HOMEWORK 1

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Problem 1

Make a list of different characteristics of metal 3D printing technologies as a means to compare with computerized numerical control (CNC) machining of metal. Under what circumstances do AM have the advantage and under what would CNC?

Main difference between 3D printing technologies and CNC is that CNC is a subtractive method (unnecessary material is removed from a single block of material and only needed material is left). While 3D printing is an additive manufacturing (we simply add needed material where necessary).

Characteristics:

- Materials
  CNC can work with a huge variety of the materials such as aluminum, steel alloys, brass, copper, different woods, thermoplastics (not same as for 3D printing), acrylic, modeling foams and machining wax. While in 3D printing plastic is mostly used (PLA, ABS, nylon) or resins. Aluminum, ceramic or wood can be mixed in thermoplastic however it won't be as robust as parts made fully out of metal, for example. 3D printing is also possible with metals and ceramics, however there materials are used for 3D printing only is specific needs (those characteristics explained later).
- Precision
  CNC mills can be very precise and usually more precise than 3D printers (tolerance of CNC +- 0.025-0.125 mm, while among 3D printers DMLS has best tolerance of 0.1mm and industrial FDM have tolerance only 0.5mm). Also sometimes 3D printed parts can deform during printing. If there is a little thing that is unprecise the whole print can go wrong. In CNC, worn mills or damaged tools can also result in inaccurate part, however that is easier to monitor (see when mill is worn out). On the other hand, SLA printers can produce parts that have very complicated structures (CNC cannot cut something behind the plane that should not be cut through unless we rotate the part). Also CNC cannot create parts with complex geometry (for example topology gained high popularity with appearance of 3D printers). In addition, CNC cannot have parts with hanging material. In 3D printing we can create flexible parts (one whole part but has rotational components for example)
- Ease of Use
  3D printing is easier to use, especially for non-professionals, while it also has a lot of flexibility that is interesting for the research engineers. CNC is labor intensive. Only a skilled operator can run the CNC process (to choose tools for example)
- Speed
  Usually 3D printing is much longer than CNC. 3D printing takes hours (on average 3 to 7 hours) to complete and commonly requires some post processing. While CNC usually does not take

more than an hour and post-processing is minimal. However, sometimes it can depend on the part.

- Noise and Vibrations
  CNC machines can be very noisy and vibrate a lot, especially with some large diameter tools. However noise on the CNC machine depends on the material. 3D printing is quite (sometime the noise from 3D printers even calms people down) and does not have vibrations.
- Messiness
  CNC machines remove the material so they produce a lot of mess. Also there is a liquid that cleans the material during the process to avoid mess interrupting the cutting. All the liquid and mess should go somewhere, therefore CNC machines are usually quite big and have special draining system. 3D printers are usually not messy if everything goes okay. If the print is messed up and not stopped on time things can get messy and hard to remove. Some post processing of 3D printing can get messy (cleaning resins from the ready made parts from SLA printing).
- Waste
  For CNC we need a full block of material and depending on the part there might be a lot of waste of material and cannot be reused. In 3D printing we only add material. In FDM we use spare material only for the supports (usually we choose best orientation to have less supports). In SLA for example, there might be a lot of material waste, however, sometimes it could be reused.

Even though CNC machine is considered more precise and can work with wider range of materials, 3D printers are irreplaceable in some circumstances. For example, when we want to have some complex geometry with a lot of curves (such as topologically optimized part – which is great because of the mass, material and cost reduction while retaining the strength needed for that part). CNC cannot produce such a part and 3D comes handy in such a situations.

Another example is when we want to have a whole peace that actually consists of multiple pieces such as chain or something inside the other part (like a sphere in the shelled cube). In 3D printer is easy to do with removable supports (or SLA technique), while in CNC it is impossible. Another circumstance is rapid prototyping in the small laboratories or companies.

3D printers are easy to operate and they are not noisy or messy. For not industrial companies 3D printing is a great tool for prototyping or even creating their own parts at the cheaper price (I was working as an intern in the drone startup and they used 3D printer to create some parts of the drone or even parts replacements. That was quick and easy solution).

Problem 2

CNC machining is often referred to as a 2.5D process. What does this mean? Why might it not be regarded as fully 3D?

To explain 2.5D it is easier to compare with 2D and 3D. So in 2D we have no depth (no Z axis, only X and Y). In 2.5D we can go to some depth (some value of Z) and at that depth we move in 2D dimension in that depth. Since we are not able to freely move in all 3-axis it is not completely 3D. So in 2.5D we are free to move on 2 axis on the specific plane (specific value of Z axis). Therefore 2.5D does not have full 3 degrees of freedom (full 2 degrees and not full 3rd degree).

2.5D machine (two-and-a-half-axis miss) can move in all 3 axis, however in can cut only in 2axis. Therefore, the drill can find a point on the plane and go to specific depth (while it can drill different shapes in terms of the 2D plane (square, oval and etc holes). However it cannot do spherical cut (some curve so on the plane tangential to the drill).

Problem 3

What a problems of the STL format data?

STL format has multiple disadvantages. It does not include colors or texture representation or material within its script (the scripts (ASCII or binary) consists of basically connected 3D triangles (approach called "tessellations") with specified faced normal and three vertices). Therefore when we print the part, STL file shows us only the geometry of the object.

In addition, STL file does not show microstructure, so that if we have a part with porosity than it is usually a huge where porosity is part of the geometry and each is represented with small triangles mentioned above. Also, STL file does not carry the information on how to orient the part in the printer, therefore we need extra communication with the build setup. Since, STL is not like a solid part for editing we mostly use Boolean (such as union, subtract and unite). However, there is not much one can do with Boolean (usually used to make supports, holes or hollow the part). Therefore, for the part editing converting to the other format is preferable.

Finally, complex geometries might have errors in STL format when we convert them form some other format such as STEP. Errors include gaps (the triangle is missing in the scrips so there is an empty space), inverted normal (the surface outside while it should be faced inside), intersecting, duplicate, multiage or overlapping triangles (when STL sees two parts nearby it can see then separately and their triangles intersect instead of uniting them in one. This error come from the fact that STL does not store the information about the connectivity of the triangular faces that it consists of. Therefore, when printer read STL file it has to guess about the connection and sometimes guess is bad and causes errors.

Based upon Internet search, find information about another format types for AM. Please, describe their advantaged and disadvantages in comparison with STL format.

Format	Advantages over STL	Disadvantages over STL
1. OBJ	Multicolor printing (carries info about color of the part). Also carries info about materials and textures. Many opportunities on how to encode the geometry – one can use tessellations (like STL – but for good precision big file size). Also OBJ offers free-form curves and free-form surfaces – so we can encode curved geometries without losing info about the geometry itself. In addition free-form curves and free-form surfaces are more precise while having less parts (files) (very important for engineering where precision is super important such as aerospace). For color storing uses separate file MTL (material template	Not as much support but various software (CAD or slicers) - however still pretty good. But for solidworks needs a plugin. It's more complicated, therefore is the file is broken it is very hard to repair it because in the internet there are not as many tools to work with OBJ.

	library) – can define material properties such as ambient color, diffuse color, specular color or even transparency.	Since working in pair with MTL one of the file can get lost and causes problems.
2. AMF	XML file format – easy to read, write and process. Triangular mashes as in STL but allows curved triangles – better precision with less faces – less file size. Support for colors (RGBA and graded) and texture mappings. Can deal with different materials (even mixed), sub-structures, microstructures and even porous and stochastic materials. “Constellation” feature – lets us to specify relative pattern of the parts (objects) in the file. Adopts to the printer capability (for example if printer can do only one color – multicolor info is ignored)/ Extensive metadata fields. ISO standard from 2013.	AM industry vary slow to adopt AMF format. STL more widely used – very limited adoption. Many CAD and slicers software does not support exporting in AMF (however most common ones do). Some features not clearly defined. Not many ready-to-use parts online
3. 3MF	Microsoft – the developer of the 3MF – made 3MF consortium which helps the development and progress of 3MF. Big names of slicers, CAD software and 3D printer developers support and are part of the consortium, therefore there is great potential great adoption for all the new technologies (and potential putting STL out of the way by not supporting STL with new developers). Single archive with all the info of the model, material and property Easy to read for human (ZIP, OPC, XML) Short and clear specification Supports extensions Support structures attached to part data Consistency when file comes from digital to physical (less errors). No geometry problems. Easy to use – print directly form CAD software. Designed for industrial manufacturing	Still is not very popular and smaller CAD and slicer software does not support it. Not as popular among people. Super free and some companies do not like it (security issues) Not many ready-to-use parts online

Other file formats such as IGES, STEP, NURBS, VRML, FBX, X3D, WRL, PLY, PRT, DAE and other 3D file formats could be used for 3D printing, however they are not designed specifically for 3D printing. They have many complicated features that are not needed for printing which makes them more complicated (unnecessary complicated). Also many slicers might not support them and since not many people use them adoption of these files for 3D printing most probably won’t happen. Some format’s such as VRLM, X3D and FBX are made more for graphical design and have features like lighting, however missing material information.

Also here I show how STL part sizes compare to the other formats. We can see how STL is most bloated, however is has the least precision. So possibility is that soon STL will go out of the use and more modern formats will be more popular.

1. PLY (binary): 1.1M
2. X3DB (binary): 1.3M
3. OBJ (ASCII): 2M
4. PLY (ASCII): 2M
5. X3D (ASCII): 2.1M
6. VRML (ASCII): 2.7M
7. STL (binary): 3M
8. STL (ASCII): 11M

Problem 4

Suppose you are the head of additive laboratory - G1 and decided to purchase an SLA installation. Please, visit on the site of 3D Systems Co. (www.3Dsystems.com) and make a choice of installation suitable for your case. Explain your choice in a short issue (min 200-300 words).

An Additive laboratory needs to and usually does a wide range of tasks so the printer should be flexible, resettable, and reconfigurable. The capacity, productivity, and huge size are not as important as it is for industrial equipment because laboratories mostly do research on small samples (for example, stress and deformation tests). High accuracy and resolution are important as well.

We have found four types of SLA printers on the 3d Systems website where all of the SLA offered printers were plastic. We excluded ProX 800 and ProX 950 because these printers are very big in size and they do not have as good accuracy on fine features as the ProJet 7000 HD or ProJet 6000 HD (Fine Feature/Outer Surface Scanning Larger: ProJet - Down to 75 μm (0.003 in) 750 μm (0.030 in); ProX - 125 μm (0.005 in) 750 μm (0.030 in) 125 μm (0.005 in)). Also, ProX (800 and 950) printers are much bigger in size - over 1000 kg - compared to ProJet (6000 and 7000) - around 300kg. Therefore, we can conclude that ProX series printers are more suitable for large manufacturing and they are not the best choice for the additive laboratory.

Choosing between ProJet 6000 and ProJet 7000 we decided to go with ProJet 6000 (Figure 4.1) because it is smaller sized and it has more additional Interchangeable Material Deliverable Modules (MDMs).

Figure 4.1 - Projet 6000 SLA 3D Printer

The ProJet 6000 offers all the benefits of SLA in a smaller footprint, so we can print with fine feature detail in a wide choice of performance-engineered materials that match or exceed traditional plastic properties. The printer with more functionality and flexibility opens more opportunities for the research in the laboratory.

After making your selection, evaluate and describe the requirements for the placement and maintenance of your installation (issue min 1000 words).

Manufacturers of 3DSystem affirm that ProJet 6000 3D Printer Size when it is uncrated is 787mm in width, 737 mm in depth and 1829 mm high. Safety requirements state that the installation of the equipment must be within one meter from the walls of the room. Therefore the bare minimum for the room where the equipment will be installed is 1787x1737x2829 mm (WxDxH). In addition, the operator of the equipment must have space for the work and samples post-processing, so we would recommend extra space for the operator of at least 1x1m. Therefore the room we recommend should be 2787x2737x2829 mm.

ProJet 6000 has rated 750W of power, which is the maximum possible energy consumption by the printer. If we take this number we find that the maximum that ProJet 6000 can use in 24 hours is 18 kWh. However, the printer does not always spend maximum power only when it is printing some huge print that lasts over 24 hours. In the laboratory set up such a huge print happens rarely. Usually in the lab researchers print smaller samples for the project that they are doing and print time usually do not exceed 10 hours. When the printer is not printing it consumes much smaller amounts of energy and energy consumptions might drop up to 7-10 kWh a day. Finally, in the laboratory on the weekends usually, printers are not used and are turned off, so they consume 0 kWh. Therefore, we can estimate about 70kWh of power consumption per week, which ends up in 3640 kWh of energy consumption per year.

- **The volume of water**

Datasheet of the Projet 6000 says it has a laser of the fourth class of danger. It means that the overall power of the laser is more than 500 mW. The power output of such lasers can vary from 20 mW to 8 kW depending on the model specification type. A usual lifetime of UV lasers starts from 4000 and more hours. To extend their lifetime it is necessary to keep a constant temperature of laser installation. It can be done by means of water cooling. There are two possible options:

- *Tap water supply;*
- *Closed-loop system.*

Tap water supply is a good choice in case of the rare use of the printer and high demand on temperature status during part production. Although it will cost an additional amount of financial resources it can be much cheaper than installation on a closed-loop cooling system. On the other hand closed-loop system wins if there is a need for constant laser work without brakes. They are presented by different chillers that can be connected to lasers. Because of long work runs it is possible to save money on water use and unhappened laser repairings. Usually, this type of chillers is used on lasers of power of 3-5 Watt and higher. The average accuracy of these modules is about ±0.3 celsius.

Assuming that Projet 6000 laser power output of 300-500 W, estimation of water usage for cooling will be gained by the use of CW-5000 (Figure 4.2) industrial closed-loop water chiller. It can effectively work with laser heat of 300-800 W. Water tank of this chiller is 6 L and uses distilled water that can be changed each month.

Figure 4.2 - CW-5000 water chiller for lasers

For part postprocessing, it is possible to use ethanol. 10 L per month is enough for parts and machinery cleaning.

At the end by Information provided in “СНиП 2.04.01-85” the standard of water consumption for laboratories of the physical profile is 125 L/per day per worker. The average amount of workdays during the month is about 20 days. Then the preliminary standard of amount of water consumption is 5000 L for the laboratory for two workers.*

- **The flow rate of exhaust ventilation**

SLA printing technologies produce ultrafine particles, VOCs and styrene (same as FDM) which are harmful to human health. If the printers are set up in the open space than the ultrafine particles, VOC and styrene from the 3D printer dissipates into the air and gets diluted by *oxygen. However, labs are commonly located in closed spaces (such as locked rooms in the building) therefore ventilation is required.*

According to Projet 6000 specification, it requires the capability of removing 1.0 kW/H of heat dissipated by the printer and keeping the optimal temperature inside the room of 20-26 degrees celsius. The air conditioning system should maintain a temperature changes of less than 1-degree Celsius per hour. The air should change two to five times per hour. It is also necessary to avoid exposure of the printer to direct airflow from the local air conditioning system to avoid affecting part production quality. Previously we proposed to use a room of dimensions 2787x2737x2829 mm. In this case, the required ventilation rate can be described by the formula below:

$$Ventilation\, rate\; (l/s) \;=\; air\; change\; rate\; *\; room\; volume\; (m^{3})\; *\; 1000(l/m^{3})/3600(s/hr)$$

Substituting numbers we obtain:

$$Ventilation\, rate\; =\; 5(t/hr)\; *\; 21.57(m^{3})\; *\; 1000(l/m^{3})/3600(s/hr)\; =\; 29.95(l/s)$$

Here ventilation rate is referred to as the absolute amount of inflow air per unit time (liter per second or l/s). And it equals 29.95 l/s.

- **shielding gases**

Shielding gases such as Argon and nitrogen are used in 3D printing to remove the reactive gasses such as oxygen around the printing area to prevent detrimental effects. Shielding gasses affect thermo-physical as well as mechanical properties of the printed parts. Each print requires a fresh volume of the gas because when setting up the print because we open the printing camera before every print to set up the print. The maximum build volume stated on the manufacturer's website is 40l.

Camera volume is usually slightly bigger than build volume since print never goes directly to the walls. Therefore we can estimate the camera volume to be around 50l. In the labs printing does not occur too frequently, more time is spent on print set up and study of the samples. On average there are around 3-5 prints per week. In addition, some prints are unsuccessful from the beginning, so that the camera would have to be refilled with the gas when print is reset. Therefore we can estimate that the 50l volume camera is filled with gas around 5 times per week so that 250l of the shielding gas is used in the lab every week.

- **the amount of material for your installation per month**

The printer has 2 L click-in cartridges for hands-free, drip-free automated refill process and it supports the use of next materials:

- *Accura Xtreme White 200 (SLA);*
- *Accura ABS Black (SL 7820) (SLA);*
- *Accura ClearVue (SLA);*
- *Accura 48 HTR;*
- *Accura 25.*

The datasheet of ProJet 6000 describes next printing specifications:

It has three build volume options: Full, half, short with next dimensions:

- *Full: 250 x 250 x 250 mm (15 L);*
- *Half: 250 x 250 x 125 mm (7.8 L);*
- *Short: 250 x 250 x 50 mm (3.1 L);*

Max part weight: 9.6 kg;
Max resolution: 4000 DPI;
Accuracy: 0.025-0.05 mm per 25.4 mm (Results may vary depending on build parameters, part geometry and size, part orientation and post-processing methods.)

As we are an additive manufacturing laboratory, assume that most of the printed productions represent samples for strength analysis tests. For example, we are going to use the ASTM D638 Type I standard for the production of specimens for the tensile strength test (Figure 4.3). According to this standard dimensions of the specimen are:

- *Full Length, l3 165 mm;*
- *Parallel length, l2 57 mm;*
- *Gauge length, l1 50 mm;*
- *Parallel section width, strong1 13 mm;*
- *Thickness, h 7 mm or less (Recommend 3.2±0.4 mm);*
- *Grip section width, strong2 19 mm;*
- *Distance between grips 115 mm.*

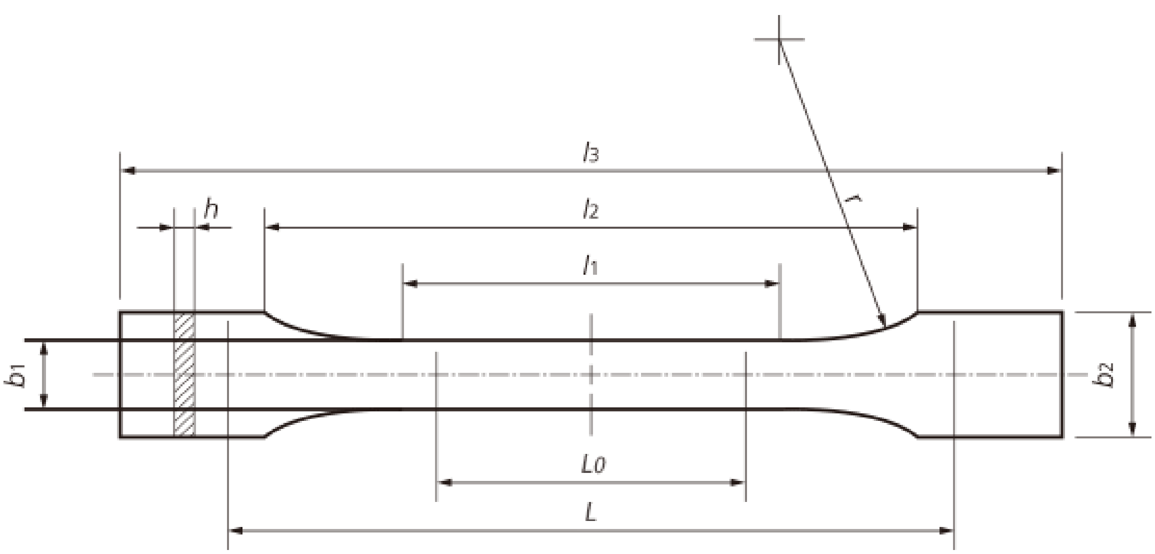


Figure 4.3 - Plastic specimen scheme

Now calculate the approximate volume of the specimen:

$V = l3 * b2 * h - l2 * (b2 - b1) * h) * 2 = 165 * 19 * 7 - 57 * (19 - 13) * 7 * 2 = 21\,945\ -\ 4\,788 =$

This equals approximately 0.0172 L. As the thickness of materials is only 7 mm, we can use the smallest volume for printing bay - 250 x 250 x 50 mm. It can contain 14 samples of the selected *size. For example, if we are going to print such samples every day during a month, the possible amount of material used will be:*

$$Vc = W * vs * 1.3$$

Where, W is the average amount of workdays during the month - about 20 days. Vs - the volume of one printing of 14 samples - 0,2408 L. 1.3 - represents the coefficient of material safety factor which equals 30% in case of printing of other items with different sizes. Then material use per month is:

$$Vc = 20 * 0.2408 * 1.3 = 6.26\,L$$

- **Describe what other tools, equipment, materials you will need to work effectively in your opinion. (Please do not take into account large equipment, the cost of which can be commensurate (equal) or half of the cost of an SLA installation).**

As we are working in the laboratory with a wide range of tasks we need always to have different types of polymer (and different colors as well), for example:

- *Accura ClearVue (transparent, polycarbonate-like / Bio-Compatible / Dental)*
- *Accura ClearVue (White easy-to-process plastic with best-in-class clarity, high durability and water resistance for a multitude of applications)*
- *Accura ABS Black (Strong and aesthetic black parts with minimal finishing to replace CNC-machined or molded ABS articles)*
- Accura 48HTR (Rigid and stiff plastic material for applications that require high-heat resistance. Material transparency allows for the visualization of internal structures in assemblies).
- Accura 25 (Accurate and flexible plastic ideal for snap-fit assemblies, master patterns for vacuum casting and durable functional prototypes with the aesthetics of molded polypropylene (PP))

All 3D-printed parts need to have post-processing executions. There are a lot of different types of finishing, they all need different tools - listed below.

- *Basic support removal (files, blades, other mechanical tools)*
- *Sanded support nibs*
- *Wet sanded*
- *Mineral oil finish*
- *Spray paint (clear UV protective acrylic)*
- *Polished to clear transparent finish*
- *Finishing in curing chamber*

Problem 5

wavelength scanning velocity wavelength scanning velocity

$\lambda1 := 375\text{nm}$ $v1 := 0.55\frac{\text{mm}}{\text{min}}$ $\lambda2 := 385\text{nm}$ $v2 := 0.4\frac{\text{mm}}{\text{min}}$

Power $P := 3\text{mW}$

What to find

1) corff of volume absorption α

2) cured volume into one point during 130 sec

$R := \frac{1.1\text{mm}}{2}$ radius of laser point

$tt := 130\text{s}$ acting time

Intensity

$Ic1 := \frac{319.7\cdot10^{-3}\text{J}}{\pi R^2} = 0.336\cdot\frac{\text{J}}{\text{mm}^2}$ $Ic2 := \frac{3.4\cdot10^{-3}\text{W}\cdot\text{s}}{\pi R^2} = 3.578\times10^{-3}\cdot\frac{\text{J}}{\text{mm}^2}$

$Imax1 := \frac{432\cdot10^{-3}\text{J}}{\pi R^2} = 4.546\times10^{5}\frac{\text{kg}}{\text{s}^2}$ $Imax2 := \frac{11.3\cdot10^{-3}\text{W}\cdot\text{s}}{\pi R^2} = 1.189\times10^{4}\frac{\text{kg}}{\text{s}^2}$

Cured depth

$C_{d1} := v1\cdot tt = 1.192\cdot\text{mm}$ $C_{d2} := v2\cdot tt = 0.867\cdot\text{mm}$

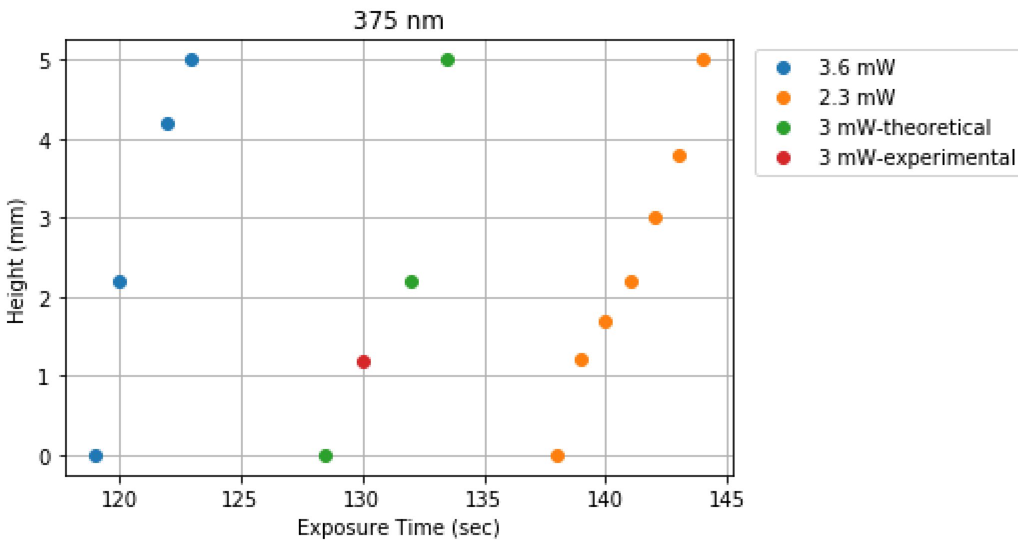
Volume absorbtion

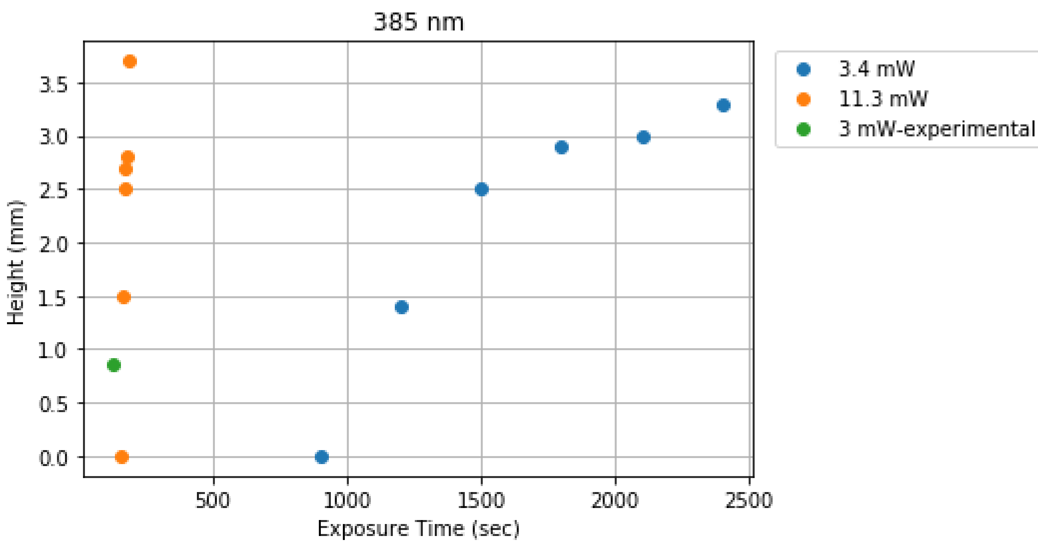
1) $\alpha1 := \frac{-\ln\left(\frac{Ic1}{Imax1}\right)}{C_{d1}} = 252.623\frac{1}{\text{m}}$ $\alpha2 := \frac{-\ln\left(\frac{Ic2}{Imax2}\right)}{C_{d2}} = 1.386\times10^{3}\frac{1}{\text{m}}$

Volume

2) $V1 := C_{d1}\cdot\left(\pi R^2\right) = 1.132\cdot\text{mm}^3$ $V2 := C_{d2}\cdot\left(\pi R^2\right) = 0.824\cdot\text{mm}^3$

Looking at figure 8 from the article (2.3 mW and 3.6 mW), we can make a theoretical plot for 3mW. When we plot the point for Cd1, we see that it lies in our theoretical plot, so the calculations are correct. The same is for the figure 10.


375 nm
3.6 mW
2.3 mW
3 mW-theoretical
3 mW-experimental
Height (mm)
Exposure Time (sec)
0
1
2
3
4
5
120
125
130
135
140
145


385 nm
3.4 mW
11.3 mW
3 mW-experimental
Height (mm)
Exposure Time (sec)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
500
1000
1500
2000
2500