3D-printer (X, Y, Z-axis) automatic calibration
Part 1

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Dr. Tõnis

Short summary

At the moment the FDM 3d printing industry is moving towards 2 print head system, or it is already there. The main issue with this approach is the calibration. The fully automatic bed calibration technology is already in the market, however something like that for X-, Y- and Z-axes does not exist or at least in the moment of writing I was not aware of it.

I am Dr. Tõnis and I worked till the end of 2018 in a startup developing our own high end 3d printer (the main competitors were Ultimaker 5S, Leapfrog Bolt and Raise3D Pro2). Our team was small and I was responsible for the electronics and software (PCB design, component selection, user interface software, firmware, etc.). After some financial difficulties the management decided to close to company. It is a pity as the printer was almost ready and I really enjoyed the work.

During the fully automatic bed leveling system implementation, I had an idea how I could build a fully automated X-, Y- and Z-axis calibration system. The prototype is an external device that is attached to the printer before the calibration process and after the calibration is done the device has to be removed.

The idea is in an early stage prototype and needs further testing and improvements. Nevertheless, the hardware of the calibration device is very cheap and would cost less than 10$ (only the measuring device, controller not included).

Since I was not able to realize the idea I'm publishing here the concept. At the same time I am explaining relatively thoroughly how a dual head 3d printer calibration is done.

Our developed printer printhead construction was very close to BCN Sigma design, thus the following discussion explains how BCN does the calibration. And how the automatic device could be used with their printer, however the same principles apply to all other printers. For example, with Ultimaker only the T0 Z calibration could not be done very precisely by using this method, all other calibrations could be done without changing anything. If we know that the calibration device is always (let say) 11.2mm thick then one can use that for Ultimaker T0 Z calibration, nevertheless most probably a fine tuning would be needed.

I assume the device could be used even with a CNC machine, although with several limitations. In the CNC machine the Z calibration is a critical component and that could be easily done with this calibration device. However, I do not have much experience with a CNC machine, thus my assumption could be wrong.

The prototype has been partially tested and for the Z axes it works well (limitations mentioned later in the Known issues chapter). The X axes has been tested too and there theoretical accuracy of 0.05mm has been achieved. Testing has been successful, nevertheless some more work would be needed.

Calibration Theory

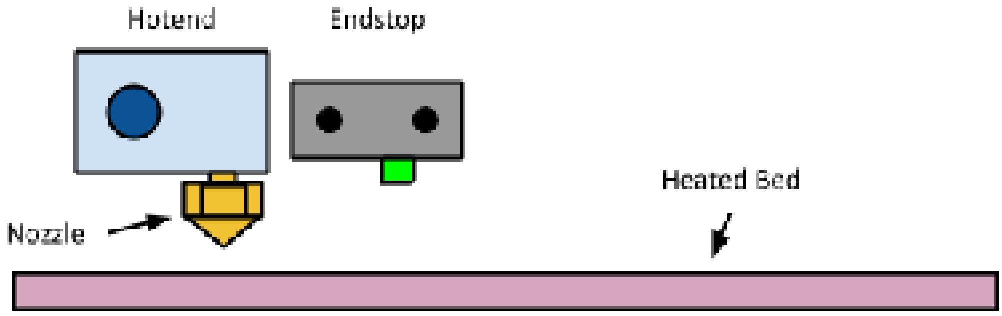
Z calibration theory

Why is the Z calibration very important? A good 3d print needs that the bed and the Z is well calibrated. The bed calibration ensures that the first layer is even and the Z calibration ensures that the layer thickness is as wished. If the Z calibration is not properly done the first layer or layers will be too thick or thin. It can cause the print to end up in a not acceptable quality level or to fail.

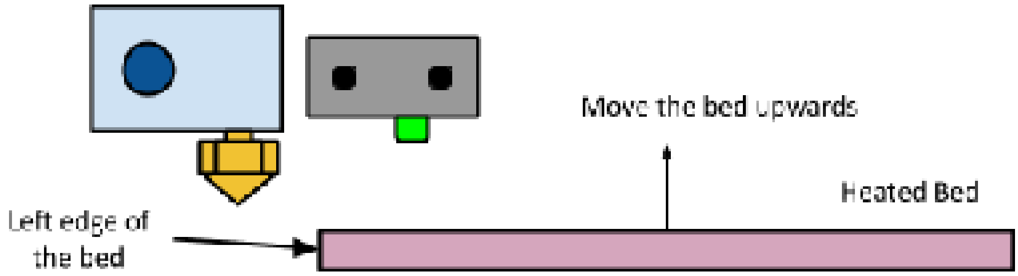
Let's start by looking at the left tool head T0.

T0 calibration

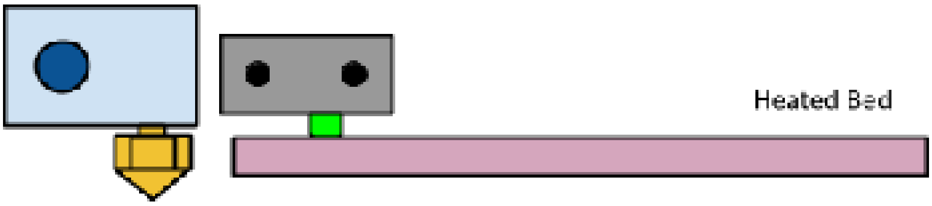
In BCN Sigma the Z endstop is placed close to the T0 nozzle (left tool head). As could be seen from the following sketch the endstop is at a higher level than the nozzle. It's important, since during the printing one needs the distance between the nozzle and the endstop.



When one does homing he needs to reach the endstop switch. That can only be achieved when the whole hotend is moved enough to the left so that the nozzle can go next to the heated bed.

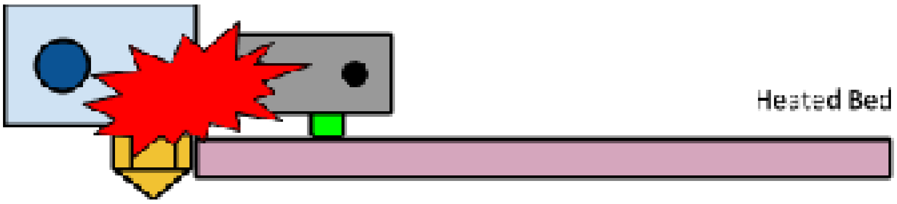


Now the bed can be moved upwards without collision between the nozzle and the bed. The bed is moved upwards until the Endstop switch is touched and triggered. The mechanical contact triggers the switch ON and one knows that the zero point (Z = 0) has been found.

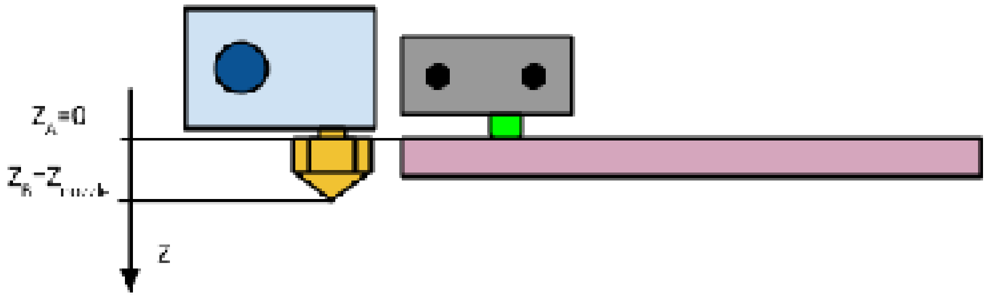


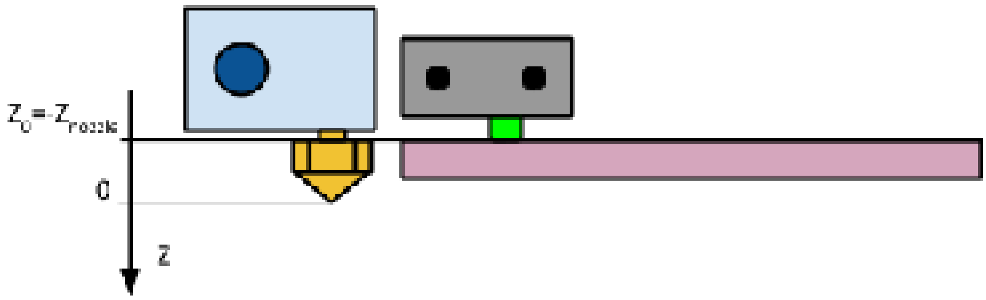
This upwards movement is done by the printer firmware (Marlin) and one doesn't have to consider the complexity about that. The homing command "G28 Z" does everything what's needed (obviously the firmware has to be configured properly).

Now the printer knows where the zero point is, however that's not the same as the nozzle tip is. When one wants to move the nozzle on top of the bed the collision between the nozzle and the bed is inevitable.



It's clear that one needs to tell the printer what is the difference.





From the above sketch one can see that the calibration tells the printer the difference between Z_A and Z_B:

$$Z_0 = Z_A - Z_B = -Z_{nozzle}$$

As one can see the correction factor for the T0 has negative value. The 0 level is shifted to the nozzle height and the endstop will be on the negative side.

The correction factor can be set in the printer by M206 command:

M206 Z[Z_0]

And saved with

M500

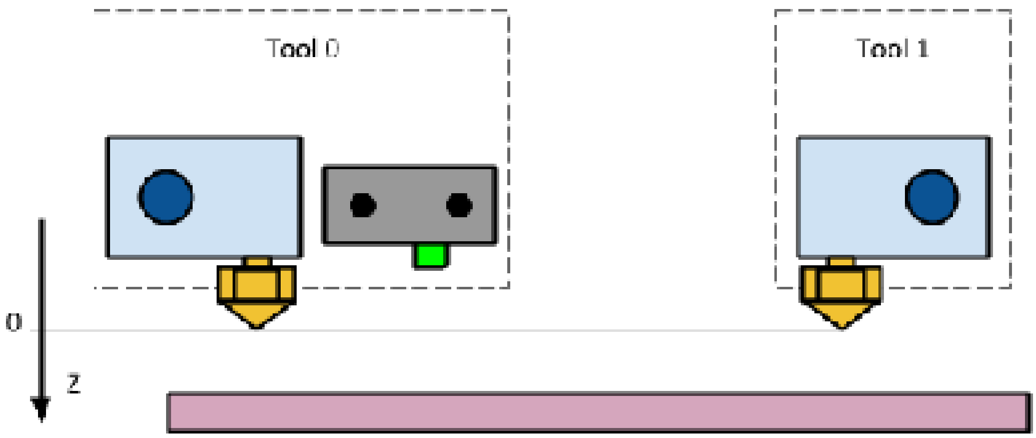
For example, when the difference between the nozzle and the endstop is 2mm then the correction factor that needs to be sent to the printer is

M206 Z-2

Like this the left extruder T0 is calibrated. There are several methods how to define the Z0 value, and the one used by BCN Sigma will be briefly explained later.

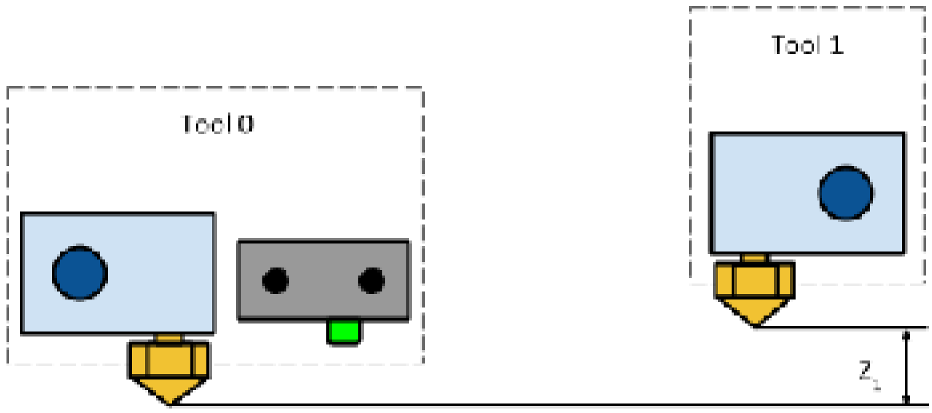
T1 calibration

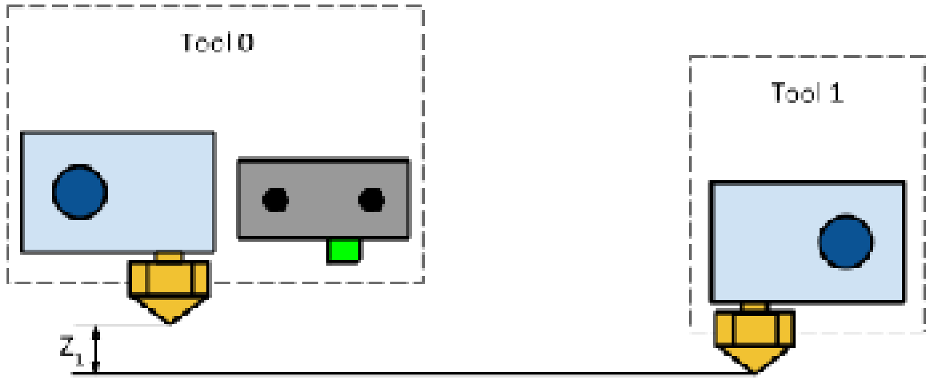
By BCN Sigma the right tool head moves independently from the left one. In the ideal case both tools are at the same height.



Unfortunately that's very rarely the case. They may look like at the same height, however when the print layer height is 0.05mm or even less then it makes a huge difference if the nozzles are at the same height or slightly different.

It can happen that the T1 is higher or lower than the T0:





Again there are several methods to determine the height difference between the tools. The correction factor in the printer can be set by M218 command:

M218 T1 Z[Z_1]

And save it with

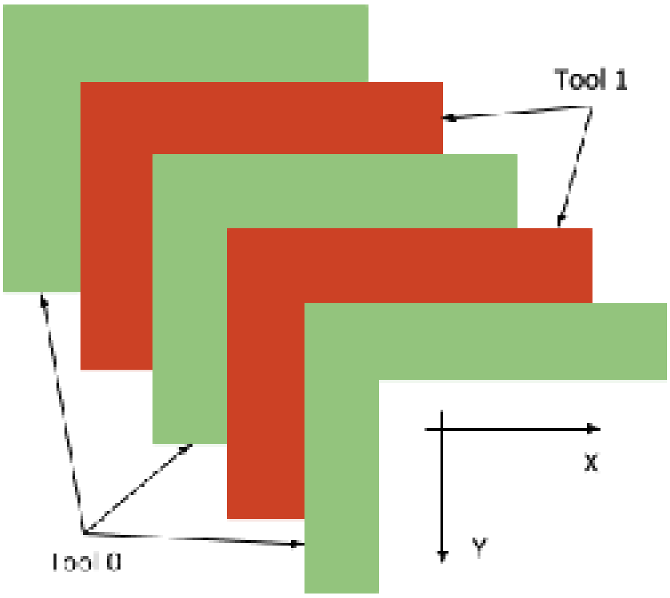
M500

If T1 is below T0 then the Z_1 is negative and vice versa.

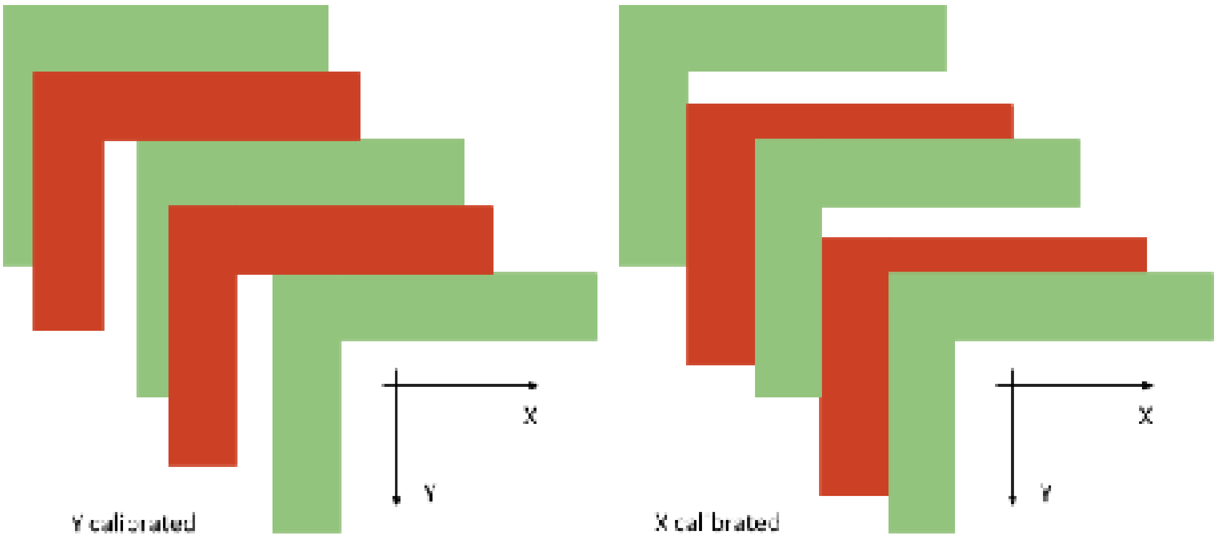
X and Y calibration theory

X and Y axes calibration process is exactly the same, just they are 90 degrees turned. When one talks about the X or Y calibration then the same is valid for the Y or X calibration, respectively. Usually it's much easier to perform the calibration separately. One focuses first on one axes and then on the other one.

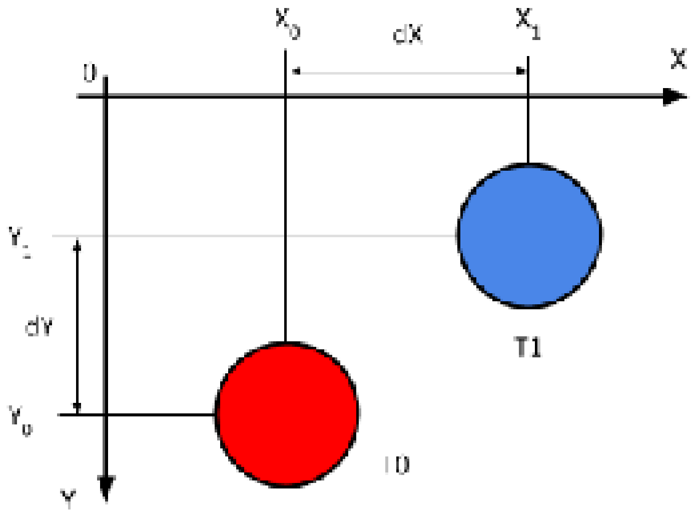
First, why is the X/Y calibration important? When doing two material print one would like to have good alignment between the printed lines.



If the calibration is not properly done the lines can overlap:



In an ideal case, when the toolheads are built, the alignment will be achieved. In reality it can happen that there is some mitchmatch (dX and dY) and the calibration compensates it.



The method how the differences dX and dY for BCN Sigma will be briefly introduced later. The correction for the printer can be set by M218 command:

M218 T1 X[dX] Y[dY]

Manual calibration

As the calibration is very important every printer has some kind of calibration procedure. In the following the calibration in BCN Sigma will be briefly explained.

Z calibration

As discussed before one needs to find the height difference between the nozzle tipp and the end stop. By BCN Sigma it can be done by using a normal piece of paper.

After homing the tool head is moved in the middle of the bed and Z is increased enough to be sure there is no collision. The bed is moved slowly upwards until there the paper has contact with the nozzle. Before that the paper can freely move, after the contact the movement is limited. To find the perfect contact strength needs some practice, however, it's relatively simple and reliable method.

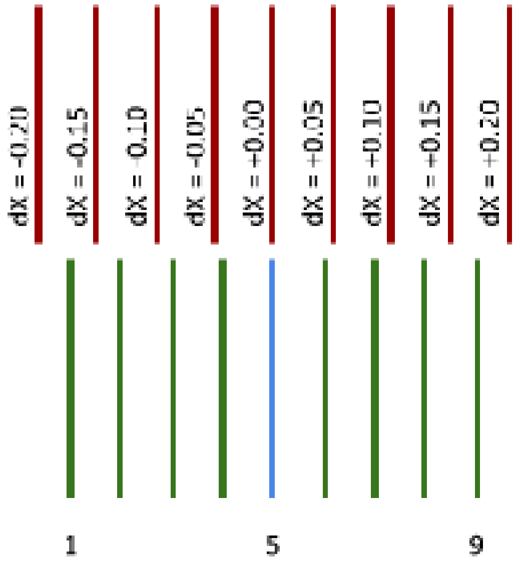
By assuming that the paper thickness is 0.1mm one can define the height difference between the nozzle and the endstop.

The same procedure can be used for the right toolhead T1 too. Then the height difference between the nozzles are defined.

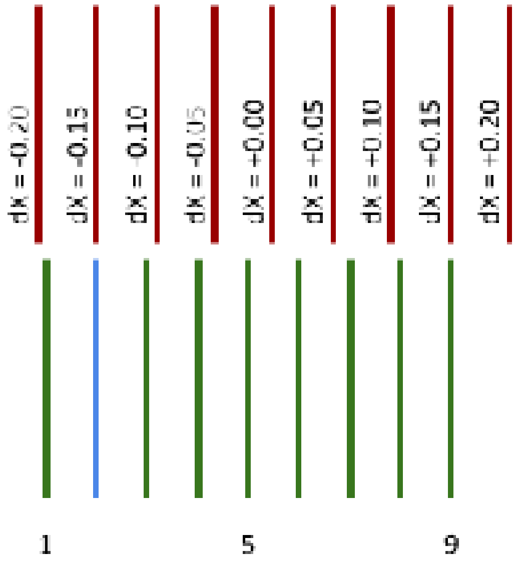
X/Y calibration

By BCN Sigma the X and the Y axes are calibrated separately. The calibration is done by drawing lines with predefined mismatches. Like this the best fitting lines can be defined and the dX defined. The example sketches are not in scale, however they try to explain the process.

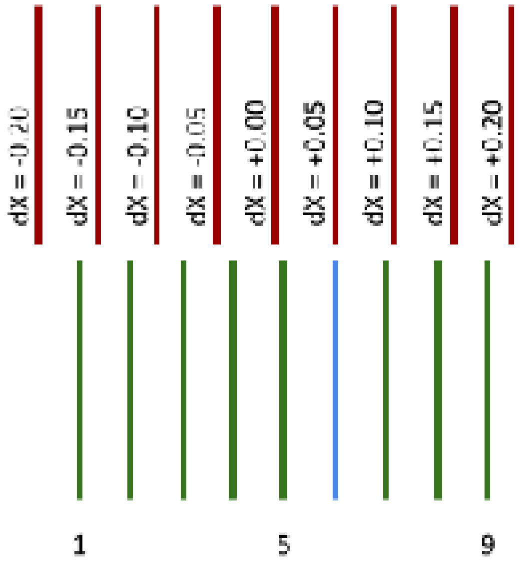
dX = 0.00



dX = -0.15


dX = -0.20
dX = -0.15
dX = -0.10
dX = -0.05
dX = +0.00
dX = +0.05
dX = +0.10
dX = +0.15
dX = +0.20
1
5
9

dX = 0.05


dX = -0.20
dX = -0.15
dX = -0.10
dX = -0.05
dX = +0.00
dX = +0.05
dX = +0.10
dX = +0.15
dX = +0.20
1
5
9

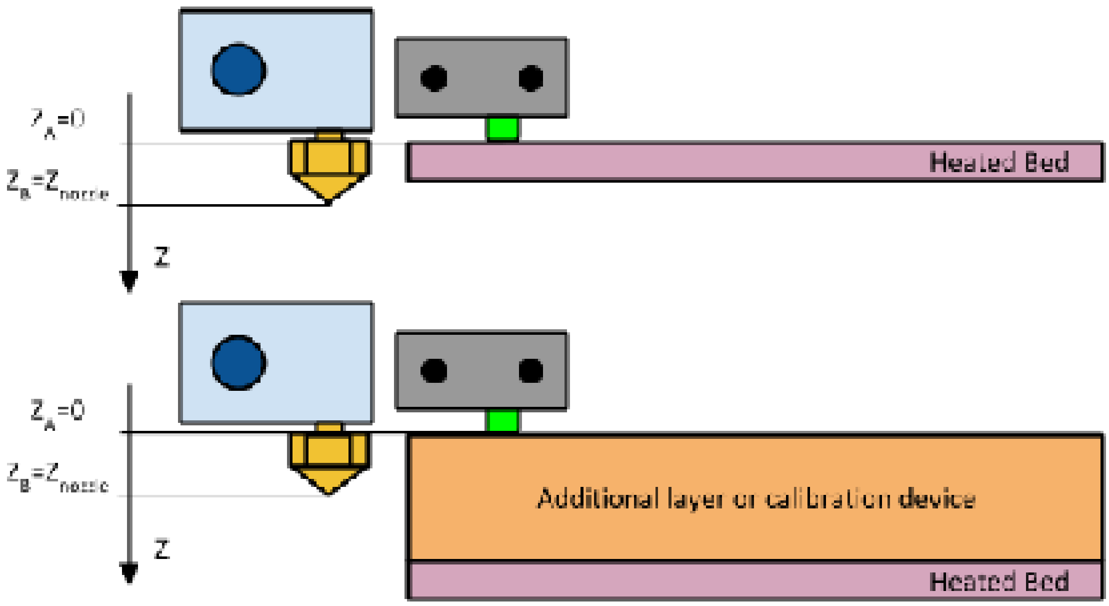
Automated calibration

Calibration is very important, however it can be quite tedious to perform it manually. In order to make it easier for the end user an automated calibration device could be offered. This device helps to determine the calibration values for each interested axes: Z_0, Z_1, X and Y. All the calibration procedures discussed further assume that the heated bed is already calibrated.

Z calibration

Before one could calibrate X and Y, Z has to be calibrated. Thus, one focuses first on the latter. Additionally, T0 is explained at first, as it defines the T1 calibration values.

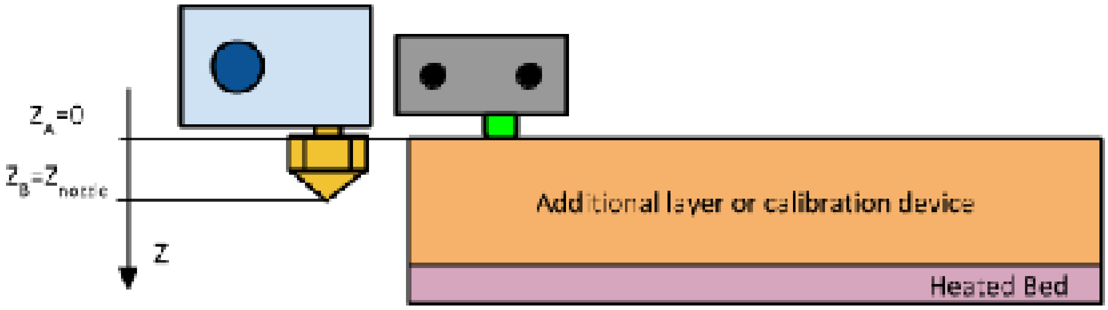
When the bed is calibrated it doesn't matter what's on the bed surface (as long as it has constant thickness) the endstop zero point is always easy to determine:



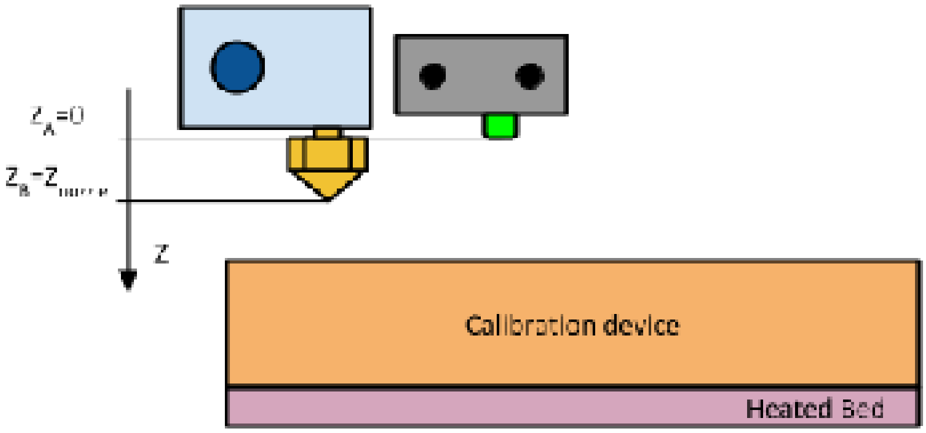
That's very useful as one can add something on the bed to determine the Z difference between the endstop and the nozzle (Z_{nozzle}).

The hotend (the whole hotend and heater with the housing [for simplicity they are not shown on the sketches]) is made from metal and is through connection PCB boards electrically grounded (assumption). Due to non perfect contacts the grounding is not perfect, nevertheless sufficient for this application. Thus, one could use this to determine when the nozzle has contact with a surface.

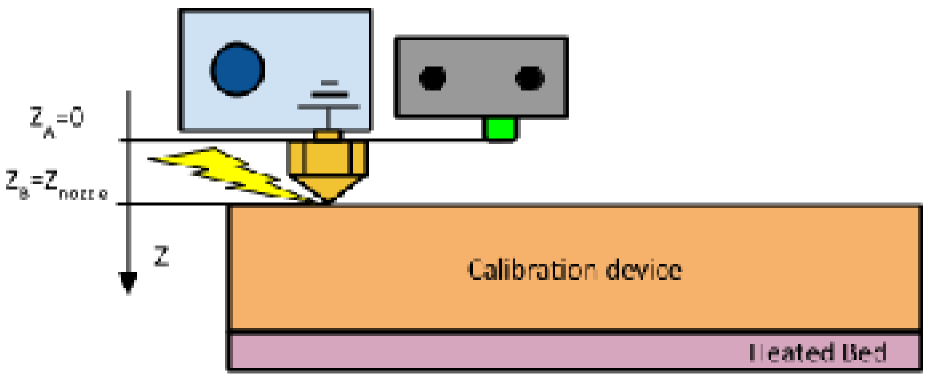
First the homing is made. By this the Z_A=0 point is determined:



Now the tool head is moved so that it can touch very close to the same point where the endstop contact was (here X and Y location is meant). As the X and Y are not calibrated the exact location can't be reached, however it has minimum effect on the accuracy:



When the tool head is moved closer and closer to the Calibration device eventually there will be a contact between the Calibration device surface and the nozzle.

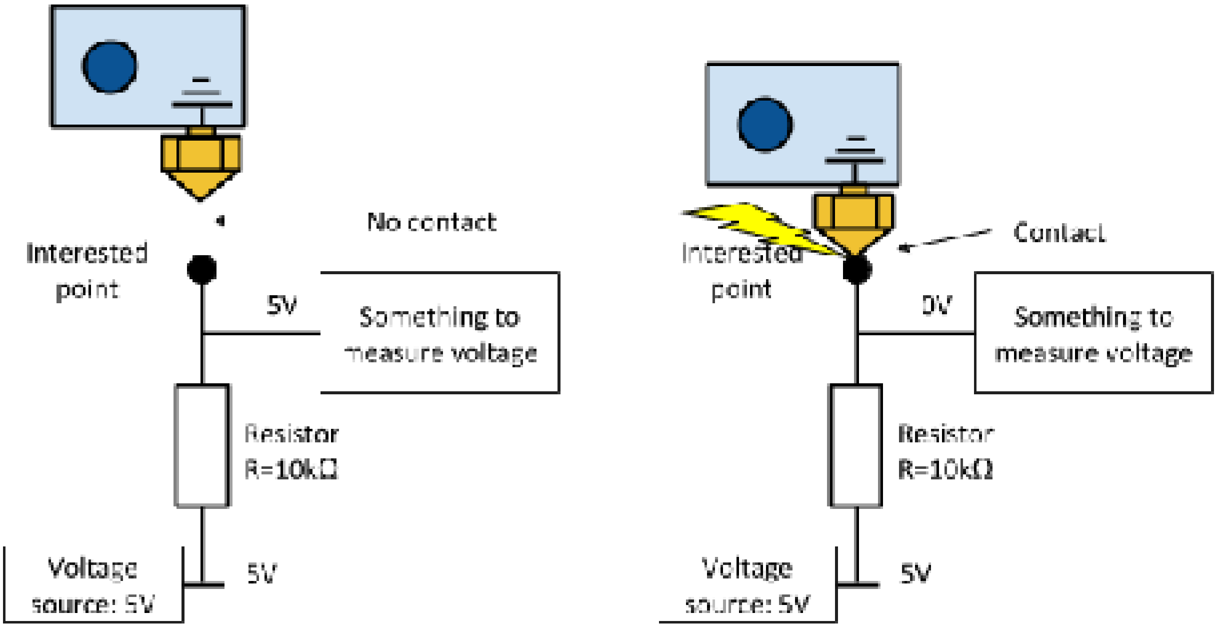


If the Calibration device could recognize the grounding moment, the $Z_0 = Z_A - Z_B = -Z_{nozzle}$ value can be determined.

To recognize the ground contact one needs the following components:

- Something to measure voltage
- Some kind of voltage source, so that there is something to measure (we use 5V)
- A pull up resistor (10kΩ is a good value)

As long as there is no contact 5V is measured, with contact the measured voltage drops to 0. In reality due to imperfect grounding of the tool head it can be higher than 0. Thus, we measure if the voltage change is sufficient. For example, if the voltage drops to 2.5V we assume that there is a contact between the calibration device and the nozzle.

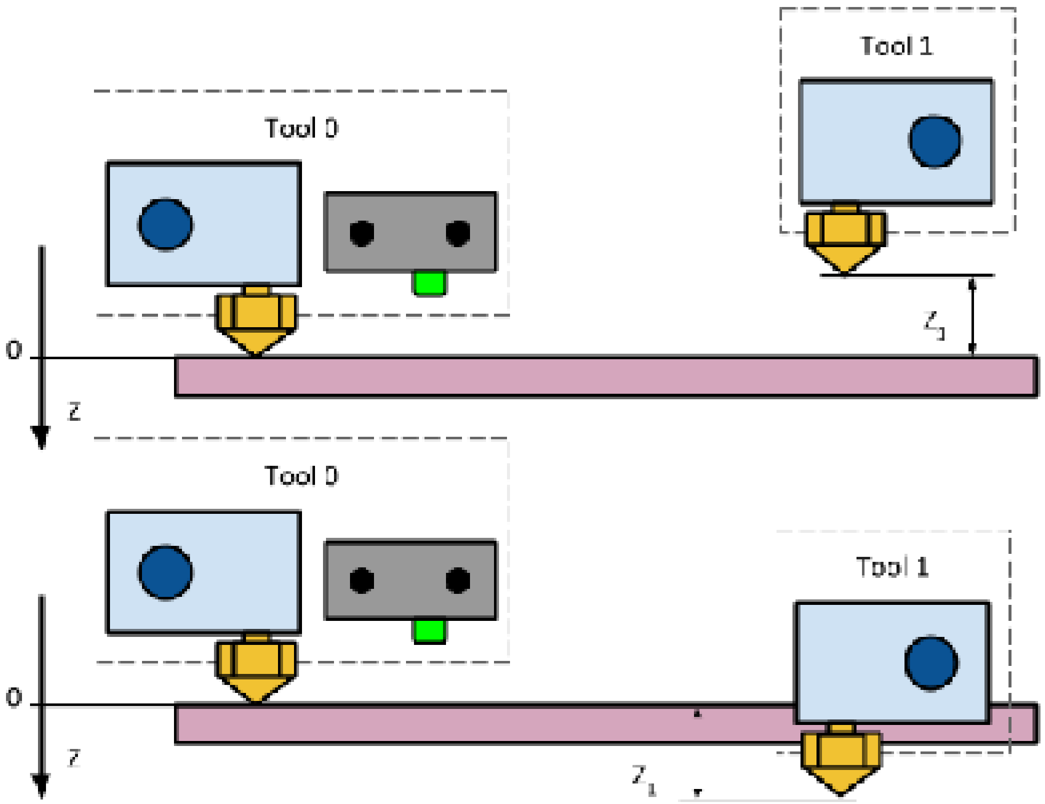


With the contact one knows the Z_0 value and the correction value can be sent to the printer:

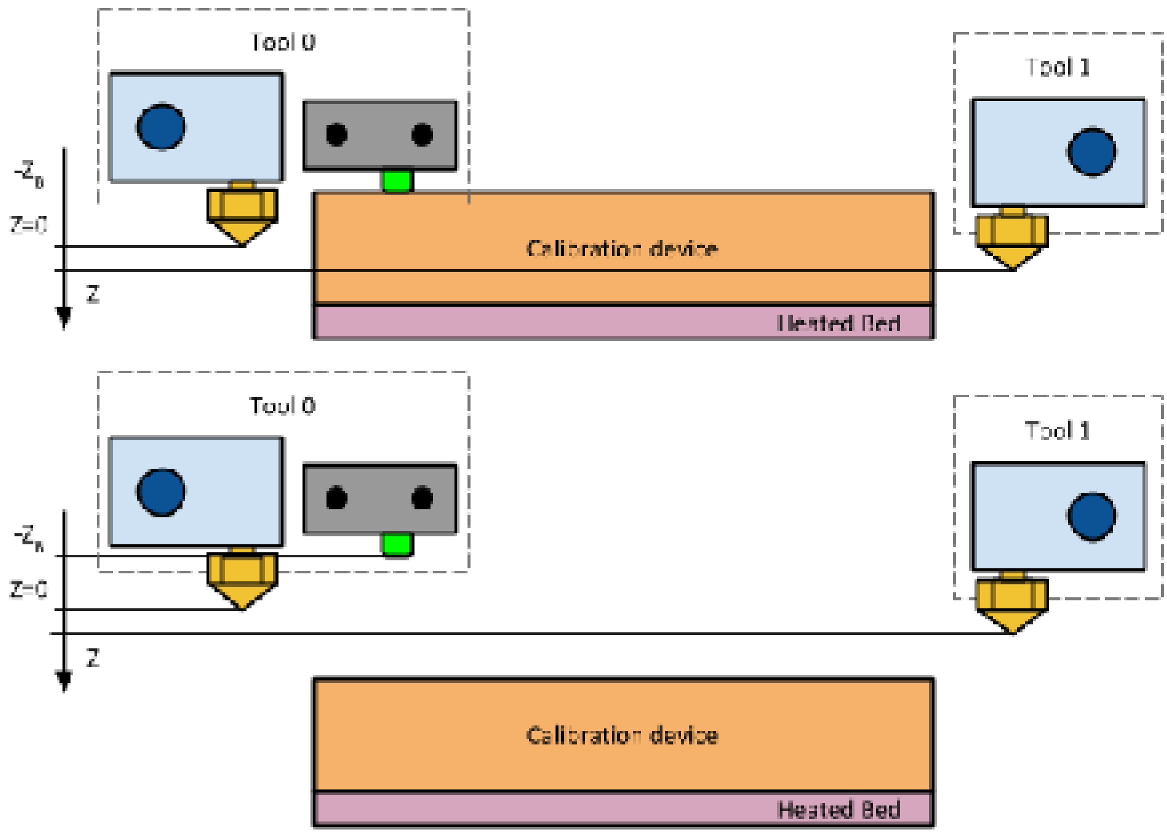
M206 Z[Z_0]

Like this the T0 Z is calibrated.

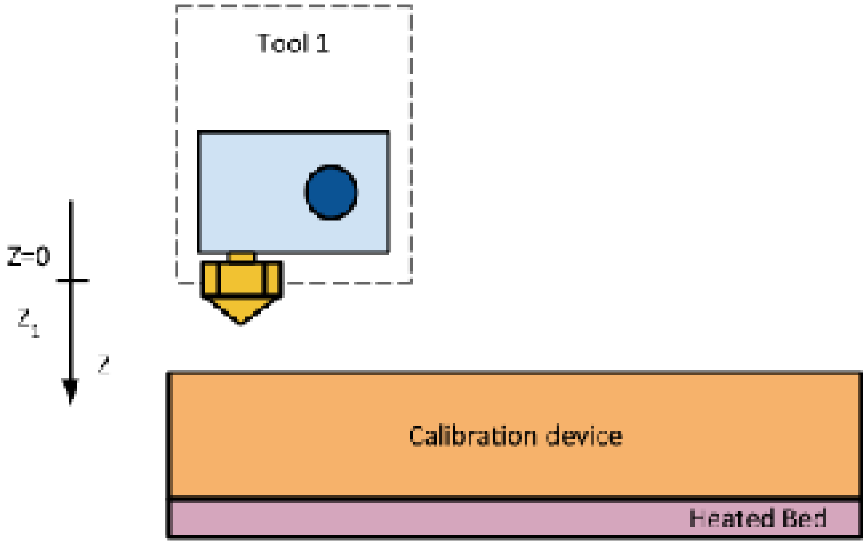
The T1 Z calibration is similar. After homing the Zone knows where T0 zero point is, however as mentioned earlier the T1 can be higher or lower than T0 (proportions are exaggerated on the sketches):

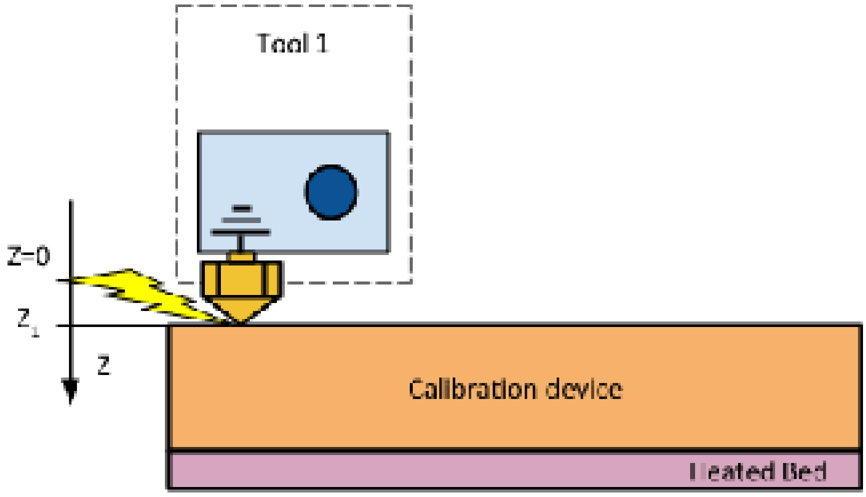


To prevent collisions after homing the Z axes one moves the bed with the Calibration device sufficient amount down (increase the Z). During the homing T1 is next to the bed and there is no collision possibility.



The T0 is moved away and the T1 is moved the same place where the T0 Z calibration was done (there is always some X, Y mismatch as these axes are not yet calibrated). As discussed earlier the exact point is not necessary, close enough is sufficient. The bed is moved upwards until there is a contact between the T1 and the Calibration device.





With the contact, the Z_1 value is known and that can be used as the calibration value for the printer:

M218 T1 Z[Z_1]

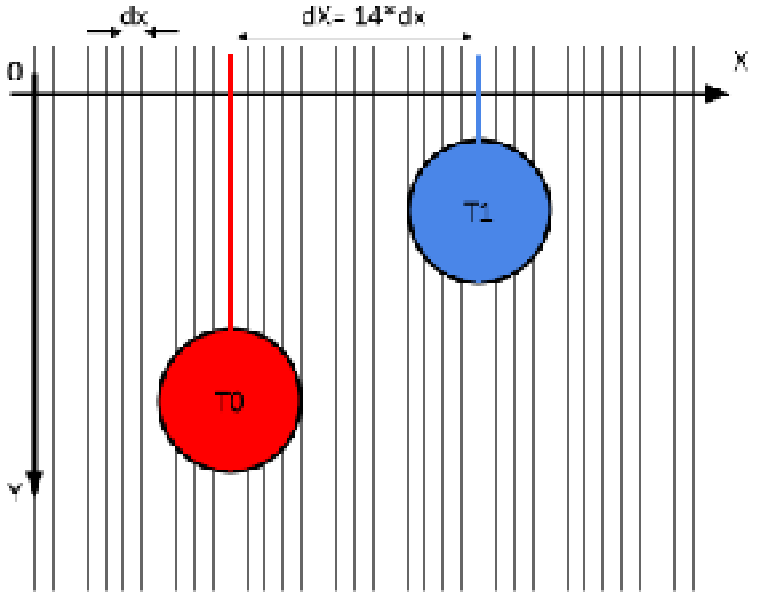
The same circuit and device can be used as with T0.

Now the Z is calibrated for the T0 and T1. Now one could focus on X and Y.

X and Y calibration

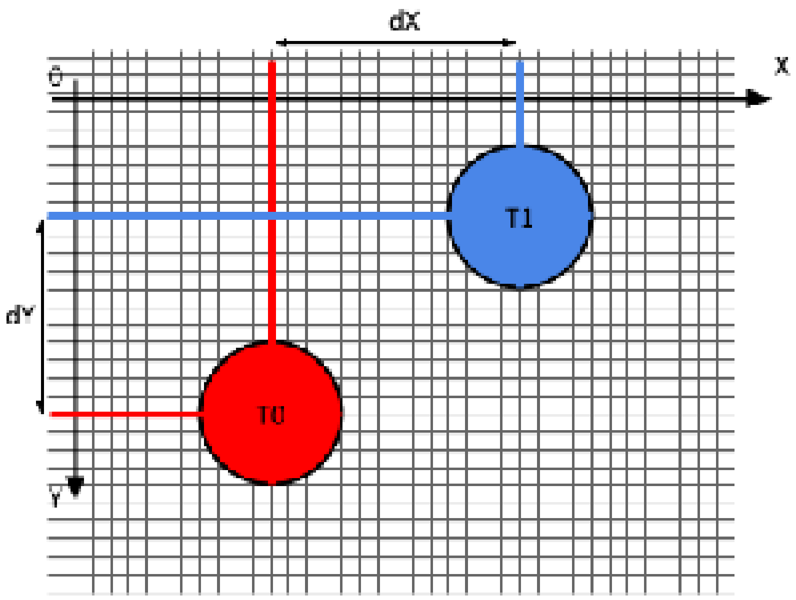
As already discussed the X and Y calibration is the same for both axes, thus only X axis calibration is discussed.

Similarly to Z calibration one can "measure" the nozzle position by having a contact. First, T0 position is defined, thereafter T1. When one knows T0 and T1 position the X difference dX can be easily defined. How to define the T0 and T1 position? It could be done by using a fine grid:



As can be seen the mismatch dX between T0 and T1 center points is 14 grid lines. When the distance between the grid lines are known, the distance between the T0 and T1 can be easily calculated. For a fine accuracy the grid has to be as fine as possible.

If the grid is at the same time in X and Y axes (so that a net is formed) one could determine the position for the both axes simultaneously. This kind of grid can be found for example in resistive touchscreens, however the resolution in such devices is not high enough. Therefore, a custom made grid will be used in the prototype PCB design.



Practical prototype

Theory is nice, however one should always test it in practice. Hence a prototype PCB has been designed and tested. These prototype has not been used with the BCN Sigma! The text is written for the developed printer, thus everything written in the following is focusing only on that specific printer.

The voltage measurement is done by an Arduino UNO. The Arduino can measure voltages and communicate with a computer (we used a Raspberry Pi) through a USB cable. The USB communication is achieved with a simple FT232 chip. It's a very common one and doesn't require any configuration.

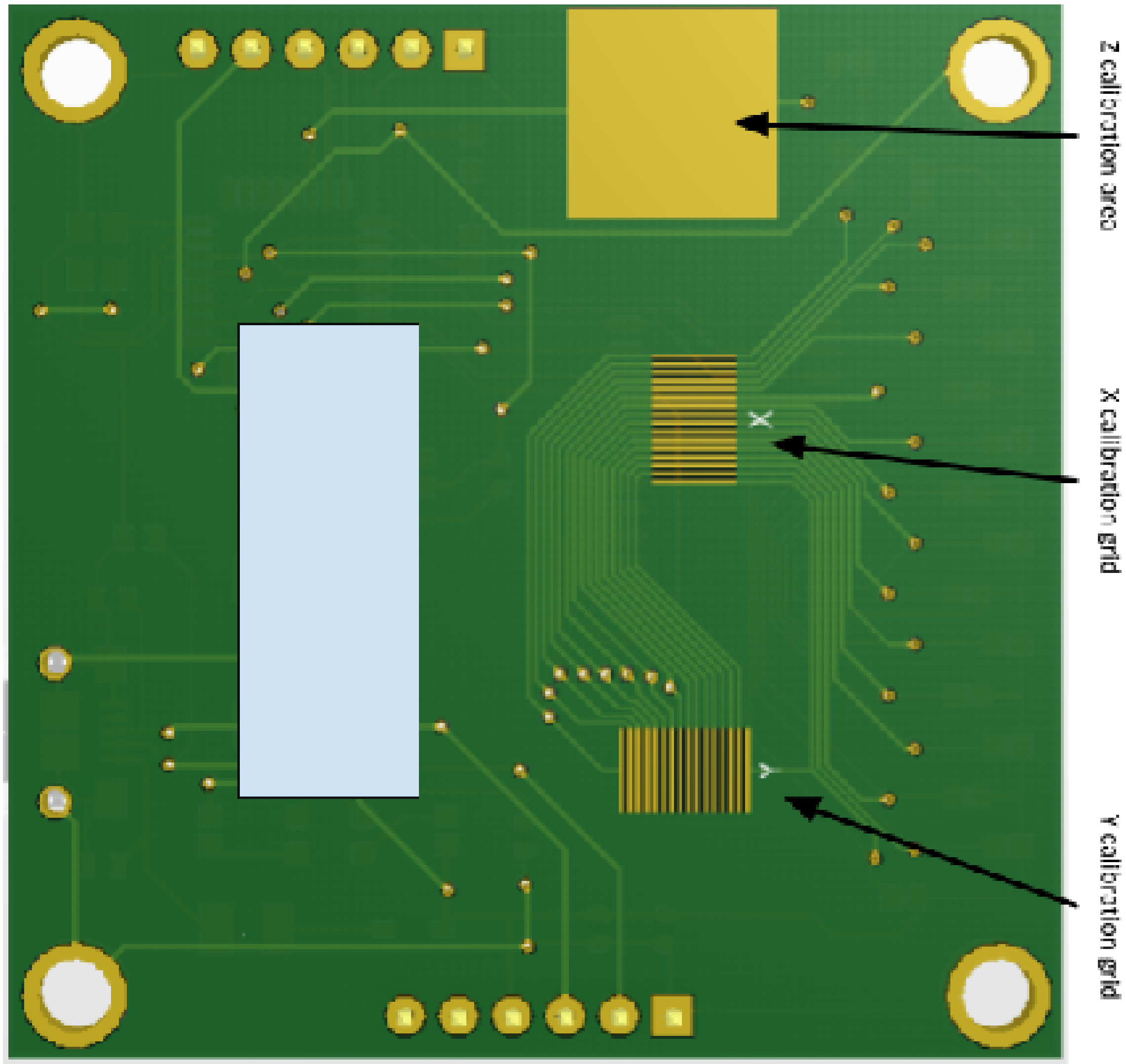
The calibration device is connected with the printer through a USB cable. The USB has many benefits- it can transfer power and data at the same time. Additionally the cables are very commonly used. A micro USB (version B) has been chosen due to its relatively small size and wide usage.

As said, the board power comes directly from the control computer. This allows using only one cable from the available USB port.

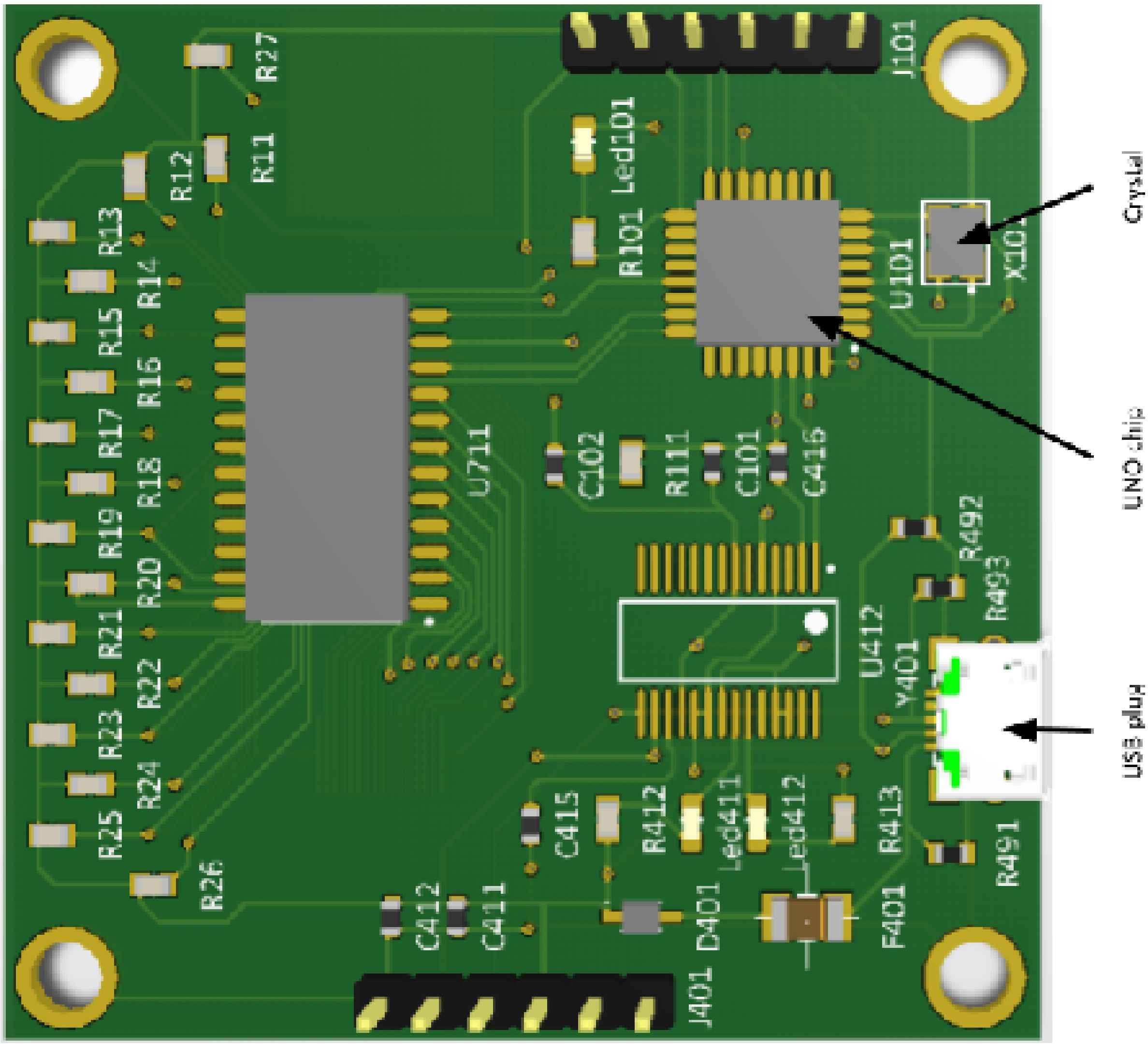
The user has to fix the calibration device properly, even with the slightest movement during the measurements means wrong calibration results. For the fixing a 3d printer frame has been used.

PCB

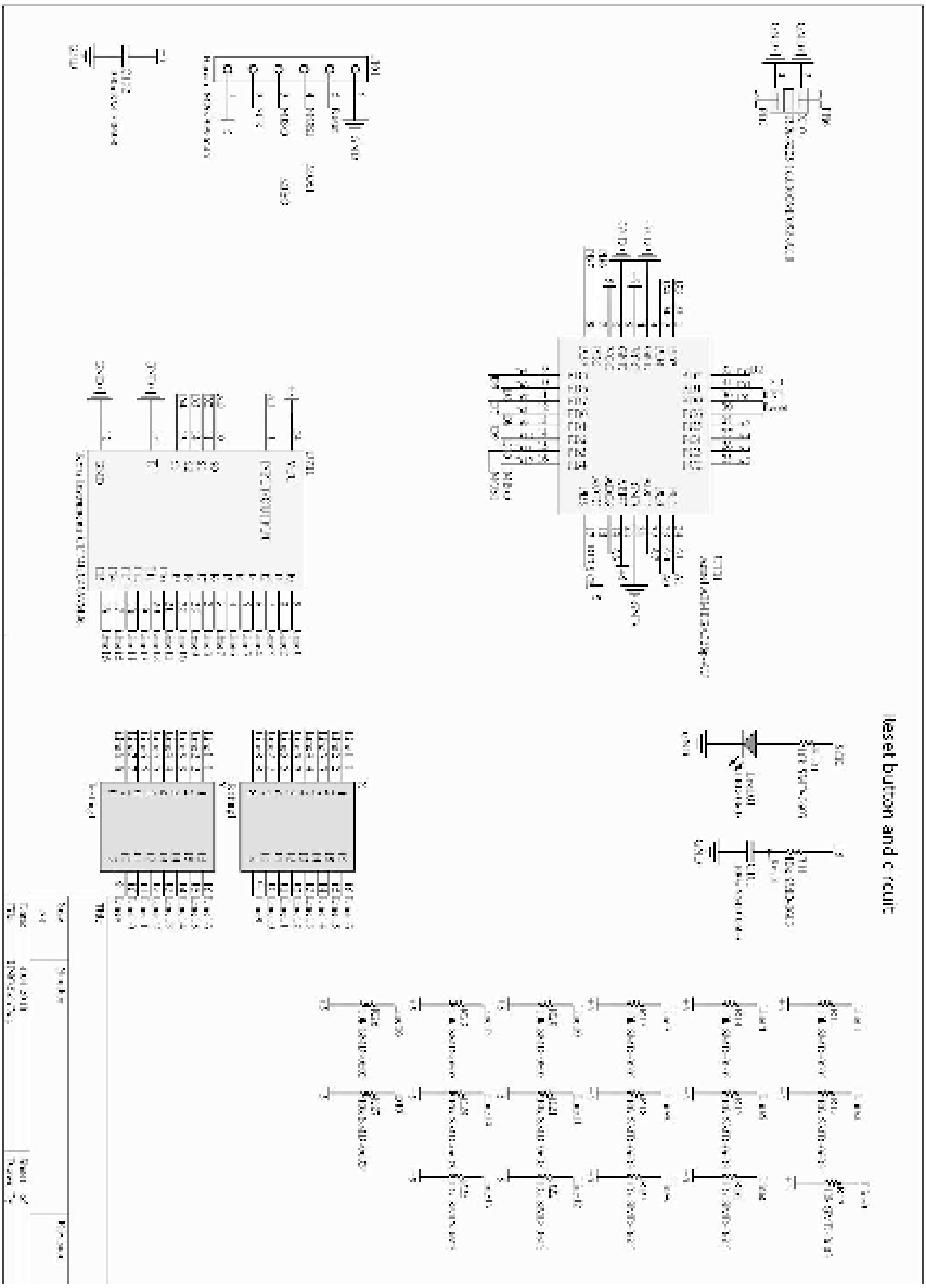
The PCB from the top:



The PCB from the bottom:


Crystal
UNO chip
USB plug

Schematics



All the capacitors are for voltage stabilization. They are there to keep the voltage stable when one has contact with the nozzle or the connection with the USB cable is suddenly weaker.

The resistors R11 to R27 are pull-up resistors for the measurement grid.

Arduino chip U101 can measure voltages, however it has only 6 pins that could do that. For reliable testing conditions one needs as wide grid as possible. Therefore a multiplexer U711 is used. The multiplexer can be used to measure voltage at up to 16 different points.

Between the Arduino and the USB cable a USB to serial converter is needed. For that U412 is placed. All the other elements are for security and or performance indication (LEDs).

Headers could be used for bootloader and program uploading, power testing and some other functions. They are not needed in the production series.

Z calibration

Very similar procedure described in the following is used by Zortrax. For the homing and bed calibration.

As described earlier, the Z calibration starts with homing. The endstop is triggered on the "Z calibration area" ensuring that the calibration height fits later with the endstop.

It is clear that the placement of the calibration device is very important. The device will be placed and fixed on the left side of the bed, where the T0 and the endstop is. The device placement in the Y axes has to be fixed so that the calibration areas are in the desired range.

The size of the "Z calibration area" is made relatively large so that even when the T0 and the T1 are very far away from each other the area can be reached. Additionally, it simplifies reaching the area with the endstop.

Before doing any homing the old Z calibration values are deleted:

M206 Z0
M218 T1 Z0
M500

After homing the bed is moved down (Z is increased to Z = 5). The height should be sufficiently high to avoid collisions even when the longest nozzles are used. On the other hand too wide distance requires longer calibration time. Total calibration time is depending on the resolution and the start height, but will be always less than 20 seconds.

When the Z height is reached the T0 is moved to the calibration point ($X = X_{cal}$ and $Y = Y_{cal}$). Step-by-step the bed is moved upwards toward the nozzle. Each time the bed moves 0.05mm upwards. The step resolution defines the accuracy of the Z calibration and could be reduced.

Each time after the bed has moved a check is made if there is a contact or not. The contact check means, measuring voltage on the large "Z calibration area". If the voltage has dropped below predefined value one can assume there is a contact between the nozzle and the metal surface.

The Z value when the contact happens, Z_0, will be used as the calibration value for T0 (the negative value of the Z_0 is the correction factor):

M206 Z[-Z_0]

After saving the value to EEPROM, homing is needed to use the newly calibrated Z value. The T0 Z is calibrated and one can now calibrate the T1 Z.

When T0 is homed the T0 is moved to its parking position (X = X_{homeT0}). The Z is increased to prevent collision as the exact position of T1 is not known. Practical tests have shown that Z = 3 is enough here, since in reality the nozzles should be more or less at the same height (Z_1 = ±0.5mm).

The T1 is moved to the same calibration point as T0 was (X = X_{cal} and Y = Y_{cal}) and the Z height will be reduced until contact. The resulting Z value, Z_1, will be used as the calibration value (sign has to be changed):

M218 T1 Z[-Z_1]

After saving and homing the new calibration values are set.

Since Marlin (printer firmware) doesn't allow moving the bed outside the possible limits (especially negative Z) one has to adjust the values slightly. After homing the endstop defines the Z = 0 point, since the endstop is the minimum point the Bed is not allowed to go negative values. That makes sense and is needed for the safety.

It can happen that one needs to go to the negative zone, that's especially with the T1. Therefore, after moving the bed to the desired height Z = 3 it's said to the printer that the actual Z height is 5 mm higher. So the printer assumes that the height is actually Z = *8* and one can move the bed even to the real negative values.

To adjust virtually the Z value one should use *M92 Z[3 + 5]*:

M92 Z8

After finding the contact point and the Z_1 value one has to subtract the 5 mm:

$Z_1 = Z_1 - 5$

Change the sign:

$Z_1 = -Z_1$

Send it to the printer

M218 T Z[Z_1]

X and Y calibration

The nozzle X and Y position could be determined by using a net of sensors. Nevertheless, in practical device it's relatively complicated and therefore the X and Y axes are separated. The Y calibration process is exactly the same as for X (the only difference is the movement axes). Thus, here only the X calibration is explained.

The measuring grid consists of 16 evenly distributed lines. This is limited by the multiplexer. The lines are 0.2mm wide and are separated by 0.2mm. This resolution is given by the PCB manufacturers (cheap Chinese ones). The resolution could be increased with exponentially increasing production costs. As will be discussed later the 0.2mm resolution is high enough and allows approximately 0.05mm calibration accuracy (assuming that the X axes can move with the 0.05mm accuracy).

The X calibration starts with homing all the axes. It's important to know the exact position and homing is the simplest way to do that.

First, T0 nozzle position is determined. After homing Z is increased to Z = 1, this prevents scratching and collisions when moving over the calibration device. The toolhead is moved to the desired position (desired X and Y position).

Since the Z is calibrated one doesn't have to worry too much about moving slowly up and down with Z. One can go fast from Z = 1 to Z = 0. In reality, as the PCB is sufficiently flexible, Z = -0.25 is used for better contact.

The theory and mathematics how to determine the nozzle center point is not described here.

In the Y axes exactly the same procedure is made.

Known issues

1. What happens when the nozzle is not perfectly flat?

   As the grid system is used to determine the nozzle center point the imperfect nozzle bottom surface affects the results. During the testing it was noticed that the used nozzles had usually deformed nozzle end and that affected largely the accuracy.

2. What happens when the nozzle is dirty?

   Used nozzles usually are covered with some filament rests and that can cause some issues. Therefore all the test with the prototype has been made with removed filament and with high temperature nozzle (@ 220°C), so that the filament between the grid and nozzle is soft and could be squeezed away if needed.

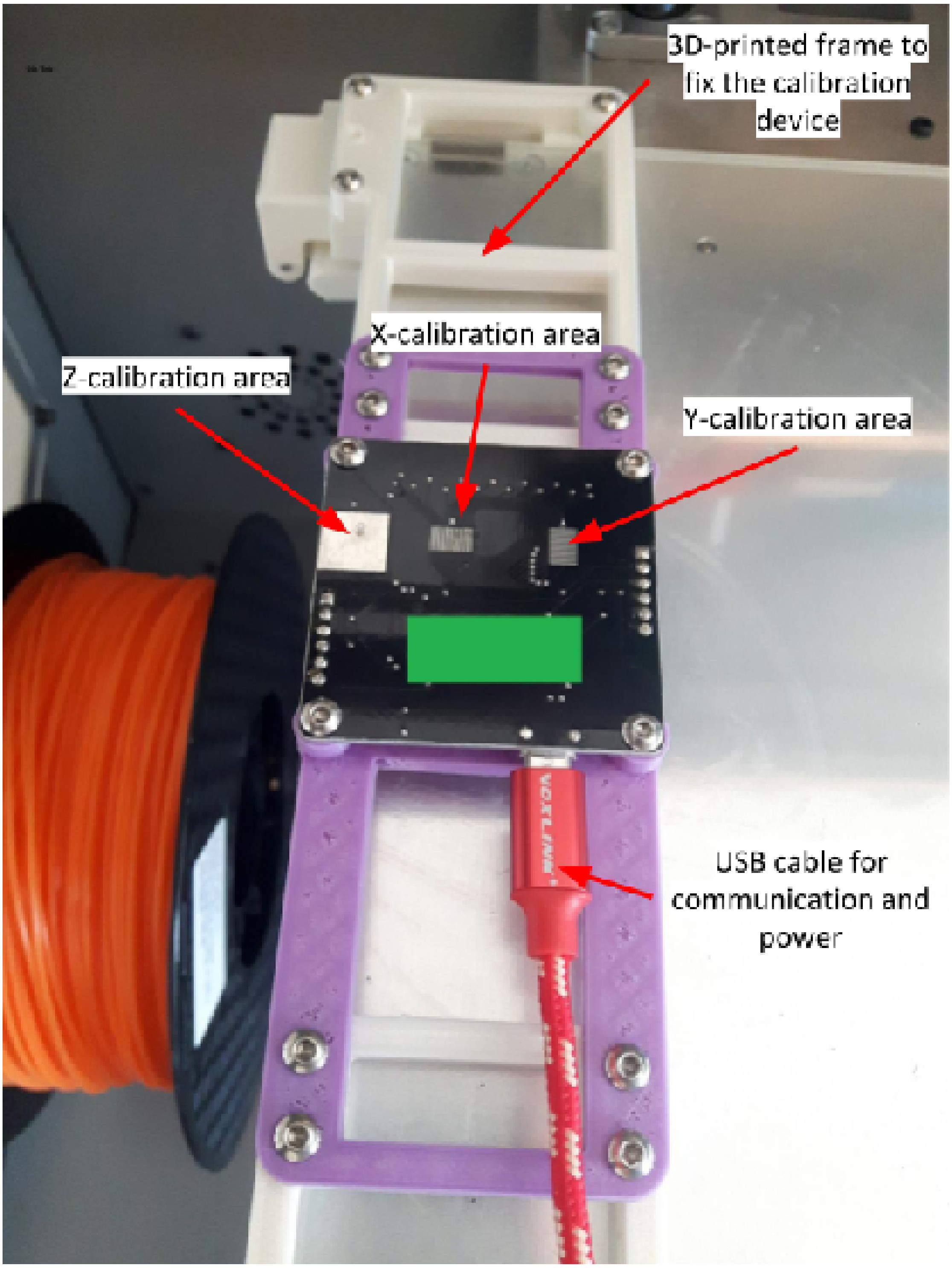
3. What happens when a non metal nozzle is used?

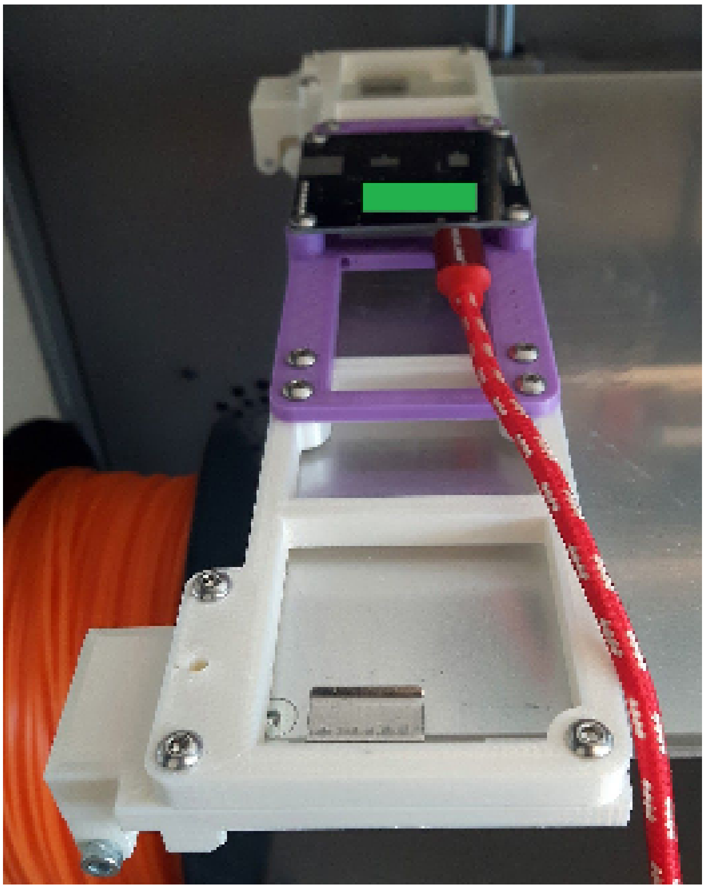
   As the procedure is based on the electrical contact non metal nozzles cannot be used with this method.

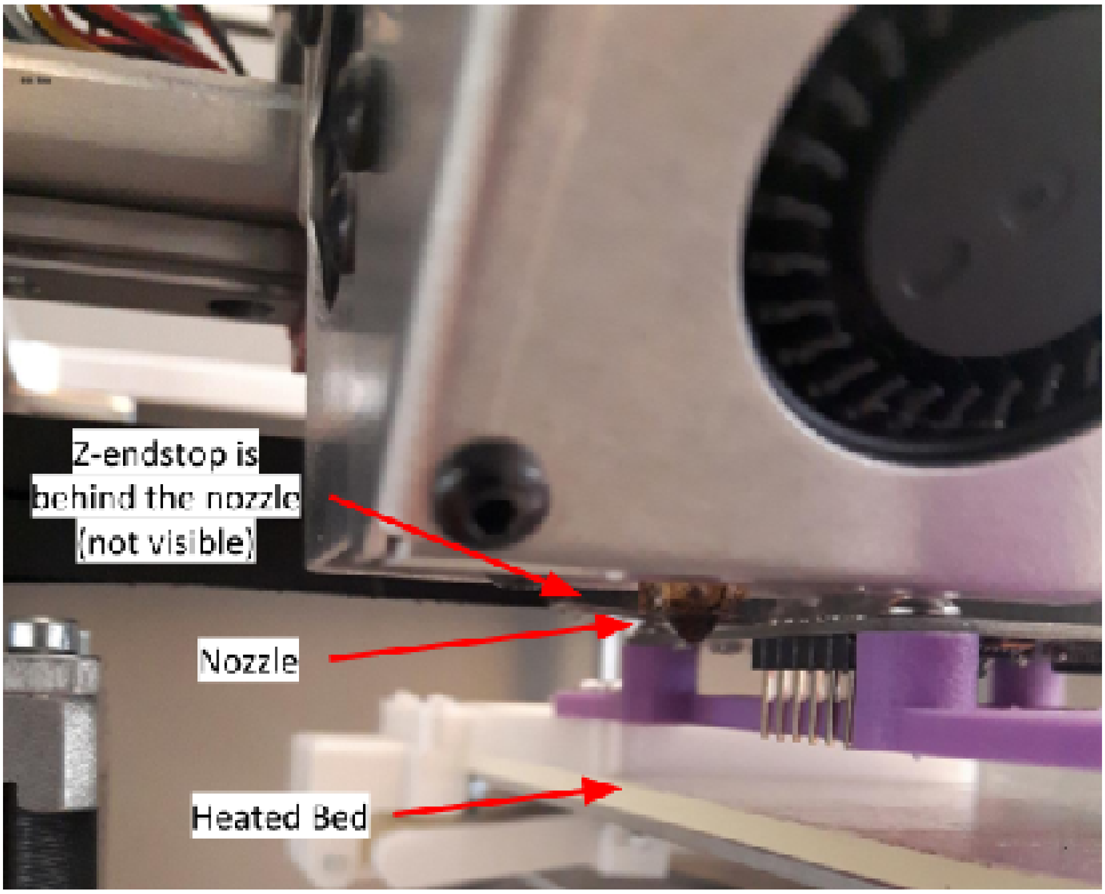
4. What happens when the calibration device is not in the correct place?

   It can happen that the nozzles are not exactly in the position that was planned, thus the nozzle is outside the grid area.

Some pictures of the prototype in our printer






Z-endstop is
behind the nozzle
(not visible)
Nozzle
Heated Bed