DIY Optical Microscope

Kevin Namink

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Abstract

Recently technology like laser-cutting and 3D printing became more easily available. With this and various electronics one can build scientific equipment at home, for instance a microscope. The optics for a microscope can all be provided by the Raspberry Pi camera module and can be controlled by a Raspberry Pi, both very affordable. We have designed a microscope that can be build in 3 hours, has a field of view of over 260 by 200 micrometers and can produce data with a resolution of approximately 4.5 micrometer. It is quite stable on the long term, drifting only 0.37 micrometer after 48 hours in our measurements, and is capable of electrophoresis measurements.

Contents

1 Introduction

Not for every scientific project expensive and big microscopes are the way to go. A do-it-yourself (DIY) microscope can actually be a very good solution for many situations. In this paper the design of a DIY microscope is documented. Without using expensive materials we have made a optical microscope that can be used for scientific purposes and can be build quickly. We use laser-cutting and 3D printing for quickly and accurately creating the base. Various electronics like the Raspberry Pi with camera module and a few extra parts take care of the optical system and necessary movement.

1.1 Current DIY microscopes overview

There are already several DIY microscopes on the internet. Below you can find a description of three that inspired us:

A one-piece 3D printed microscope and flexure translation stage

From a group of researchers from the University of Cambridge comes a paper about a 3D printed microscope[2]. In this paper their mechanical design, stability data and more is described. They used 3D printed hinges of thin plastic which worked very well. Similar 3D printed are used in our design.
See figure 1 for their design.

Figure 1: Photograph of the one-piece 3D printed microscope. The three big gears control lateral motion and focus respectively the outer and center gears. The sample is held by the printed clips, a white LED is mounted on a printed arm at the top and the lens from the Raspberry Pi camera module is visible though the hole in the sample stage. The camera sensor mounts underneath the microscope.

iGEM

Also from the University of Cambridge comes iGEM with the OpenScope[1], an open source microscope that is almost fully 3D printed. This microscope has been a welcome example for this project. Since their design for the optics was very good for the cost, it was an easy decision to use a similar optic system. Figure 2 shows their microscope.

Figure 2: Photograph of the iGEM OpenScope. The three big gears control lateral motion and focus respectively the outer and center gears. The lens and camera sensor are above the sample as in traditional microscopy. A LED illuminates the sample from below. The OpenScope can mount a filter between lens and sensor to do fluorescence measurement.

FlyPi

The FlyPi is an open source project aiming to make a cheap microscopy system. Their project is still ongoing and new logs appear weekly on their project site[3]. See figure 3 for their microscope

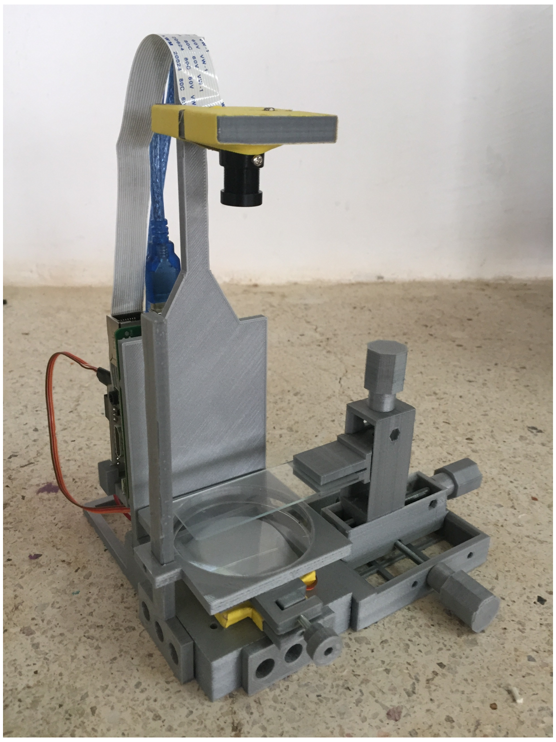

Figure 3: The FlyPi microscope. It is cheap and its possibilities are a growing. These possibilities include fluorescence measurement and more.

1.2 Goals

For the microscope we made there was a list of characteristics that it should fulfil. They will be described here with some explanation.

- **Affordable**

Since it is a DIY style microscope the final design should not cost more than 500 Euro. This goal is quite important since if it was expensive it would not be a good replacement for commercial microscopes.

- **Quickly made**

It should not take more than 2 hours to assemble it. Since there was already some project where it was planned to use it, it was supposed to take as little time as possible to produce a few of them. This goal is harder to keep than it seems, as 3D printing takes a lot of time. But we can use laser-cutting instead to significantly reduce building times for the final design.

- **Reliable**

It should be very reproducible. Since it is supposed to be used for scientific purposes it has to be reliable.

- **Multi purpose**

This microscope is supposed to be multifunctional. The things it had to be able to were white and dark field imaging and electrophoresis. But motor support has also become an option.

2 Fabrication details

With the goals in mind the choice of fabrication methods had shrunk a lot. Especially with the combination of our goals of cheap costs, high manufacturing speed and reliability. The final choices for the different methods will be explained.

2.1 3D printing

As seen in similar microscopy projects 3D printing is a reliable and cheap method of production, the only problem is the time it takes to print something. In the similar projects the time it takes to print their microscope is not mentioned. This time can easily be a day, especially when you have a failed overnight print or a printer stopped printing. 3D printing technology has not been around for long, so there are still a lot of little issues to deal with.

While 3D printers have low printing speed, this doesn't hurt the fact that 3D printers are amazing tools for making anything that needs to be cheap and sturdy. That is why the microscope we made can be completely 3D printed if necessary. The 3D printed version of it is presented on figure 4.

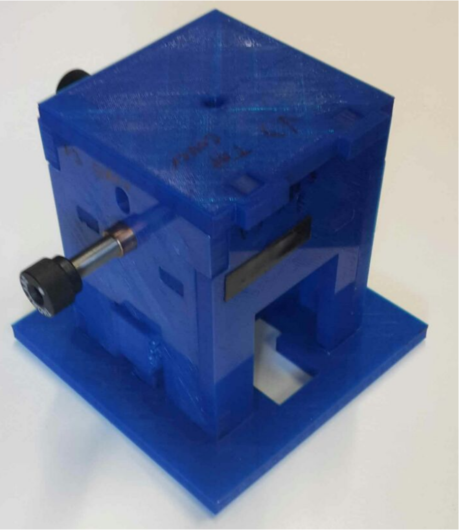

Figure 4: A fully 3D printed version of the microscope. This takes approximately 15 hours of 3D printing.

The final design uses 3D printing technology for all custom parts that are too complicated for alternative construction methods. Most importantly the z-translation focusing mechanism.

The 3D printer we used was the Ultimaker 2. This is a commercial machine that is relatively affordable and used quite a lot[4]. Parts were printed using PLA plastic. PLA is one of the most common plastics to print with. It is durable and strong, but can be bent when printed in certain ways. It is also able to cover difficult printing orders like overhanging structures reasonably well.

2.2 Laser-cutting

After the first trials with the 3D printing, our eyes quickly fell upon laser-cutting technology. Its biggest advantage over 3D printing is the fabrication speed. It can cut complicated patterns in a matter of minutes. Many 3D printers, i.e. the Ultimaker Original, are made using laser cut material.

A laser-cutter cuts sheets of material. So only 2D shapes can be produced. This is quite a big limitation. But there are a lot of things you can create putting 2D parts together. And many materials to choose from, including the sturdy choice of 6 millimetre thick plywood. We chose to laser-cut plywood to make the largest parts that provide the basic structure of the microscope.

By using laser-cut plywood for these big parts they can be produced in minutes compared to hours when 3D printing while maintaining the structural strength. The burned edges from the laser-cutting give the microscope a nice look, i.e. figure 16 on page 23.

2.3 Optics

Good optics are the core of every microscope. The similar projects used the Raspberry Pi with camera module and had a great magnification and resolution. In our project we use the Raspberry Pi camera to save time.

- **Lens**

We used the Raspberry Pi NoIR camera module which has a small lens (1.25mm diameter) with a very small focal distance (3.6 mm)[10]. After taking this from the camera board, we can use it as the lens for our system.

For our optical design we will only use one lens. This allows us to simplify the optical system by sacrificing resolution. Also we have seen that this system has been used for great results in other DIY microscopy projects.

For dark field imaging a second lens is needed to focus the illumination light. We use a simple aspheric lens of 18.4 mm focal distance.

- **Sensor**

The Pi NoIR camera sensor has 2592 by 1944 pixels, and the board is capable of binning pixels together for faster imaging.

2.4 Electronics

- **Raspberry Pi**

The easiest way to control the Pi NoIR camera is with a Raspberry Pi, a credit card sized computer. The Raspberry Pi is quite powerful for its cost and functions as a full computer. The ability to use the camera controlling device for more than getting the data can be very useful, for example in very long measurements where the data can be processed during the measurement to save time later.

- **LED**

LED's are a good way to illuminate a sample. They emit light of known wavelengths, use little power, are lightweight and cheap.

- **Miscellaneous electronics**

Like any computer the Raspberry Pi needs a screen, mouse and keyboard to function. Note that there are only hdmi and usb connections available on the Raspberry Pi.

There are also touch screens available for the Raspberry Pi. Raspberry sells official Raspberry Pi Displays that are touch-screen but there are also third party touch-screens that might be cheaper and more advanced. A touch-screen is a good option to make the microscope more mobile. And they also reduce the amount of wires that can get tangled.

- **Stepper motors (optional)**

For automatically moving the sample and focussing some motors are needed and stepper motors are perfect for this kind of work. They can turn short distances when needed and are usually quite small and cheap. Like any motor they draw a lot of power, so an external power source is needed.
For using motors it is also necessary to use a driver IC.

2.5 Miscellaneous parts

We need some special parts that just cannot be made with laser-cutting or 3D printing.

- **Micro adjusters**

For achieving manual micrometer accuracy translation we use micrometer adjusters. They are small, lightweight, relatively cheap and, most important, smooth and repeatable.
We use 100 windings per inch micrometer adjusters, so we get 254 micrometer movement per revolution[12].

- **Petri-dishes with cover glass**

We chose to use Petri dishes for making the microscopy slides, to keep the microscope small we had to change to different microscopy slide than the usual 5 by 2 inch slides. Our translation system works with circular samples. We quickly figured Petri-dishes to be useful and they are available with build in cover glass for microscopy.

- **Tubes**

For dark field imaging light needed to be focused, the easiest design we could think of included 2 tubes. These 2 tubes have different diameters with the smaller one fitting in the bigger one.

3 Theory of operation

3.1 xy-translation

This microscope translates the sample with a quite simple design. Our sample is mounted on a circular holder that can freely move in the horizontal plane but fixed vertically. From 2 directions perpendicular to each other micrometer adjusters push the sample around. It is pushed back by a plate spring.

To remove any chance of the sample moving up or down the sides of the holder are angled up. The micrometer adjusters and plate spring will always push the holder down.
See figure 5.

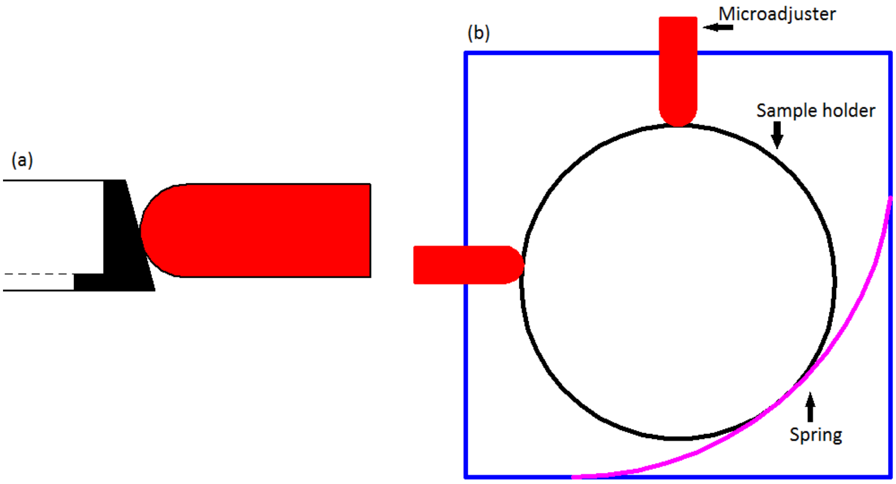

Figure 5: A sketch of the design to keep the sample from moving vertically (a) and a sketch of the xy translation system (b). The micrometers (red) can push the sample holder (black) around while the plate spring (purple) pushes the sample holder back. The square (blue) is the solid wall of the microscope.

This design was chosen because it works properly without being unnecessarily complicated. Because of its shape this design doesn't translate completely orthogonal, but this is hardly noticeable with the distances it moves.

The round sample holder is made to perfectly fit a standard 30 mm Petri-dish but other samples can be made to fit as well.

3.2 z-translation focusing

The focus is the most important part to move precisely. So we needed a solid system for this. We had to use the 3D printer for this, as it could produce the perfect combination of accuracy, flexibility and sturdiness for this.

We made use of the flexibility of PLA hinges to make a parallelogram structure with bending corners. With the flexibility of the PLA this shape returns to the original shape after it is bent. So no additional spring was needed. The parallelogram shape makes it possible to keep the lens movement straight up vertically when moving it up and down.

The structure spans between two sides of the support structure. On one side it is fixed and on the other side it is free to slide up and down. On the free side an micrometer adjuster is used to change the focus. See figure 6 for the actual design.

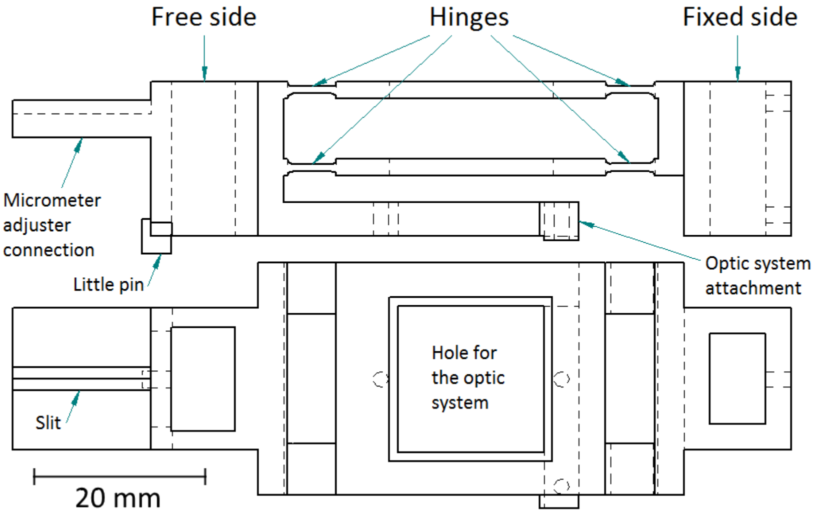

Figure 6: The z-translator focusing design side and top view respectively above and below. On the left the micrometer adjuster can push it down and the part is free to move up and down. On the right the part is fixed with screws tot the supporting structure. In the center there are hinges that make it move like a parallelogram with adjustable hinges and there is a hole where the optics go trough.

3.3 Optics

Our optic system is very simple and consists of the lens from the Raspberry Pi camera module. This lens has a focal distance of 3.6 mm. The optical scheme design is presented on figure 7.

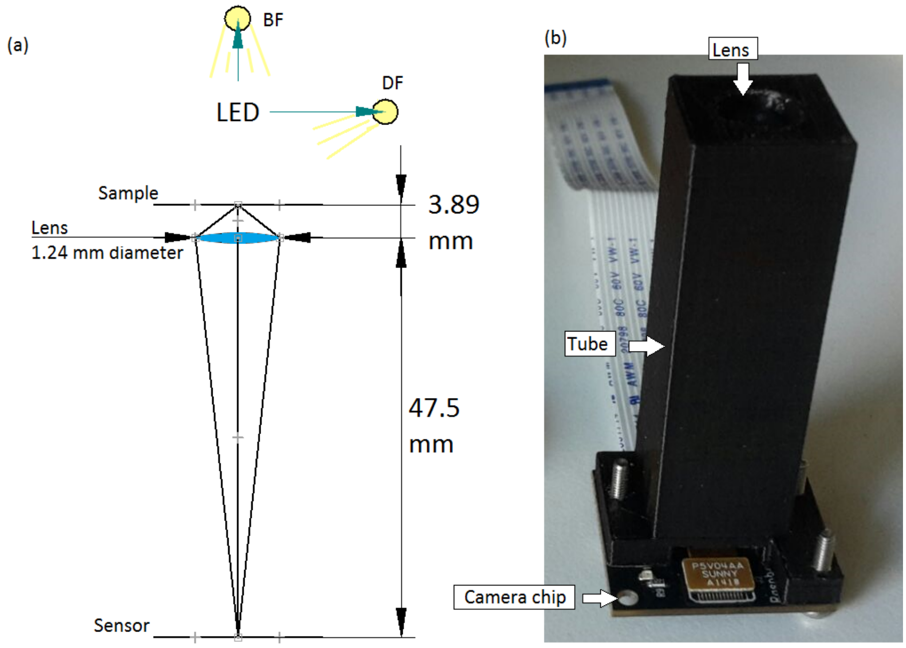

Figure 7: Sketch of the optical design (a) and the actual optical tube (b). Not everything in the sketch is to scale. Light the bright field (BF) LED for bright field imaging and light the dark field (DF) LED for dark field imaging. The optical tube blocks any unwanted stray light from hitting the sensor.

To keep any unwanted stray light from reaching the sensor we made a black tube around it. This had to be made by a 3D printer. We made it so that it can be attached to the sensor board with screws and the lens can be pushed inside a perfectly fitting hole.

We can estimate the wavelength of the LED emission spectra is 550 nm and the refractive index of air is 1. The numerical aperture (NA = sin(half angle of light from the sample to the lens) = $\sin 0.158$) of the lens is 0.158.
With this information we can find the approximate resolution for the system using the Rayleigh Criterion. We don't take into account spherical aberrations because its effects are small.

$$r = \frac{0.5\lambda}{n * \mathrm{NA}} = \frac{0.5 * 550 \text{ nm}}{1 * 0.158} = 1.75 \text{ micrometer} \tag{1}$$

So our theoretical approximation of the resolution is 1.75 micrometer.

For dark field imaging we needed our lens to focus the light from the LED on the sample. We designed a system similar to our optic tube for this, seen in figure 8.

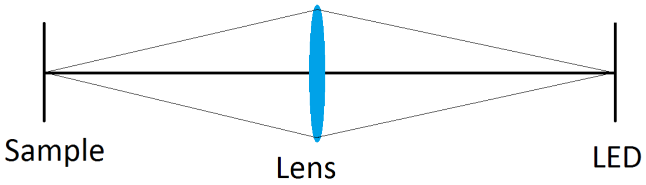

Figure 8: Sketch of the path of light for dark field illumination.

3.4 Software

For controlling the microscope a program was written. Options for controlling the Raspberry Pi camera used were the Linux terminal and Python. Python is a powerful language and is also widely used in science already. Two main advantages of Python is that it is open-source and has libraries for nearly every assignment.

We made use of many libraries in python. We needed to control the camera with the picamera[5] package. And for controlling the LED's and motors we used the RPi.GPiO[6] package. The user interface was made with Tkinter[7]. Packages like numpy[8] and time[9] are very useful for programming measurements.

Our final preview program has a few functions next to the preview and it is easily customizable. It has buttons to start and stop a preview, it can take multiple pictures on the press of a button and it can move the motors with buttons. Extra buttons that can be programmed as necessary for measurements can be added to the interface.

There are many possibilities for programming measurements. It is possible to take pictures and video at various resolutions. With respectively different interval and frame rate. Only little programming skill is needed when setting up a measurement.

When using our program it is important to move the interface popup to the side of the screen to be able to give commands after a preview starts. See figure 9 for how it looks.

Figure 9: Preview program in action. To the left are the buttons which have to be dragged there manually to avoid being unable to use them when behind the preview. Because of the way the packages we used work it is not possible to have a more user friendly preview.

3.5 Motors (optional)

Stepper motors usually require five wires. There are four that control different magnet coils inside the motor and one that completes the circuits. To turn the stepper motor the magnet coils inside need to be activated in a certain sequence. Depending on the delay between the different states it turns at different speeds.

Stepper motors are not very strong, so it is important to have them fitting perfectly. We decided to mount them on rails to push them into the micrometer adjuster with low tension springs (for instance a simple pen spring). This way they can still move into and away from the adjuster, which is necessary when moving more than a few millimeters. See figure 10 for the design where rails with motors can be attached to.

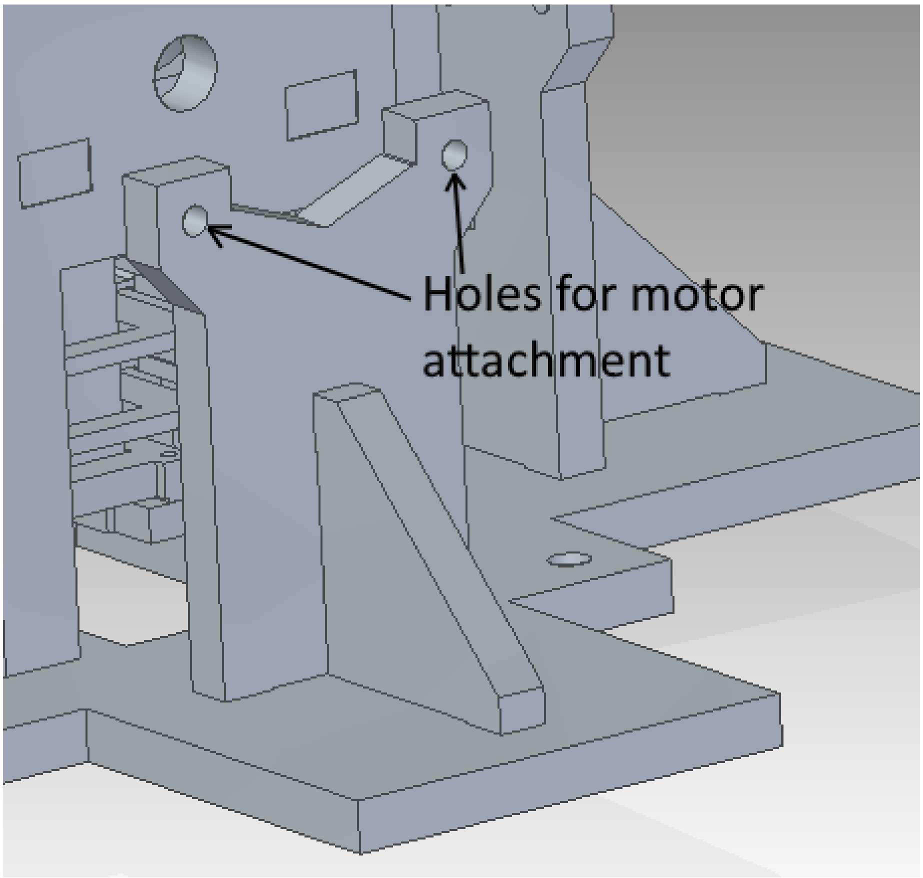

Figure 10: Design for motor holders in the final design. The rails for the motors are made by a normal screw and 2 bolts. A spring and the motor go between the screw-head and one bolt. And it is secured through the holes shown in the structure, fastened with the second bolt.

4 Final design

In this chapter the final design will be described in more practical detail. The laser-cut parts that form the base of the microscope could also be 3D printed.

4.1 Laser-cut parts

The laser-cut parts are the base of the structure. So they need to form a solid piece that can hold all the other parts in place. To keep it as solid as possible we designed it somewhat like a cube. See figure 11 for the assembled laser-cut base and figure 12 for the 2D drawing.

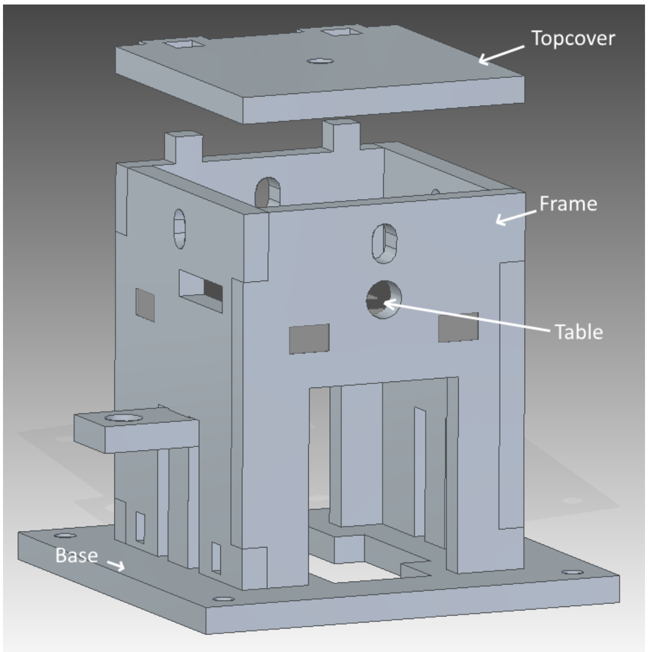

Figure 11: The assembled design of the laser-cut base without motors. Above the top cover floats. There are holes for LED lighting visible and bigger holes for the micrometer adjusters. The table on which the sample holder will rest is slightly darkened. Attachment bars for the focus system and holder for the focus' micrometer adjuster are visible at the bottom half. And finally the bottom board is visible with holes for attaching it to anything when desired.

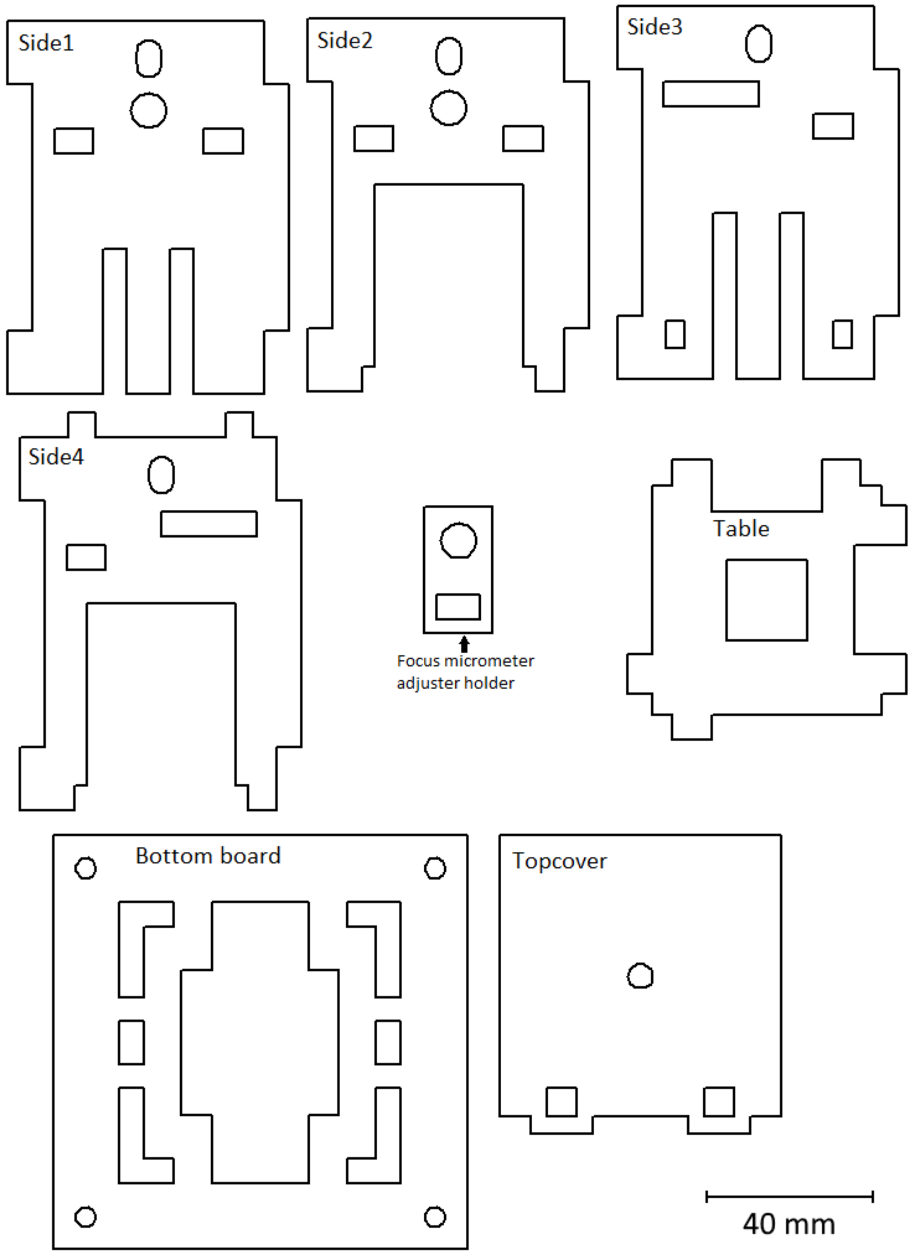

Figure 12: Laser-cuttable 2D design. Three of the sides in the top row. The fourth side, focus micrometer adjuster holder and sample holder table in the middle row. And the bottom board and top cover in the bottom row.

A laser-cutter follows the lines with the laser to burn a thin line of matter away. This is an important factor that needs to be considered in the design. If parts need to fit together it is desirable to have some extra space between joined pieces. With the laser-cutter this is not necessary everywhere because the line it tracks is already approximately 0.2 mm wide.

4.2 3D printed parts

Only four parts need to be 3D printed, the focus mechanism being the biggest by far. Both the sample holder and xy-spring can be printed by about a dozen at a time in the Ultimaker 2. The lens tube also takes some time to print, but less than the focus mechanism.

- **z-translator**

The z-translation or focus system is already shown on figure 6 but some details were not explained yet. In the micrometer adjuster connection there is a slit to help a little with sidewards stability. The little pin somewhere under that connection can be used by an extra plate spring to push the focus back in case the focus loses the ability to spring back on its own. Three screws are used to completely secure the optics tube, camera board and z-translation focus together. One side of the optical system attachment is slightly higher to counteract and fine tune the tilt of the lens tube.

The focus is by far the most complicated and thus printing it is demanding. This is a real strain on the production time goal.

- **Sample holder**

The sample holder is a simple ring like piece that holds the sample. With the tilted sides it will always slide over the table in one plane. It is designed to perfectly fit a standard Petri-glass of 35 mm diameter. There are Petri-glasses available with build in cover-glass[11], a sample can be mounted without modifying these. The sample holder can be seen in figure 13.

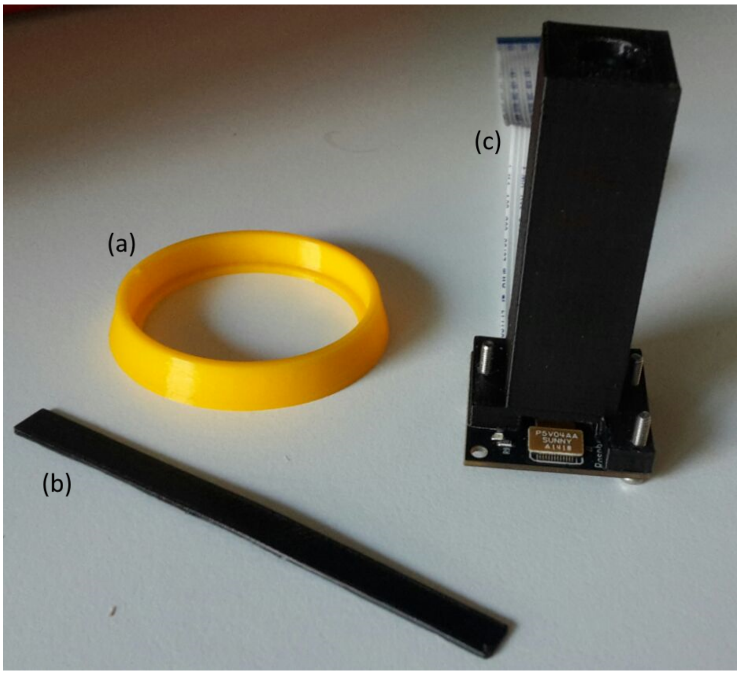

Figure 13: The sample holder (a), xy-spring (b) and optic tube (c).

- **Lens tube**

The lens tube turns the Raspberry Pi camera instantly into a microscope. By blocking all stray light and holding the camera's lens at 47.5 mm it fulfils everything for making the camera a microscope. See figure 13.

4.3 Dark field illumination

With the part in figure 14 we keep the LED and lens for dark field illumination at the correct positions.

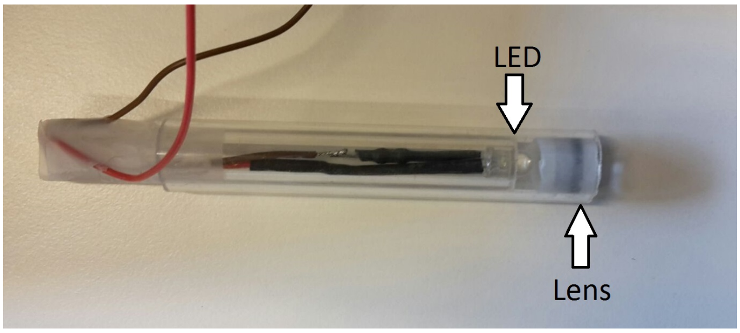

Figure 14: Dark field holder. There is a tube with the LED at the end, fixed by the wires on the other end with tape. And a tube with the lens on one side, the lens widened by layers of sticky tape around it until fitting tight. The tubes slide together to create a simple focusable light source. With this design the LED and lens stay in the correct orientation.

4.4 Electronics

Most electronics are connected as ordinary, only the LED's and the motors require soldering. For using the LED's with the Raspberry as a power source they can simply be assembled with one 330 ohm resistor and connected on the GPiO pins of the Raspberry. Each LED needs its own connection on the Raspberry, But the ground can be shared. The dark field LED's and the normal lighting LED need to be powered separately. The motor requires multiple GPiO attachments and an external power source and it will be fully explained in the Fabrication manual.

We used a touch screen for the Raspberry Pi. This screen takes its power from the Raspberry and doesn't use the HDMI output. With this touch screen it is al lot more portable, this is nice when moving the microscope to a vibration free environment for measuring. Also it still allows to use another additional external screen.

4.5 Motors (optional)

For the motor design only the base board needs to be changed and some GPiO's need to be used on the Raspberry Pi. A picture of one of the added structures is shown in figure 15.

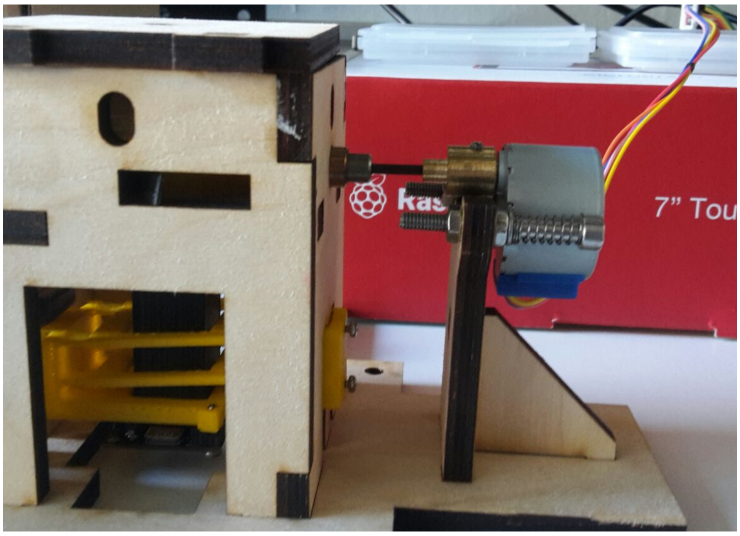

Figure 15: Motor attached to the microscope. The motor is free to move slightly forward an backwards to ensure it has no problems translating the x or y direction or focus. And is pushed back by some simple springs.

4.6 Fully assembled microscope

See figure 16 and figure 17 for pictures of the fully assembled microscope.

The microscope is fixed with glue and screws where necessary to make it solid. The laser-cut parts are glued together with wood glue and the micrometer adjusters are glued with epoxy glue. The optic tube and z-translator are fixed with screws.

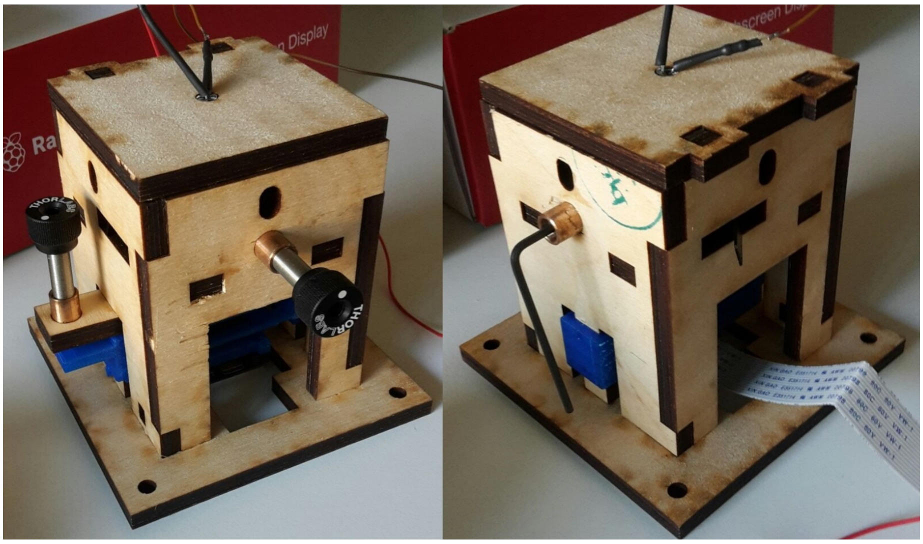

Figure 16: The final design of the microscope without motors from different angles. One of the sample translating micrometer adjusters has no knob but a hex key to rotate it. For using motors the knobs have to be taken off, a hex key can be used to turn the screw while no knob is attached.

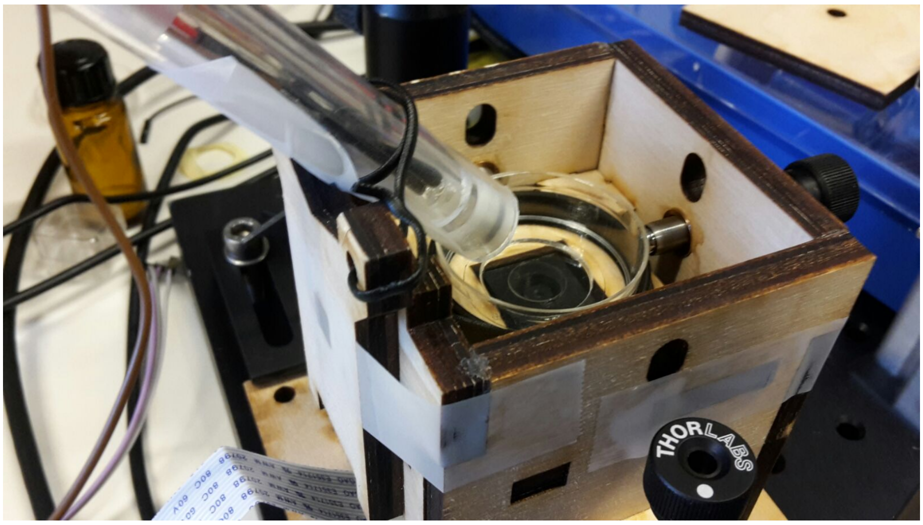

Figure 17: The final microscope without motors with dark field imaging tube attached. On this build we attached it with sticky tape, a spare microscope part and some ”iron wire in plastic”.

5 Calibration and final specifications

5.1 Handling

When translating the sample it is possible to get micrometer precision manually. It takes one turns to move the sample 254 micrometer, which is about the field of view of our system.

Focussing the microscope manually works fine. It needs more precision than translation, but this is possible with our system. In our experience the most difficult part of handling the microscope is deciding what focus has the best resolution, not the precision needed when turning the micrometers when focussing.

5.2 Magnification

The magnification can be found using a calibration target, in our case it was a stage micrometer. In figure 18 on the left there are 27.5 bars of 10 micrometer visible over 2592 pixels, so the pixels are about 0.1 micrometer big in the x direction. On the right there are about 21.7 bars of 10 micrometer visible over 1944 pixels, so the pixels are about 0.1 micrometer big in the y direction.

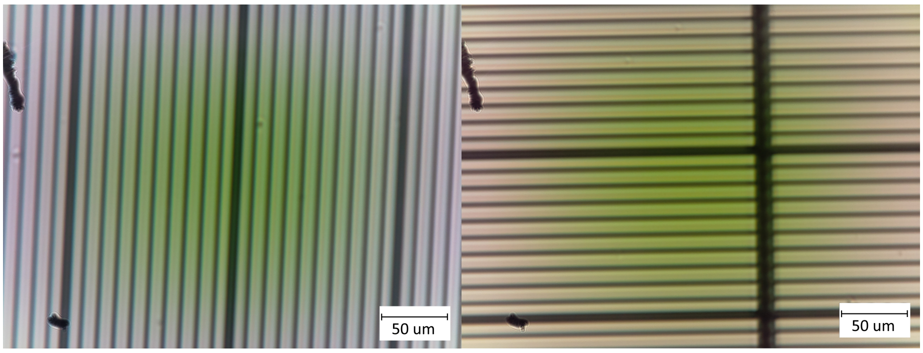

Figure 18: Bright field pictures of the calibration grid with 10 micrometer divisions[13] left and right used for respectively the dx and dy pixel size. While it might seem obvious that the x an y size of pixels are the same, this has caused some problems before the z-translation focusing system was slightly altered. There are some black stains which is because of dirt on the sensor.

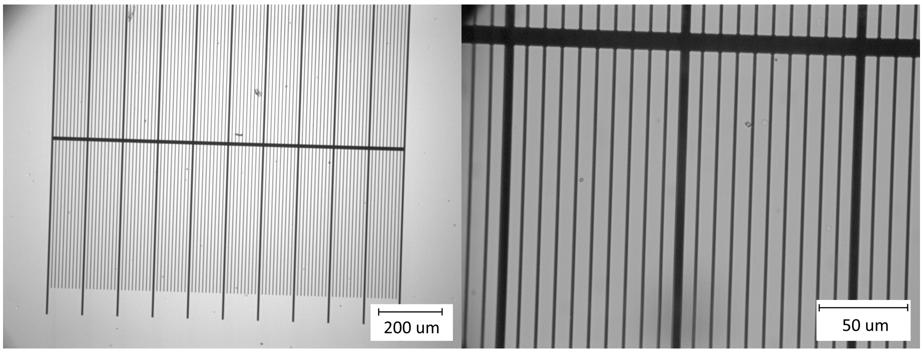

Figure 19: Bright field pictures of 100x and 500x magnification with a commercial microscope. We made these to compare our microscope to a commercial one and to find the width of the lines, needed for finding our resolution. The commercial microscope used 10x with NA=0.30 and 50x with NA=0.55 objectives. The eye piece had a 10x magnification.

5.3 Resolution

Resolution is the minimal distance between two features, e.g. visible particles, to be able to distinguish between them. It is defined using a point spread function of the optical system, which is a sinc^2 function (sinc $= \dfrac{\sin x}{x}$), as the distance between the first minimum and the maximum of the point spread function. We approximate this distribution of light by a Gaussian ($= e^{-x^2/2\sigma^2}$) because it can be more easily fitted to a dataset. We correct for this with figure 20. This Gaussian we will use to construct a function of the distribution we should see. We used the lines with the smallest width of the calibration grid from figure 18 to fit the function to.

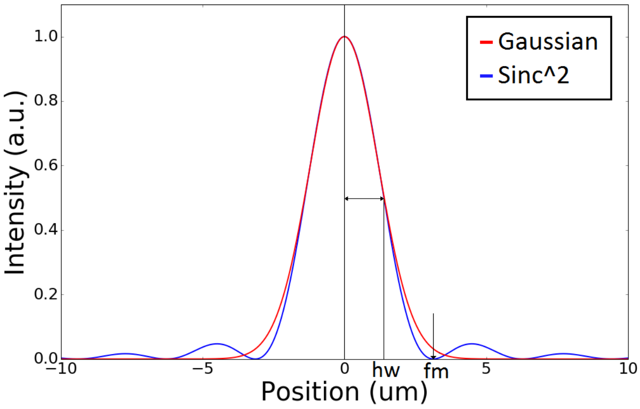

Figure 20: A Gaussian and sinc^2 function. We plotted a sinc^2 function and fitted the width of our Gaussian to it. The half width (hwhw = approximately 1.4) of the Gaussian and the first minimum (fm = approximately 3.1) of the sinc^2 are shown.

To correct for using the Gaussian function we need to translate the parameters found to the correct ones. From the data in figure 20 we found a factor 2.2 as the difference between the half width of the Gaussian and the first minimum from the sinc^2 function.

A Gaussian, equation 2, and a approximation of the distribution of the stage micrometer with width h, equation 3.

$$G(x) = a \exp\left(\frac{-x^2}{b}\right) \text{ with b} = 2\sigma^2 \tag{2}$$

$$D(x) = \begin{cases} D(x) = 1 \text{ for } x < -h/2 \\ D(x) = 0 \text{ for } -h/2 \leq x \leq h/2 \\ D(x) = 1 \text{ for } x > h/2 \end{cases} \tag{3}$$

We integrate the Gaussian over the distribution of the stage micrometer.

$$R(x) = \int_{-\infty}^{\infty} G(x-x')D(x')dx' = \int_{-\infty}^{h/2} G(x-x')dx' + \int_{h/2}^{\infty} G(x-x')dx' \tag{4}$$

Equation 4 can be calculated using the standard integral in equation 5. This standard integral includes the error function, which is $\mathrm{erf}(x) = 2/\sqrt{\pi}\int_0^x \exp(-t^2)\mathrm{dt}$.

$$\int \exp -cx^2 = \sqrt{\frac{\pi}{4c}}\mathrm{Erf}(\sqrt{c}x) \tag{5}$$

$$R(x) = \frac{a\sqrt{\pi b}}{2}\left(2 - \mathrm{Erf}\left(\sqrt{1/b}(h/2-x)\right) + \mathrm{Erf}\left(\sqrt{1/b}(-h/2-x)\right)\right) + C \tag{6}$$

We used function 6 to fit to the data. With $h = 1.7$ micrometer as can be estimated from the commercial microscope. In figure 19 the commercial microscope pictures are shown.

Our data and the part used for the measurement are visible in figure 21.

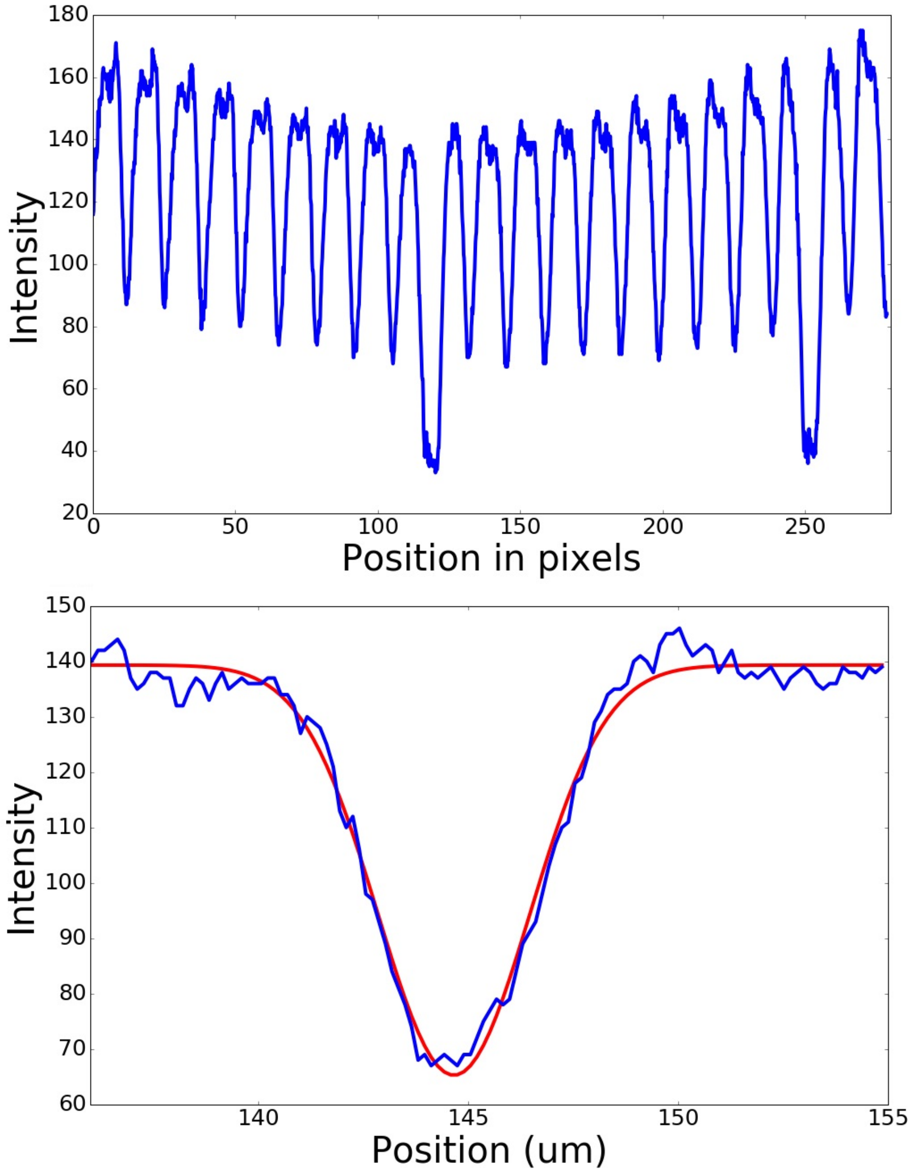

Figure 21: One full vertical line of pixels in the top and on the bottom the part used with the fitted function in red.

From the fit we found the parameter b to be 6.05. We can translate this using the following:

$$b = 2\sigma^2 \text{ and } HWHM = \sqrt{2\ln 2}\sigma \text{ and } FM = 2.2 * HWHM \tag{7}$$

Where FM corresponds to the resolution of the system. We end up with a experimental resolution of:

$$\text{resolution} = 2.2 * \sqrt{2\ln 2} * \sqrt{b/2} = 4.506 \pm 0.804 \tag{8}$$

5.4 Stability

To get an idea of the long term stability we measured the drift of a static sample for 48 hours. Our static sample was made by pressing sticky tape on the dusty bottom of a shoe and sticking it on the sample glass. We took a picture every 4 minutes for 48 hours and used python to do the particle tracking. The drift of the sample is visible in figure 22.

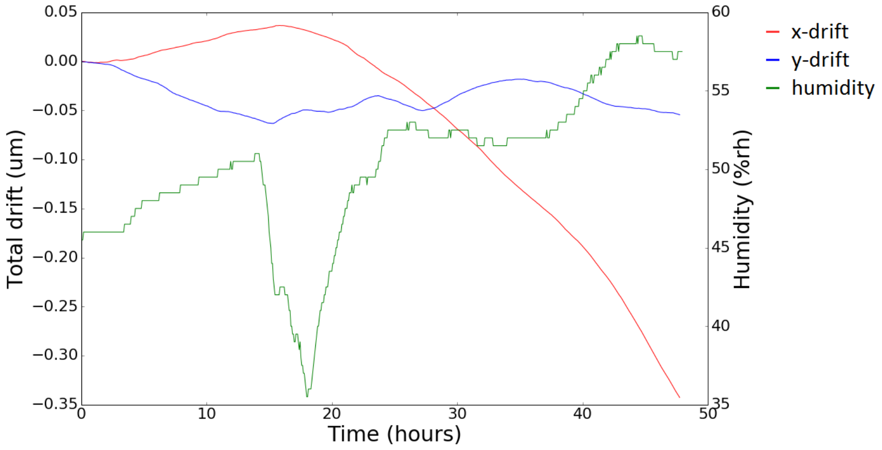

Figure 22: The total drift and humidity of the sample. The temperature was constant at 21.0 ± 0.3.

The drift in the x direction is much bigger than in the y direction. This difference is probably due to our design. We translate our optic with hinges partly moving in the x direction, these hinges seem to slowly deform over days of constant tension.

5.5 Dark field illumination

With our dark field illumination setup we are able to produce dark field images. In figure 23

Figure 23: A picture taken with dark field illumination. This picture is from our electrophoresis measurements. There are a lot of particles.

5.6 Electrophoresis

We are able to do electrophoresis measurements with our system. From the known voltage function over the electrodes the movement of the particles can be predicted. This movement can be found in the tracking data of the measurement. The parameters found can give us information about the particles.

See figure 24 for our measurement.

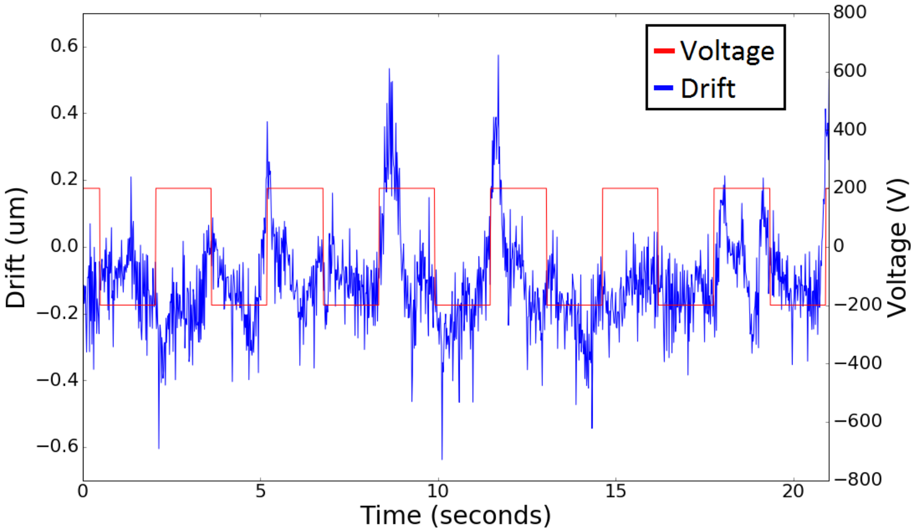

Figure 24: Electrophoresis measurement. The drift peaks after every switch of the voltage. This system had a preference of going in the positive drift direction, so especially these peaks are visible.

5.7 Repeatability of motors (optional)

The motor system has reproducible steps. The distance of the steps can be changed. We set them at 10 times the minimal distance they can turn, this gave us steps of about 4 micrometer. The movement can be seen in figure 25.

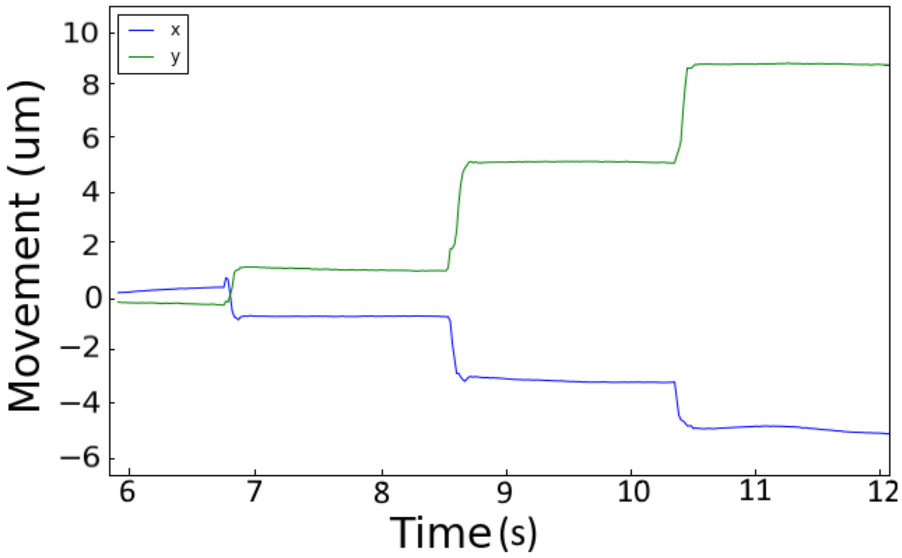

Figure 25: Measurement of the movement of our motor translation. One motor translates the sample every 5 seconds. The movement was done with a motor connected to the micrometer translating in the y direction. We see a lot of movement in both directions because the sample was not placed close enough to the center of the translation system. The time after translation are not very stable for the first seconds, system needs some time to come to rest after every translation.

Our motor system can produce translation of our sample which is useful, but it introduces a lot of vibration. This can be seen even better on the actual recordings. While it is a fun way to do stuff with the microscope, the motor system has not proven very practical for us yet.

6 Discussion

We have achieved all of our goals set in the beginning except for building time. We are satisfied with our results. Here we will discuss each goal and results in detail.

- **Cost**

Our estimate of the costs were 500 Euro at the very beginning of the project and the costs have stayed below it by a decent amount. One microscope can be made for less then 200 Euro.

- **Quickly made**

The two hour building time was one of the harder goals to achieve. With very fast 3D printer settings it is possible to achieve it. But this is not a very reliable technique, as if the print fails it only takes longer. An estimate of 3 hours for a single microscope is more accurate.

However when not including the time it is printing or making a lot of microscopes, it is possible to take less then 2 hours. During the printing time it is possible to do other things, like putting previously printed parts together. It is also possible to start the 3D print at the end of the day and collect the completed print the next day.

- **Reliable**

It has proven to be quite a stable construction and the simple design helps avoid complicated problems. A few microscopes have been made while designing it and all have had near identical specifications.

It has around 4.5 micrometer resolution which is similar to good commercial objectives of 10x or 20x magnification. But the pixel size of approximately 0.11 by 0.11 micrometer is closer to 50x or 100x magnification of commercial microscopes. Also we found small long term drift of 0.4 um after 2 days.

- **Multi functional**

With the simple design used the microscope is relatively easy to modify for more functions. Our dark field illumination and electrophoresis possibility have also been added after the base of the microscope had been completed.

7 Conclusion

We made a DIY microscope that is cheap, quickly made, portable, reliable and multi purpose.

This microscope has a field of view of over 260 by 200 micrometers and can produce 2592 by 1944 pixel data. With a resolution of approximately 4.5 micrometer.

It can be made within a few hours. With laser-cutting and 3D printing technology quickly and accurately producing all custom parts. Some scientific standard items provide the rest of the mechanics. And everything is controlled by a Raspberry Pi with its Pi NoIR camera module also providing most parts for the optics.

8 Words of thanks

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Gerhard, for helping me a lot with the 3D printing.
Dave, for using the lab for 3D printing and helping find some parts I didn't think of.

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