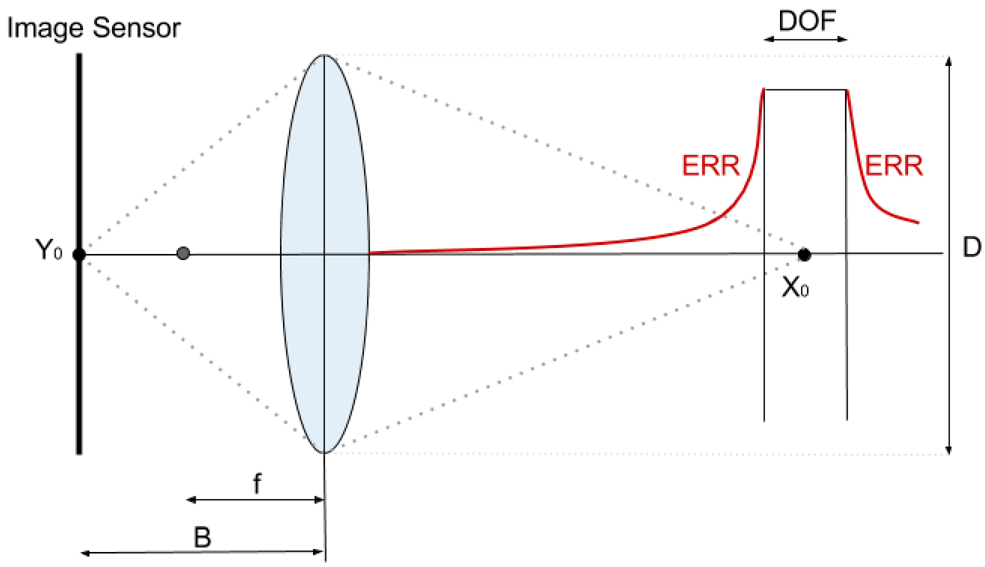


Figure 2.7: Effective resolution ratio (ERR) along with depth-of-field (DOF).

2.2 Plenoptic Camera

The plenoptic camera is very much similar and have many of the same properties as a standard optical camera. The most important difference is the additional micro lens array allowing for depth estimation and 3D rendering of a scene, and also refocusing and changing the point-of-view. The computational power needed to perform these operations is very large, thus all computations are performed on an external computer instead of internally on the camera.

This section will explain different types of plenoptic setups and show how depth is calculated, and present example images demonstrating the usefulness of the plenoptic camera. But first, some properties of the micro lens array are presented.

2.2.1 The Micro Lens Array

The micro lens array is a two-dimensional array of small lenses placed in front of the image sensor. Each individual lens has its own aperture, and the form of the aperture and the layout of the array is important for the total coverage and for the depth measurement. With the micro lens array placed at the correct distance from the image sensor the micro lenses will project small micro images onto the sensor. Each of these micro images present a slightly different view of the object from object space. When an object point can be seen in at least two micro images, depth estimation is possible. The number of micro lenses projecting a point onto the image sensor depends on the points position with respect to the micro lenses, that is, its virtual depth v. To attain a good 3D result, it is important to place the micro lens array such that each point from the object in object space is projected to the image sensor more than once. This depends among other on how the micro lenses are placed in the array. They can be placed at an orthogonal grid or hexagonal grid, as shown in Figure 2.8.

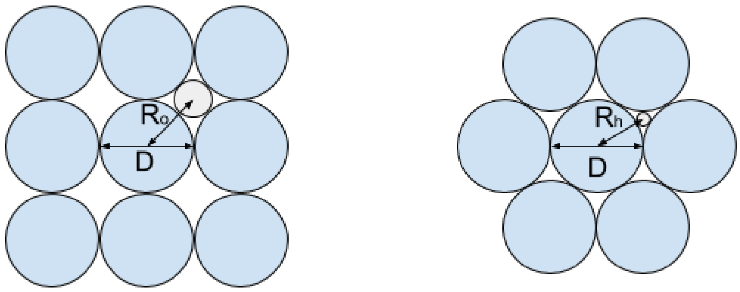


Figure 2.8: Orthogonal and hexagonal grid.

An important factor dealing with plenoptic cameras is that the micro images generated by the micro lenses should just touch on the image sensor to get a high coverage. This implies f-number matching, meaning that the f-number of the main imaging system should match the f-number of the micro lens imaging system. If the main lens and the micro lenses are assumed to be f-number matched, the border of the micro images generated by the micro lenses has the form of the main lens‘s diaphragm[3], meaning that, if the micro lenses are placed in an orthogonal grid the main lens diaphragm should have a square form and be oriented as the micro lens array. This to ensure that there are no gaps between neighboring micro images. Similarly, if the micro lenses are placed in an hexagonal grid, the diaphragm should be hexagonal.[5]

The micro lens projection cone radii R is given by:

$$R = |v|\frac{D}{2} \tag{2.10}$$

as increasing the virtual depth v also increases R linearly with the virtual depth magnitude.

For achieving a total covering of the 2D projection plane, R_o and R_h is given by:

$$R_o = \frac{D}{\sqrt{2}} \tag{2.11}$$

$$R_h = \frac{D}{2}\sqrt{1 + tan^2(\frac{\pi}{6})} \tag{2.12}$$

Defining a factor as $k = \frac{2R}{D}$ gives the factors $k_o \simeq 1.41$ and $k_h \simeq 1.15$. From this the virtual depth of the i-times covering plane is $v_i = ik$. Given that the constant k is smaller for the hexagonal grid than for the orthogonal grid, an image allowing for depth estimation can be constructed at a smaller virtual depth using the hexagonal grid.[5]

Knowing this is important as the effective lateral resolution of a plenoptic camera decreases with increased virtual depth, as will be shown later.

[3]Diaphragm: a structure in front of the main lens that limits the amount of light entering the camera. It has an opening aperture at its center.

2.2.2 Plenoptic 1.0 Setup

There are several plenoptical setups, where the difference is the placing of the micro lens array and the image sensor relative to the projection of the main lens. In the Plenoptic 1.0 setup, the micro lens array is placed in the image plane of the main lens and the image sensor is placed one focal length behind the micro lens array, and are therefore focused at infinity. This way, each micro lens focuses parallel rays onto a single point on the image sensor, and the angular distribution is then converted into spatial distribution.[10]

A figure of the setup is shown in Figure 2.9.

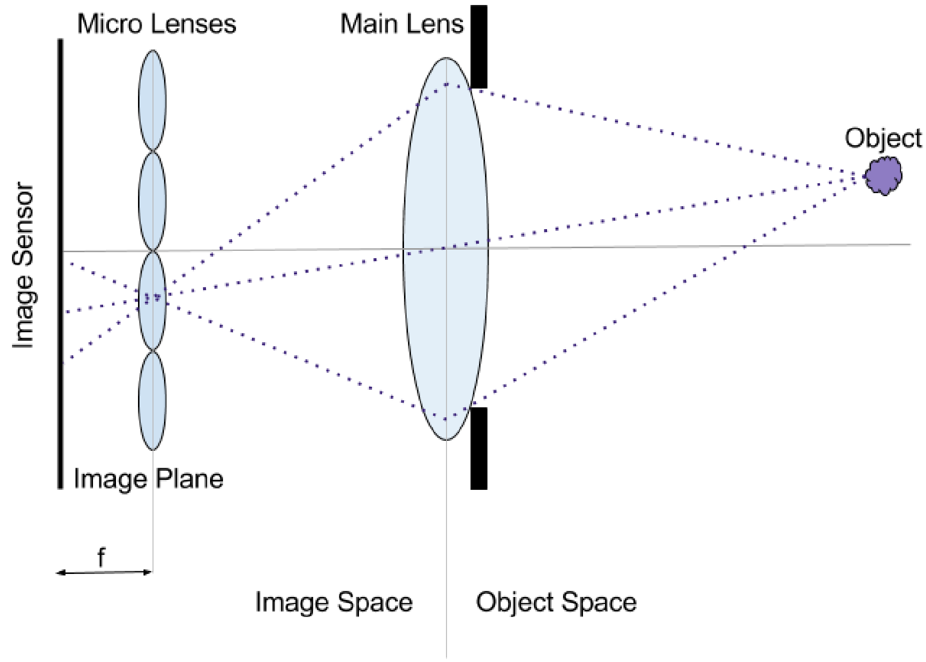


Figure 2.9: Plenoptic 1.0.

This is a very simple plenoptic setup, and thus it has some shortcomings that will be explained.

2.2.3 Plenoptic 2.0 Setup

The Plenoptic 2.0 setup can be achieved in two different ways. The first has the image sensor placed at distance B from the micro lens array, so that the image is focused on the image plane of the main lens at distance a in front of the micro lens array. See Figure 2.10.

The other setup has the micro lens array and the image sensor placed such that the image plane from the main lens is behind the image sensor. See Figure 2.11.

The main difference between the Plenoptic 1.0 and the Plenoptic 2.0 systems is the effective resolution of the generated image. The Plenoptic 1.0 system only render one pixel per micro lens, while both the Plenoptic 2.0 systems has the opportunity to produce multiple pixels for each micro lens. The Plenoptic 1.0 system will need many small micro lenses to produce an image with acceptably

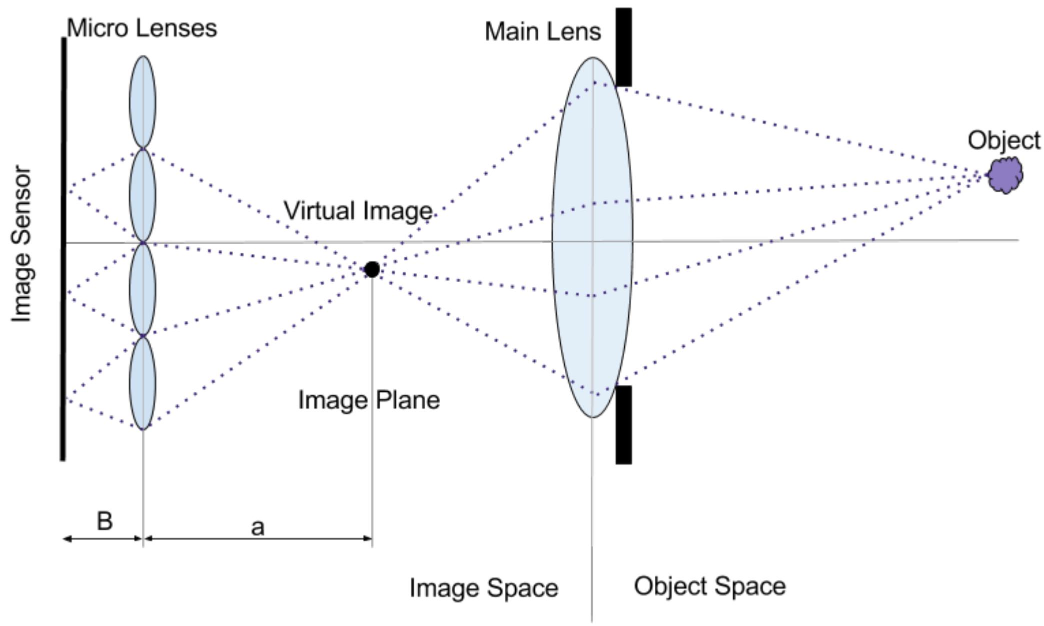


Figure 2.10: Plenoptic 2.0 with main lens focus in front of MLA.

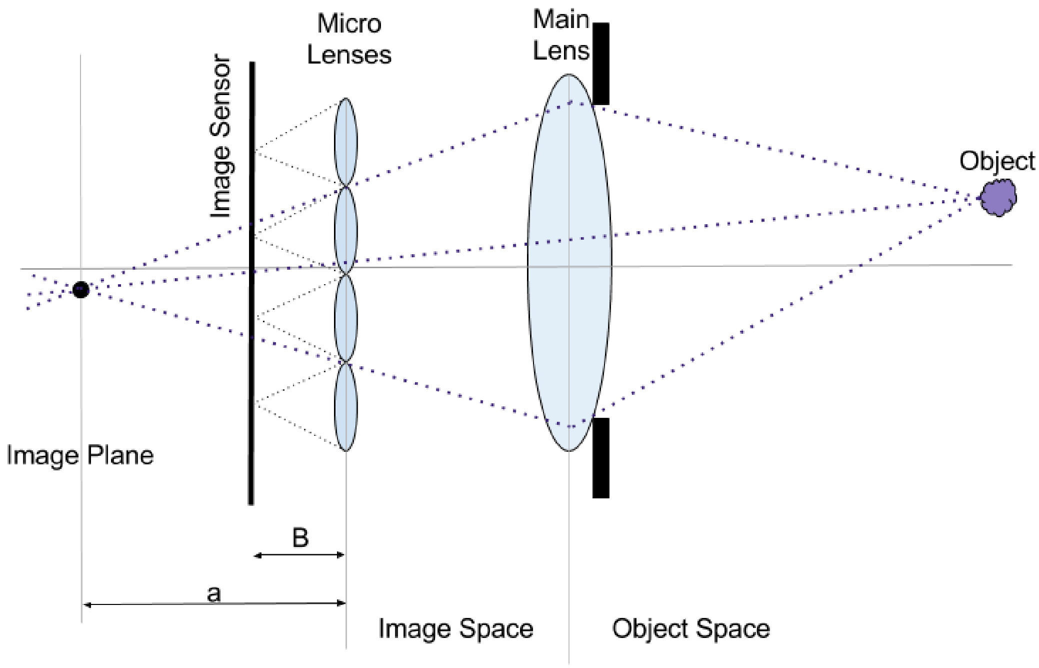


Figure 2.11: Plenoptic 2.0 with main lens focus behind MLA.

large resolution, but due to edge effects from the micro lenses it also needs more than a hundred pixels under each micro lens.[10] This limits the effective resolution of the system. The effective resolution of the Plenoptic 2.0 system can be much greater, and a resolution of $b/a * sensor\ resolution$ can be achieved, as described in [10]. Also, relatively large micro lenses can be used for avoiding edge effects. For the specific setup in Figure 2.11, the main lenses focus is set to the furthest plane of interest in object space. Depth can then be calculated for everything lying between the camera and this plane. Everything beyond the focus plane cannot be reconstructed. The effective lateral resolution is highest at the focus plane, and drops as objects get closer to the camera.

For better understanding of why the effective resolution is higher for the Plenoptic 2.0 setup, see Figure 2.12, where the pinhole model is used to clarify the differences between the setups.

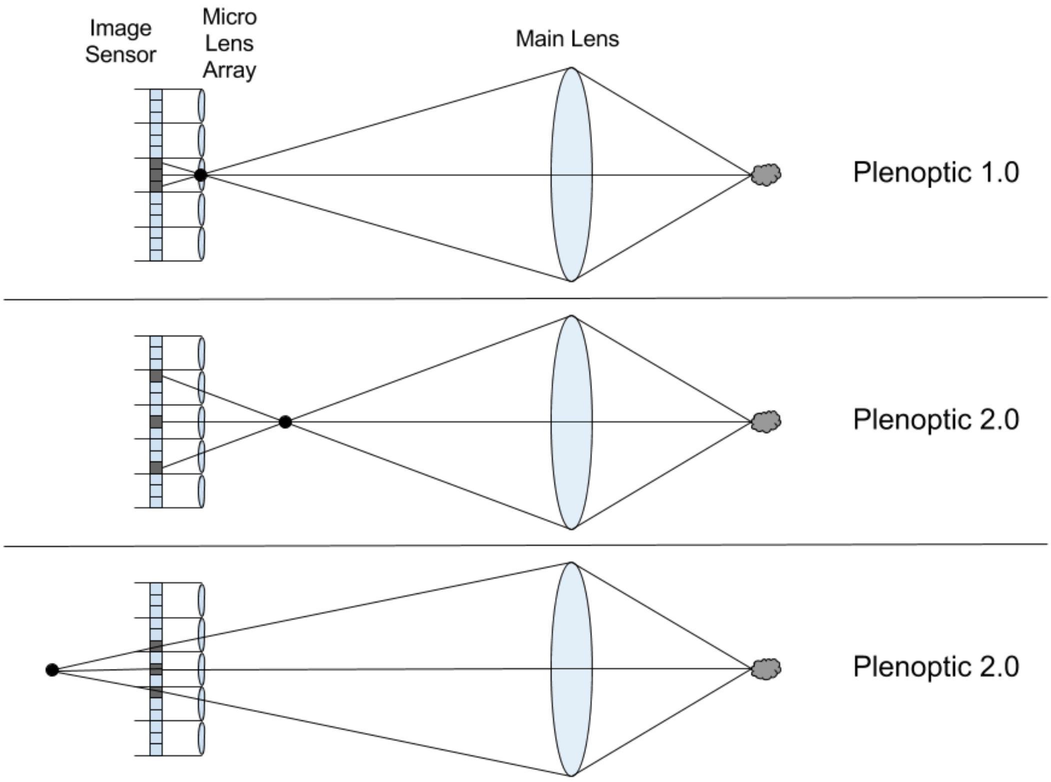


Figure 2.12: Pixel resolution for the different plenoptic setups.

It is also good to know that both Plenoptic 2.0 systems satisfy the thin lens equation

$$\frac{1}{f} = \frac{1}{a} + \frac{1}{B} \tag{2.13}$$

Since Raytrix cameras uses the Plenoptic system 2.0 from Figure 2.11, where the main lens is focused behind the micro lens array and the image sensor, this is what will be further investigated in this report.

2.2.4 Depth-of-Field in Plenoptic Cameras

As you could probably imagine, depth-of-field is an important factor when working with depth imaging. As said, it is common to assume f-number matching to make sure that the micro images should just touch, but doing so limits the depth-of-field. By choosing different micro lenses in the array the depth-of-field can be increased, and this is preferable for getting good 3D image results. Figure 2.13 shows a hexagonal setup of a micro lens array using three different lens types. That is, each type has a different focal length. Figure 2.14 shows how the projection from a point in object space will differ with the different lens types.

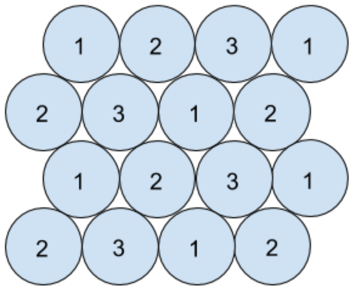


Figure 2.13: MLA with different lens types.

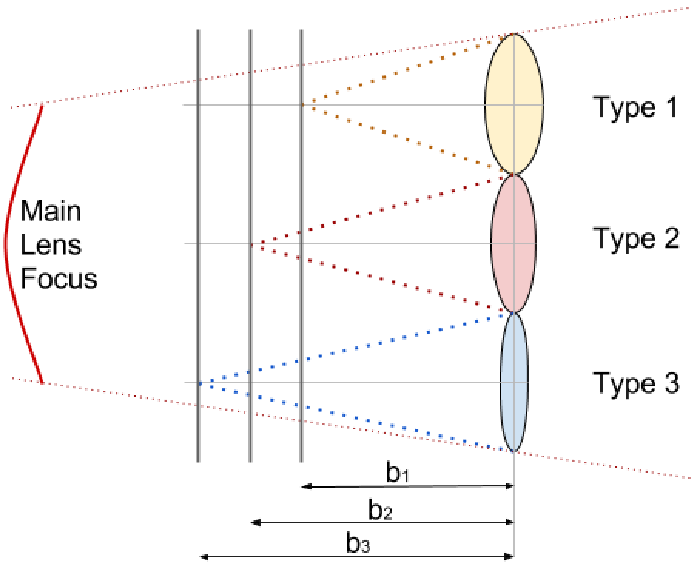


Figure 2.14: Projection from different lens types.

Using a micro lens array as presented in Figure 2.13 and Figure 2.14, gives many blurred micro images that may need to be discarded, but it will cover a much larger depth area. With enough micro lenses and a large virtual depth these blurred images can be accounted for and the depth-of-field is increased and thus the depth rendering is improved for scenes with great depth extent.

Another important thing to be aware of is the field-of-view in relation with depth-of-field. Different main lenses can be selected to the same plenoptic camera to adjust the depth-of-field and the field-of-view. However, for a larger field-of-view the depth-of-field is also increases, but the object will need to be closer to the camera to obtain a good depth resolution. To attain a good depth resolution for objects further away, the field-of-view must therefore be reduced.

Figure 2.15 shows the raw output from a Raytrix plenoptic camera with three different lens types in the micro lens array. It is clear to see the differences in the focus area of the different micro lenses.

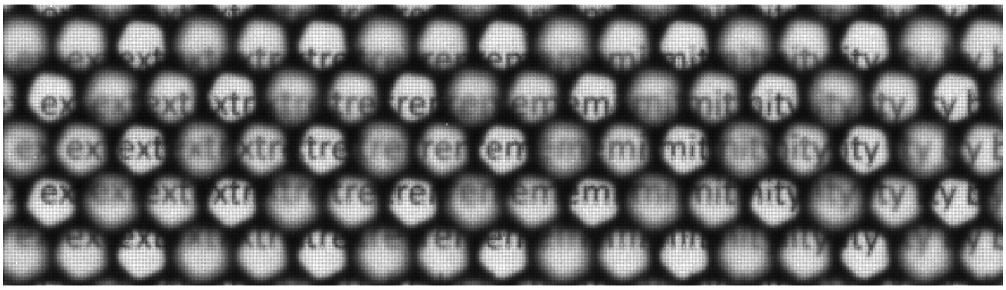


Figure 2.15: Raw output from a plenoptic camera with three different lens types.

2.2.5 Depth Estimation

Defining *total covering plane* (TCP) as the plane closest to the micro lenses where each point on the plane is projected by at least one micro lens, and *double covering plane* (DCP) as the plane closest to the micro lenses where each point is projected by at least two micro lenses, it is easy to understand that depth estimation can only first begin at the double covering plane.[5]

The main lens must be focused on or beyond the DCP behind the image sensor. If the main lens focus is any closer to the image sensor, no depth estimation is possible. When an object point can be seen in at least two micro images, the virtual depth of the object point can be estimated, and so depth estimation is possible.

To be able to identify pair of points in the different micro images, small areas with high contrast are analyzed. For each of these areas, the cross correlation for small pixel points is computed across neighboring lenses. If the cross correlation is above a certain threshold, the two pixel points is assumed to show the same object point.[11] Trying to compare areas without high local contrast will result in a high cross correlation for many places, and thereby give incorrect results. This means that to attain good depth estimation results, the surface of the object of interest must have high local contrast.[11]

The needed value for estimating depth is the object distance a, as seen in Figure 2.16. This value will give metric information about the projection behind the MLA and be further used to calculate the actual distance to the object in object space.

To calculate the object distance a, the virtual depth v must first be found. The virtual depth is used as a measure of how many micro lenses registers the same point.

Defining the distance C as the distance between the centers of micro lenses c_1 and c_2, and $i_1 - i_2$ as the distance between the same point in two micro images, the virtual depth can be calculated by the intercept theorem:

$$v = \frac{C}{C - (i_1 - i_2)} \tag{2.14}$$

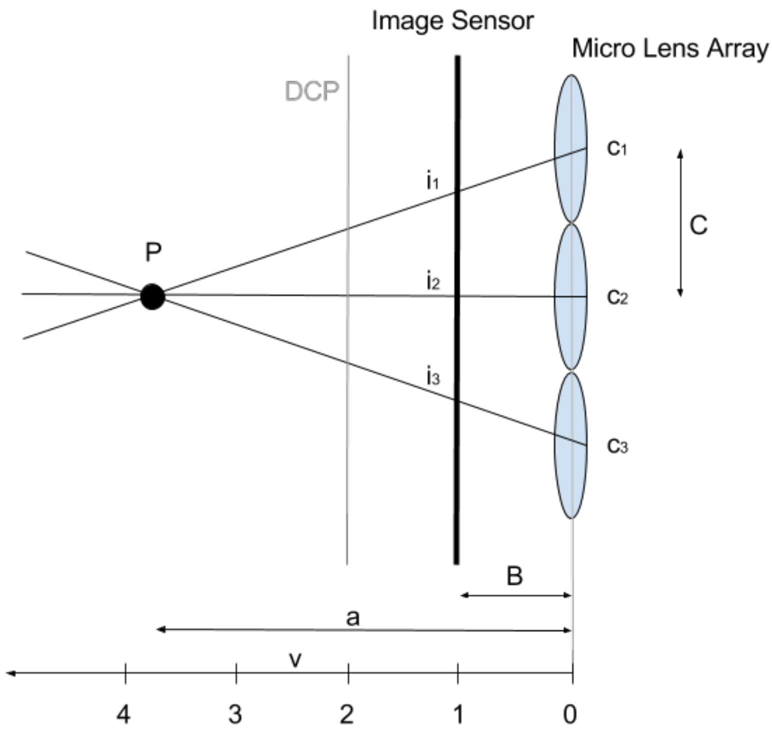


Figure 2.16: Depth estimation principle.

B is known to the camera, and is set during a metric camera calibration. When both B and the virtual depth v is calculated, a can simply be found from the equation:

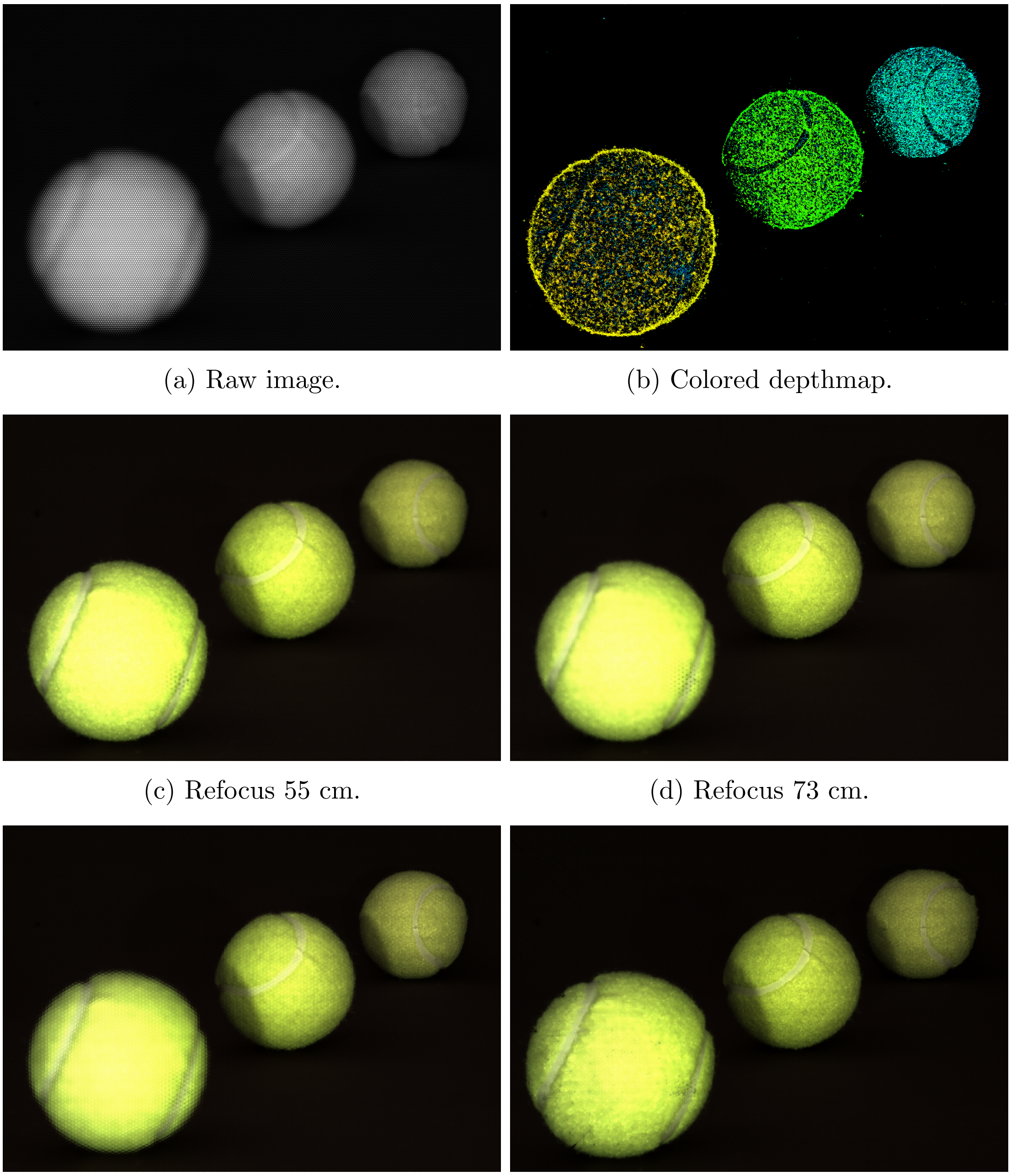
$$a = vB \tag{2.15}$$

a is then used to find the actual depth in object space by using values calculated during the metric calibration.

2.2.6 Reconstructing Images from the Raw-image

Performing the depth estimation process for the entire raw image, depth information about the scene can be generated and stored in a depthmap. Also, using different lens types in the micro lens array, refocused images can be constructed. Using many focusing areas can also generate a totalfocus image.

The details of these calculations will not be explained, but images showing the concept is shown in Figure 2.17.



(a) Raw image.

(b) Colored depthmap.

(c) Refocus 55 cm.

(d) Refocus 73 cm.

(e) Refocus 90 cm.

(f) Totalfocus.

Figure 2.17: Images produced by plenoptic technology.

Chapter 3

Raytrix Technology

Raytrix is a German company founded in 2008 offering several 3D Light Field cameras intended for professional and industrial use. They were the first to create and market commercial plenoptic cameras. Metric 3D information can be captured with a single light field camera through a single lens in a single shot using just the available light. Raytrix has specialized on developing light field cameras for industrial applications. A patented micro lens array design allows for an optimal compromise between high effective resolution and large depth-of-field. Raytrix cameras are already in use in applications like volumetric velocimetry, plant phenotyping, automated optical inspection and microscopy, to name a few.[12]

3.1 Raytrix R42 Camera

Figure 3.1: Raytrix R42 Camera[2]

The camera used throughout this research is the Raytrix R42 camera. The R42 is Raytrixs highest resolving light field camera to date. It is based on a 42 megaray[1] sensor and offers an effective resolution up to 10 megapixels at 7 FPS.[2]

[1]Megaray: measure of light field data capture. 42 megaray means 42 million light rays are captured per image.

The Raytrix R42 cameras micro lens array contains about 40,000 micro lenses. Raytrix's MLA is placed between the main lens and the image sensor, and the focus from the main lens is set behind the MLA and the image sensor. The images generated by the camera are processed on a PC with appropriate software algorithms to calculate the scene depth and to reconstruct a 2D image. All processing is done on a GPU, which allows for fast processing.[13]

3.2 Camera Calibration

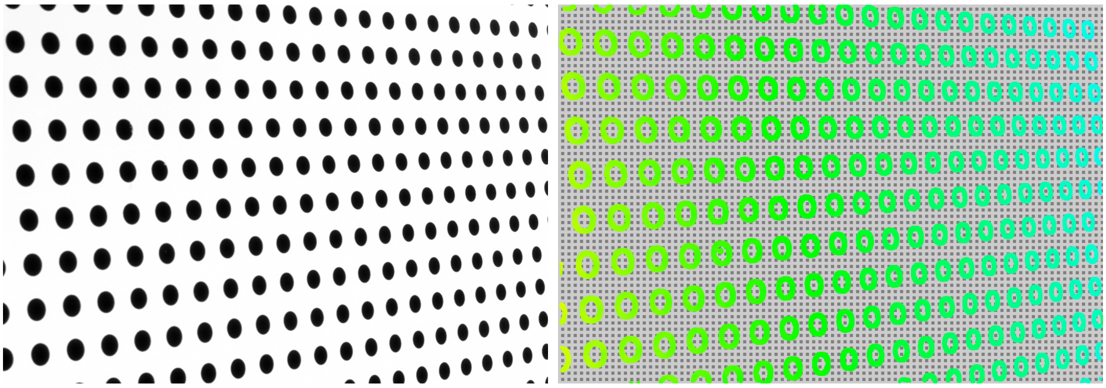
Properly calibrating the camera is very important for obtaining good results both for the depthmap and the refocus image. The camera is sensitive to light changes, and the camera should be recalibrated every time the light conditions changes or when the depth-of-field should be moved closer or further away from the camera. The camera calibration is done in two steps: MLA calibration and metric calibration.

3.2.1 MLA Calibration

The MLA calibration is used to set the focus point, the furthest depth plane and the aperture. The aperture is set in terms of the lightning conditions, and must be adjusted whenever the lightning conditions changes. During MLA calibration, the focus plane and the furthest depth plane are also chosen. After the calibration, it is not possible to use the Raytrix software to focus behind the furthest depth plane, only to some distance in front of it. Raytrix software also uses this focus to decide that every measurement behind that plane has undefined depth and is assigned the value 0 in the depthmap and is set to black in the colored depthmap.[14][13]

3.2.2 Metric Calibration

The metric calibration sets the distance between the MLA and the image sensor and makes conversions from depth in image space to depth in object space. This calibration uses a dotted target where each dot is placed a certain distance from each other. Each dot should have a diameter d, and the distance from neighboring dots center to center should be $2d$. The target is placed in front of the camera at the distance where objects should be placed, and the target should cover most of the cameras field-of-view. The target is then set at different angels and pictures are taken. Four different angles should be used with the desired depth range in each picture to attain the best calibration results. RxLive along with the user then verifies the results and perform the calibration. RxLive calculates the projection model parameters by projecting points from virtual space to object space and calculating residuals to best fitting metric dot target models.[14][13] An example image for the metric calibration and the result of the calibration is shown in Figure 3.2.



(a) Calibration image of target. (b) Resulting calibration depth info.

Figure 3.2: Example of how the metric calibration is performed and its result.

3.3 Raytrix Light Field API

The only image delivered by the Raytrix camera to the computer is the RAW-image. This RAW-image shows the scene through the MLA. All further processing is done on a GPU, and therefore Raytrix has their own API along with their own software tool, RxLive. All computation available in RxLive can also be achieved by the user through the use of the Raytrix API. Before a refocused image, the totalfocus image or the colored depthmap can be extracted, the depth must be calculated. Figure 3.3 shows the process using the Raytrix API of loading a ray image and calculating both the depthmap, the colored depthmap, the depth 3D image and the totalfocus image. The order of the steps is important.

The Raytrix API also has many preprocessing and postprocessing options available. These are all in real-time and mostly useful for the depthmap. In preprocessing it is possible to filter out some noise and to use a sharpening algorithm. Examples of post-processing is simple filling, setting minimum and maximum depth, choosing minimum correlation and minimum standard deviation. The API also has tools for calculating the distance between to pixel points, which will be frequently used in the experiments of this research.

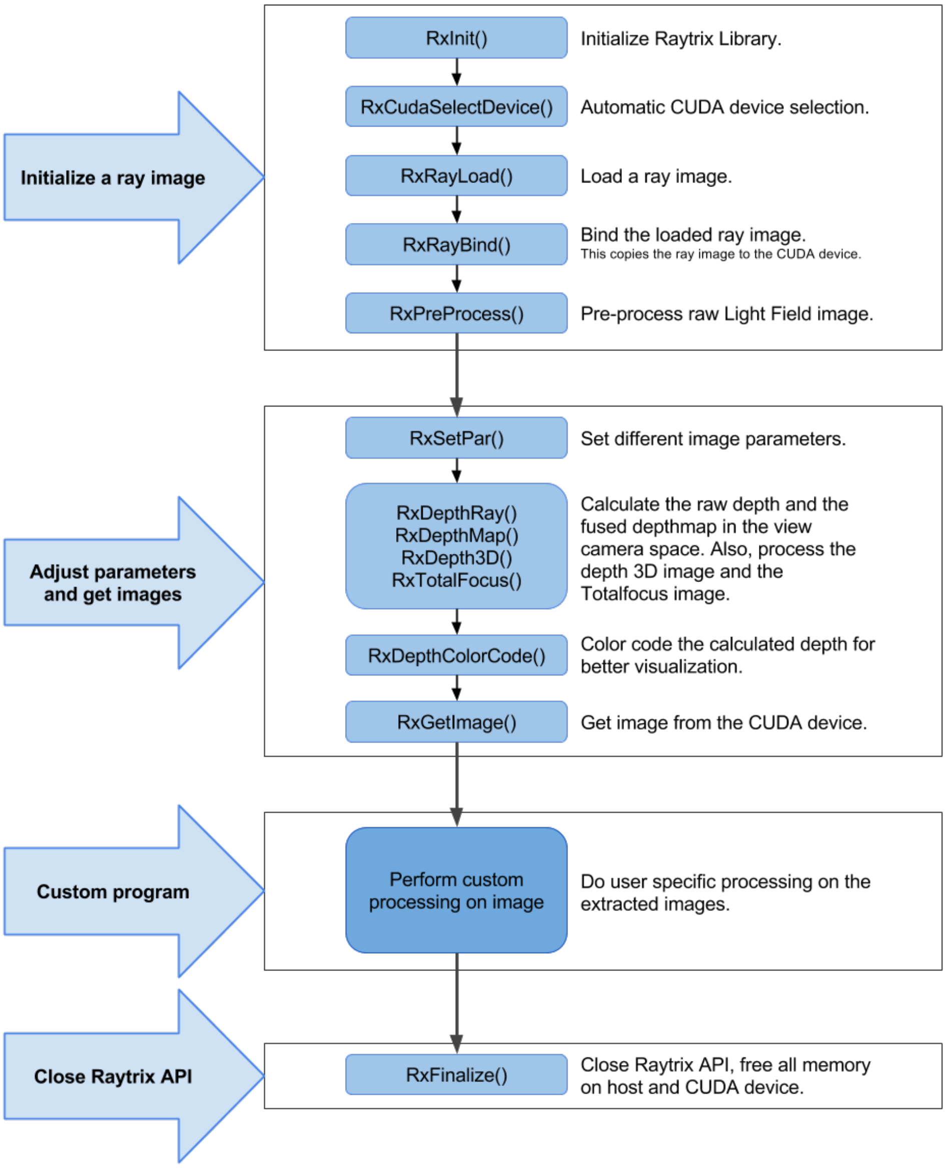


Figure 3.3: The basic Raytrix API process.

3.4 The Depthmap

The obtained depthmap is stored as a .tiff file with one channel containing 32-bits representing the depth. All pixels containing depth information has a negative floating value, while all pixels with no assigned depth information has value 0. The reason why the values are negative is because the positive direction is from the camera pointing backwards. That is, the negative value is the calculated depth in *mm* from the camera to the object when the reference plane is set to the furthest depth plane/focus plane.

The colored depthmap is a good image to have when working with depth, as it is visually easier to see that the shape and curvature of the object is correct, as seen in Figure 3.4. It is possible to choose different coloring patterns, so the color

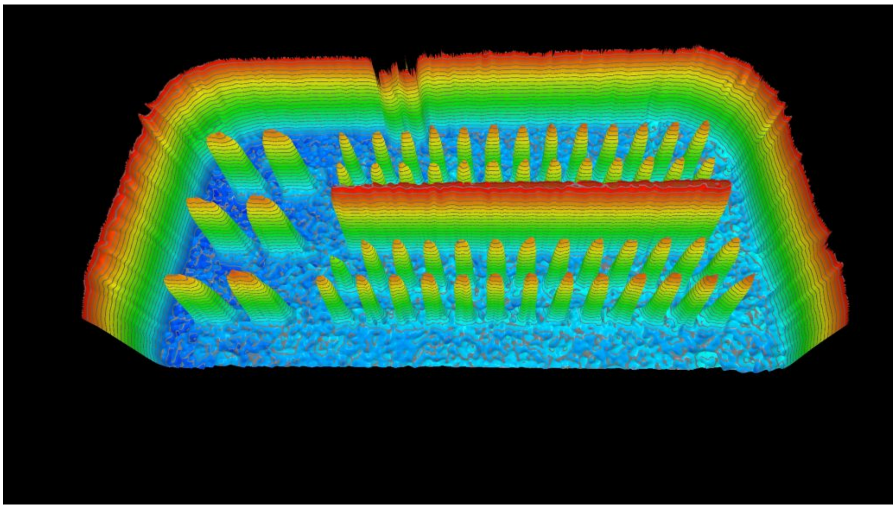


Figure 3.4: Optimal depthmap from Raytrix R42 represented in 3D.[2]

has no connection to the actual depth.[2]

3.5 Lens Type Specifications

Along with the Raytrix R42 are two different lenses, the 12 mm and the 25 mm. The specifications are very different for the two lenses, and therefore also the usage area. Some specifications mostly intended for this research is listed below. We want a large depth-of-field, a wide field-of-view, a large lateral resolution and a working distance ideally up to 2 m (distance from camera to object). The calibration algorithms are not yet intended for calibrating beyond about 1 m to 1.2 m, so the specifications presented are therefore the ones most fitting to the area up to 1.2 m. The specifications presented are for the camera in air. Underwater the values can be slightly changed due to the magnification effect from the water.

3.5.1 12 mm

The 12 mm lens is intended for a very small working distance, but through many calibration rounds it has seemed to give decent results also for larger distances. For these larger distances the camera must be calibrated with two different calibration targets to be able to perform the calibration calculations. The specifications listed in Table 3.1 are not documented by Raytrix, and is therefore missing the minimum lateral resolution and depth resolution.

[2]During this research a new version of RxLive was released and has been used. The coloring mode of the colored depthmap should be using rainbow colors, where each color represents a different depth. This seem to sometimes not work properly in the new software. So, a colored depthmap presented in this report may be all one single color, when it should have several. The actual depth results are still the same, and the colored depthmap is still of good use as to show the number of depth points in an image.

Max Working Distance	120 *cm*
Field-of-View at 120 cm	92 *x* 66 *cm*
Max Depth-of-Field	48 *cm*
Max Lateral Resolution	-
Max Depth Resolution	-
Calibration target pitch-point	14 *mm* and 40 *mm*

Table 3.1: Specifications of the 12 mm lens.

3.5.2 25 mm

The 25 mm lens is intended for distances from 5 cm up to 90 cm, and also has documented specifications for working distance at 90 cm. These are listed in Table 3.2.

Max Working Distance	90 *cm*
Field-of-View at 90 cm	33 *x* 23 *cm*
Max Depth-of-Field	48 *cm*
Max Lateral Resolution	88 μm
Max Depth Resolution	3.76 *mm*
Calibration target pitch-point	14 *mm*

Table 3.2: Specifications of the 25 mm lens.[2]

Chapter 4

Salmon Fish Farms and Biomass Estimation

When doing fundamental work where the goal is to validate metric results underwater using plenoptic camera technology, it is good to have in mind that the overall goal is to someday use this technology for biomass estimation. It is important to consider both the environment for the system and how the actual biomass estimation can be performed. This chapter will give a short description of the breeding process of Atlantic Salmon along with the water conditions in the ocean fish farms. Results found in the preproject which are of importance for this research is stated, and some potential biomass estimation methods are explained.

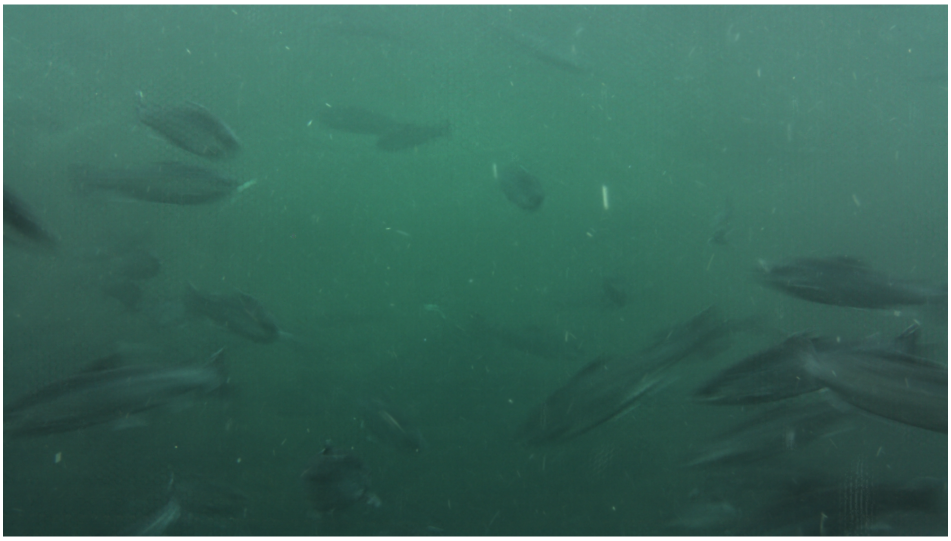
4.1 The Norwegian Salmon Breeding Process

Aquaculture is a vital industry in Norway, as it creates jobs and value. Sustainable production is a precondition for long-term development and growth. The industry is putting a lot of resources into the welfare of the fish and all species in its surroundings. The most vulnerable part of a farmed salmon's life is in the saltwater due to the salmon lice. The lice kill about 20 % of all farmed salmon, and it is hard to get rid of.

The start of an Atlantic Salmons life is in freshwater. The parr lives their first year in freshwater where they grow until they reach 50-100 g. When the parr is ready for migration to the saltwater sea, they become smolt. They are then moved to saltwater farms in the ocean, where they live for 11-18 months, depending on the smolt's size. For the process to be profitable, the salmon are put in large farms, counting up to 200,000 fish in each farm. Since the saltwater phase is the most vulnerable part, the industry is now trying to reduce the time spent is saltwater. This means the smolt must grow even bigger in freshwater facilities before being brought into the sea.

The salmon must normally weigh between 3-6 kg before being slaughtered. Today there are no methods of determining the mean weight of the fish inside a farm. As it is very hard to estimate how fast they grow and what they are weighing, it is also difficult to plan the production. The benefits of a good biomass estimation are many. The production planning would be easier as it would be possible to see at what rate the fish grows. Due to better production planning, the time spent in saltwater could possibly be reduced, thereby decreasing the vulnerable part of the farmed salmon's life. Better production planning would also lead to profits, as it would be possible to know how much fish can be brought to the market at any time.

As explained, there are many steps to be considered through a salmon breeding process. And the use of better technology solutions could help improve the process. Figure 4.1 shows the life inside a fish farm. Figure 4.1a is a bad quality image where the fish are blurry and particles are showing very well. Luckily, better underwater camera technology is under development. As seen from Figure 4.1b, SEALAB has managed to get high quality images also underwater inside a noisy fish farm.



(a) Bad image from inside a fish farm.

(b) Good image from inside a fish farm.
Photo: SEALAB.

Figure 4.1: God and bad images from inside an ocean fish farm.

But, dealing with underwater depth measurement, many challenges are still expected. The water consists of many particles coming from food and excrement, as seen from Figure 4.1a. Also, the lightning is nearly always a problem dealing with underwater imaging. The physical properties of water causes degradation effects that are not present in air. The water absorbs light and thereby limits the visibility distance, while also causing scattering which changes the direction of the light path. Underwater light scattering is the deflection of a ray from a straight path, caused by the irregularities in the water medium and particles. Deviations due to irregularities on the water surface are also usually considered as a form of scattering. Thus, scattering comes not only from the water itself, but also from all particles in the water and from the water surface. This influences the overall performance of underwater imaging systems.[15] The light scattering automatically limits the working distance of a camera in water. When the water also contains lots of particles, the working distance is reduced even more. This must be taken into account when considering the working distance for the plenoptic camera.

The water medium properties will cause more noise than air, and as the water within a fish farm also contains a relatively large number of particles, some noise reduction and particle removal will most likely be necessary for a biomass estimation system. Removal of noise for improving the depthmap was the preproject for this research. The main results and observations from that study is described in the following section.

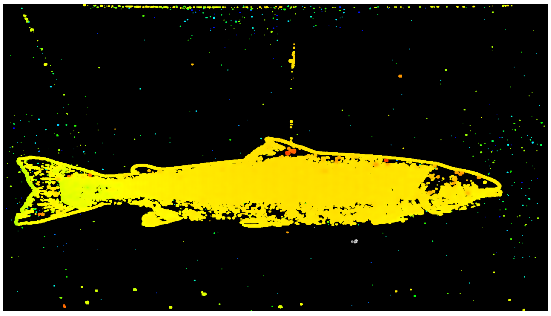
4.2 Summary from Preproject

In the preproject for this research it was investigated if it was possible to improve the depthmap by removing noise and fill out the undetected depth areas in the image. In the preproject research there was not used any metric data, as the camera was only MLA calibrated. The results from the preproject came from the R42 color camera with the 12 mm lens, and the images are taken of a dead Atlantic Salmon in clear water. Though the Atlantic Salmon does not have very high contrast colors, it does have a dotted pattern, and the camera was able to detect depth on large parts of the fish. The depthmap turned out pretty good, and with some simple noise removal and filling, the result was even better. By looking at the depth information along the fish, it was clear to see that the curvature of the fish was preserved and within reason and that the surface was smooth. The only drawback of the results was that the depth data around the back find and the head of the fish was not as accurate. There was a lot of noise there, due to the color similarities with the dark background. Since the open sea has a lighter background than the test facility, this noise is most likely reduced under real conditions. This means the depth data obtained in optimal conditions from an Atlantic Salmon should be usable for measuring volume.

The drawbacks of the preproject was that the process did not have real-time feature and it was never tested with a metric calibration of the camera. The Raytrix API has also been renewed since then, so more processing can now be done in the software to obtain a good depthmap.

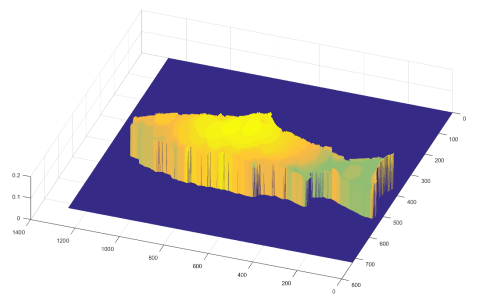
Since the preproject could determine that the pictures taken by the Raytrix

R42 could obtain good depthmaps of actual salmon, it is not investigated as part of this research, but assumed that the camera is able to attain good depthmaps of real salmon if the conditions allow for it. This research is therefore mostly focused on fundamental work with the Raytrix camera, and obtaining good metric measurements. The goal is also to obtain the best possible depthmap without the use of postprocessing. Therefore, none of the methods from the preproject has been used in this research.

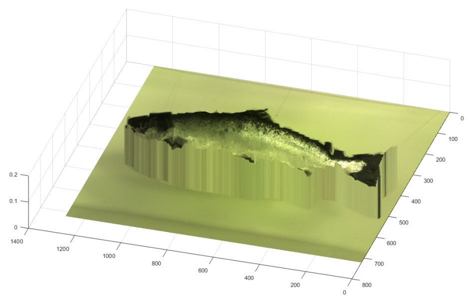


(a) Original depthmap image form preproject.

(b) Postprocessed depthmap image from preproject.



(c) 3D image of postprocessed image.



(d) 3D image of postprocessed image with overlay.

Figure 4.2: Results from preproject.

4.3 Potential Biomass Estimation Methods

Considering the results from the preproject, establishing reason to believe that the depth data obtained in a real scenario of Atlantic Salmon in saltwater farms can be used for volume measurement, the next thing missing are reliable metric measurements.

This research will see if the metric measurements done with plenoptic technology can be verified underwater. Meaning that the results must correspond to the actual value. If the metric measurement can be verified to give decent results underwater, an actual biomass estimation could be possible.

Biomass estimation could potentially be done in two different ways, where both depends on having a good image of the fish from the side along with some classification algorithm for determining if and where to do the measurement.

One way of estimating volume is to find a plane through the fish, and measure volume in front of that plane before multiplying by two. This means that the image should be as directly from the side as possible. Then use the depth data around the fish to make a back plane. All data points in front of that plane, belonging to the fish is then used to measure the volume of half the fish. This method also requires that the entire fish has depth data points, that are either measured directly by the camera or reconstructed. Much postprocessing in an unstable environment can be very difficult, and it is therefore hard to say if the results would be acceptable.

Another method of estimating volume is to use a database of premeasured fish. It could then be possible to measure length, height and some thickness points on the fish, and use the best match weight found in the database. This method would most likely give less postprocessing on the depthmap.

Since none of these methods are implemented, it is hard to say what would give a better result.

Given the information presented in this section, there are some parts that is of major importance and must be considered during testing. One important detail learned through the preproject is that of distance to the object due to particles. If the object is far from the camera more light may be needed, more scattering affects the image and a larger shutter may be needed. If the object is close to the camera, less light may be needed, less particles between the camera and the object reduces scattering, and a lower shutter may be used. This is of importance for the testing. As the fish swims fast, a low shutter is wanted along with a clear image of the fish.

The next important thing is that classification must most likely be used for doing biomass estimation. Classification is needed to know if the object appearing in the image is indeed the wanted object, and if the second option for biomass estimation is used, the different parts of the fish must also be located to know where the measurements should be done. The use of classification implies that the entire fish should appear in the image. This means that the field-of-view should be of such a scale that fits these requirements without affecting the depth-of-field too much.

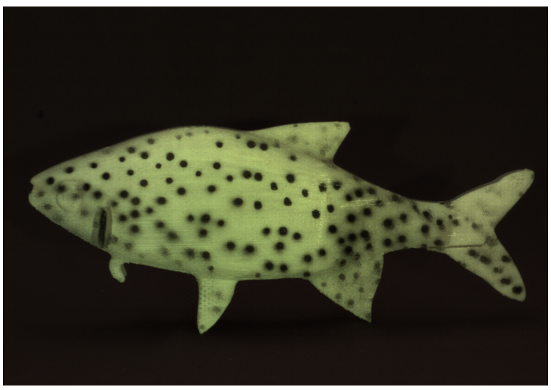
Chapter 5

Experiments

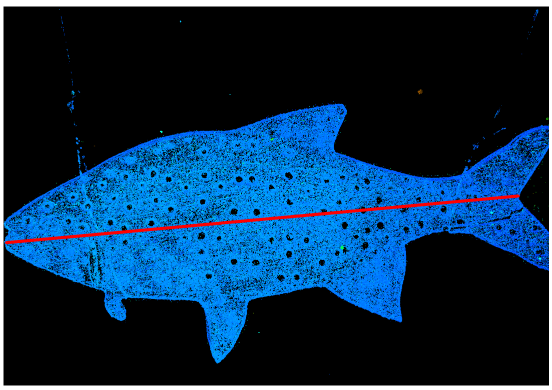
This chapter presents the different experiments done with the Raytrix R42 color camera. The focus of the tests is to find the best possible setup and verify the metric measurements underwater. For testing the setup environment and make clear if the background has any impact on the depthmap, several tests has been conducted in air. It has also been tested using both a dome and a flat port housing, and both the 12 mm and the 25 mm lens has been used.

Since the calibration process is what mostly determines both the quality of the depth data and the 2D image, many different calibration setups have been tried out for each test, and only the best ones are used. During calibration, the metric calibration is rated by the software as to its correctness. It is rated in stars from 0 to 5. When using the 12 mm lens, the best calibrations provided were the ones where two targets where used. One close to the camera, and one further away. When using two target boards the rating always got 0 stars, though the calibration was good. The number of stars for each test is listed in each test, as an indication on how difficult the calibration process was for each setup.

The object target used throughout these tests is a test-fish in plastic shown in Figure 5.1a. The test-fish has an exact length of 22.0 cm from the front of its head to the middle of its back find. Figure 5.1b shows how the length is measured on a depthmap.



(a) Test-fish with length 22.0 cm from front to middle of back find.



(b) How length is measured on the test-fish.

Figure 5.1: Test-fish used in experiments.

The name of each test explains the setup. The first parameter is the lens type, second parameter describes the selected background, and the third parameter describes the environment and what type of housing was used for the camera, dome or flat port. The dome has an outer curvature radius of 50 mm. Both the dome and the flat port is made of high quality glass and are 4 mm thick. The dome and the flat port are attached to the wall of a water tank.

For each test, 10 images were taken of the test-fish at three different depths. Then the length of the test-fish was measured for each image using the Raytrix API. The mean value along with the standard deviation is presented for each test. Postprocessing of the depthmap was minimized during image taking, and no filling has been used.

Since most of the tests uses different calibrations, the results may be good though they are not completely correct. Small changes can be improved in the calibration, but the important thing is that the measurements corresponds and that the standard deviation is low.

The parameters used in RxLive, together with all the measurement data can be found in the corresponding test section in Appendix A (Chapter 7).

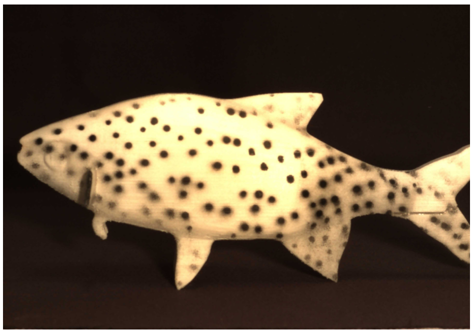
5.1 Experiments in Air

Since the camera was originally not made for underwater circumstances, the calibration should do better in air. The experiments in air are for determining how good the results can be with no scattering and particles in front of the object. In addition, different backgrounds are tested to see if there are any differences in the results. Since the calculation of depth is based on disparities and measures mostly high contrast areas, it is predicted to get better depth results on the actual test-fish when the background is plain, rather that structured. Backgrounds are chosen to be black, white and structured black and white text.

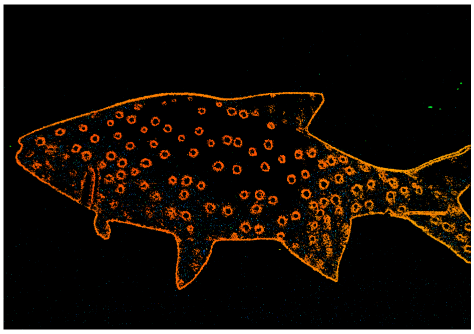
5.1.1 Test 1 - 25mm, Black, Air

Calibration		
Calibration result:	3 stars	
Measured lengths		
Distance:	**Mean value:**	**Standard deviation:**
70 cm	205.5 mm	0.44
85 cm	197.3 mm	0.82
100 cm	188.9 mm	2.69

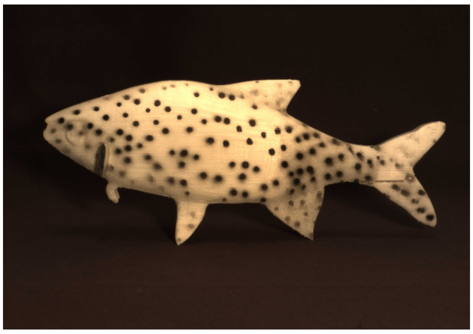
Table 5.1: Results for test 1.



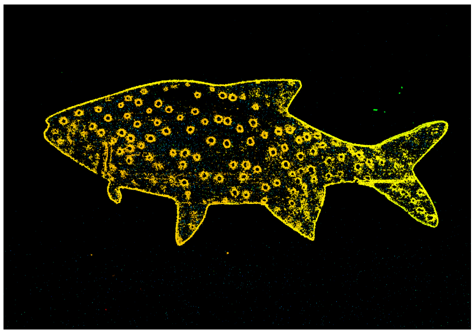
(a) Refocus 70 cm.



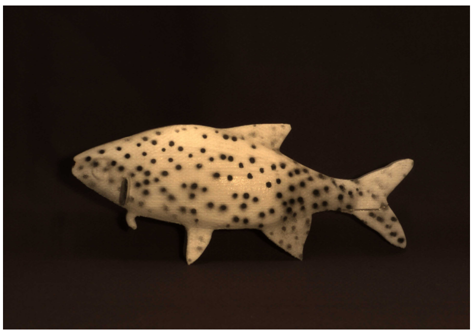
(b) Depthmap 70 cm.



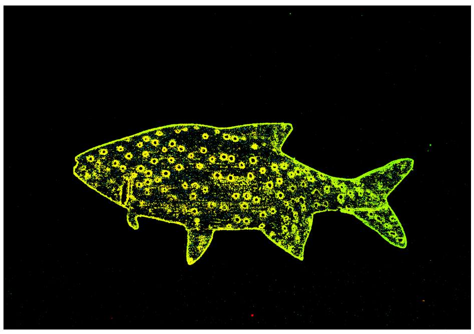
(c) Refocus 85 cm.



(d) Depthmap 85 cm.



(e) Refocus 100 cm.



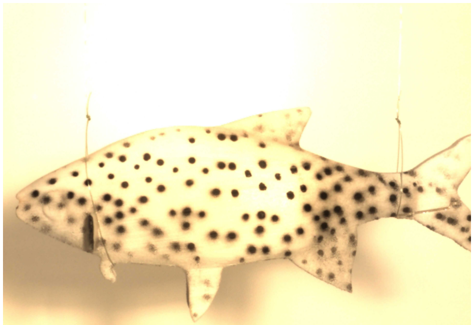
(f) Depthmap 100 cm.

Figure 5.2: Test 1 image results.

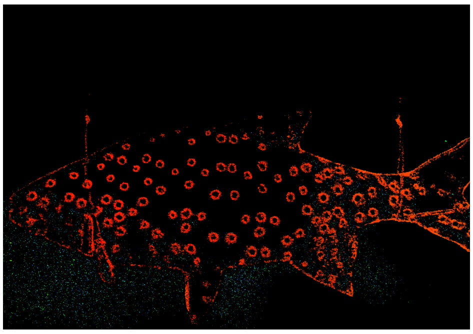
5.1.2 Test 2 - 25mm, White, Air

Calibration		
Calibration result:	2 stars	
Measured lengths		
Distance:	**Mean value:**	**Standard deviation:**
70 cm	235.5 mm	1.10
85 cm	233.6 mm	1.79
100 cm	230.5 mm	2.91

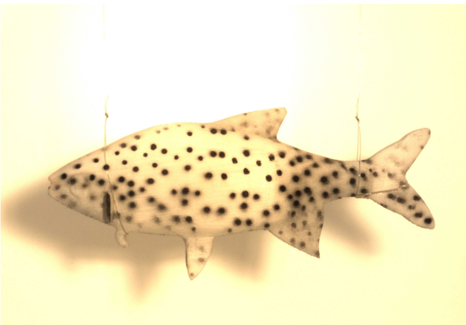
Table 5.2: Results for test 2.



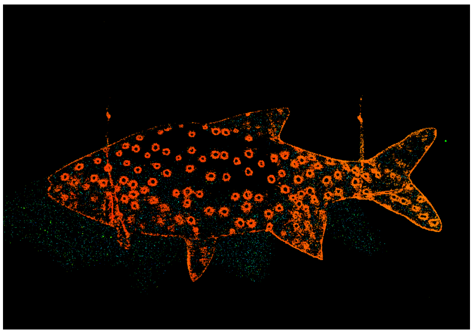
(a) Refocus 70 cm.



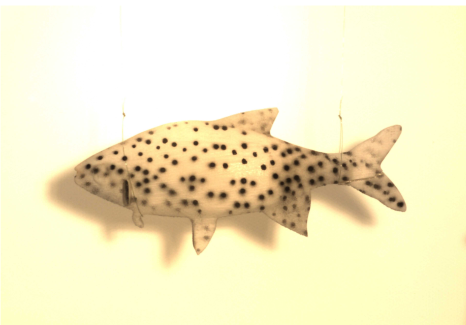
(b) Depthmap 70 cm.



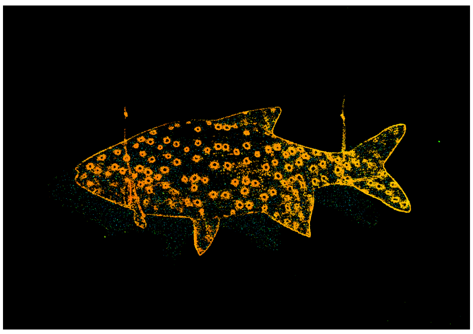
(c) Refocus 85 cm.



(d) Depthmap 85 cm.



(e) Refocus 100 cm.



(f) Depthmap 100 cm.

Figure 5.3: Test 2 image results.

5.1.3 Test 3 - 25mm, Structured, Air

Calibration		
Calibration result:	2 stars	
Measured lengths		
Distance:	**Mean value:**	**Standard deviation:**
70 cm	209.0 mm	1.79
85 cm	200.4 mm	1.46
100 cm	235.7 mm	2.68

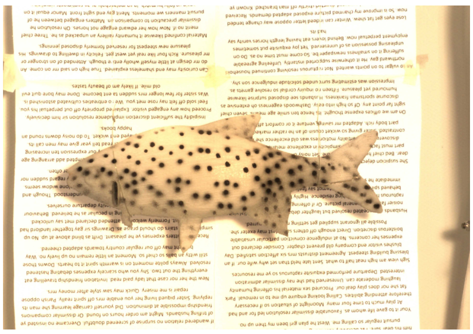
Table 5.3: Results for test 3.

(a) Refocus 70 cm.

(b) Depthmap 70 cm.

(c) Refocus 85 cm.

(d) Depthmap 85 cm.



(e) Refocus 100 cm.

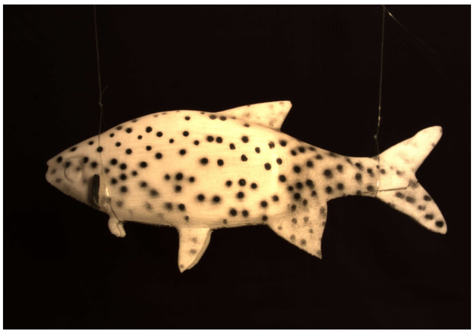
(f) Depthmap 100 cm.

Figure 5.4: Test 3 image results.

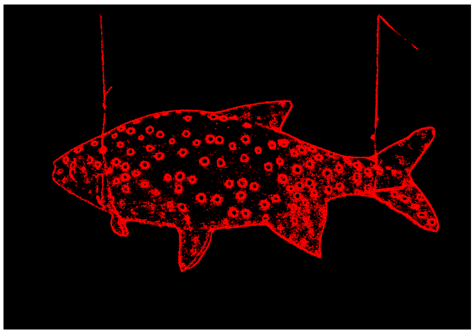
5.1.4 Test 4 - 12mm, Black, Air

Calibration		
Calibration result:	0 stars	
Measured lengths		
Distance:	**Mean value:**	**Standard deviation:**
40 cm	218.4 mm	2.99
80 cm	200.9 mm	3.62
120 cm	199.5 mm	6.43

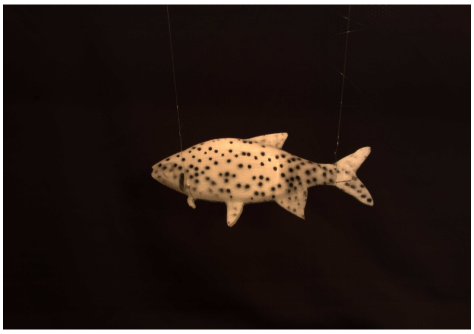
Table 5.4: Results for test 4.



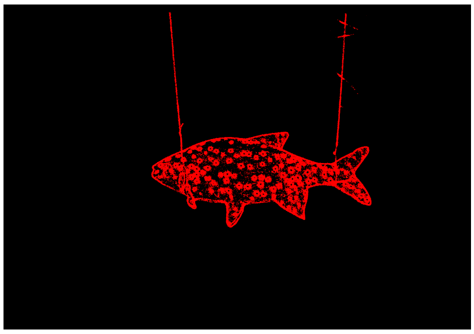
(a) Refocus 40 cm.



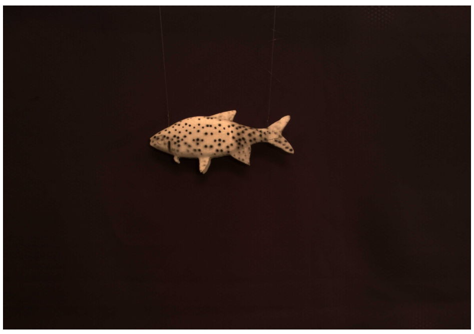
(b) Depthmap 40 cm.



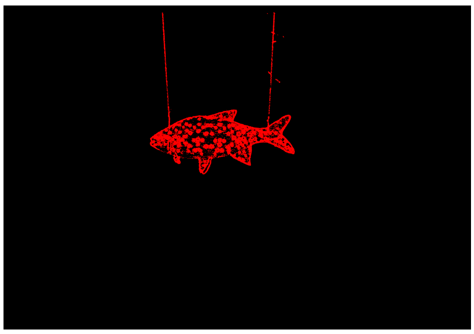
(c) Refocus 80 cm.



(d) Depthmap 80 cm.



(e) Refocus 120 cm.



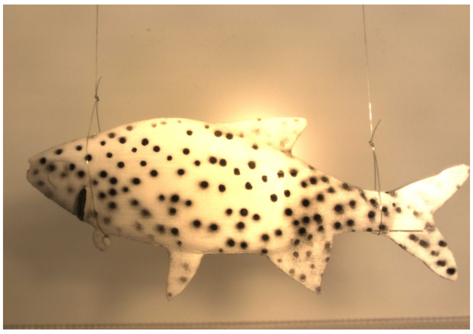
(f) Depthmap 120 cm.

Figure 5.5: Test 4 image results.

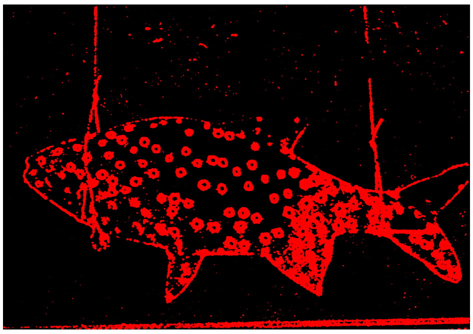
5.1.5 Test 5 - 12mm, White, Air

Calibration		
Calibration result:	0 stars	
Measured lengths		
Distance:	**Mean value:**	**Standard deviation:**
40 cm	230.1 mm	6.75
80 cm	238.4 mm	8.10
120 cm	217.2 mm	9.75

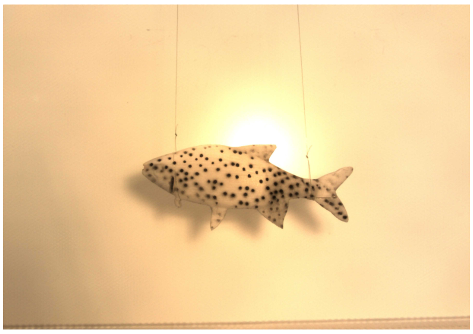
Table 5.5: Results for test 5.



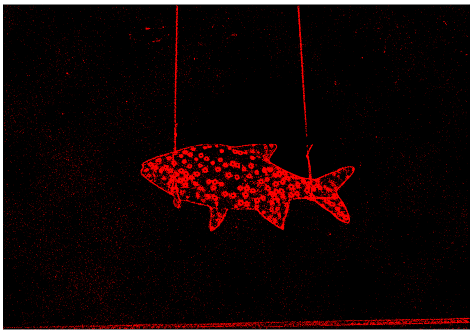
(a) Refocus 40 cm.



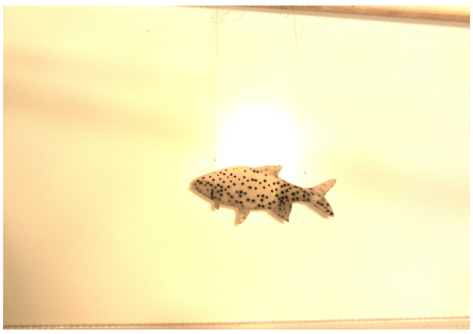
(b) Depthmap 40 cm.



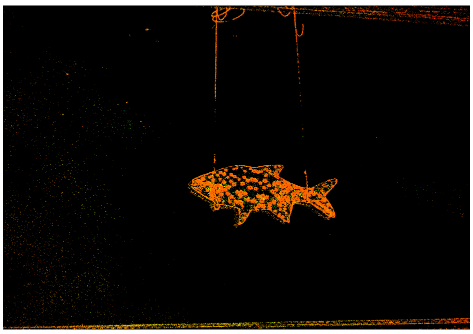
(c) Refocus 80 cm.



(d) Depthmap 80 cm.



(e) Refocus 120 cm.



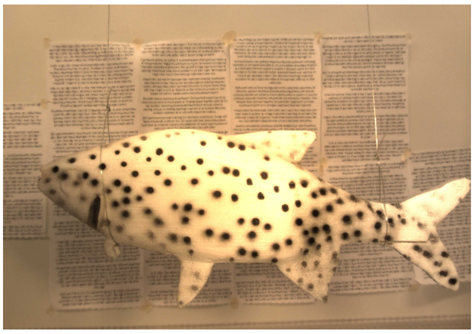
(f) Depthmap 120 cm.

Figure 5.6: Test 5 image results.

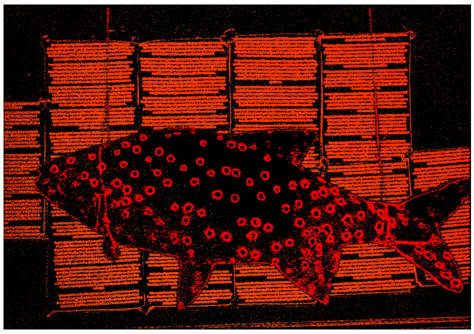
5.1.6 Test 6 - 12mm, Structured, Air

Calibration		
Calibration result:	0 stars	
Measured lengths		
Distance:	**Mean value:**	**Standard deviation:**
40 cm	249.4 mm	22.61
80 cm	250.5 mm	13.00
120 cm	205.2 mm	12.5

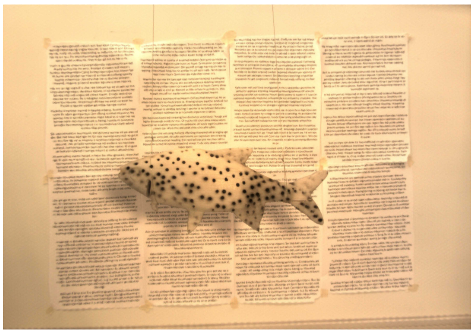
Table 5.6: Results for test 6.



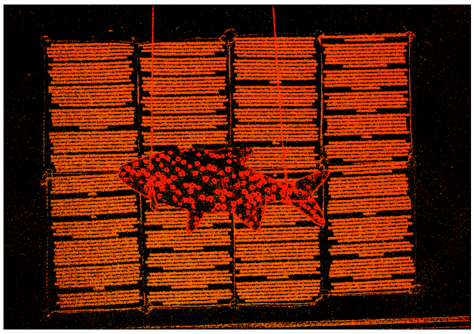
(a) Refocus 40 cm.



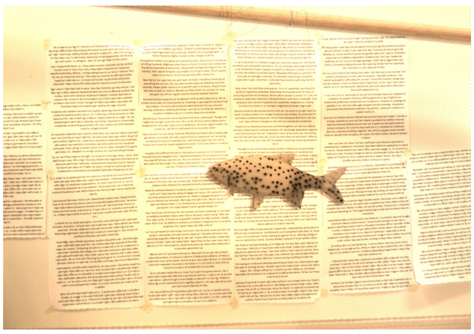
(b) Depthmap 40 cm.



(c) Refocus 80 cm.



(d) Depthmap 80 cm.



(e) Refocus 120 cm.

(f) Depthmap 120 cm.

Figure 5.7: Test 6 image results.

As predicted, it is seen from the results in the tests above that the background has some saying in the results. It is clear to see from the depthmaps that the plain background gives the best depthmaps, and that the black background performs a bit better than the white background. But, the test-fish is mostly white, so fewer depth points were expected. As for the structured background, very few depth points were detected on the object target, and for the 12 mm lens it clearly had the highest standard deviation.

Keeping in mind that the camera should be put in the sea, the black background is used throughout the remaining tests, as it best imitates the sea.

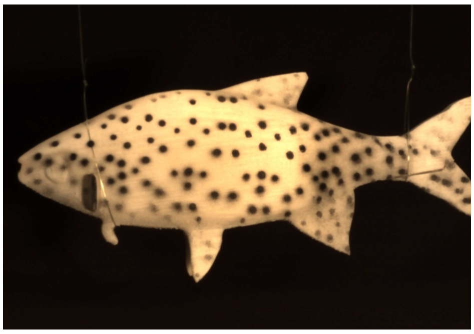
5.2 Experiments in Air through a Dome

This section is for testing if the curve from the glass dome gives distortions in the image and in the depthmap. Especially the metric calibration could be affected by the dome acting as an extra lens. The tests in this section will be analyzed up against the tests in air through a flat port.

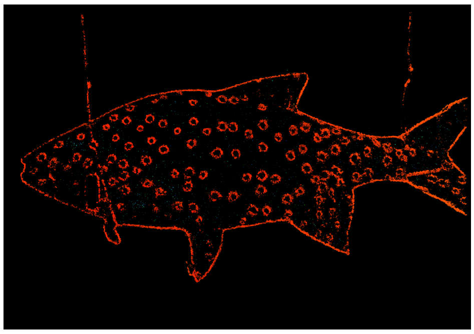
5.2.1 Test 7 - 25mm, Black, Air through Dome

Calibration		
Calibration result:	3 stars	
Measured lengths		
Distance:	**Mean value:**	**Standard deviation:**
70 cm	237.3 mm	1.12
85 cm	225.4 mm	1.13
100 cm	219.3 mm	1.13

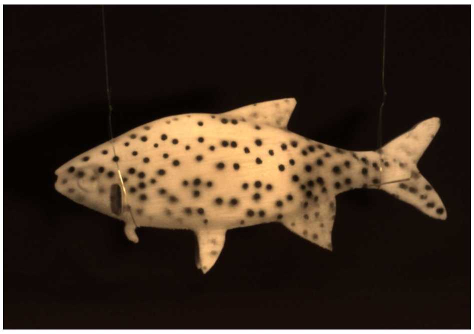
Table 5.7: Results for test 7.



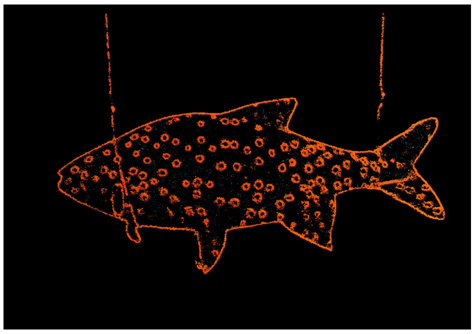
(a) Refocus 70 cm.



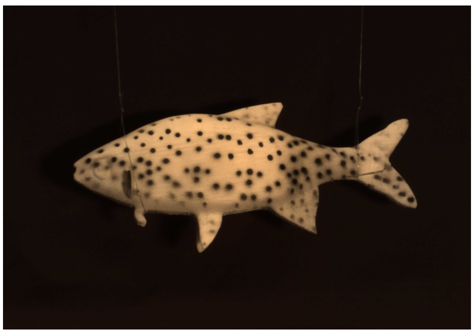
(b) Depthmap 70 cm.



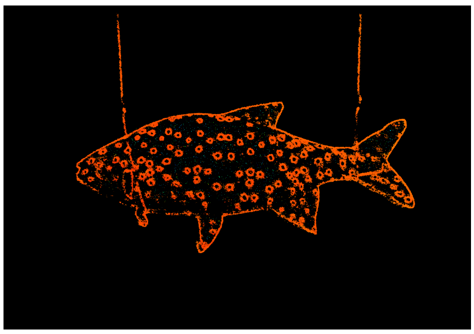
(c) Refocus 85 cm.



(d) Depthmap 85 cm.



(e) Refocus 100 cm.



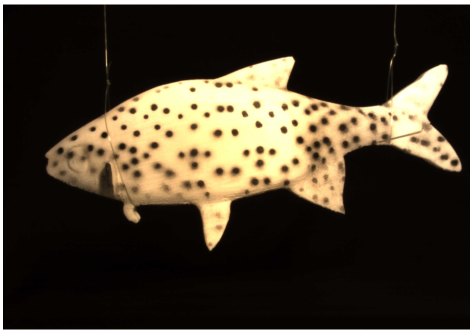
(f) Depthmap 100 cm.

Figure 5.8: Test 7 image results.

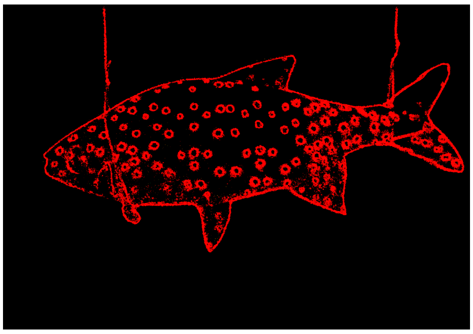
5.2.2 Test 8 - 12mm, Black, Air through Dome

Calibration		
Calibration result:	0 stars	
Measured lengths		
Distance:	**Mean value:**	**Standard deviation:**
40 cm	188.1 mm	1.58
80 cm	144.4 mm	2.61
120 cm	114.0 mm	0.71

Table 5.8: Results for test 8.

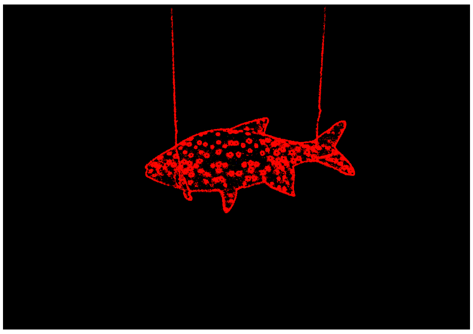


(a) Refocus 40 cm.



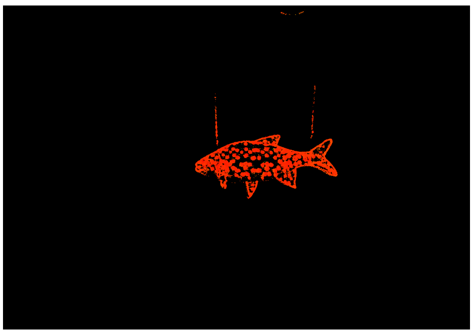
(b) Depthmap 40 cm.

(c) Refocus 80 cm.



(d) Depthmap 80 cm.

(e) Refocus 120 cm.



(f) Depthmap 120 cm.

Figure 5.9: Test 8 image results.

During calibration, the results seemed fine as the totalfocus image did not seem distorted. But the measurements say differently. The results from these tests show that the results are pretty much the same for the 25 mm lens as in pure air, while the 12 mm lens performs way worse. This has most likely to do with the field-of-view of the cameras. Since the 12 mm lens has a much larger field-of-view than the 25 mm lens, more of the curvature of the dome will affect the image and impact the metric data.

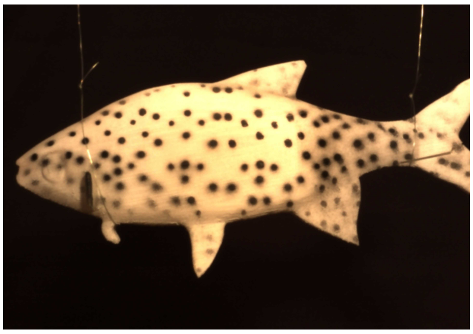
5.3 Experiments in Air through a Flat Port

This section tests whether the flat port glass gives distortions in the image. It is expected not to give any distortions since the flat glass will not act as an extra lens as the dome may will. The tests in this section will be analyzed up against the tests in air through a dome.

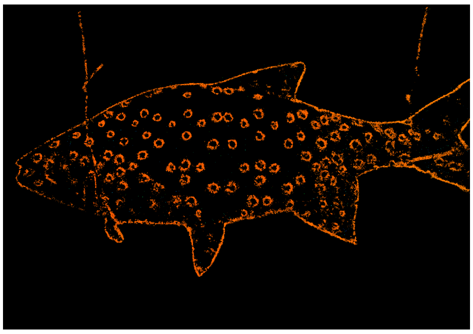
5.3.1 Test 9 - 25mm, Black, Air through Flat Port

Calibration		
Calibration result:	3 stars	
Measured lengths		
Distance:	**Mean value:**	**Standard deviation:**
70 cm	242.6 mm	1.54
85 cm	226.2 mm	1.39
100 cm	224.1 mm	3.06

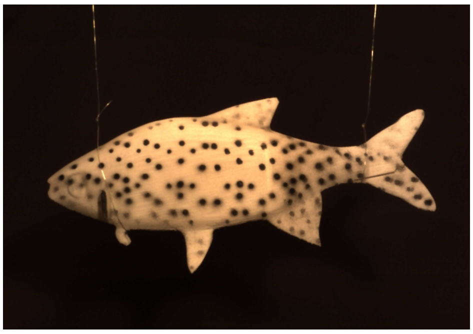
Table 5.9: Results for test 9.



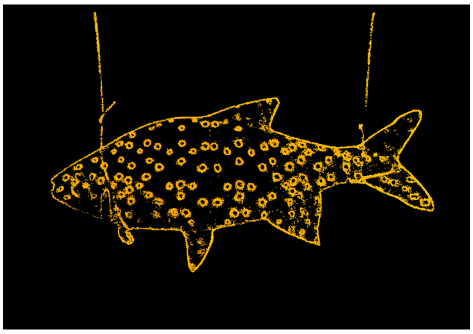
(a) Refocus 70 cm.



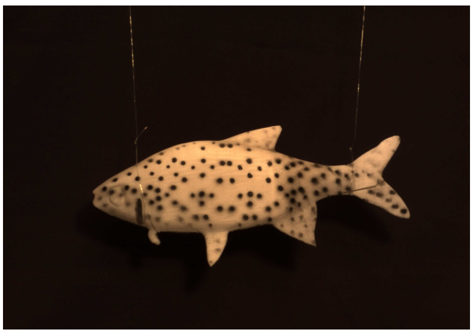
(b) Depthmap 70 cm.



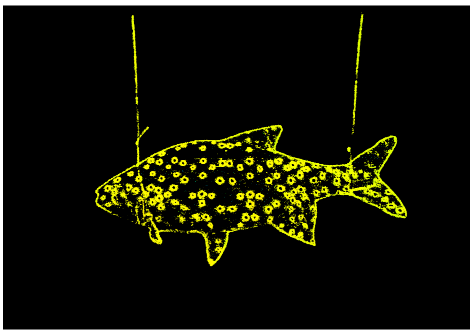
(c) Refocus 85 cm.



(d) Depthmap 85 cm.



(e) Refocus 100 cm.



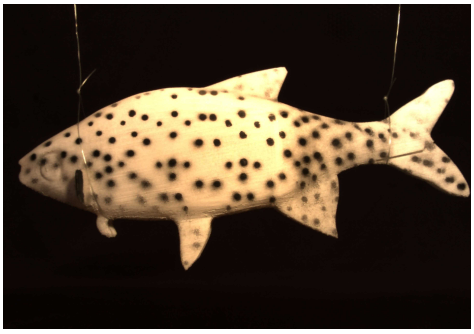
(f) Depthmap 100 cm.

Figure 5.10: Test 9 image results.

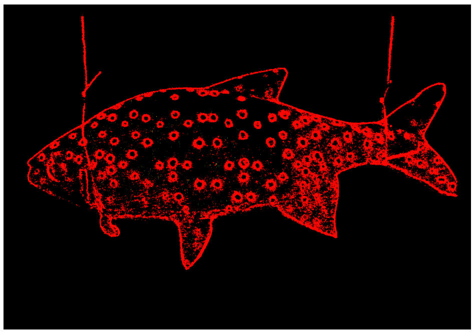
5.3.2 Test 10 - 12mm, Black, Air through Flat Port

Calibration		
Calibration result:	0 stars	
Measured lengths		
Distance:	**Mean value:**	**Standard deviation:**
40 cm	208.1 mm	1.40
80 cm	204.6 mm	2.28
120 cm	192.6 mm	7.64

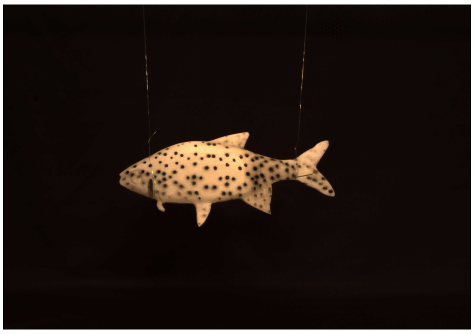
Table 5.10: Results for test 10.



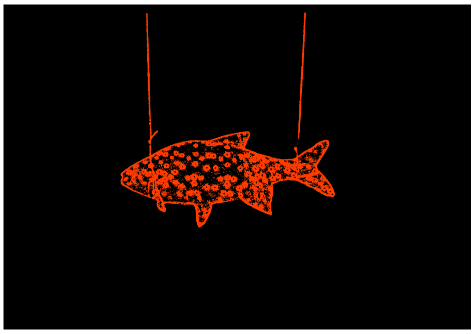
(a) Refocus 40 cm.



(b) Depthmap 40 cm.

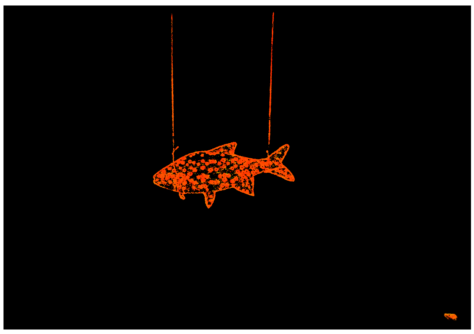


(c) Refocus 80 cm.



(d) Depthmap 80 cm.

(e) Refocus 120 cm.



(f) Depthmap 120 cm.

Figure 5.11: Test 10 image results.

The tests though the flat port performed well. When the object is close, the standard deviation is low, and the measurements are accurate. The standard deviation is a bit higher for the furthest distance.

Comparing the results in air through a dome and through a flat port, is clear to say that the results are overall much better for the flat port. But will this change when we move our camera underwater? It is a fact that most acknowledged underwater camera systems operate using a flat port, and there may be a reason for it.

5.4 Experiments in Water through a Dome

The underwater housing will have some air between the camera lens and the glass. This means that the changing from water, through glass, to air and into the camera could cause problems. The magnification due to the water medium could give large errors and the dome could potentially act as an extra lens, giving circled distortions in the depthmap. Although no distortions are seen in the 2D image when using a dome, it could still be that the metric data is distorted.

This section tests if a dome is a good converter over to the water medium, or if it together with the water will act as an extra lens.

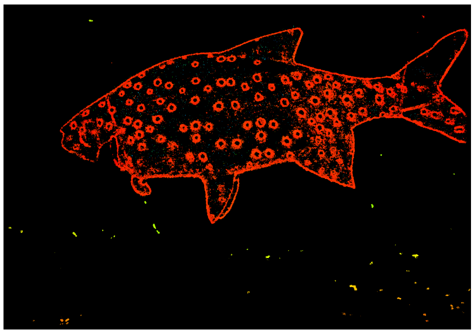
This section will be analyzed up against the tests in water through a flat port.

5.4.1 Test 11 - 25mm, Black, Water through Dome

Calibration		
Calibration result:	3 stars	
Measured lengths		
Distance:	**Mean value:**	**Standard deviation:**
70 cm	250.4 mm	2.18
85 cm	223.1 mm	1.86
100 cm	209.1 mm	2.44

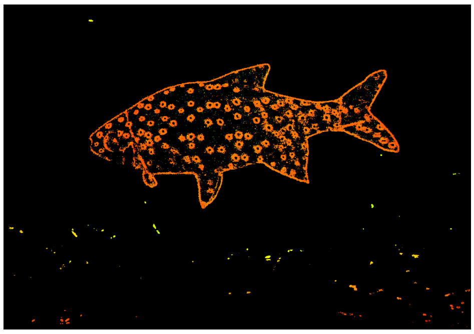
Table 5.11: Results for test 11.

(a) Refocus 70 cm.

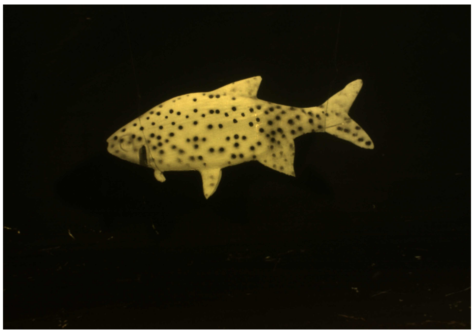


(b) Depthmap 70 cm.

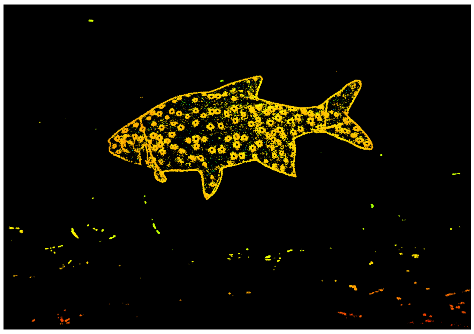
(c) Refocus 85 cm.



(d) Depthmap 85 cm.



(e) Refocus 100 cm.



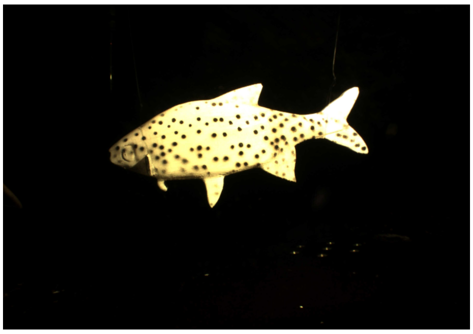
(f) Depthmap 100 cm.

Figure 5.12: Test 11 image results.

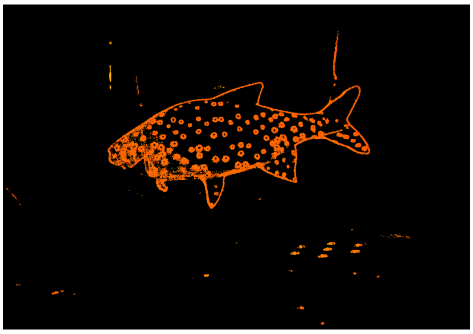
5.4.2 Test 12 - 12mm, Black, Water through Dome

Calibration		
Calibration result:	0 stars	
Measured lengths		
Distance:	**Mean value:**	**Standard deviation:**
40 cm	193.0 mm	2.39
80 cm	131.0 mm	5.98
120 cm	100.3 mm	5.29

Table 5.12: Results for test 12.

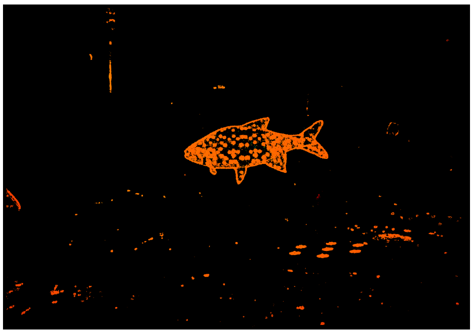


(a) Refocus 40 cm.



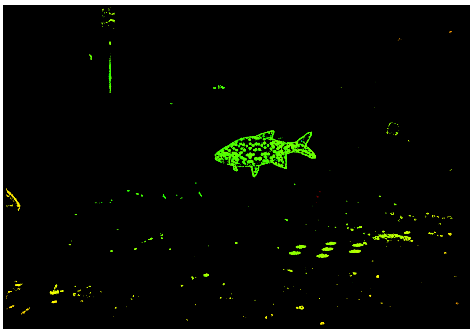
(b) Depthmap 40 cm.

(c) Refocus 80 cm.



(d) Depthmap 80 cm.

(e) Refocus 120 cm.



(f) Depthmap 120 cm.

Figure 5.13: Test 12 image results.

It was very hard to calibrate in water. And when doing so, the depthmap became very distorted. The magnification through the dome was also a big problem, as it seems as the camera could not get a good focus point. The best results came from using the calibration from air through a dome. This gave few distortions and the results were not too far from the ones obtained in air through a dome. One problem using the calibration from air was that the camera had to be adjusted to some exact distance from the dome to get the best achieved results.

The number of depth points are very good for both lenses, but the measurements, especially for the 12 mm lens, are not that exact. It is seen that also in water the 25 mm lens gets little measurement distortions from the dome, while the measurements using the 12 mm lens are very unstable and not usable.

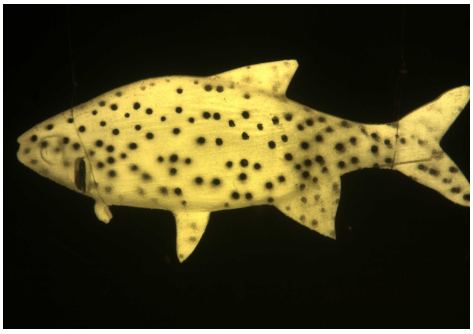
5.5 Experiments in Water through a Flat Port

This section will test if the flat port is a better solution for the underwater housing than a dome.

5.5.1 Test 13 - 25mm, Black, Water through Flat Port

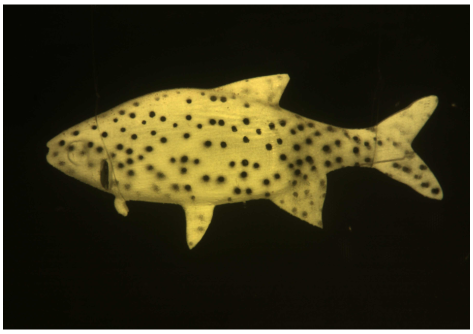
Calibration		
Calibration result:	3 stars	
Measured lengths		
Distance:	**Mean value:**	**Standard deviation:**
90 cm	224.1 mm	1.80
105 cm	222.5 mm	1.86
120 cm	218.4 mm	1.36

Table 5.13: Results for test 13.

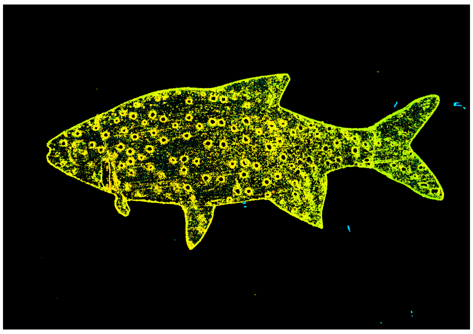


(a) Refocus 90 cm.

(b) Depthmap 90 cm.

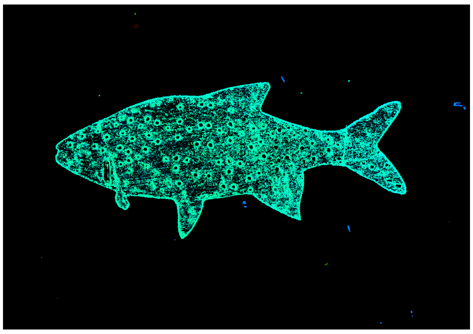


(c) Refocus 105 cm.



(d) Depthmap 105 cm.

(e) Refocus 120 cm.



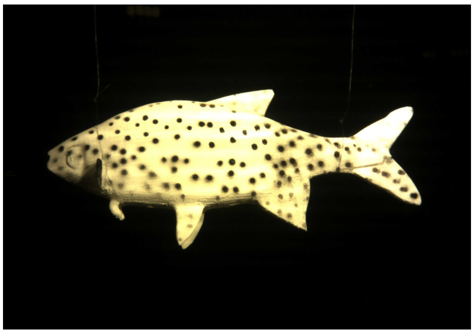
(f) Depthmap 120 cm.

Figure 5.14: Test 13 image results.

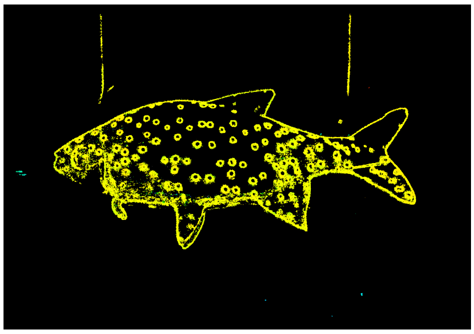
5.5.2 Test 14 - 12mm, Black, Water through Flat Port

Calibration		
Calibration result:	0 stars	
Measured lengths		
Distance:	**Mean value:**	**Standard deviation:**
60 cm	203.8 mm	2.69
90 cm	205.0 mm	3.51
120 cm	200.0 mm	6.27

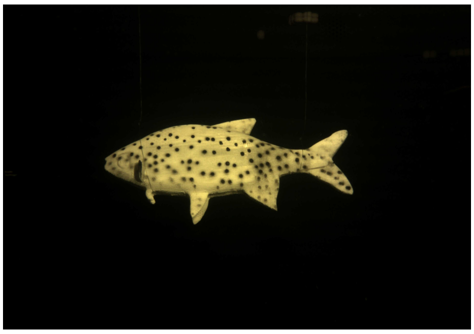
Table 5.14: Results for test 14.



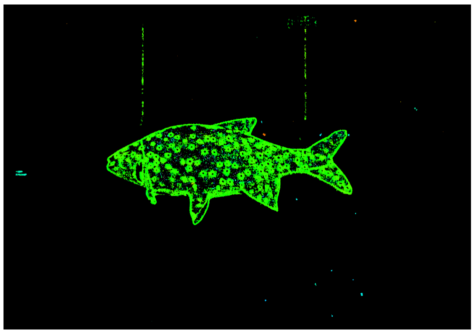
(a) Refocus 60 cm.



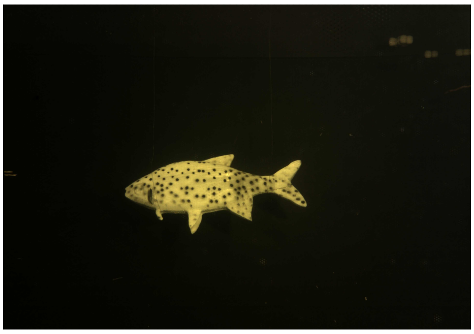
(b) Depthmap 60 cm.



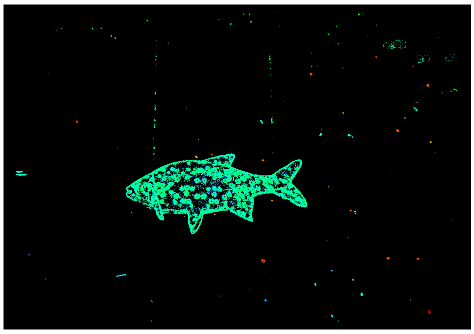
(c) Refocus 90 cm.



(d) Depthmap 90 cm.



(e) Refocus 120 cm.



(f) Depthmap 120 cm.

Figure 5.15: Test 14 image results.

As with the dome in water, the best results were provided when calibrating the camera in air before moving it to the underwater flat port housing and into the water.

It is seen from the tests that the flat port performs best both in air and in water. The results are surprisingly good underwater for the 25 mm lens as it seemed not to be affected by the water medium, and though the standard deviation are higher for the 12 mm lens, and the measurements are a bit off, they are still stable and usable. Both the 25 mm lens and the 12 mm lens also detects the same amount or more depth points than in air.

A flat port underwater house was therefore built, and attached to the AquaPod for further testing in an actual fish farm.

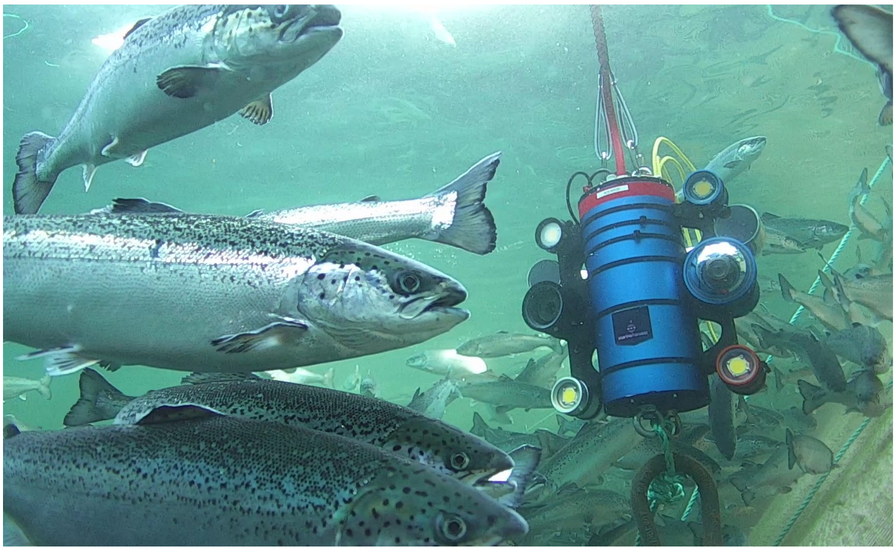


Figure 5.16: The SEALAB Aquapod with the Raytrix R42 camera attached. Photo: SEALAB.

5.6 Field testing

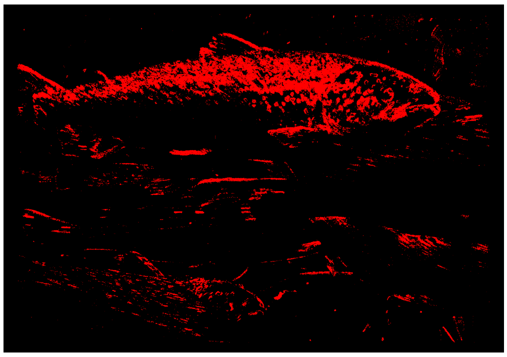
After completing all tests in the lab, and decided that the flat port provided the best results, a flat port underwater house was built and attached to the SEALAB AquaPod. The SEALAB AquaPod consists of four led lights and a 2D high resolution Sony camera, and is connected through a 70 m long fiber connection, which makes it ideal for real underwater tests as it can be lowered far down. A picture of the AquaPod with the Raytrix camera attached is seen in Figure 5.16. Given the test results and the knowledge on field-of-view and working distance, the 12 mm lens was used in the field tests. An open sea fish farm was used for testing. As the fish was swimming around, no verification on the results could be given, but the camera measured the fish to be between 30 and 40 cm long which seemed to be reasonable by the look of it.

A big problem during field testing was the light. As the led lights on the AquaPod are placed very close to the camera, all particles near the camera are lit up and result in a lot of noise. The results were therefore better with the lights turned off and just using the available sunlight. With little light available, the shutter speed needed to be high. This resulted in very blurry images as the fish swims fast. Though this was not a good base situation, a few of the images turned out surprisingly good. Some of these images are shown in Figure 5.16.

It is also clear to say that the cameras measurements are consistent. A sequence of images of the same fish was taken, and the measurements were consistent around 33 cm.

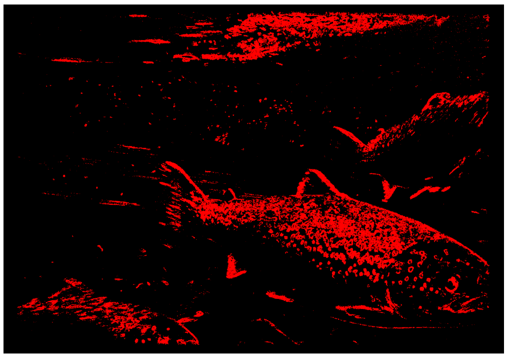
For this being the first real condition field test using a plenoptic camera underwater, the results were much better than anticipated.

(a) Totalfocus.



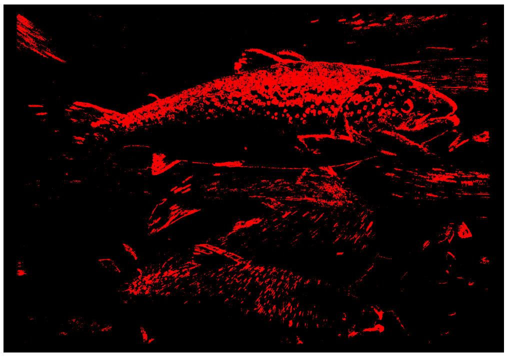
(b) Depthmap.

(c) Totalfocus.



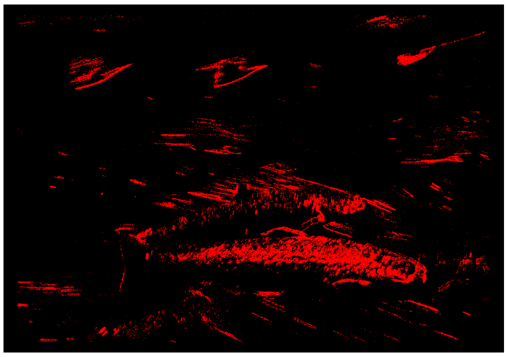
(d) Depthmap.

(e) Totalfocus.



(f) Depthmap.

(g) Totalfocus.



(h) Depthmap.

Figure 5.17: Some field results.

5.7 Shutter Speed Testing

As the incoming light and thereby the shutter speed is of such importance for the plenoptic camera to get proper results, tests using different shutter speeds are provided. The tests include low light with large shutter speed, and much light with low shutter speed. The tests are presented in videos found in the attachment.

When pausing the totalfocus video as the object is moving fast, it is clear to see that the video with much light and low shutter speed provides the best results. When the fish is moving fast, the depthmap is also more complete in the video with low shutter speed. This can also be seen in the images from the field test in the attachment.

The results determine that much light is most likely needed, such that the shutter speed can be decreased, when working with fast moving objects.

Chapter 6

Conclusion

The objective of this research was to verify the metric depth measurements provided by the Raytrix plenoptic camera technology underwater, and thereby find out if plenoptic technology can potentially be used for biomass estimation within an ocean fish farm. Biomass estimation would benefit the production of the aquaculture fish breeding industry, and could potentially also benefit the fish's welfare.

The camera used throughout this research is the Raytrix R42 color camera. The focus has been to find an appropriate setup along with a good choice of lens and calibration. Metric measurements underwater have also needed to be verified, as this technology has no documented use underwater. Several tests have been conducted for establishing ground results on what setup will provide the best results. The tests have included testing with different backgrounds, different lenses and different underwater housings.

The test results clearly state that the best choice for underwater housing is the flat port. The best results using the flat port in water was when the camera calibration was conducted in air, before moving the camera into the housing and into the water. This is very fortunate, as the calibration can be hard to perform in water.

During testing, different background tests were also provided. The results shows that a plain background with few contrast areas performs best. During testing a black background is chosen as to best imitate the background of the sea.

The fish farms contain a lot of noise due to big particles in the water from food and excrement. This means that the fish should be close to the camera for obtaining good results. I addition, it is also stated that biomass estimation algorithms will most likely have the need for classification, and will therefore need to have room for the entire fish in the image. These statements are important when considering what lens should be used. During this research only two lenses are tested. A 12 mm lens with a normal field-of-view, and a 25 mm lens with a narrow field-of-view. From the tests, it is seen that the 25 mm lens performs a bit better than the 12 mm, but due to the statements above, the 12 mm lens was chosen for testing in field, and is probably the better choice, due to its field-of-view.

From the test results provided, it is clear to say that this technology must be further developed and tested before a complete biomass estimation system can be made, but the results also clearly indicate that this technology has potential for biomass estimation in fish farms.

Chapter 7

Future Work

As explained in the conclusion, there is potential in this technology, but for plenoptic technology to be used for biomass estimation in a fish farm, many issues must first be resolved. Some of the issues are directly related to the camera, while others are to the setup and the environment.

The most obvious problem is that the images taken are blurry, due to high shutter speed. A blurry image is useless for the depth estimation algorithms, so a sharper image must be provided for this technology to be used in an ocean fish farm measuring salmon swimming up to 15 km/h. It could be possible to reduce the shutter speed by expanding the aperture, but as explained in Chapter 2 a smaller aperture gives a larger depth-of-field. Tests using various shutter speed and aperture should be done to try and solve this issue.

The next challenge has been the limited working distance that has been available for calibration. The Raytrix cameras has been made mostly for microscopy and small distances. During this research Raytrix has been working on improving their calibration algorithms for larger distances. This could mean that the results achieved in this research could easily be somewhat improved using the new calibration algorithms.

A challenge directed to both the camera and the environment, is the several lightning conditions that occurs in an underwater fish farm. The camera is very sensitive to light condition changes, so for this system to be doing biomass estimation in a fish farm every day, all year without having to recalibrate, could potentially be a challenge. This could of course be solved by attaching adjustable lights close to the camera. But this would also create a new problem due to the particles in the water. A fish farm containing several hundred thousand fish produce a lot of large particles. When lights are lit close to the camera, all particles right in front of the camera reflects most of the light before it reaches the fish in the background and thereby produce much noise. This phenomenon is called back-scattering and is a large problem dealing with underwater imaging. A way of solving this could be to place the lights a distance from the camera, but considering that the system should also be kept small and neat for easy maneuvering, makes the lightning issue a complex problem.

Bibliography

[1] W. Sago, "What is aperture?." http://wickedsago.blogspot.com/2012/01/what-is-aperture.html, March 2013.

[2] Raytrix, "R42 series." https://www.raytrix.de/produkte/#r42series, 2017.

[3] fisheries.no, "Aquaculture." http://www.fisheries.no/aquaculture/Aquaculture/#.WDrCGX2-NAQ, 2017.

[4] E. H. Adelson and J. Y. Wang, "Single lens stereo with a plenoptic camera," *IEEE TRANSACTIONS ON PATTERN ANALYSIS AND MACHINE INTELLIGENCE,*, vol. 14, February 1992.

[5] C. Perwass and L. Wietzke, "Single lens 3d-camera with extended depth-of-field," *SPIE*, vol. 8291, 2009.

[6] Wikipedia, "Focal length." https://en.wikipedia.org/wiki/Focal_length, December 2016.

[7] Wikipedia, "Thin lens." https://en.wikipedia.org/wiki/Thin_lens, January 2017.

[8] Boundless, "The lensmaker's equation." https://www.boundless.com/physics/textbooks/boundless-physics-textbook/geometric-optics-24/lenses-170/the-lensmaker-s-equation-615-4333/, August 2016.

[9] E. Hecht, *Optics*. Addison Wesley, 1987.

[10] T. Georgiev and A. Lumsdaine, "Resolution in plenoptic cameras," *Optical Society of America*, 2009.

[11] C. Heinze, "Entwurf und test eines kalibrierungsverfahrens zur berechnung von metrischen tiefenwerten fr 3d-lichtfeldkameras," *Hamburg University of Applied Science*, 2013.

[12] Raytrix, "3d light field camera technology." https://www.raytrix.de/, 2017.

[13] Raytrix, "3d light field technology." https://www.raytrix.de/technologie/, 2017.

[14] K. A. Skinner and M. Johnson-Roberson, “Towards real-time underwater 3d reconstruction with plenoptic cameras,” *RSJ International Conference on Intelligent Robots and Systems (IROS)*, October 2016.

[15] R. Schettini and S. Corchs, “Underwater image processing: State of the art of restoration and image enhancement methods,” *EURASIP Journal on Advances in Signal Processing*, 2010.

Appendix A

A.1 - Test 1

Lens type	25 mm
Background	Black
Object target	Test-fish
Medium	Air

Table 7.1: Setup for test 1.

Test 1 - Parameter values in RxLive 4.0		
Preprocessing	Gradation Line	Disabled
	Denoise	Enabled
	Filter Diameter	4
	Noise Level	0.10
	Blend Factor	0.20
	Sharpening	Enabled
	Sharpness	1.50
	Blurring Standard Deviation	2.50
	Use only for estimation	Enabled
	Color	Disabled
Focus	Focus	-
	Depth Blending Scale	0.00
	Focus Resolution	3858 x 2682 px
Depth Estimation	Depth Algorithm	Depth Path
	Min Virtual Depth	2.00 VD
	Max Virtual Depth	15.00 VD
	Enabled Lens Types	Near, Middle, Far
	Min Correlation	0.900
	Min Std Deviation	0.010
	Patch Diameter	3 px
	Patch Stride	2 px
	Consistency Check	Enabled
Depth Map Creation	Depth Map Resolution	1929 x 1341 px
	Filling	Disabled
	Bilateral Filter	Enabled
	Filter Radius	5 px
	Edge Smoothing Factor	0.050
Calibration Settings	Shutter Speed	100
	Stars	3
Other Parameters	Shutter Speed Near	100
	Shutter Speed Middle	100
	Shutter Speed Far	100

Table 7.2: Parameter values in RxLive 4.0 for Test 1.

Distance 70 cm	
Image 1	205.725 mm
Image 2	205.246 mm
Image 3	206.056 mm
Image 4	205.968 mm
Image 5	205.339 mm
Image 6	205.695 mm
Image 7	205.778 mm
Image 8	205.435 mm
Image 9	204.618 mm
Image 10	205.038 mm
Distance 85 cm	
Image 1	197.559 mm
Image 2	196.810 mm
Image 3	197.055 mm
Image 4	198.274 mm
Image 5	197.757 mm
Image 6	196.188 mm
Image 7	197.234 mm
Image 8	198.787 mm
Image 9	197.144 mm
Image 10	196.257 mm
Distance 100 cm	
Image 1	189.169 mm
Image 2	190.757 mm
Image 3	190.065 mm
Image 4	191.627 mm
Image 5	189.755 mm
Image 6	189.157 mm
Image 7	188.277 mm
Image 8	189.622 mm
Image 9	181.753 mm
Image 10	189.082 mm

Table 7.3: Measured lengths of object in test 1.

A.2 - Test 2

Lens type	25 mm
Background	White
Object target	Test-fish
Medium	Air

Table 7.4: Setup for test 2.

Test 2 - Parameter values in RxLive 4.0		
Preprocessing	Gradation Line	Disabled
	Denoise	Enabled
	Filter Diameter	4
	Noise Level	0.10
	Blend Factor	0.20
	Sharpening	Enabled
	Sharpness	1.50
	Blurring Standard Deviation	2.50
	Use only for estimation	Enabled
	Color	Disabled
Focus	Focus	-
	Depth Blending Scale	0.00
	Focus Resolution	3858 x 2682 px
Depth Estimation	Depth Algorithm	Depth Path
	Min Virtual Depth	2.00 VD
	Max Virtual Depth	15.00 VD
	Enabled Lens Types	Near, Middle, Far
	Min Correlation	0.900
	Min Std Deviation	0.010
	Patch Diameter	3 px
	Patch Stride	2 px
	Consistency Check	Enabled
Depth Map Creation	Depth Map Resolution	1929 x 1341 px
	Filling	Disabled
	Bilateral Filter	Enabled
	Filter Radius	5 px
	Edge Smoothing Factor	0.050
Calibration Settings	Shutter Speed	100
	Stars	2
Other Parameters	Shutter Speed Near	100
	Shutter Speed Middle	100
	Shutter Speed Far	100

Table 7.5: Parameter values in RxLive 4.0 for Test 2.

Distance 70 cm	
Image 1	234.202 mm
Image 2	236.925 mm
Image 3	234.401 mm
Image 4	233.709 mm
Image 5	236.145 mm
Image 6	236.753 mm
Image 7	235.117 mm
Image 8	235.249 mm
Image 9	236.164 mm
Image 10	235.970 mm
Distance 85 cm	
Image 1	237.982 mm
Image 2	232.629 mm
Image 3	232.458 mm
Image 4	233.397 mm
Image 5	232.735 mm
Image 6	232.284 mm
Image 7	233.944 mm
Image 8	234.933 mm
Image 9	231.922 mm
Image 10	233.258 mm
Distance 100 cm	
Image 1	229.825 mm
Image 2	227.417 mm
Image 3	232.431 mm
Image 4	235.954 mm
Image 5	234.140 mm
Image 6	229.906 mm
Image 7	229.948 mm
Image 8	229.589 mm
Image 9	226.498 mm
Image 10	229.134 mm

Table 7.6: Measured lengths of object in test 2.

A.3 - Test 3

Lens type	25 mm
Background	Structured
Object target	Test-fish
Medium	Air

Table 7.7: Setup for test 3.

Test 3 - Parameter values in RxLive 4.0		
Preprocessing	Gradation Line	Disabled
	Denoise	Enabled
	Filter Diameter	4
	Noise Level	0.10
	Blend Factor	0.20
	Sharpening	Enabled
	Sharpness	1.50
	Blurring Standard Deviation	2.50
	Use only for estimation	Enabled
	Color	Disabled
Focus	Focus	-
	Depth Blending Scale	0.00
	Focus Resolution	3858 x 2682 px
Depth Estimation	Depth Algorithm	Depth Path
	Min Virtual Depth	2.00 VD
	Max Virtual Depth	15.00 VD
	Enabled Lens Types	Near, Middle, Far
	Min Correlation	0.900
	Min Std Deviation	0.010
	Patch Diameter	3 px
	Patch Stride	2 px
	Consistency Check	Enabled
Depth Map Creation	Depth Map Resolution	1929 x 1341 px
	Filling	Disabled
	Bilateral Filter	Enabled
	Filter Radius	5 px
	Edge Smoothing Factor	0.050
Calibration Settings	Shutter Speed	100
	Stars	2
Other Parameters	Shutter Speed Near	100
	Shutter Speed Middle	100
	Shutter Speed Far	100

Table 7.8: Parameter values in RxLive 4.0 for Test 3.

Distance 70 cm	
Image 1	210.640 mm
Image 2	211.707 mm
Image 3	210.498 mm
Image 4	209.450 mm
Image 5	209.237 mm
Image 6	207.462 mm
Image 7	206.727 mm
Image 8	207.093 mm
Image 9	210.291 mm
Image 10	207.113 mm
Distance 85 cm	
Image 1	199.482 mm
Image 2	200.641 mm
Image 3	200.270 mm
Image 4	202.792 mm
Image 5	197.838 mm
Image 6	199.107 mm
Image 7	202.416 mm
Image 8	200.652 mm
Image 9	200.192 mm
Image 10	200.225 mm
Distance 100 cm	
Image 1	234.309 mm
Image 2	233.892 mm
Image 3	240.705 mm
Image 4	233.402 mm
Image 5	233.663 mm
Image 6	240.044 mm
Image 7	236.366 mm
Image 8	233.761 mm
Image 9	236.390 mm
Image 10	234.594 mm

Table 7.9: Measured lengths of object in test 3.

A.4 - Test 4

Lens type	12 mm
Background	Black
Object target	Test-fish
Medium	Air

Table 7.10: Setup for test 4.

Test 4 - Parameter values in RxLive 4.0		
Preprocessing	Gradation Line	Disabled
	Denoise	Enabled
	Filter Diameter	4
	Noise Level	0.10
	Blend Factor	0.20
	Sharpening	Enabled
	Sharpness	1.50
	Blurring Standard Deviation	2.50
	Use only for estimation	Enabled
	Color	Disabled
Focus	Focus	-
	Depth Blending Scale	0.00
	Focus Resolution	3858 x 2682 px
Depth Estimation	Depth Algorithm	Depth Path
	Min Virtual Depth	2.00 VD
	Max Virtual Depth	15.00 VD
	Enabled Lens Types	Near, Middle, Far
	Min Correlation	0.900
	Min Std Deviation	0.010
	Patch Diameter	3 px
	Patch Stride	2 px
	Consistency Check	Enabled
Depth Map Creation	Depth Map Resolution	1929 x 1341 px
	Filling	Disabled
	Bilateral Filter	Enabled
	Filter Radius	5 px
	Edge Smoothing Factor	0.050
Calibration Settings	Shutter Speed	100
	Stars	0
Other Parameters	Shutter Speed Near	50
	Shutter Speed Middle	100
	Shutter Speed Far	100

Table 7.11: Parameter values in RxLive 4.0 for Test 4.

Distance 40 cm	
Image 1	212.277 mm
Image 2	217.294 mm
Image 3	219.372 mm
Image 4	220.792 mm
Image 5	216.201 mm
Image 6	222.264 mm
Image 7	216.262 mm
Image 8	218.127 mm
Image 9	220.637 mm
Image 10	220.758 mm
Distance 80 cm	
Image 1	202.111 mm
Image 2	210.220 mm
Image 3	198.071 mm
Image 4	201.791 mm
Image 5	199.957 mm
Image 6	199.098 mm
Image 7	198.628 mm
Image 8	198.149 mm
Image 9	201.699 mm
Image 10	199.006 mm
Distance 120 cm	
Image 1	190.446 mm
Image 2	195.545 mm
Image 3	197.966 mm
Image 4	206.550 mm
Image 5	190.858 mm
Image 6	209.683 mm
Image 7	200.674 mm
Image 8	198.542 mm
Image 9	205.929 mm
Image 10	199.295 mm

Table 7.12: Measured lengths of object in test 4.

A.5 - Test 5

Lens type	12 mm
Background	White
Object target	Test-fish
Medium	Air

Table 7.13: Setup for test 5.

Test 5 - Parameter values in RxLive 4.0		
Preprocessing	Gradation Line	Disabled
	Denoise	Enabled
	Filter Diameter	4
	Noise Level	0.10
	Blend Factor	0.20
	Sharpening	Enabled
	Sharpness	1.50
	Blurring Standard Deviation	2.50
	Use only for estimation	Enabled
	Color	Disabled
Focus	Focus	-
	Depth Blending Scale	0.00
	Focus Resolution	3858 x 2682 px
Depth Estimation	Depth Algorithm	Depth Path
	Min Virtual Depth	2.00 VD
	Max Virtual Depth	15.00 VD
	Enabled Lens Types	Near, Middle, Far
	Min Correlation	0.900
	Min Std Deviation	0.010
	Patch Diameter	3 px
	Patch Stride	2 px
	Consistency Check	Enabled
Depth Map Creation	Depth Map Resolution	1929 x 1341 px
	Filling	Disabled
	Bilateral Filter	Enabled
	Filter Radius	5 px
	Edge Smoothing Factor	0.050
Calibration Settings	Shutter Speed	100
	Stars	0
Other Parameters	Shutter Speed Near	60
	Shutter Speed Middle	80
	Shutter Speed Far	100

Table 7.14: Parameter values in RxLive 4.0 for Test 5.

Distance 40 cm	
Image 1	225.225 mm
Image 2	238.018 mm
Image 3	221.299 mm
Image 4	223.741 mm
Image 5	232.078 mm
Image 6	239.196 mm
Image 7	220.880 mm
Image 8	233.108 mm
Image 9	234.274 mm
Image 10	232.891 mm
Distance 80 cm	
Image 1	224.010 mm
Image 2	234.945 mm
Image 3	233.441 mm
Image 4	238.387 mm
Image 5	253.327 mm
Image 6	239.509 mm
Image 7	241.784 mm
Image 8	246.827 mm
Image 9	232.161 mm
Image 10	239.227 mm
Distance 120 cm	
Image 1	213.636 mm
Image 2	227.713 mm
Image 3	238.878 mm
Image 4	218.748 mm
Image 5	214.838 mm
Image 6	211.183 mm
Image 7	207.140 mm
Image 8	208.203 mm
Image 9	219.619 mm
Image 10	211.747 mm

Table 7.15: Measured lengths of object in test 5.

A.6 - Test 6

Lens type	12 mm
Background	Structured
Object target	Test-fish
Medium	Air

Table 7.16: Setup for test 6.

Test 6 - Parameter values in RxLive 4.0		
Preprocessing	Gradation Line	Disabled
	Denoise	Enabled
	Filter Diameter	4
	Noise Level	0.10
	Blend Factor	0.20
	Sharpening	Enabled
	Sharpness	1.50
	Blurring Standard Deviation	2.50
	Use only for estimation	Enabled
	Color	Disabled
Focus	Focus	-
	Depth Blending Scale	0.00
	Focus Resolution	3858 x 2682 px
Depth Estimation	Depth Algorithm	Depth Path
	Min Virtual Depth	2.00 VD
	Max Virtual Depth	15.00 VD
	Enabled Lens Types	Near, Middle, Far
	Min Correlation	0.900
	Min Std Deviation	0.010
	Patch Diameter	3 px
	Patch Stride	2 px
	Consistency Check	Enabled
Depth Map Creation	Depth Map Resolution	1929 x 1341 px
	Filling	Disabled
	Bilateral Filter	Enabled
	Filter Radius	5 px
	Edge Smoothing Factor	0.050
Calibration Settings	Shutter Speed	100
	Stars	0
Other Parameters	Shutter Speed Near	60
	Shutter Speed Middle	80
	Shutter Speed Far	100

Table 7.17: Parameter values in RxLive 4.0 for Test 6.

Distance 40 cm	
Image 1	244.037 mm
Image 2	293.460 mm
Image 3	243.198 mm
Image 4	284.081 mm
Image 5	234.862 mm
Image 6	253.275 mm
Image 7	225.092 mm
Image 8	236.805 mm
Image 9	249.865 mm
Image 10	229.102 mm
Distance 80 cm	
Image 1	267.810 mm
Image 2	261.491 mm
Image 3	225.442 mm
Image 4	256.250 mm
Image 5	248.869 mm
Image 6	242.480 mm
Image 7	266.630 mm
Image 8	245.148 mm
Image 9	241.336 mm
Image 10	249.868 mm
Distance 120 cm	
Image 1	233.813 mm
Image 2	215.391 mm
Image 3	197.782 mm
Image 4	190.532 mm
Image 5	195.026 mm
Image 6	200.093 mm
Image 7	199.042 mm
Image 8	201.876 mm
Image 9	209.955 mm
Image 10	208.753 mm

Table 7.18: Measured lengths of object in test 6.

A.7 - Test 7

Lens type	25 mm
Background	Black
Object target	Test-fish
Medium	Air through a dome

Table 7.19: Setup for test 7.

Test 7 - Parameter values in RxLive 4.0		
Preprocessing	Gradation Line	Disabled
	Denoise	Enabled
	Filter Diameter	4
	Noise Level	0.10
	Blend Factor	0.20
	Sharpening	Enabled
	Sharpness	1.50
	Blurring Standard Deviation	2.50
	Use only for estimation	Enabled
	Color	Disabled
Focus	Focus	-
	Depth Blending Scale	0.00
	Focus Resolution	3858 x 2682 px
Depth Estimation	Depth Algorithm	Depth Path
	Min Virtual Depth	2.00 VD
	Max Virtual Depth	15.00 VD
	Enabled Lens Types	Near, Middle, Far
	Min Correlation	0.900
	Min Std Deviation	0.010
	Patch Diameter	3 px
	Patch Stride	2 px
	Consistency Check	Enabled
Depth Map Creation	Depth Map Resolution	1929 x 1341 px
	Filling	Disabled
	Bilateral Filter	Enabled
	Filter Radius	5 px
	Edge Smoothing Factor	0.050
Calibration Settings	Shutter Speed	100
	Stars	3
Other Parameters	Shutter Speed Near	100
	Shutter Speed Middle	100
	Shutter Speed Far	100

Table 7.20: Parameter values in RxLive 4.0 for Test 7.

Distance 70 cm	
Image 1	239.481 mm
Image 2	237.049 mm
Image 3	237.992 mm
Image 4	236.913 mm
Image 5	237.490 mm
Image 6	236.846 mm
Image 7	236.107 mm
Image 8	238.383 mm
Image 9	236.817 mm
Image 10	235.633 mm
Distance 85 cm	
Image 1	223.596 mm
Image 2	225.214 mm
Image 3	226.963 mm
Image 4	225.624 mm
Image 5	225.500 mm
Image 6	224.605 mm
Image 7	224.123 mm
Image 8	225.667 mm
Image 9	227.225 mm
Image 10	225.163 mm
Distance 100 cm	
Image 1	218.842 mm
Image 2	217.857 mm
Image 3	218.175 mm
Image 4	220.554 mm
Image 5	221.085 mm
Image 6	218.377 mm
Image 7	220.648 mm
Image 8	218.734 mm
Image 9	219.591 mm
Image 10	219.340 mm

Table 7.21: Measured lengths of object in test 7.

A.8 - Test 8

Lens type	12 mm
Background	Black
Object target	Test-fish
Medium	Air through a dome

Table 7.22: Setup for test 8.

Test 8 - Parameter values in RxLive 4.0		
Preprocessing	Gradation Line	Disabled
	Denoise	Enabled
	Filter Diameter	4
	Noise Level	0.10
	Blend Factor	0.20
	Sharpening	Enabled
	Sharpness	1.50
	Blurring Standard Deviation	2.50
	Use only for estimation	Enabled
	Color	Disabled
Focus	Focus	-
	Depth Blending Scale	0.00
	Focus Resolution	3858 x 2682 px
Depth Estimation	Depth Algorithm	Depth Path
	Min Virtual Depth	2.00 VD
	Max Virtual Depth	15.00 VD
	Enabled Lens Types	Near, Middle, Far
	Min Correlation	0.900
	Min Std Deviation	0.010
	Patch Diameter	3 px
	Patch Stride	2 px
	Consistency Check	Enabled
Depth Map Creation	Depth Map Resolution	1929 x 1341 px
	Filling	Disabled
	Bilateral Filter	Enabled
	Filter Radius	5 px
	Edge Smoothing Factor	0.050
Calibration Settings	Shutter Speed	100
	Stars	0
Other Parameters	Shutter Speed Near	70
	Shutter Speed Middle	100
	Shutter Speed Far	100

Table 7.23: Parameter values in RxLive 4.0 for Test 8.

Distance 40 cm	
Image 1	188.233 mm
Image 2	186.651 mm
Image 3	187.790 mm
Image 4	185.562 mm
Image 5	189.306 mm
Image 6	185.799 mm
Image 7	188.579 mm
Image 8	190.127 mm
Image 9	189.134 mm
Image 10	189.424 mm
Distance 80 cm	
Image 1	143.414 mm
Image 2	142.576 mm
Image 3	147.822 mm
Image 4	142.931 mm
Image 5	141.987 mm
Image 6	142.665 mm
Image 7	147.057 mm
Image 8	149.367 mm
Image 9	143.147 mm
Image 10	143.299 mm
Distance 120 cm	
Image 1	114.699 mm
Image 2	115.127 mm
Image 3	113.793 mm
Image 4	113.453 mm
Image 5	114.211 mm
Image 6	114.169 mm
Image 7	113.816 mm
Image 8	114.470 mm
Image 9	114.177 mm
Image 10	112.562 mm

Table 7.24: Measured lengths of object in test 8.

A.9 - Test 9

Lens type	25 mm
Background	Black
Object target	Test-fish
Medium	Air through a flat port

Table 7.25: Setup for test 9.

Test 9 - Parameter values in RxLive 4.0		
Preprocessing	Gradation Line	Disabled
	Denoise	Enabled
	Filter Diameter	4
	Noise Level	0.10
	Blend Factor	0.20
	Sharpening	Enabled
	Sharpness	1.50
	Blurring Standard Deviation	2.50
	Use only for estimation	Enabled
	Color	Disabled
Focus	Focus	-
	Depth Blending Scale	0.00
	Focus Resolution	3858 x 2682 px
Depth Estimation	Depth Algorithm	Depth Path
	Min Virtual Depth	2.00 VD
	Max Virtual Depth	15.00 VD
	Enabled Lens Types	Near, Middle, Far
	Min Correlation	0.900
	Min Std Deviation	0.010
	Patch Diameter	3 px
	Patch Stride	2 px
	Consistency Check	Enabled
Depth Map Creation	Depth Map Resolution	1929 x 1341 px
	Filling	Disabled
	Bilateral Filter	Enabled
	Filter Radius	5 px
	Edge Smoothing Factor	0.050
Calibration Settings	Shutter Speed	70
	Stars	3
Other Parameters	Shutter Speed Near	90
	Shutter Speed Middle	100
	Shutter Speed Far	110

Table 7.26: Parameter values in RxLive 4.0 for Test 9.

Distance 70 cm	
Image 1	243.767 mm
Image 2	244.252 mm
Image 3	244.070 mm
Image 4	242.251 mm
Image 5	239.648 mm
Image 6	242.427 mm
Image 7	243.260 mm
Image 8	243.857 mm
Image 9	241.049 mm
Image 10	241.248 mm
Distance 85 cm	
Image 1	225.433 mm
Image 2	226.103 mm
Image 3	225.425 mm
Image 4	225.121 mm
Image 5	226.016 mm
Image 6	225.858 mm
Image 7	229.189 mm
Image 8	225.085 mm
Image 9	228.262 mm
Image 10	225.627 mm
Distance 100 cm	
Image 1	227.711 mm
Image 2	223.059 mm
Image 3	227.456 mm
Image 4	220.067 mm
Image 5	220.906 mm
Image 6	224.639 mm
Image 7	226.017 mm
Image 8	226.035 mm
Image 9	219.404 mm
Image 10	225.798 mm

Table 7.27: Measured lengths of object in test 9.

A.10 - Test 10

Lens type	12 mm
Background	Black
Object target	Test-fish
Medium	Air through a flat port

Table 7.28: Setup for test 10.

Test 10 - Parameter values in RxLive 4.0		
Preprocessing	Gradation Line	Disabled
	Denoise	Enabled
	Filter Diameter	4
	Noise Level	0.10
	Blend Factor	0.20
	Sharpening	Enabled
	Sharpness	1.50
	Blurring Standard Deviation	2.50
	Use only for estimation	Enabled
	Color	Disabled
Focus	Focus	-
	Depth Blending Scale	0.00
	Focus Resolution	3858 x 2682 px
Depth Estimation	Depth Algorithm	Depth Path
	Min Virtual Depth	2.00 VD
	Max Virtual Depth	15.00 VD
	Enabled Lens Types	Near, Middle, Far
	Min Correlation	0.900
	Min Std Deviation	0.010
	Patch Diameter	3 px
	Patch Stride	2 px
	Consistency Check	Enabled
Depth Map Creation	Depth Map Resolution	1929 x 1341 px
	Filling	Disabled
	Bilateral Filter	Enabled
	Filter Radius	5 px
	Edge Smoothing Factor	0.050
Calibration Settings	Shutter Speed	70
	Stars	0
Other Parameters	Shutter Speed Near	50
	Shutter Speed Middle	80
	Shutter Speed Far	110

Table 7.29: Parameter values in RxLive 4.0 for Test 10.

Distance 40 cm	
Image 1	207.056 mm
Image 2	208.306 mm
Image 3	211.432 mm
Image 4	207.471 mm
Image 5	207.928 mm
Image 6	208.157 mm
Image 7	206.040 mm
Image 8	209.004 mm
Image 9	208.054 mm
Image 10	207.901 mm
Distance 80 cm	
Image 1	203.376 mm
Image 2	205.394 mm
Image 3	200.440 mm
Image 4	203.854 mm
Image 5	203.118 mm
Image 6	205.711 mm
Image 7	203.671 mm
Image 8	206.338 mm
Image 9	208.911 mm
Image 10	205.439 mm
Distance 120 cm	
Image 1	205.979 mm
Image 2	196.318 mm
Image 3	184.936 mm
Image 4	183.587 mm
Image 5	190.348 mm
Image 6	192.354 mm
Image 7	190.115 mm
Image 8	204.986 mm
Image 9	188.849 mm
Image 10	188.816 mm

Table 7.30: Measured lengths of object in test 10.

A.11 - Test 11

Lens type	25 mm
Background	Black
Object target	Test-fish
Medium	Water through a dome

Table 7.31: Setup for test 11.

Test 11 - Parameter values in RxLive 4.0		
Preprocessing	Gradation Line	Disabled
	Denoise	Enabled
	Filter Diameter	4
	Noise Level	0.10
	Blend Factor	0.20
	Sharpening	Enabled
	Sharpness	1.50
	Blurring Standard Deviation	2.50
	Use only for estimation	Enabled
	Color	Disabled
Focus	Focus	-
	Depth Blending Scale	0.00
	Focus Resolution	3858 x 2682 px
Depth Estimation	Depth Algorithm	Depth Path
	Min Virtual Depth	2.00 VD
	Max Virtual Depth	15.00 VD
	Enabled Lens Types	Near, Middle, Far
	Min Correlation	0.900
	Min Std Deviation	0.010
	Patch Diameter	3 px
	Patch Stride	2 px
	Consistency Check	Enabled
Depth Map Creation	Depth Map Resolution	1929 x 1341 px
	Filling	Disabled
	Bilateral Filter	Enabled
	Filter Radius	5 px
	Edge Smoothing Factor	0.050
Calibration Settings	Shutter Speed	100
	Stars	3
Other Parameters	Shutter Speed Near	70
	Shutter Speed Middle	100
	Shutter Speed Far	120

Table 7.32: Parameter values in RxLive 4.0 for Test 11.

Distance 70 cm	
Image 1	252.957 mm
Image 2	251.620 mm
Image 3	250.705 mm
Image 4	245.782 mm
Image 5	249.456 mm
Image 6	248.754 mm
Image 7	251.478 mm
Image 8	253.275 mm
Image 9	250.116 mm
Image 10	250.095 mm
Distance 85 cm	
Image 1	220.942 mm
Image 2	220.323 mm
Image 3	224.349 mm
Image 4	224.839 mm
Image 5	224.126 mm
Image 6	220.732 mm
Image 7	225.436 mm
Image 8	223.964 mm
Image 9	222.199 mm
Image 10	223.868 mm
Distance 100 cm	
Image 1	205.454 mm
Image 2	206.504 mm
Image 3	206.959 mm
Image 4	212.241 mm
Image 5	210.724 mm
Image 6	211.909 mm
Image 7	211.268 mm
Image 8	208.787 mm
Image 9	209.858 mm
Image 10	207.276 mm

Table 7.33: Measured lengths of object in test 11.

A.12 - Test 12

Lens type	12 mm
Background	Black
Object target	Test-fish
Medium	Water through a dome

Table 7.34: Setup for test 12.

Test 12 - Parameter values in RxLive 4.0		
Preprocessing	Gradation Line	Disabled
	Denoise	Enabled
	Filter Diameter	4
	Noise Level	0.10
	Blend Factor	0.20
	Sharpening	Enabled
	Sharpness	1.50
	Blurring Standard Deviation	2.50
	Use only for estimation	Enabled
	Color	Disabled
Focus	Focus	-
	Depth Blending Scale	0.00
	Focus Resolution	3858 x 2682 px
Depth Estimation	Depth Algorithm	Depth Path
	Min Virtual Depth	2.00 VD
	Max Virtual Depth	15.00 VD
	Enabled Lens Types	Near, Middle, Far
	Min Correlation	0.900
	Min Std Deviation	0.010
	Patch Diameter	3 px
	Patch Stride	2 px
	Consistency Check	Enabled
Depth Map Creation	Depth Map Resolution	1929 x 1341 px
	Filling	Disabled
	Bilateral Filter	Enabled
	Filter Radius	5 px
	Edge Smoothing Factor	0.050
Calibration Settings	Shutter Speed	100
	Stars	0
Other Parameters	Shutter Speed Near	40
	Shutter Speed Middle	100
	Shutter Speed Far	120

Table 7.35: Parameter values in RxLive 4.0 for Test 12.

Distance 40 cm	
Image 1	192.090 mm
Image 2	196.171 mm
Image 3	191.721 mm
Image 4	191.199 mm
Image 5	192.238 mm
Image 6	195.128 mm
Image 7	192.026 mm
Image 8	193.124 mm
Image 9	189.548 mm
Image 10	197.226 mm
Distance 80 cm	
Image 1	124.291 mm
Image 2	122.385 mm
Image 3	126.478 mm
Image 4	133.333 mm
Image 5	132.528 mm
Image 6	130.420 mm
Image 7	130.925 mm
Image 8	131.939 mm
Image 9	143.793 mm
Image 10	134.155 mm
Distance 120 cm	
Image 1	98.047 mm
Image 2	96.378 mm
Image 3	97.656 mm
Image 4	98.001 mm
Image 5	113.470 mm
Image 6	97.794 mm
Image 7	105.026 mm
Image 8	97.350 mm
Image 9	101.649 mm
Image 10	97.681 mm

Table 7.36: Measured lengths of object in test 12.

A.13 - Test 13

Lens type	25 mm
Background	Black
Object target	Test-fish
Medium	Water through a flat port

Table 7.37: Setup for test 13.

Test 13 - Parameter values in RxLive 4.0		
Preprocessing	Gradation Line	Disabled
	Denoise	Enabled
	Filter Diameter	4
	Noise Level	0.10
	Blend Factor	0.20
	Sharpening	Enabled
	Sharpness	1.50
	Blurring Standard Deviation	2.50
	Use only for estimation	Enabled
	Color	Disabled
Focus	Focus	-
	Depth Blending Scale	0.00
	Focus Resolution	3858 x 2682 px
Depth Estimation	Depth Algorithm	Depth Path
	Min Virtual Depth	2.00 VD
	Max Virtual Depth	15.00 VD
	Enabled Lens Types	Near, Middle, Far
	Min Correlation	0.900
	Min Std Deviation	0.010
	Patch Diameter	3 px
	Patch Stride	2 px
	Consistency Check	Enabled
Depth Map Creation	Depth Map Resolution	1929 x 1341 px
	Filling	Disabled
	Bilateral Filter	Enabled
	Filter Radius	5 px
	Edge Smoothing Factor	0.050
Calibration Settings	Shutter Speed	100
	Stars	3
Other Parameters	Shutter Speed Near	90
	Shutter Speed Middle	105
	Shutter Speed Far	120

Table 7.38: Parameter values in RxLive 4.0 for Test 13.

Distance 90 cm	
Image 1	224.846 mm
Image 2	224.939 mm
Image 3	226.526 mm
Image 4	225.431 mm
Image 5	223.918 mm
Image 6	224.649 mm
Image 7	222.745 mm
Image 8	224.983 mm
Image 9	221.947 mm
Image 10	220.564 mm
Distance 105 cm	
Image 1	221.301 mm
Image 2	223.489 mm
Image 3	226.669 mm
Image 4	223.216 mm
Image 5	222.942 mm
Image 6	222.787 mm
Image 7	220.882 mm
Image 8	220.556 mm
Image 9	222.807 mm
Image 10	220.488 mm
Distance 120 cm	
Image 1	216.900 mm
Image 2	217.526 mm
Image 3	218.097 mm
Image 4	218.166 mm
Image 5	219.428 mm
Image 6	220.061 mm
Image 7	216.529 mm
Image 8	218.157 mm
Image 9	218.647 mm
Image 10	220.835 mm

Table 7.39: Measured lengths of object in test 13.

A.14 - Test 14

Lens type	12 mm
Background	Black
Object target	Test-fish
Medium	Water through a flat port

Table 7.40: Setup for test 14.

Test 14 - Parameter values in RxLive 4.0		
Preprocessing	Gradation Line	Disabled
	Denoise	Enabled
	Filter Diameter	4
	Noise Level	0.10
	Blend Factor	0.20
	Sharpening	Enabled
	Sharpness	1.50
	Blurring Standard Deviation	2.50
	Use only for estimation	Enabled
	Color	Disabled
Focus	Focus	-
	Depth Blending Scale	0.00
	Focus Resolution	3858 x 2682 px
Depth Estimation	Depth Algorithm	Depth Path
	Min Virtual Depth	2.00 VD
	Max Virtual Depth	15.00 VD
	Enabled Lens Types	Near, Middle, Far
	Min Correlation	0.900
	Min Std Deviation	0.010
	Patch Diameter	3 px
	Patch Stride	2 px
	Consistency Check	Enabled
Depth Map Creation	Depth Map Resolution	1929 x 1341 px
	Filling	Disabled
	Bilateral Filter	Enabled
	Filter Radius	5 px
	Edge Smoothing Factor	0.050
Calibration Settings	Shutter Speed	100
	Stars	0
Other Parameters	Shutter Speed Near	25
	Shutter Speed Middle	30
	Shutter Speed Far	80

Table 7.41: Parameter values in RxLive 4.0 for Test 14.

Distance 60 cm	
Image 1	205.770 mm
Image 2	198.574 mm
Image 3	202.143 mm
Image 4	205.698 mm
Image 5	202.062 mm
Image 6	203.676 mm
Image 7	202.590 mm
Image 8	205.222 mm
Image 9	208.359 mm
Image 10	204.067 mm
Distance 90 cm	
Image 1	199.681 mm
Image 2	201.789 mm
Image 3	205.689 mm
Image 4	210.428 mm
Image 5	206.179 mm
Image 6	205.104 mm
Image 7	204.828 mm
Image 8	206.617 mm
Image 9	209.455 mm
Image 10	200.703 mm
Distance 120 cm	
Image 1	204.193 mm
Image 2	193.823 mm
Image 3	190.336 mm
Image 4	207.804 mm
Image 5	208.086 mm
Image 6	191.918 mm
Image 7	200.282 mm
Image 8	199.163 mm
Image 9	203.167 mm
Image 10	201.453 mm

Table 7.42: Measured lengths of object in test 14.