Imaging

[Version 12.02.2019]

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Contents

1 Objective and overview

To introduce the following subjects:

- Acquiring images with a webcam sensor (meaning of gain, integration time, saturation)
- Adjusting the light intensity with polarizers
- Measuring the basic parameters of a camera and objective (focal length, F# - number, numerical aperture, magnification, field of view)

To get this done, you need to read the reference documents provided and you should be able to answer the questions under Appendix A of this document.

2 Safety Issues

In this experiments laser sources and low power electrical equipment are used. The laser is of class II.
Class II: low-power visible lasers that emit a radiant power not above 1 mW. The concept is that the human aversion reaction to bright light will protect a person. Only limited controls are specified. (http://www.osha.gov, Laser Hazards)
The laser is safe because the blink reflex of the eye will limit the exposure to less than 0.25 seconds. It only applies to visible-light lasers (400–700 nm). Intentional suppression of the blink reflex could lead to eye injury. In our experiment the laser sources are collimated and should be handled with care. A strongly divergent beam will not be focused on the eyes retina and represents often no danger. Collimated beams will lead to small focus spots onto the retina special care is needed.
Do not stare into a collimated beam!
The electrical equipment used in the experiments is based on USB power (5V, 0.5 A, 2.5 W) and not subjected to any particular security issues. Nevertheless you should **not produce short circuits** on the printed circuit board (PCB) or to the computers USB connection to avoid damage to the material. Make proper use of screwdrivers. Do not force any mechanical parts.

3 Background

3.1. Measuring with a pixelated detector

An array detector is a matrix of photo-sensitive pixels which samples the incident light flux. At each pixel, the incident photons are converted into electrons and stored. After this acquisition phase, the stored electrons are read electronically (with amplification) and digitalized to form the image.
The dynamic range of the image is the number of encoded light levels. The C600 camera has 256 gray levels. It is an 8-bit camera. A properly exposed image has some pixels with level close to the maximum value. The exposure can be adjusted by varying the integration duration or integration time (controlling the number of detected photons) and the electronic gain (controlling the conversion). When a pixel level is at its maximum value, it is saturated. The numeric value is than 255 and cannot be evaluated. AVOID SATURATION OF THE DETECTOR! On the other hand, when the number of detected photons is very small, the

effect of detector and electronic noise is strongly visible, leading to unsatisfying images. The detector has a dark noise and signals are measured even without light on the detector. The electronics of the camera will correct this by subtracting such dark counts. This also fixes a minimum sensitivity level. Such a correction led to the situation that the no noise is found for certain low light illumination condition because the camera electronics suppresses it. Carefully adjust the exposure to the light level to obtain properly exposed images.

Most of the color cameras have an array of filters to modify the spectral sensitivity of the pixels to different colors. A common arrangement is the "Bayer pattern" that is used in the C600 camera. The color information is obtained by reducing the spatial sampling. However, the number of data points in the image is not reduced because it is compensated by interpolation.

The main parameters of the camera chip are the size of active area and the pixel number. The camera can have different shutter modes: global shutter and rolling shutter. Only the global shutter allows to record an image at the same time over the whole sensitive surface.

If you would like to get more information about CMOS or CCD technology please refer to specialized literature. [Gerald C. HOLST, CCD ARRAYS, CAMERAS, and DISPLAYS, PIE Publishing Bellingham 1998, ISBN: 0-8194-2853-1]

3.2 Transmission of light by two polarizers

Polarization is a property of light waves. A polarizer is a device that selects out of unpolarized (or natural) light a given state of polarization. We use linear polarizer to control transmission and intensity.

Monomode laser sources are polarized too. When a linear polarizer is brought in front of a linear polarized laser beam the intensity can be modulated by rotating one of the element against the other. If this rotation is done by an angle Θ the resulting intensity I becomes:

$$I = I_0 \cos^2 \Theta \tag{1}$$

The minimum intensity depends on the extinction ratio of the polarizer. In our case, the extinction ratio reaches 1/1000. Only relative adjustments will be used.

3.3 Basic parameters of the cameras and the objective

The basic layout of a photographic camera is shown below.

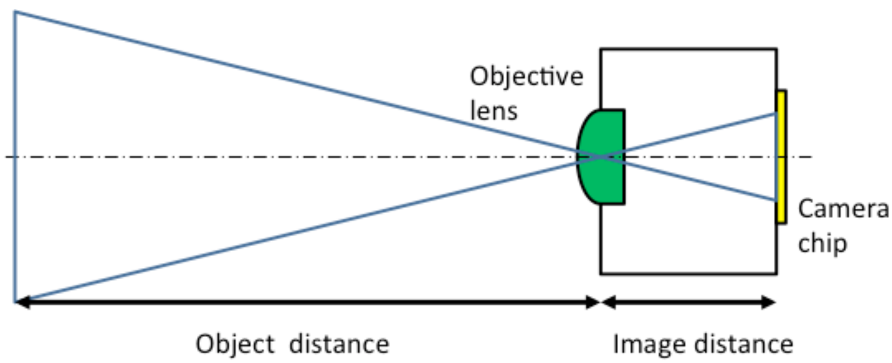


Figure 1: A camera consists of an objective and a photosensitive area brought into imaging positions to get a sharp image.

A camera objective is characterized by a focal length and an F# number usually imprinted on the lens rim. For instance for the camera objective Macro-Elmar-M shown here we read 1.4/90 which means F#=1.4 and focal length = 90 mm.
The focal length of a lens is determined by how strongly the system bends light rays. If collimated (strictly parallel propagating) rays are sent onto an optical system the focal length is the distance over which rays are brought to a focus as shown below.

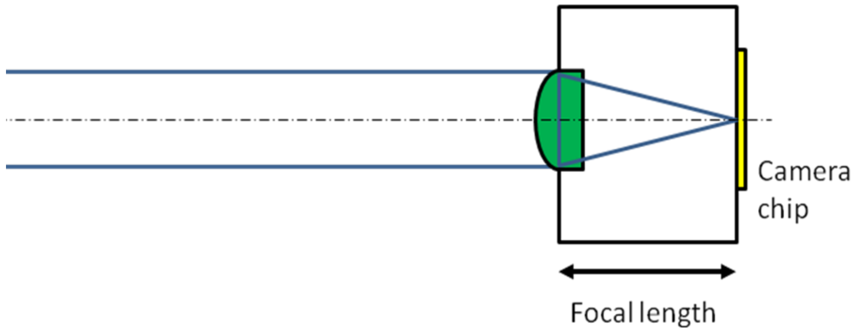


Figure 2: The focal length of a camera is given by the point where collimated rays are brought to focus.

The F#-number expresses a relation between the diameter of the entrance pupil and the focal length of the lens.

$$F\# = \frac{f}{D_{entrance}} \tag{2}$$

The number's value is the focal length divided by the effective aperture $D_{entrance}$ diameter and has no dimension. For a simple lens mounted in a housing, the lens diameter given by the lens rim represents the effective aperture. In a system of lenses the situation is more complicated. In such a case the effective aperture diameter $D_{entrance}$ is usually not the diameter of the first lens of an objective. The smaller the F# number is the brighter will be the image because more light is transmitted for larger apertures.
The numerical aperture gives a relation between the exit pupil (in contrary to the entrance pupil for the F# number) and the focal length.

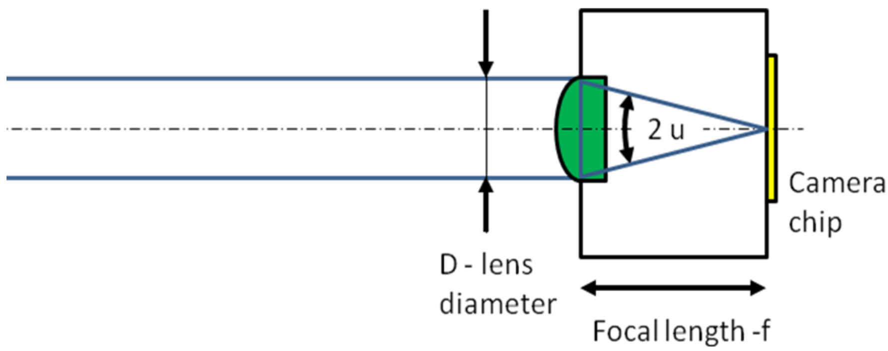


Figure 3: The numerical aperture is given by the ratio of the half diameter and the focal length and a measure for the angle u.

The numerical aperture (NA) is a dimensionless number and characterizes the range of angles over which the system accepts (or emits) light. The NA depends on the refractive index. It stays constant when the beams go from one material to another. Note that its definition might vary slightly between different areas of optics. Here we use the following definition and approximation:

$$NA = n \sin u = n \frac{D_{exit}}{2f} \tag{3}$$

Where n is the refractive index of the surrounding medium. When the medium is air the refractive index equals n=1 and we get:

$$NA = \sin u = \frac{D_{exit}}{2f} \tag{4}$$

3.4 Focal length measurement

In an situation were an image is formed of an object at an distance d_O the relation between the different distance is

$$\frac{1}{f} = \frac{1}{d_O} + \frac{1}{d_I} \tag{5}$$

where d_O is the object to lens distance, d_I is the image to lens distance, and f is the focal length of the lens. If one plans to use this relation to obtain the focal length f then you need to know the two distances d_O and d_I with good precision. When the lens (or lens system) is thick, it is not simple to know from where to measure. A way around this problem is to acquire two images of the object from two different distances, with **proper refocusing**. Then the focal length is found from the known displacement of the lens and the measured magnification of the two images. The magnification is related to the distances d_O, the object distance and d_I, the image distance through

$$m = \frac{d_I}{d_O} \tag{6}$$

By combing equations (5) and (6) for two different measurements the focal lengths can be extracted.

Example

Consider a first generation cell phone camera. The dimensions of the sensitive area of the pixelated detector is 3.2 mm times 1.92 mm. When an image is taken this number will define the maximum image size that can be recorded. The objective is assumed to be a single lens with focal length of 3 mm. The system is adjusted to focus an object at a distance of 30 cm. Calculate the magnification m.

$$\frac{1}{f} = \frac{1}{d_I} + \frac{1}{d_O} \qquad \frac{1}{3\text{mm}} = \frac{1}{d_I} + \frac{1}{30\text{cm}} \qquad d_I = 3.0303\text{mm}$$

$$m = \frac{d_I}{d_O} = \frac{0.30303\text{cm}}{30\text{cm}} = 0.01$$

The magnification is smaller than one because we create an image of a macroscopic object on a rather small detector with a lens of short focal length. Next we want to evaluate the field of view of the assembly objective and detector. Calculate the width h_O of an object that can be still completely seen with the camera? (also called the field of view) First we refer to the definition of the magnification m which is the ration between the size of the image h_I divided by the size of the object h_O, $m= h_I/h_O$. When m is known it is easy to find the maximum object size as

$$h_O = \frac{h_I}{m} = \frac{\text{width of camera chip}}{\text{magnification}} = \frac{3.2\text{mm}}{0.01} = 320\text{mm}$$

3.5. Field of view

The field of view (angle of view) is defined as the maximal angle a camera sees. It is limited by the detector size and the parameter of the objectives and mainly depended on the focal length. In a standard situation the focal lengths of an objective is chosen to be the same as the diagonal of the photosensitive area. For instance for a full frame detector with 36mmx24mm surface often a 50 mm focal length objective is set as a standard objective. For a Nikon camera the field of view of a 50 mm objective is about 47°. Nikon provides a tool to see the effect of the focal length on the size captured in object space. Please have a look at

http://imaging.nikon.com/lineup/lens/simulator/

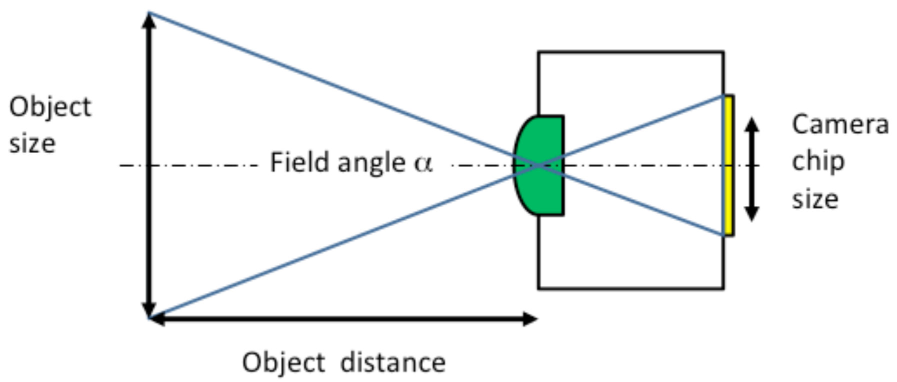


Figure 4. Definition of different parameters around the field angle.

The field angle can be measured by triangulation using a given object size and distance from the camera objective. If the effective focal length of the objective is known it could also me calculated.
If the detector size S (camera chip size, usually the longer side is taken) and the focal length f of the objective are known, it is also possible to calculate a theoretical field angle for an object at infinity. In this case the image appears at the focal plane and triangulation allows find the field angle (angle of view) α as

$$\alpha = 2\arctan\frac{S}{2f} = 2\arctan\frac{h_o}{2d_o} \approx \frac{h_o}{d_o} \tag{7}$$

when f is measured at the middle of the detector or camera chip.

3.5 F-number determination for the objective

The F#-number can be approximated from the numerical aperture NA as

$$F\# \approx \frac{1}{2NA} \tag{8}$$

To measure the F#-number one can determine the NA by using a collimated laser beam (to be assembled). Shine the beam on-axis through the optical system and measure the beam diameter on the sensor. This divergence angle u in equation (4) is obtained by measuring the beam diameter for different and known distances between the lens and the sensor.

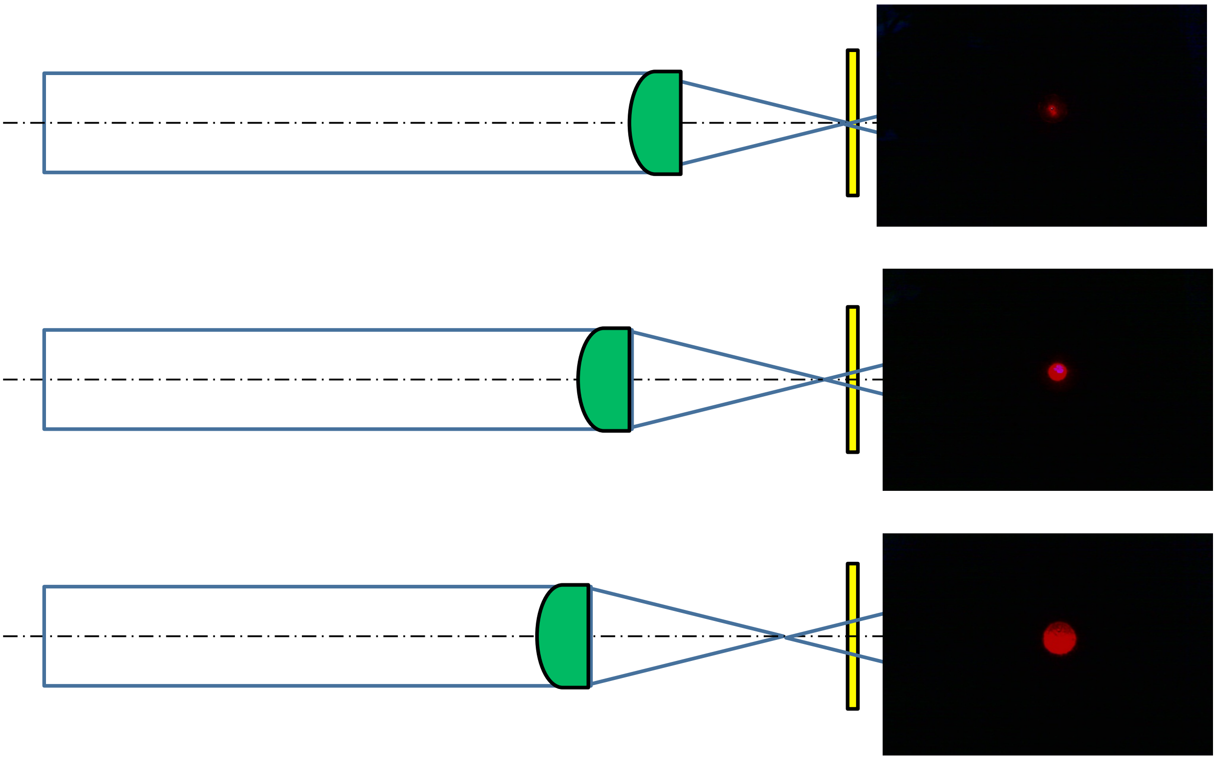


Figure 5. Collimated laser light produces a light cone that can be probed in the imaging space by defocusing the objective. Left: the effect of defocusing and the position of the focal point. Right: Images taken with the collimated laser at different defocusing positions.

4 Setup and equipment

4.1. Materials

A camera sensor (1600x1200 pixels, color, pixel pitch (size) 2.835 um) C600 from Logitech is used as the detector.

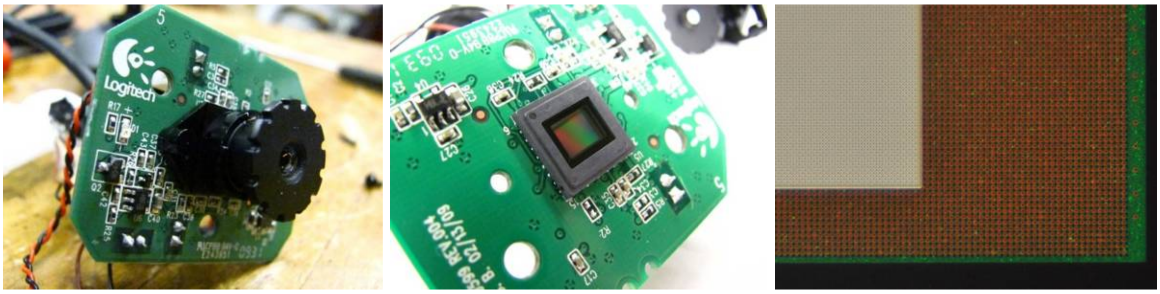


Figure 6: The camera PCB (printed circuit board) with (left) and without (middle) objective and a microscopy image of the detectors surface

Detector

The sensor appears to be a 1/3.2" Type sensor with 4:3 aspect ratio. Testing seems to indicate that the sensor has a global shutter.

Photosensitive detector area size is 4.536 mm x 3.416 mm.

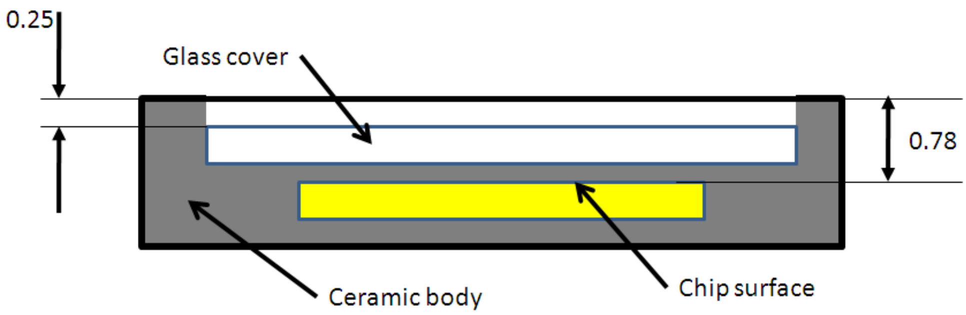


Figure 7: Side view with dimensions (mm).

The distance between the ceramic body top (surface touched with flat specimens) and the chip surface is about 0.780 mm.

Objectives

We use the original camera objective that is mounted on the camera PCB by means of a black plastic art. This is a lens made of glass elements. The focal length is currently undetermined. The lens support is threaded M10x0.3. ***After one turn, it moves axially by 0.333 mm.***

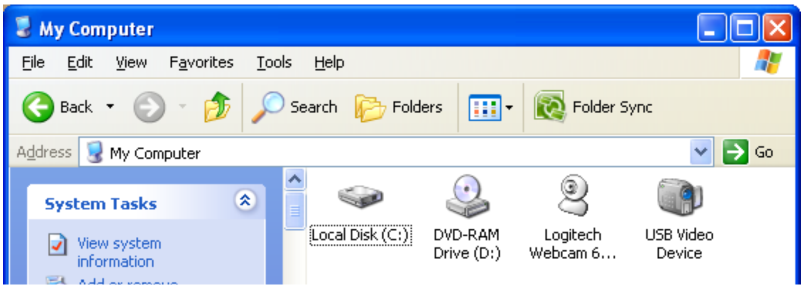
EPFL

Figure 8: The original glass lens of the C600 camera in its black plastic holder.

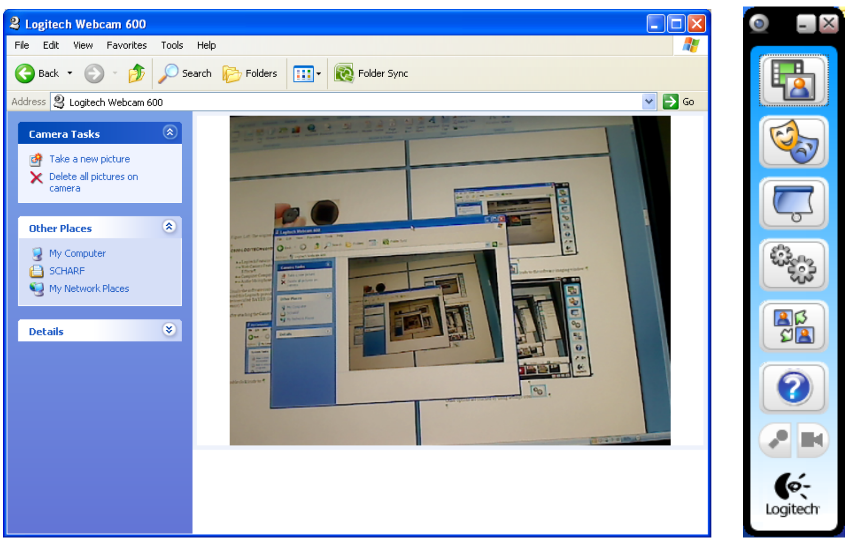
C600 LOGITECH control software

- Logitech Features Video Size: HD 1600 x 1200
- Web Camera Features: Activity Light, HD video recording, RightSound, Video Effects
- Computer Compatibility: PC Image, Video Size: HD 1600 x 1200
- Audio Microphone: [Logitech® Video Effects™, Logitech® Vid™]

Usually the software controls large part of the sampling and the exposure parameters. To avoid this Logitech provides a Raw mode enabling/disabling tool for Logitech QuickCam devices called BAYER (linked to the BAYER pattern of the color filter in front of the sensor). After attaching the Camera via USB bus you will find an icon on "My computer"

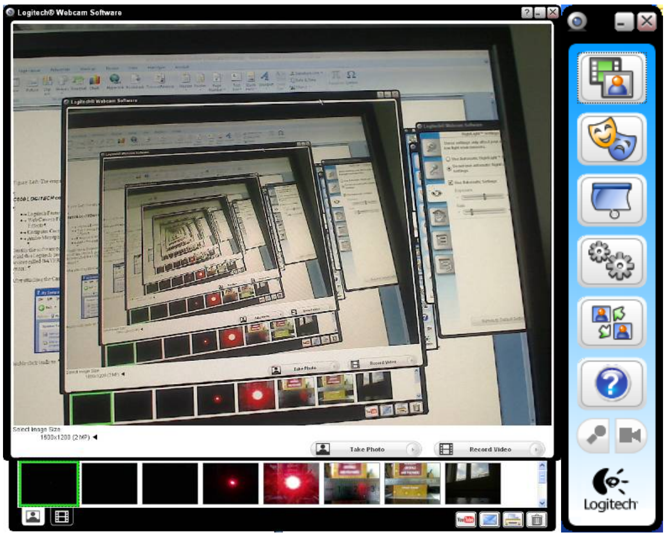


Double click leads to:

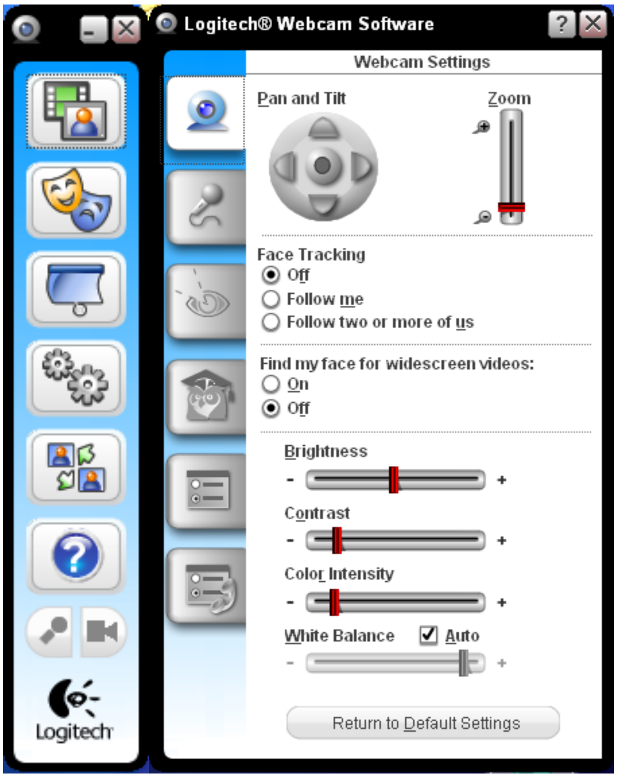


The Logitech software starts automatically and a control bar is provided. Stop the explorer application and use the C600 software from now on.

Using  leads to the software imaging window.

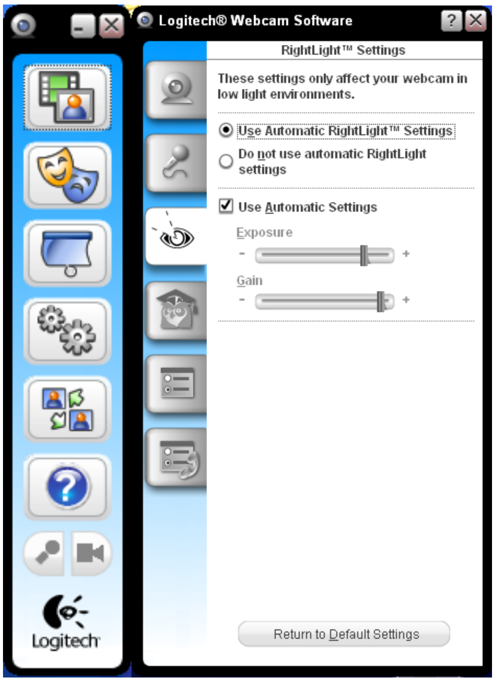


Other options are reached by using settings icon .

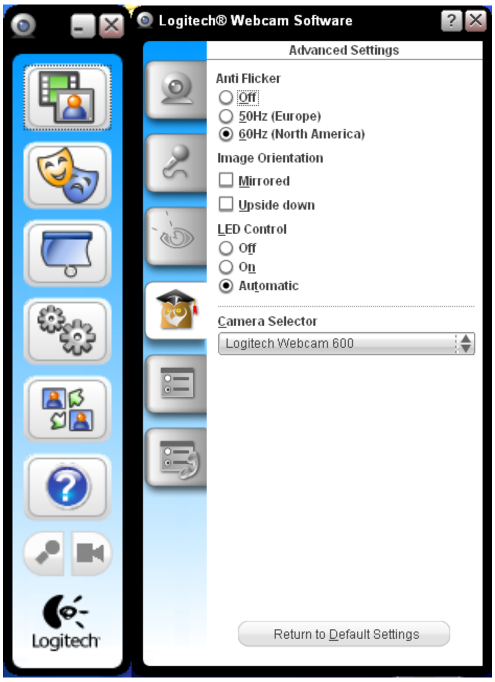


DO NOT USE BRIGHTNESS, CONTRAST, COLOR INTENSITY AND WHITE BALANCE option. This are software controls that will falsify your measurement.

Most important for us here is the light settings tab. .



Here you get control over exposure time and gain. Sometimes it is needed to get access to further options reached under advanced settings 



Especially useful is the option to switch of the LED for measurement under low light conditions and better stray-light (unwanted light) suppression.

4.2 Saturation and intensity adjustment of the camera.

First we proceed to check the camera basic adjustments. To do so a simple setup has to be mounted. Start with the breadboard and mount the translation stage.

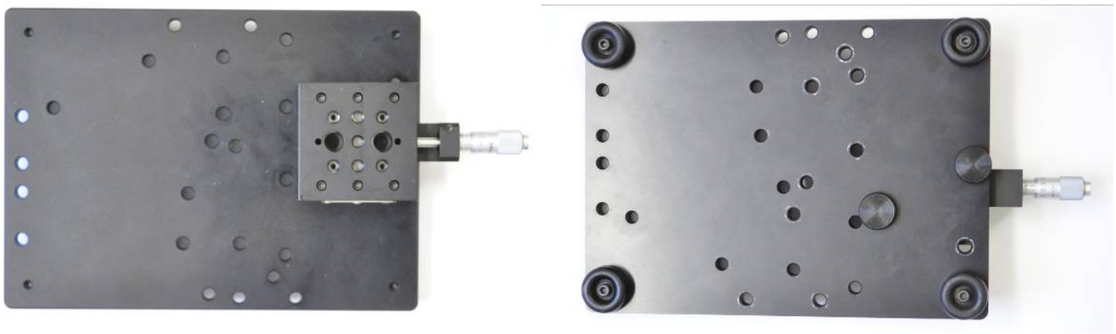


Figure 9: Breadboard with translation stage

The stage is fixed with screws arranged asymmetric (see the right picture). Continue by mounting the adapter plate and the intermediate piece as below.

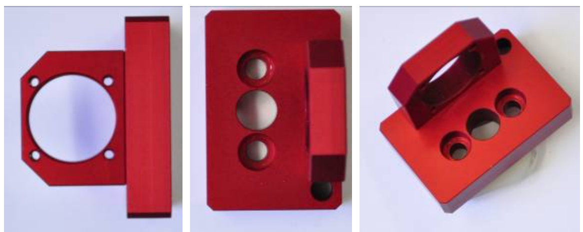


Figure 10: Adapter plate and intermediate fixing have to be screw together.

The cameras PCB (printed circuit board) special holder is mounted as shown below.

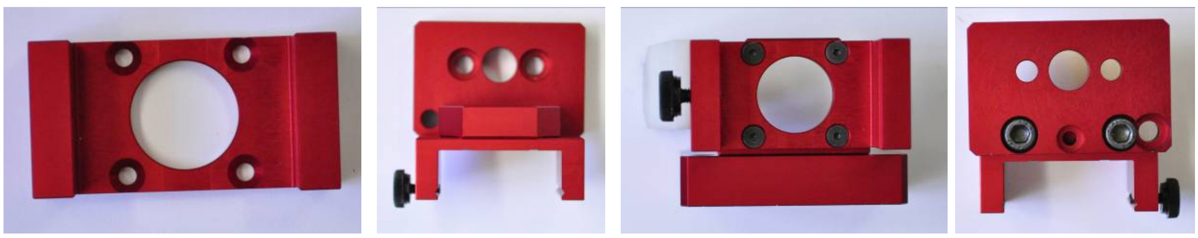


Figure 11: Camera holder (left) mounted on the adapter plate with the intermediate piece. Right: as seen from below.

The assembly has to be fixed on the translation stage before the camera PCB is put into place.

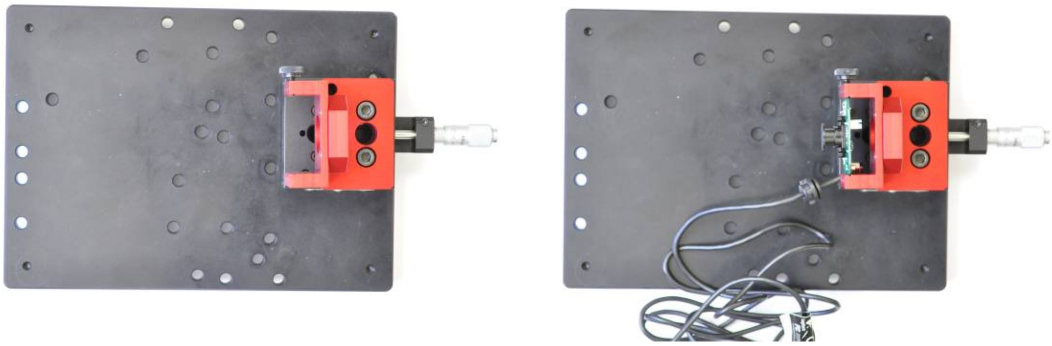


Figure 12: Camera mounts on the translation stage with and without camera in its holder.

Figure 13: Camera PCB in the mount ready for shooting.

The aim is to take a few images and determine basic parameter of the camera like saturation and dark count level.

- Images for different illumination conditions have to be taken and saved in folder ('C:\....filename').
- Images have to be uploaded into Matlab and line plots for different illumination conditions for the same image have to be made.
- Identify a suitable folder so that you can find your images back easily

Do the following
- Determine a scene
- Set the exposure conditions of the camera to automatic
- Take a first picture and save it (use preferably the MATLAB folder to have easy access to the data afterwards)
- Open Matlab
- Use the program "readimage.m" (provided) to read an image and get a line plot
- Adjust the Region Of Interest ROI at your wish (present is center points x=200, y=100, widths w=200, height h=200, you have 1600 x 1200 image points)

MATLAB Example file (provided)

```
% Read an image
I = imread('Picture 43.jpg');

% display an image
imagesc(I);
```

What you get is similar to the images below

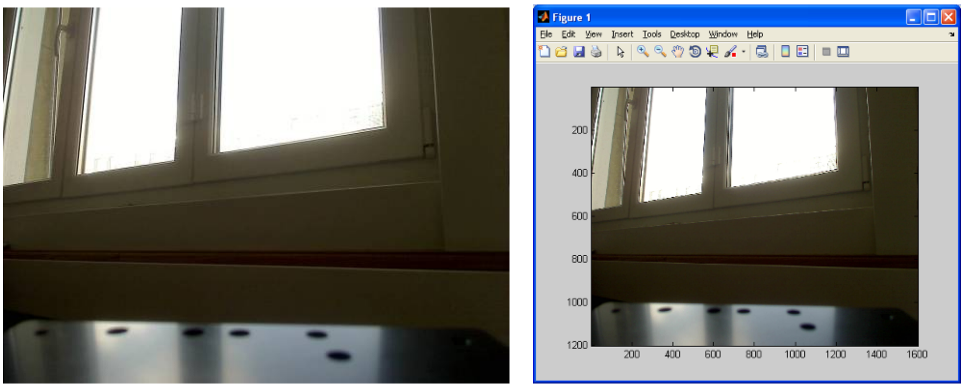


Figure 14: Original JPEG image and as seen in Matlab

To get line plots you need to convert the images into black and white, choose a region of interest and plot a graph. Matlab commands for an unweight black and white conversion look like this:

```
% Read an image
I = imread('Picture 44.jpg');
% display an image - shows the coordinates of images points for x and y
figure
imagesc(I);
% convert to B&W - makes a mean of three intensity values for blue, green
% and red
I = mean(I,3);
% select a region of interest ROI
% x - start x value
% y - start y value
% w - x range (width)
% h - y range (height)
x = 1;
y = 400;
w = 1599;
h = 1;
I = I(y:y+h,x:x+w);
% vertical average over the ROI - averages over the height h and results a
% vector with lengths w
M = mean(I);
% plot the average profile - plots value against x (w)
figure
plot(M);
```

A typical line plot at line 400 (x=1..1599, y = 400) is shown in the figure below.

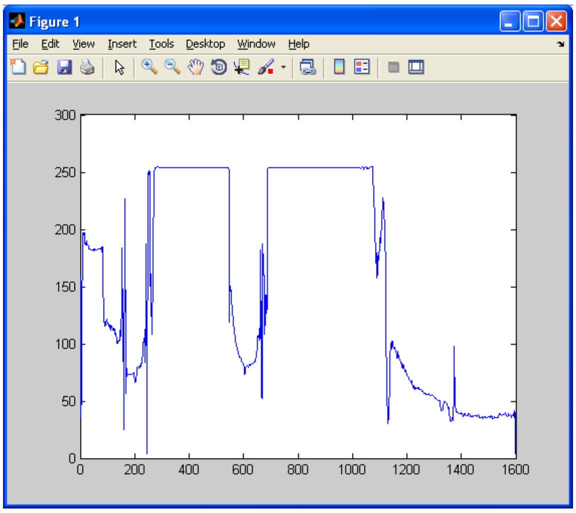


Figure 15: Intensity line plot at position y=400. The saturation is easily seen as the two flat parts of the curve with the maximum pixel count of 256.

The Matlab program allows also averaging over different horizontal lines by setting the height at a certain value.
Next action

- Set the exposure condition to values so that the camera does not saturate.
- Take a image and make the line plot

In our example we find the following image and plots:

Figure 16: Photo and line plot without saturation. The values are always smaller that 256!

For measurements avoid saturation (Saturation exist for pixel values at 255!). It does not give useful results.

TO BE DONE FOR THE REPORT: Take an image of the same scene at different exposure levels: one with automatic exposure, one with no saturated pixel, one with only a few saturated pixel. Make line plots at areas were automatic exposure gave saturation and compare the plots for the three exposure conditions. (three images and corresponding line plots)

4.3 Procedure to measure the focal lengths

Now we are ready to start measurements of the basic parameters of our camera objective. By measuring the object and image height for two different magnifications the focal lengths can be measured. To find a formula that allows us to calculate the focal lengths for this situation we consider two measurements A and B. We use the lens equation of a thin lens that relates object and image distance and focal lengths. We find:

For A:

$$\frac{1}{f}=\frac{1}{d_{OA}}+\frac{1}{d_{IA}} \qquad (9) \qquad \text{and} \qquad m_A=\frac{h_{IA}}{h_{OA}} \qquad (10)$$

For B:

$$\frac{1}{f}=\frac{1}{d_{OB}}+\frac{1}{d_{IB}} \qquad (11) \qquad \text{and} \qquad m_B=\frac{h_{IB}}{h_{OB}} \qquad (12)$$

The values h_I and h_O are the image and object sizes or heights. The magnification is the ratio between the image height h_I and the object height h_O. The setup does not allow to have access to images distance d_I. This is unknown. Only the difference between two positions d_{IA} and d_{IB} can be found. The secret of the measurement is the focusing. **ONE NEEDS TO HAVE PERFECT FOCUS TO GET GOOD RESULTS.** Taking well focussed images of a ruler allows direct calculation of m_A and m_B because we know the size of the detector, hence the image size h_I. The measurement is based on the knowledge that **each rotation of the objective changes** the imaging distance d_I by 0.333 mm. (Detector width is 4.536mm and height is 3.416mm)

- Choose a convenient image distance (20-30cm) and put the ruler there.
- Focus the camera by turning the objective (Fig. 17).
- Take an image and determine m_A
- Turn the objective by **ONE COMPLETE TURN** (to have 0.333 mm change of d_I). If needed make a mark on the plastic rim of the objective. The objective should move out of the mount (increasing d_I)

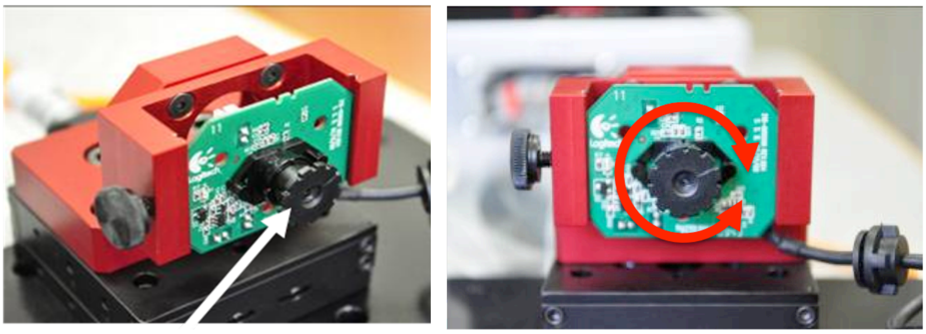


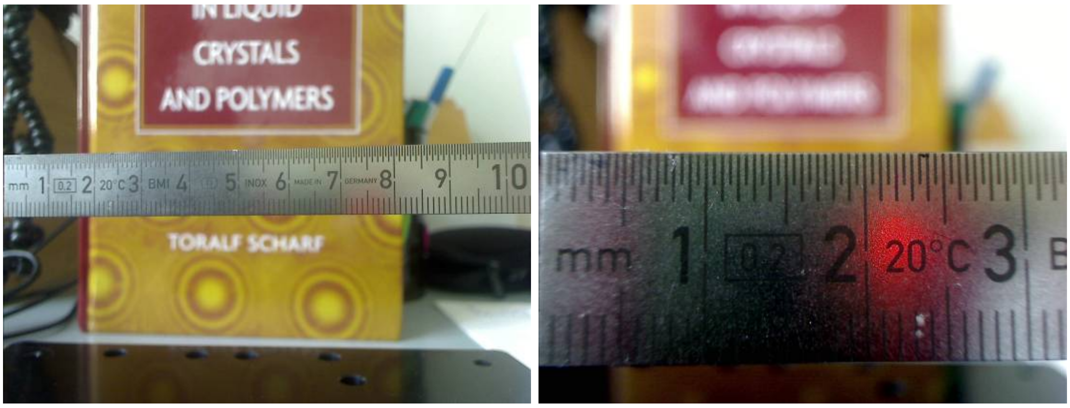
Figure 17 The objective is the small black piece carrying the lenses. This part can be rotated to change the distance between it and the detector. (Focusing). One full turn of the objective will move the objective by 0.333mm. **The sense of rotation of the objective depends on your experimental conditions and is subjected to change without notice.**

- Move the ruler to be in focus.
- Take an image and determine m_B

The focal length can then be calculated by the formula

$$f = \frac{d_{IB} - d_{IA}}{(m_B - m_A)} \qquad (13)$$

A sample sequence of images may look like this:



A B

Figure 18: Sample images to determine the magnification for two different focalization (magnification) positions.

In our concrete situation the image height is constant because we observe with the same detector!
For A one finds a width of 104.5 mm and for B one gets 32.5mm. The detector width is 4.536mm. Magnification can be calculated by dividing the image width (or height) by the object width (or height). **In our concrete situation the image width is constant because we observe with the same detector and look at the total width of the image on the detector!** Here one finds m_A=1/23 and m_B= 1/7. The de-focalisation distance for one turn is d_{IB}-d_{IA}=0.33 mm and one can find the focal length with the help of equation (13).

TO BE DONE FOR THE REPORT: Show your two images with different magnifications. Determine the focal length and show the numbers used for the calculation. Make an error estimation.

4.4 Measurement of the field of view (angle of view)

We want to measure the field of view of our camera. This is the maximum angle that can be captured. To do so one measures the full field (object width) that is imaged and the distance of the object (d_O). If you look at Figure 18 you see that the full field is given by 10.3cm which is the maximum object size at this specific distance d_O. If one measures additionally the distance of the ruler from the objective the angle can be easily calculated by triangulation (compare Figure 4) Take a focused image of known dimension and measure with the ruler the distance of the object to the first lens of the objective.

TO BE DONE FOR THE REPORT: Calculate the angle of view (field of view) and make an error estimation.

4.5 Measurement of the F# number.

Collimated beam setup

The parameters of the objective can be measured by using a collimated laser beam. This can be produced by using the laser and a lens. We use the camera as already mounted and send a collimated beam on it.

- Mount the source holder at the other side of the breadboard so that the source is in front of the camera
- Put the laser in place
- Switch on the laser (just connect to USB of the PC)
- Apply the lens cap

You should have a setup as shown below.

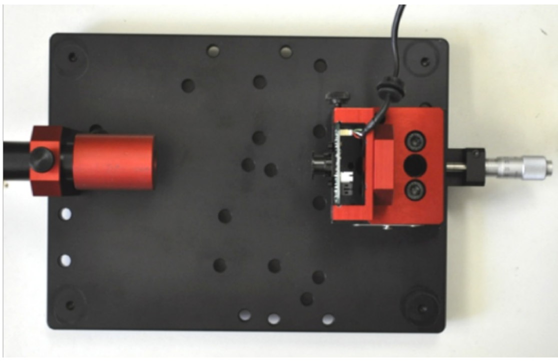


Figure 19: Collimated beam setup. The laser with the lens cap on the left illuminates the camera to the right.

The red tube that needs to be fixed over the source carries a plano-convex lens with f=12 mm and diameter 9 mm made from BK7 (Thorlabs L1576). In addition a polarizer is fixed inside the tube (Edmund Scientific part number ES45668). Moving the tube longitudinally (along the optical axis) focuses the light. Turning the tube adjusts the intensity (because there is a polarizer in the tube and the source is polarized too).

Figure 20: Source mounted with the lens cap (on the right) to achieve focusing and collimation

A collimated beam is a beam that has parallel wavefronts and does not shows any change diameter when seen at different distance. Of course this is an approximation. This can be probed with a sheet of paper as shown in the image sequence below.

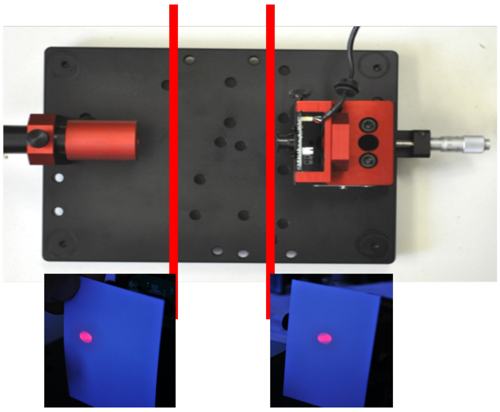


Figure 21: Light spot at different distances from the collimated source. There is nearly no change.

To make it happen the lens cap has to be moved along the optical axis to adjust the focus and the sheet of paper has to be used regularly to probe the collimation quality.

Adjustment of exposure conditions with the polarizer

If a laser is send directly on the camera the intensity is too high to be measured without getting into saturation. To adjust the intensity polarizers are used. The laser is already linear polarized (mono-mode laser). An additional polarizer foil is provided to adjust the intensity further. Before using the external sheet polarizer, please assure that there is no protection foil on the polarizer anymore, which would make the polarizer slightly diffusing. Sources are polarized in a certain direction and **rotation of the source** with respect to the sheet polarizer **allows intensity adjustment** (cosine square law). The polarizer can be put in front of the camera or in front of the source.

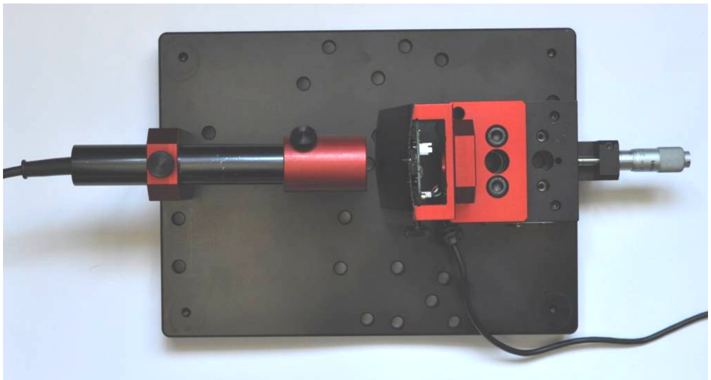


Figure 22: A polarizer is put in front of the camera. Rotating the source or/and the lens cab allows adjusting the intensity.

To measure the focalization properties follow the procedure below using collimated beam:

- Focus by turning the objective of the Logitech C600
- Find the smallest focus
- Adjust intensity (insert the sheet polarizer, rotate the source!)
- Adjust exposure conditions (low gain, play with exposure time)
- Make a picture at smallest focus point size with appropriate intensity adjustment.
- It is very important to avoid saturation because this falsifies the size measurement.

The series of images below gives you an idea how the intensity can be adjusted and what you should looking for.

Figure 23: Left: Overexposed image by using automated exposure. Middle: Image with lowest gain and shortest exposure time. Right: Image of the focal spot without saturation at highest attenuation.

Note: The intensity can be adjusted by two means. First by adjusting the lens cap on the source and secondly by adjusting the assembly lens-source and the supplementary polarizer.

F#-number of the objective

The F#-number can be approximated from the numerical aperture NA as F# = 1/(2 NA), with NA = n sin u and n the refractive index of the medium (Fig. 3). The angle u is **half the angle** that the system creates. To measure the F#-number we use a collimated laser beam (as assembled). Shine the beam on-axis through the optical system and measure the divergence angle on the sensor side by looking at different distances behind the lens (Fig. 5). With then angle u you can find the F#-number.

- Mount the camera - laser arrangement as shown above
- Collimate the laser with the lens (red cap on laser, parallel beam)
- Adjust the intensity of the laser by rotating the lens (polarizer inside)
- Adjust the intensity by introducing the sheet polarizer and rotate the lens and laser together
- Adjust exposure conditions
- Focus with the camera objective
- Defocus by turning the objective (quarter turn as shown below) and measure the light cone evolvement as a function of the defocus (Thread M10.- 0.3 on the camera objective)

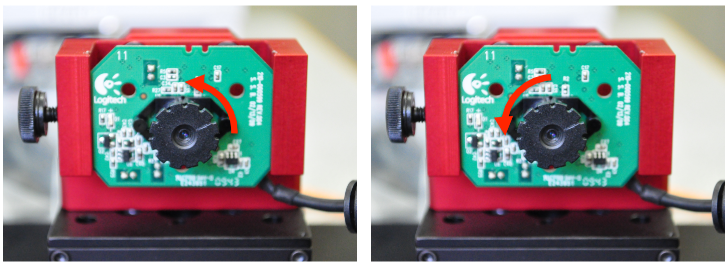
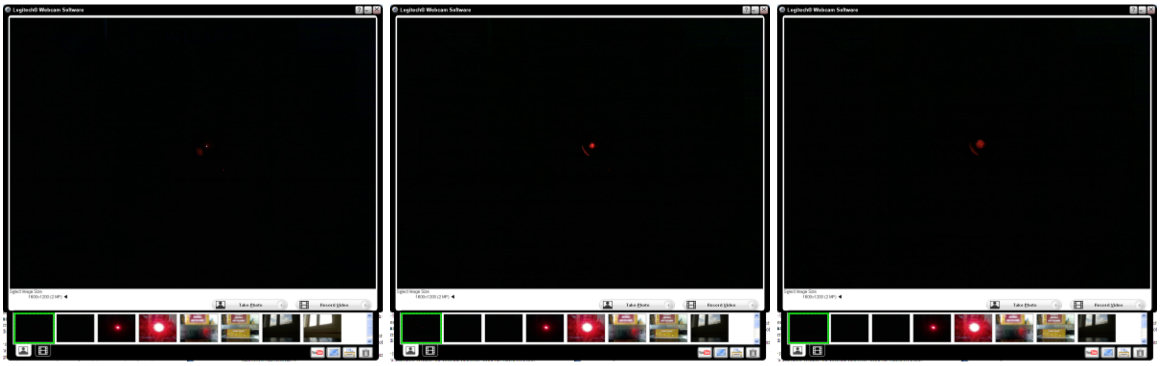


Figure 24 Defocussing (by turning the objective) will change the distance between the objective and the sensor and allows to probe the light in the image space.

A typical sequence of images for quarter turns is shown below.



0 quarter round rotation half round rotation

Figure 25: Typical defocus images at different camera lens positions starting from the focus.

It is easily seen that the illumination disc diameter changes. You can do the evaluation of disc diameter in Matlab or directly in the image because you know the absolute image size (the because the size of detector is known in mm). The resulting angle u as a function of the relative position is given by the rotation angle of the objective and should be tabulated. Calculate the numerical aperture and F# number.

TO BE DONE FOR THE REPORT: A picture of the smallest spot size. A table of luminous disc size versa relative focusing position (min 5 positions). Calculation of u, NA and F#. Give the value used for the calculations.

4.6. Example from real world

TO BE DONE FOR THE REPORT: Find an example in the internet of **one photographic lens** with small F# number. Try to find something what not all your classmates have. You might look at websites of well-known lens produces such as Nikon, Canon, Leica, Zeiss, Rodenstock, Fuji….. You can also include c-mount lenses (used for automated machine vision) in your search. One example for instance is the Leica Noctilux 50 mm f/0.95 ASPH which is shown below. Add a photo of the source!

5. Summary of tasks of the experimental work

5.2. Saturation and intensity adjustment of the camera (20 min)

Take an image of the same scene at different exposure levels: one with automatic exposure, one with no saturated pixel, one with only a few saturated pixel. Make line plots at areas were automatic exposure gave saturation and compare the plots for the three exposure conditions. (three images and corresponding line plots)

5.3 Procedure to measure the focal lengths (25 min)

Show your two images with different magnifications. Determine the focal length and show the numbers used for the calculation. Make an error estimation. (Error formula)

5.4 Measurement of the field of view (angle of view) (15 min)

Calculate the angle of view (field of view) and make an error estimation.

5.5 Measurement of the F# number. (45 min)

A picture of the smallest spot size. A table of luminous disc size versa relative focusing position (min 5 positions). Calculation of u, NA and F#. Give the value used for the calculations.

5.6. Example from real world

Find an example in the internet of **one photographic lens** with small F# number. Try to find something what not all your classmates have. You might look at websites of well-known lens produces such as Nikon, Canon, Leica, Zeiss, Rodenstock, Fuji….. You can also include c-mount lenses (used for automated machine vision) in your search. Add a photo of the objective!