

Operation Manual for
P μ SL 3D-Printer
in precision mode
(McKay 304)

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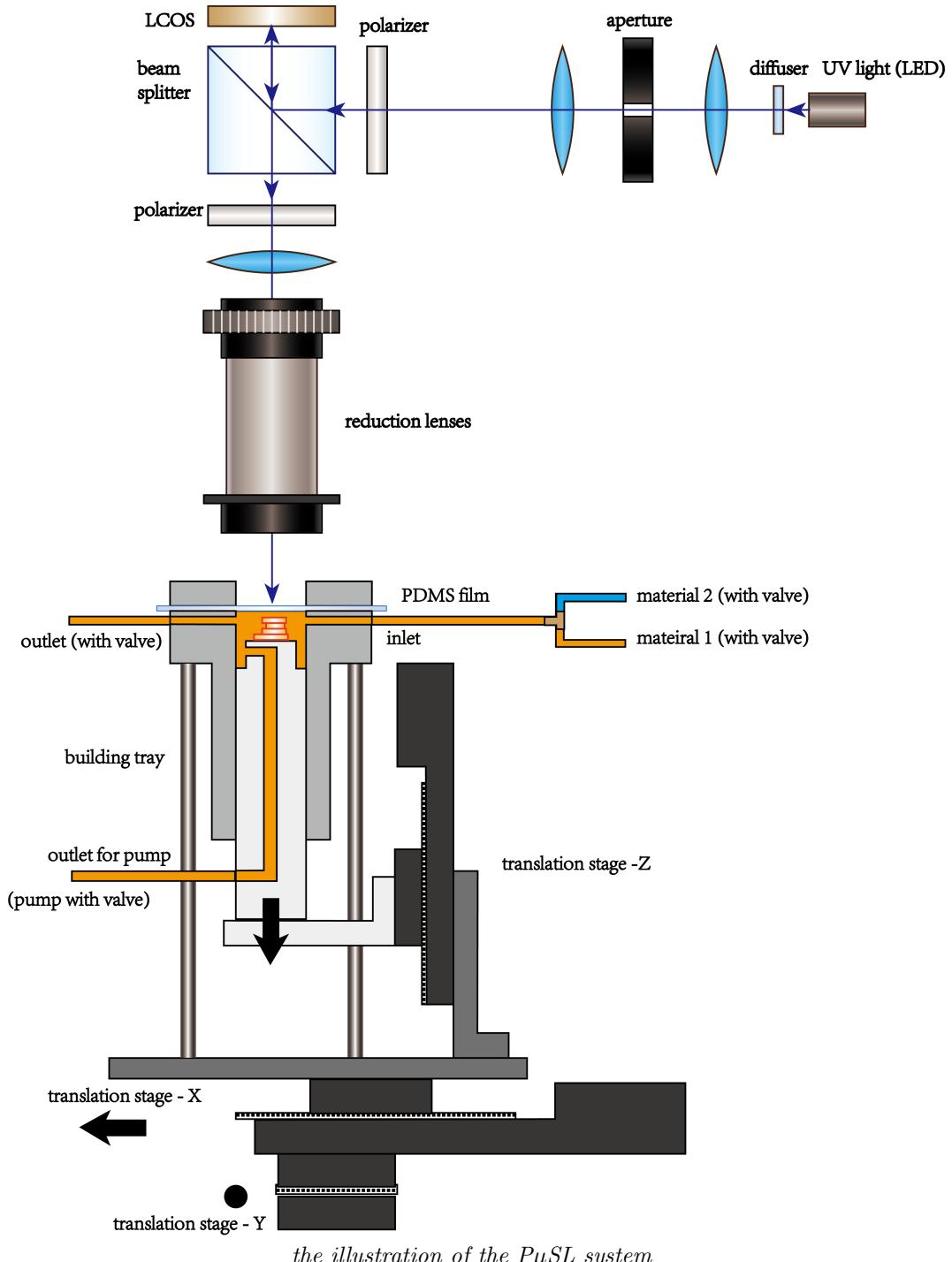
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1 System introduction

Projection micro-stereolithography ($P\mu SL$) offers unique opportunities to incorporate various material systems into micro structures and micro devices to achieve exceptional functionality. Also due to the freedom of manufacturing three-dimensional architectures at micron scale, $P\mu SL$ makes it possible to fabricate sophisticated structures with complex geometries and dimensions. With the help of $P\mu SL$, many designs and inspirations which could not be rapidly realized otherwise can be easily explored and investigated.

$P\mu SL$ is a novel 3D microfabrication technique capable of making highly complex 3D micro structures in an additive, layer-by-layer fashion with micro scale resolution. $P\mu SL$ utilizes the most advanced digital micro display technology, a liquid crystal on silicon (LCOS) chip , as a dynamic mask generator, to function as a virtual photomasks capable of producing digitally and dynamically configured patterns.The illustration of the $P\mu SL$ system was shown in the picture below.¹



¹ Howon Lee, THREE-DIMENSIONAL MICRO FABRICATION OF ACTIVE MICRO DEVICES USING SOFT FUNCTIONAL MATERIALS ,P10

Number	name	company	catalog number	comments
1	Projector	Canon	REALIS SX-50	LCOS
2	UV LED	Innovations in optics	2600N-700	365nm 405nm wavelength
3	Pump	Parker	L.3M06E2.A12VDC	LTC Diaphragm Pump
4	Motorized stage	Thors Lab	MTS50-Z8	Linear stage
5	Stage controller	ThorsLab	TDC-001	To control the stage movement
6	Powersupply	Agilent	E3633A	Power UV LED and valves
7	Electronic microscope	Supereye	A005+	For microscopic observation
8	Printing chamber	Machine shop	none	Customer-made

Table 1: The purchasing list of the hardware

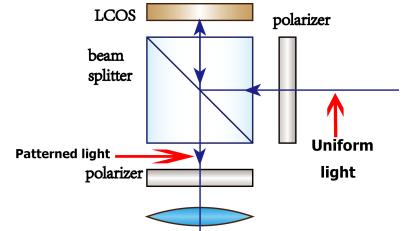
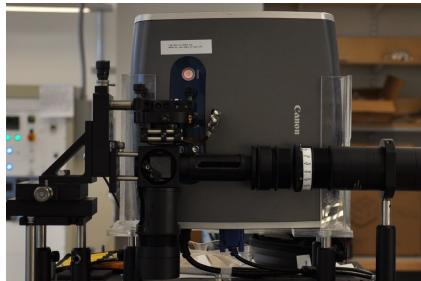
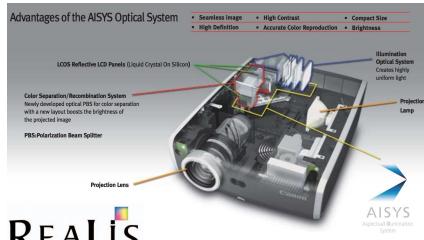
All the actions are set to **BOLD** and all equipments are in italics. The underlined part should be paid attention!

1.1 Hardware

1.1.1 List of the hardware

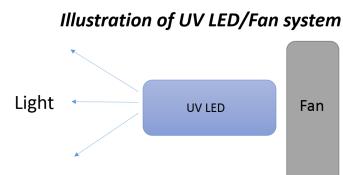
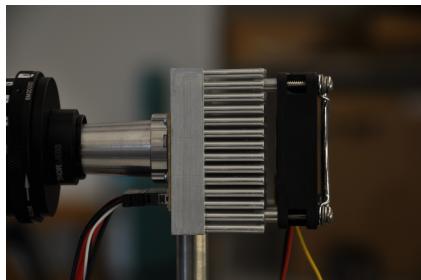
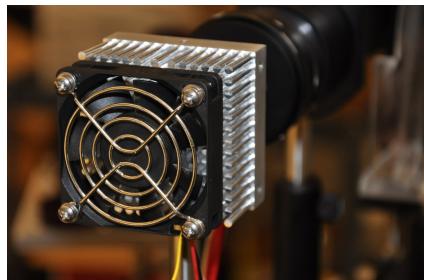
1.1.2 LCOS chip(Projector)

LCOS chip, which stands for liquid crystal on silicon², is the core part in both the projectors and the whole system. It can dynamically generate digital-masks and reflect the flood of Ultra-violet light into desired projection image.



1.1.3 UV LED source

UV LED source generates 405nm wavelength Ultra-violet light which is capable of curing the prepolymer solution. *Fans* are installed right behind the light source to ensure that the intense heat generated by the *UV LED* could be dissipated into the air.



1.1.4 Optical system

The optical system consists of the convex lens, polarizing beam splitter and reduction lens. See figure 1.

- *Convex lens*: **Converge** the uniform light emitted by *UV LED source* into collimated light and function as the light source of the LCOS. Two *apertures* can be used to individually **adjust**³ the diameter and brightness of the collimated beam.
- *Polarizing beam splitter*: The core part in the LCOS.
- *Reduction lens*: They were taken from the projectors and can reduce the image generated by the LCOS, which could be pretty big, before projecting the image onto the printing plane. Every pixel in the reduced image should be equal to 15 micrometers in the current optical path. The position and precision of the reduced image can be changed by simply **rotate** the lens.

²The underlined part should be paid attention!

³All the actions are set to **BOLD**.

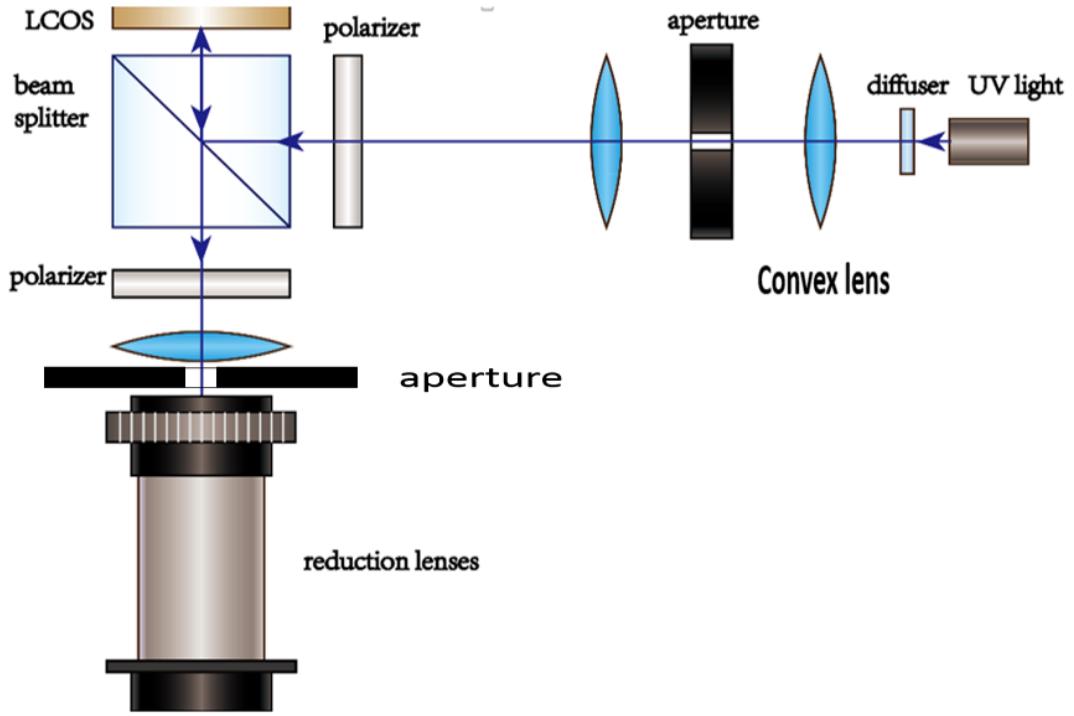
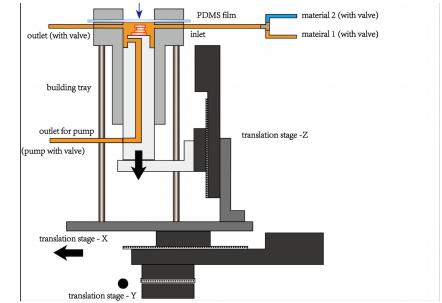
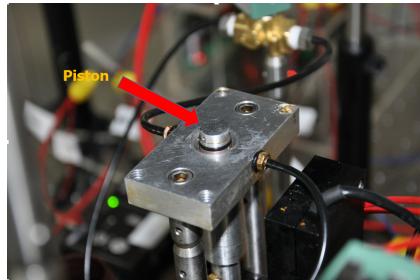
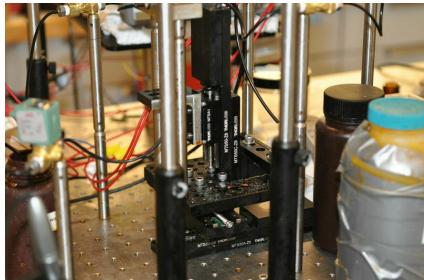


Figure 1: the illustration of the optical system

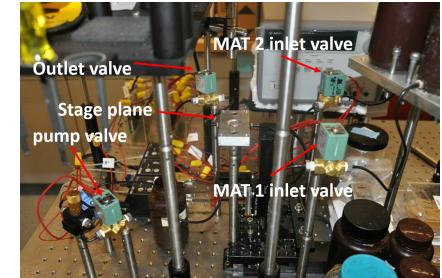
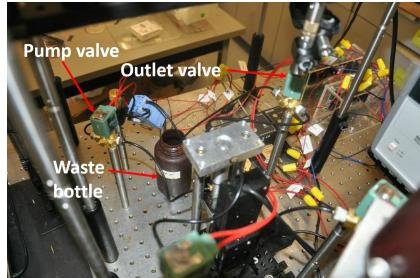
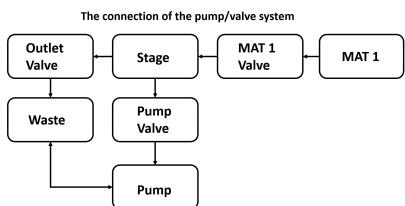
1.1.5 Motorized stage

Motorized stage consists of two parts. The first part is *stage plane* that can be moved in x,y direction. However, the stage position in x-y plane should be fixed under normal circumstances. The second part is the piston that can be moved vertically in z-axis. **Remember** the positive direction for piston movement in z-axis is downwards.



1.1.6 Fluids system

Fluids system is consist of four *valves* and several *tubes*. The four valves and its connection via tubes on both left and right sides are listed as below in the table 2:



1.1.7 Powersupply

Powersupply (Agilent E3633A) powers the *electrical device(UV light, valve)* in the system. **Check** operation manual for details⁴.

⁴http://www.trs-rentelco.com/Specs-Manuals/AT_E3633A_Manual.pdf

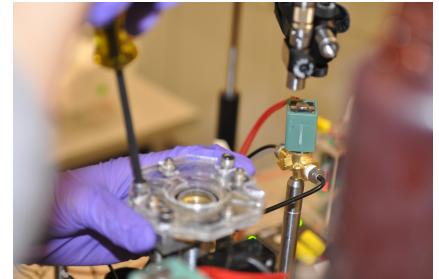
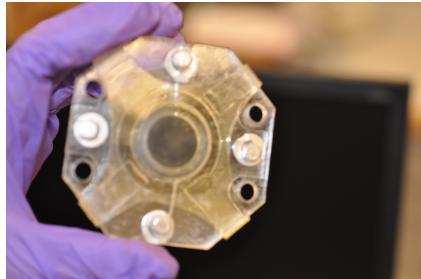
name	left side connection	right side connection
valve for material 1 inlet	chamber with prepolymer solution	material 1 inlet bottle
valve for material 2 inlet	chamber with prepolymer solution	material 2 inlet bottle
outlet valve	waste bottle	chamber with prepolymer solution
pump valve	pump which is connected to waste bottle	chamber with prepolymer solution

Table 2: The left/right side connection of the valves



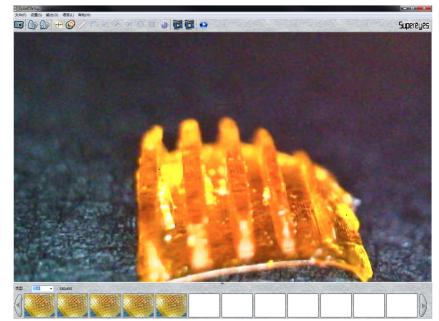
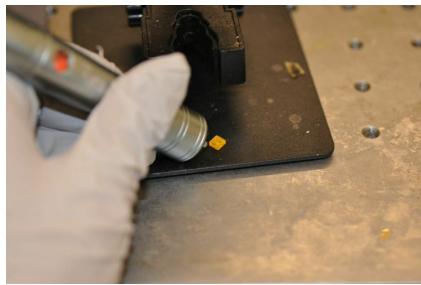
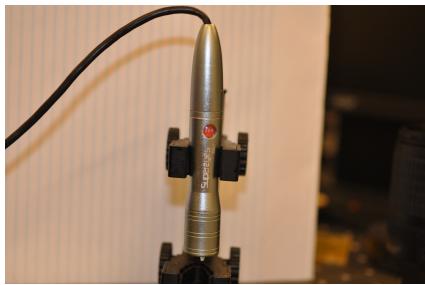
1.1.8 Printing chamber

Printing Chamber is enclosed by a customer-made cover , which is composed of two laminated parts fixed together by the screws. The top part is an octagonal acrylic board with a circular opening in the middle and several openings designed for screw-bonding at the periphery. The lower part is a piece of PDMS film used for creating an oxygen-free environment within the *chamber*. The cover is fixed onto the stage through screws in the corner.The *piston* can move vertically within the chamber to perform the printing.



1.1.9 Electronic Microscope

Supereye is a hand-held microscopic device. **Click** open the *Supereye* icon at the desktop, and the microscopic image of the printed sample can be easily observed from the computer screen *in details*. It could also be used to observe the precision of the projected image at 2.1 step 6.The definition of the image on display could be changed by **rotating** the knob at the top of the *supereye*. The scale of the microstruture could also be **measured** on the software interface.



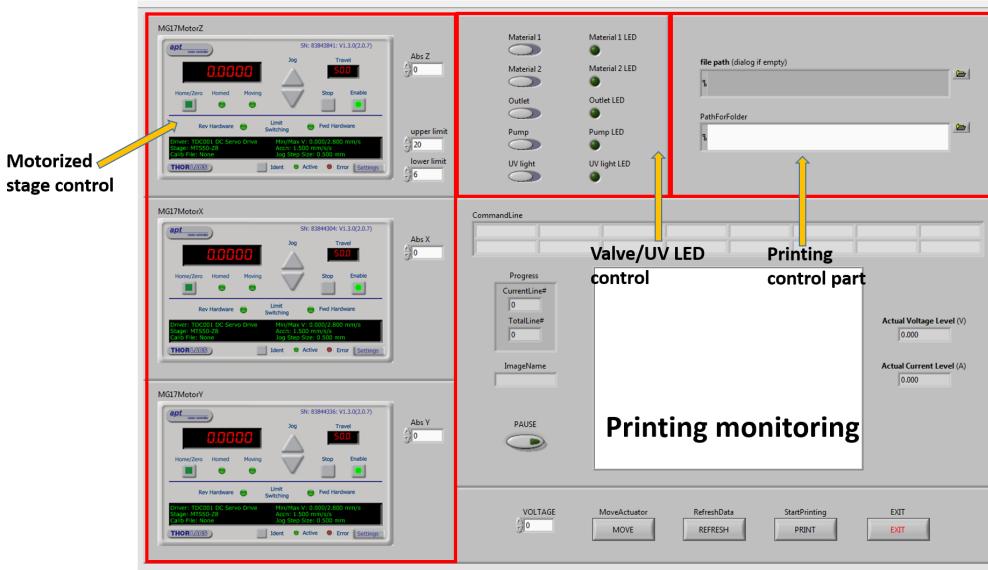


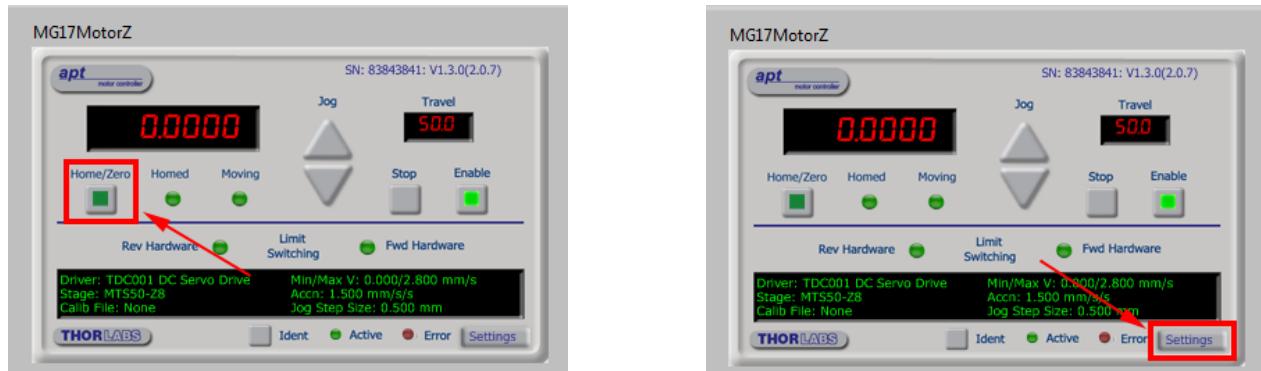
Figure 2: The illustration of the user interface in Labview

1.2 Software

1.2.1 User interface in Labview

There are **three parts** that need to be highlighted in the labview interface: *motorized stage control part*, *valve/UV LED control part* and *printing control part*

The three stage control parts from top to bottom individually adjust the stage movement in z,x,y axis. **Home Z** axis every time *Labview* is started while never home x,y axis unless there is an assembly need. **Type in** the values to change the stage position. The default parameter is recommended for the z-axis movement while you can **change it** according to your need by **clicking settings** at the lower-right corner.

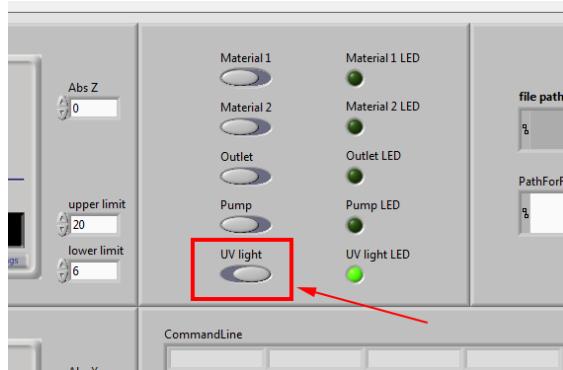


In the valve/UV LED interface, a **click** is all you need to open the valve and the UV LED.

Remember not to simultaneously open the *valve* and the *UV LED* because of the following reasons:

(1) Their working voltages are different(*UV LED* at 4.3V and *valve* at 9V). Higher working voltage can cause damage to *UV LED*.

(2) *UV LED* works at the printing step while the *valve* works at the cleaning and the material inlet steps. They never work simultaneously in one step in the operation procedure.



The printing control part is used to set the root path of printing script and image.

Remember to click refresh when you have finished your settings and double check the #total lines in the scripts.

Column 1	Column 2	Column 3	Column 4	Column 5
number	the target	the target	time	execution value

Table 3: the explanation of different columns in the script

Click print to execute the printing.

When a script has been executed, **click** stop at the top left corner and **run** the *Labview* again to begin another printing



1.2.2 Runsheet

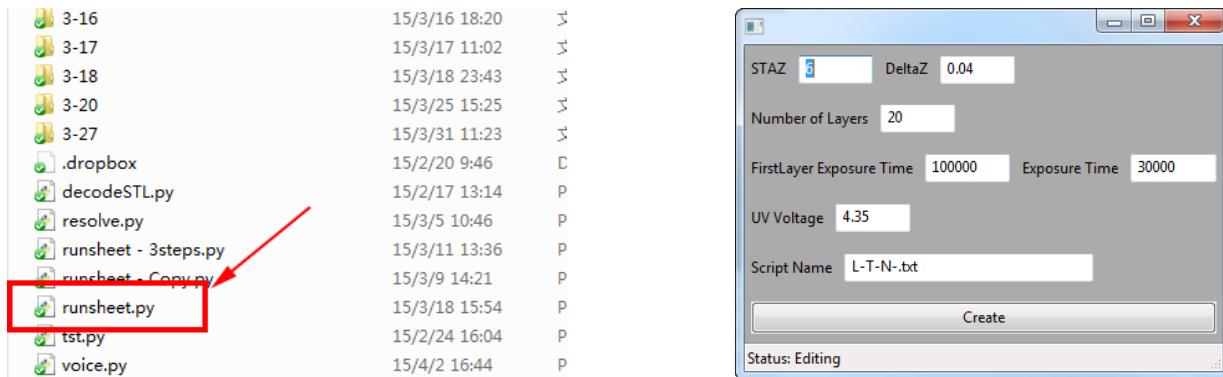
The tool to automatically generate the script used for 3D printing. **Type in** the parameters(layers,exposure time etc) and **click** create to produce the script under the same directory.

(1)2D extrusion structure:

Put the 2D cross-section to be printed and the script under the **same catalogue** and **choose** the correct path at the *labview* printing control part.

(2)Arbitrary 3D struture:

Slicing the 3D structures into layers of 2D cross-section using *CAD* and **name** them according to the corresponding layer. For example, if there are a hundred 2D pictures which correspond to the cross-sections of the 3D-structures, from the first cross-section at the bottom and the hundredth cross-section at the very top. Then **name** the 100 pictures from pic.1 to pic.100. **Put** the pictures and the script under the same directory. **Choose** the right path in the *Labview* printing control part.



1.2.3 Script introduction

The script is used to control the *PμSL* 3D printing process. Every line in the script stands for a certain operation of a certain device. For example in line 18(underlined with red line) in *Fig 2*, the combination of the second and third column means that the target device to operate on is the *UV LED*. Column 5 means the execution value is 0, which equals to turning the *UV LED* off. The Column 4 means the execution time, which indicates that the *UV LED* should be off for 1.5 seconds.

```

1      6      1      1500    1
2      6      2      1500    9.000000
3      4      0      1500    1
4      4      2      1500    1
5      3      1      6500    6.000000
6      4      0      2000    0
7      4      2      2000    0
8      6      2      1500    9.000000
9      4      0      1500    1
10     3      1      6500    7.040000
11     4      0      2000    0
12     4      2      500     1
13     3      1      6500    6.040000
14     4      2      2000    0
15     7      1      0       9      0       0       0
16     6      2      2500    4.350000
17     5      1      90000   1
18     5      1      1500    0
19     6      2      1500    9.000000

```

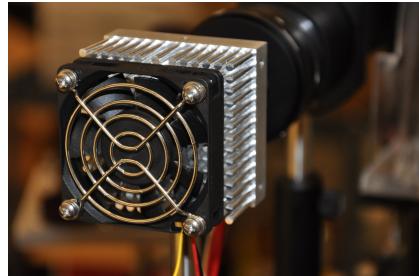
Figure 3: The script of $P\mu SL$ 3D printing

2 Operation Procedure

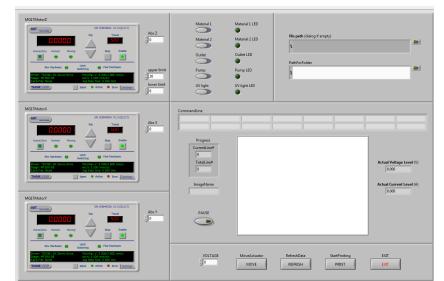
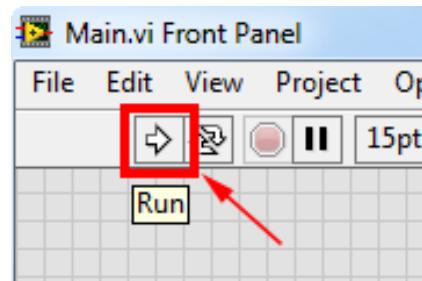
In this section, the normal operation procedure of the 3d-printer will be introduced. Just follow the steps. To your own safety, always wear gloves before doing anything and wash hands after experiments.

2.1 Printing preparation

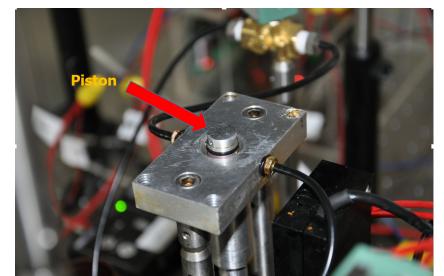
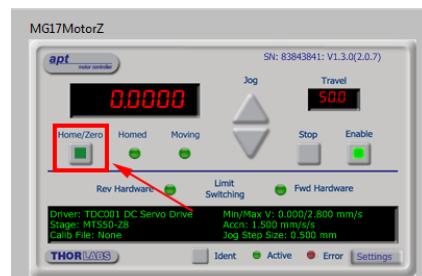
- Step 1 :** Turn on the *power strip* on the ground. make sure the *fan* behind the *UV Light* function well before turning on the *projector*, *light-source*, *computer* and *power source* in sequence.



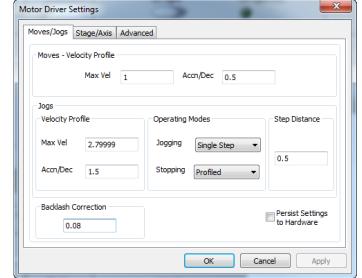
- Step 2 :** Open *Labview* at the desktop and click *main.vi*. After the interface pops out, click the *run* icon at the top left corner and wait for the pre-running self-check to be completed. When the initialization is done, you will see parameters in green and red appear at the left side of the interface.



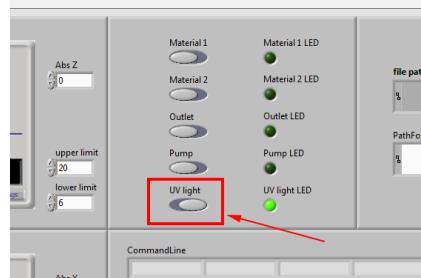
- Step 3 : Return** the *piston* to zero by clicking the home button. Wait until the z-axis position is reset to zero. (*Only the z axis!!never home x or y axis*)



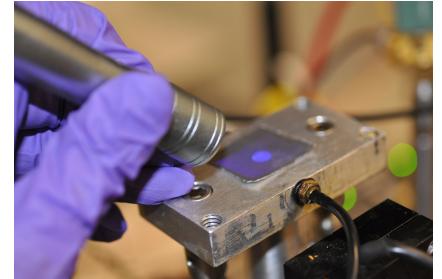
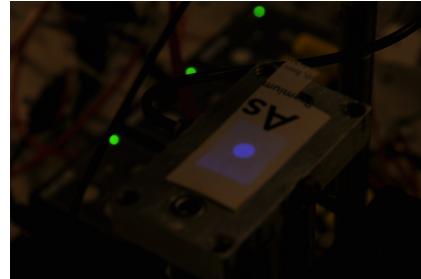
- **Step 4 :** Click setting icon and change the parameter of z-axis movement of the piston.(velocity, jogging distance,acceleration etc). See 1.2 for parameter details.



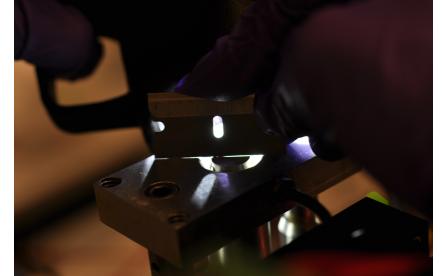
- **Step 5 :** Click the *UV Light* button to turn it on. Check the screen display of the power supply and make sure the voltage output is below 4.35V.



- **Step 6:**Lower the piston back to 7mm.Put a piece of paper on the motorized piston to check the precision of projected image. The trick is: White paper is recommended for direct observation while black paper is preferred under *Supereye* microscope. If the projected image is not clear, See Appendix 3.2.2 for solution.



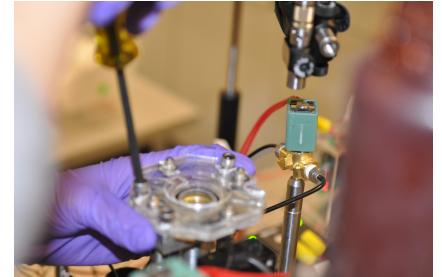
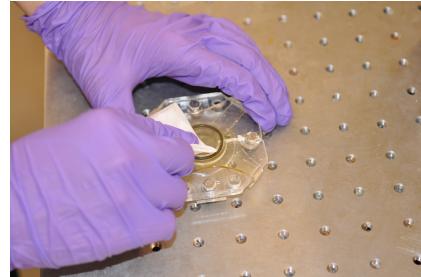
- **Step 7:**Remove the paper. Use a blade to find the initial Z for printing following the steps in Appendix 3.1



- **Step 8 :** Check all the valves. Click open each valve in the interface and feel it by hand to make sure magnetic valve is working. You will feel a slight trembling if the **magnetic valve** is popped open. If it doesn't work, see Appendix 3.2 for solution.



- **Step 9 :** Clean up the chamber and fix the chamber onto the stage through 3 screw-bonding corners.

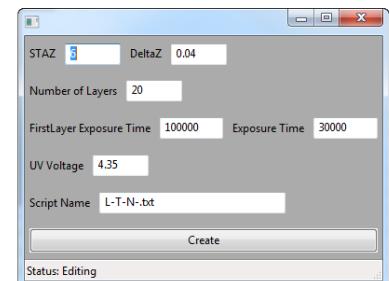
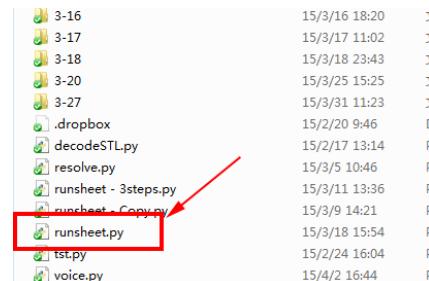


- **Step 10 :** Pour the pre-polymer solution(see 1.3 for the recipe) into the material inlet bottle and then put the cover with a hole on it.
Caution: Avoid light as much as possible

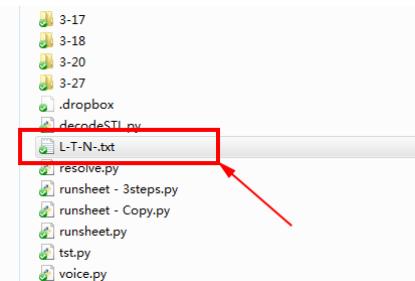


2.2 Printing

- **Step 1 :** Open 'runsheet.py' to create the scripts. Set the parameters according to your printing need and click to create the script files in the same folder.

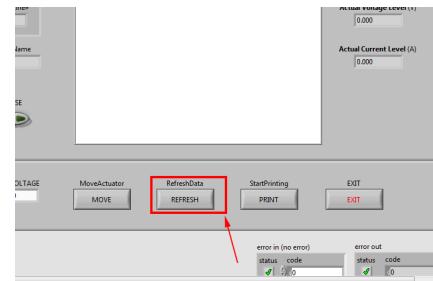
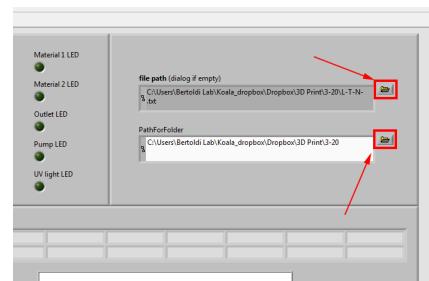


- **Step 2 :** Open the scripts with notepad and double check the parameter carefully. see appendix for the script introduction



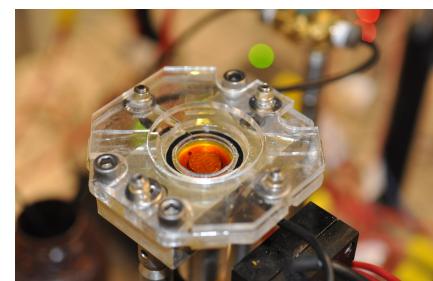
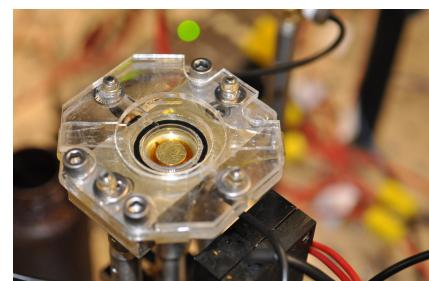
1	6	1	1500	1	
2	6	2	1500	9.000000	
3	4	0	1500	1	
4	2	0	1500	1	
5	3	1	6500	6.000000	
6	4	0	2000	0	
7	2	0	2000	0	
8	6	2	1500	9.000000	
9	4	0	1500	1	
10	3	1	1500	7.040000	
11	4	0	2000	0	
12	4	2	500	1	
13	3	1	1500	6.040000	
14	4	2	2000	0	
15	7	1	0	9	0
16	6	2	2000	4.350000	
17	5	1	90000	1	
18	5	1	1500	0	
19	6	2	1500	3.600000	

- **Step 3 :** Select the script file in the Labview programme as well as the image folder and then click refresh.



Now we are ready to fill the printing chamber with prepolymer solution!

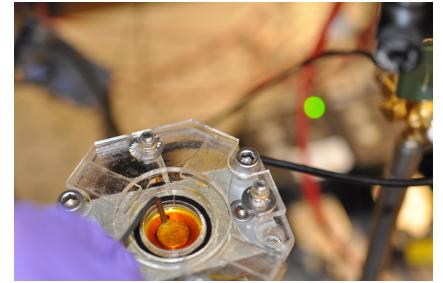
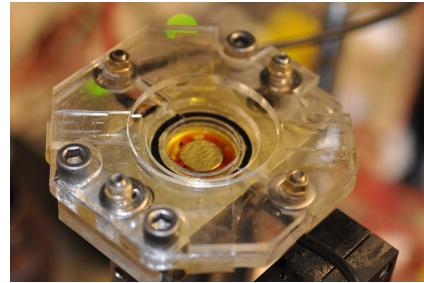
- **Step 4 :** Firstly click open the *inlet valve* and *pump*. Wait until there are no bubbles flow through the *chambers*. Secondly close the pump and lower the piston to 7mm. Wait about 10 seconds. Thirdly click close the *pump* to let the prepolymer solution flow in.



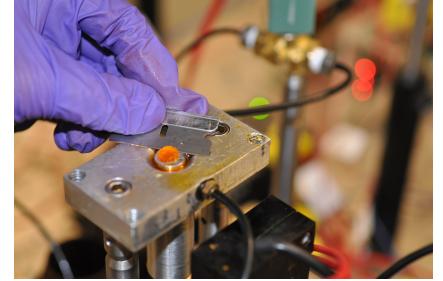
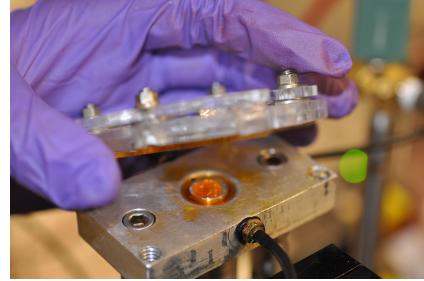
Number	Valve	1	2	3	4	5
1	Inlet valve	open	open	open	close	close
2	Outlet valve	close	close	open	open	close
3	pump	open	close	close	close	close
4	comment	Accelerate the material inlet	Material fulfilling	Drive off bubbles	Return the piston to initial Z	Finish material fulfilling

Table 4: Steps for material inlet procedure

- **Step 5 :** Click open the *outlet valve* and use a *tweezer* to **push away** the bubbles into the outlet hole. Then click close the *inlet valves* and **Return** the Z axis to initial Z. Wait about 10s. Finally Click close the *outlet valve*. Click to begin printing. Table 4 shows the valve status of material inlet procedure in Step 4 and 5

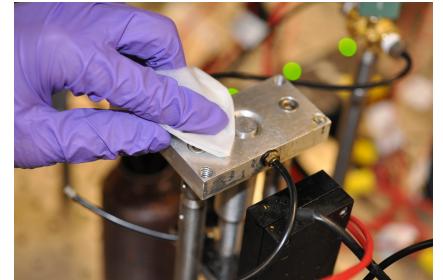


- **Step 6 :** Click print to start and have a cup of coffee. When the printing is done, lift the chamber off the stage and use razor blade carefully to **remove** the sample from the piston.

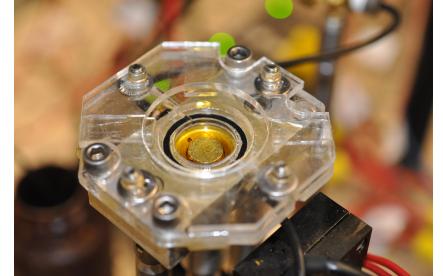
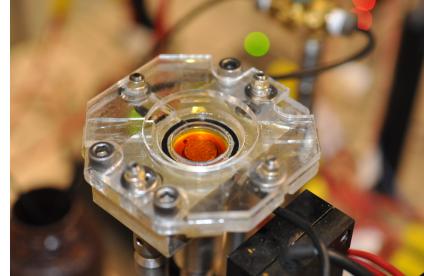


2.3 Cleaning

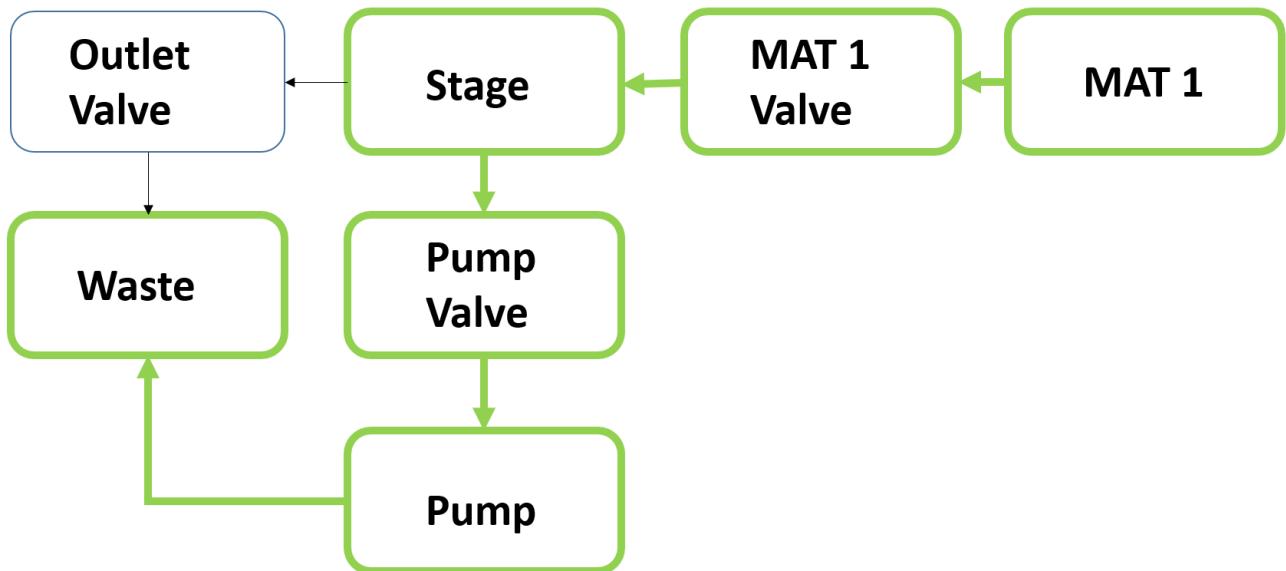
- **Step 1 :** Pour Isopropyl Alcohol into the *material inlet bottle* and **clean** the piston plane. Clean the chamber.



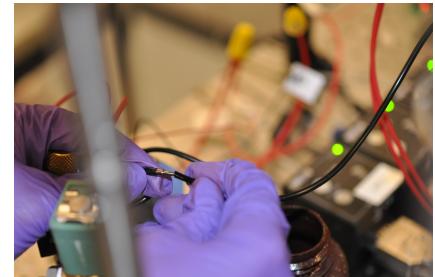
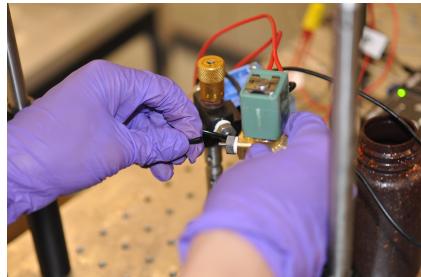
- **Step 2:** Fix the *Chamber* back again onto the *stage plane*. Open *inlet valve*, then *pump*. The liquid within the chamber will gradually become lighter in color. Close the *inlet valve* and *pump* when the liquid within the chamber has no color.



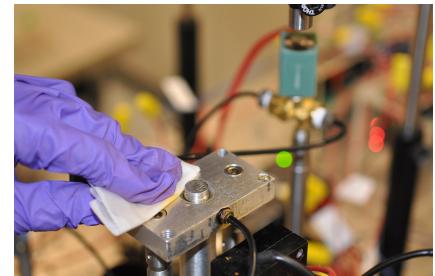
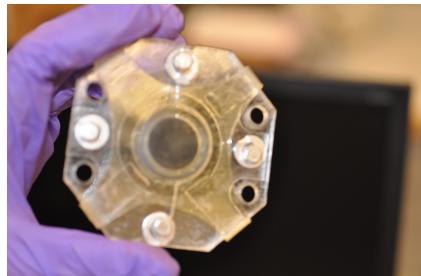
The initial connection of the pump/valve system



- Step 3: Reconnect the *pump* to the *outlet valve* before **opening inlet, outlet valve and pump**. Wait until all Isopropyl Alcohol is pumped out.



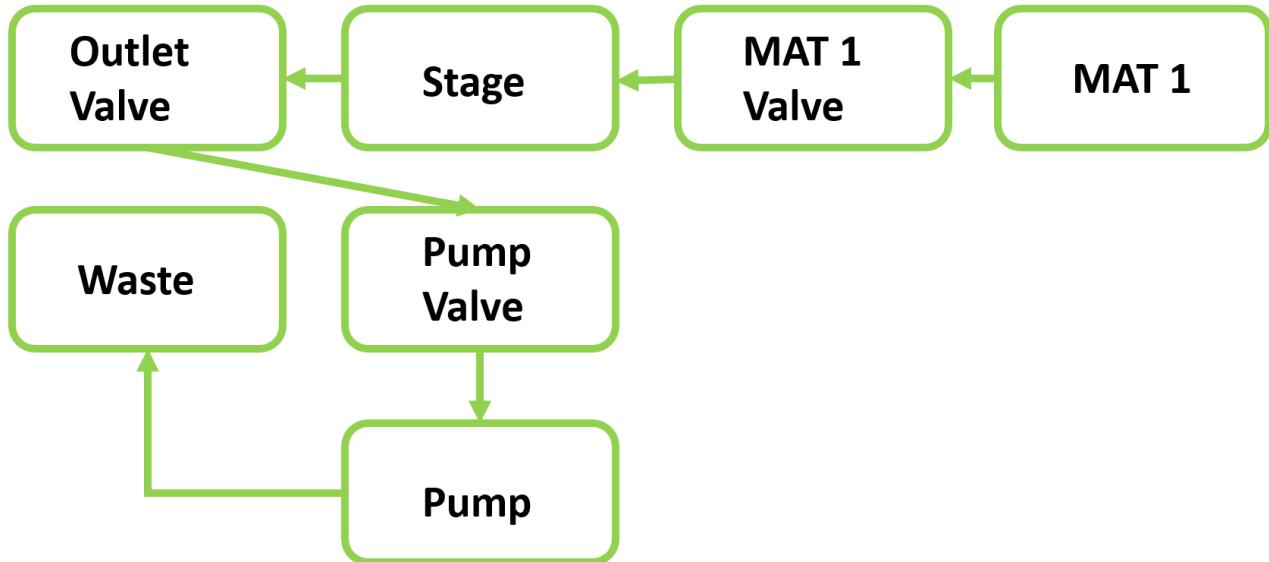
- Step 4: Reinstate the connection in step 2 and **put** the tubes of *outlet valve, pump* into the waste bottle. Remove the chamber and **clean it up**. **Adjust** the *piston* to **3mm** and in order to completely clean it. **Return** the piston back to **7mm**.



- Step 5: Close the projector, power-supply, computer before **turning off** the powerstrip. **Pour** the residue in the *waste bottle* into the *waste tank*



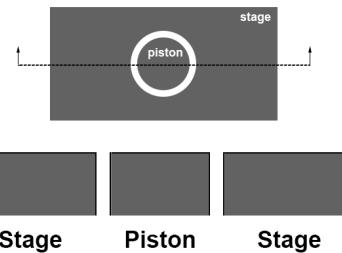
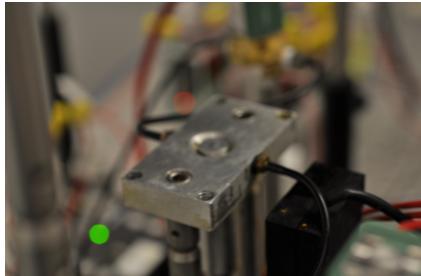
The connection of the pump/valve system to clean outlet pump



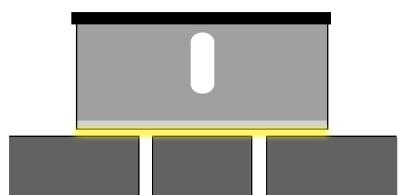
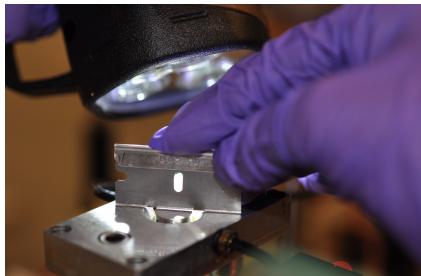
A Appendix

A.1 Razor blade method to determine the printing plane(initial Z)

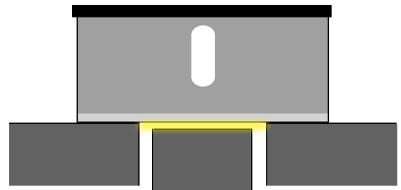
- 1: Press the *blade edge* to the stage plane which is at 7mm in z direction. **Elevate** the piston to 6mm(the default printing position).



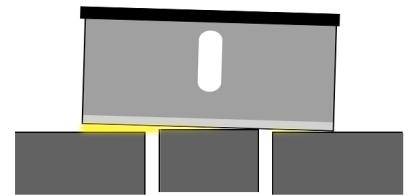
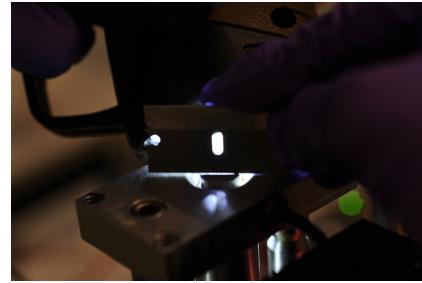
- 2:Shine the interface between the blade and the stage plane from behind using a *torch* and **observe** directly from the front.



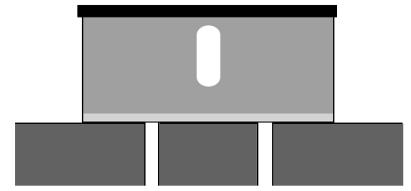
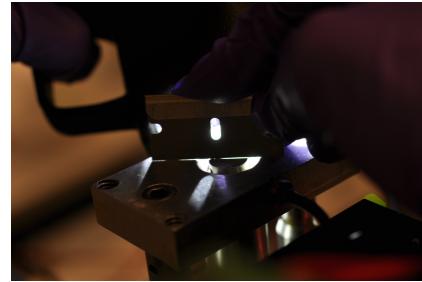
- If there is continuous light leaking from *piston-blade interface* while there is no light leaking from *stage-blade interface*, it indicates that the piston is **too low** in Z position(*the number is too big*). **Lower** the piston to 7mm and **elevate** it back again to 5.9mm.



- If there is no light leaking from *piston-blade interface* while you observe continuous light at *stage-blade interface*, it indicates that the piston is **too high** in Z position (*the number is too small*). **Lower** the piston to 7mm and elevate it back again to 6.1mm.



- Repeat** the lower/elevate cycle until no light leakage is observed from both *stage-blade* and *piston-blade* interface. **Set** the current Z positon as the *initial Z*.



A.2 Maintainece

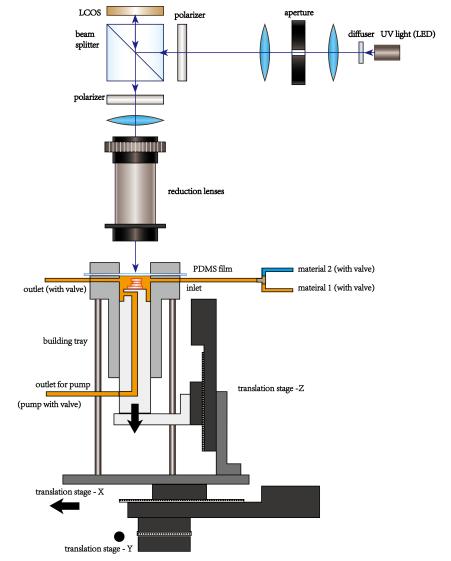
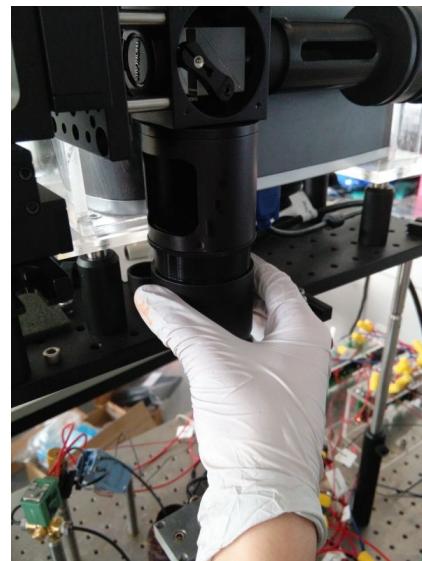
A.2.1 Elevate the voltage supply to open the valve

If the valve doesn't work when the voltage supply is 9V, **Try** elevate the voltage manually to 10-12V. **Feel** it by hand whether the magnetic valve is popped open under higher voltage. **Never** elevate the voltage beyond 12V. It will cause permanent damage to the valve.



A.2.2 Adjust the focal length of the projected image

Change the focal length by rotating the focusing ring of the *reduction lens* until the precision of the projected image reaches its best.



name	content	company	catalog number	comments
Poly(ethylene glycol) diacrylate(Mw 575)	98%	Sigma-Aldrich	437442	Hydrogel backbone
phenylbis(2,4,6-trimethylbenzoyl) phosphine oxide	2%	Sigma-Aldrich	511447	photo-initiator(PI)
Sudan I	0.1%	Sigma-Aldrich	103624	photo-absorber

Table 5: PEGDA SYSTEM RECIPE

name	content	company	catalog number	comments
Poly(ethylene glycol) diacrylate(Mw 575)	33%	Sigma-Aldrich	437442	Hydrogel backbone
Poly(ethylene glycol)(Mw 200)	66%	Sigma-Aldrich	1546401	Pore generator
phenylbis(2,4,6-trimethylbenzoyl) phosphine oxide	0.67%	Sigma-Aldrich	511447	photo-initiator(PI)
Sudan I	0.1%	Sigma-Aldrich	103624	photo-absorber

Table 6: PEG/PEGDA SYSTEM RECIPE

A.3 Materials

A.3.1 PEGDA SYSTEM

Features:

- (1)The most mature system for hydrogel printing.
- (2)The printed hydrogel is hardest and most brittle among three material systems listed.
- (3)It exhibits almost no elasticity.
- (4)Its volume swelling ratio in water is 120%.

A.3.2 PEG/PEGDA SYSTEM

Features:

- (1):This system is basically employed in the printing the backbone of bio-materials due to the bio-compatibility and hydro-philicity of PEG.(Peptides or cells can be grafted onto PEG, thus fabricating a soft biological scaffold with unlimited potential.)
- (2)The PEG/PEGDA system hydrogel is softer than PEGDA system but much harder than NIPAM/Sodium acrylate/PEGDA system.
- (3)The PEG/PEGDA system hydrogel has around 10-20% elongation before rupture.
- (4) It exhibits around 160% volume expansion ratio in the water.
- (5) It can be bonded very well with PEGDA hydrogels.

A.3.3 NIPAM/Sodium Acrylate/PEGDA Hydrogel SYSTEM

Features:

- (1)This system features the extremely high swelling ratio in water.In our current recipe, PEGDA:MONOMERS(NIPAM:SODIUM ACRYLATE) is 1:5 by weight and 330% volume expansion can be achieved in water.
- (2)By tuning the weight ratio of PEGDA to monomers, different volume expansion ranging from 200% to 800% can be realized.The correlation between the volume expansion and the PEGDA/MONOMER weight ratio is illustrated in the picture below.
- (3)Hydrogels in this system is the softest among the three material systems listed. (4)Hydrogels in this system enjoys 30-40% elongation before rupture. (5)Hydrogels in this system cannot be bonded very well with the PEGDA hydrogels.

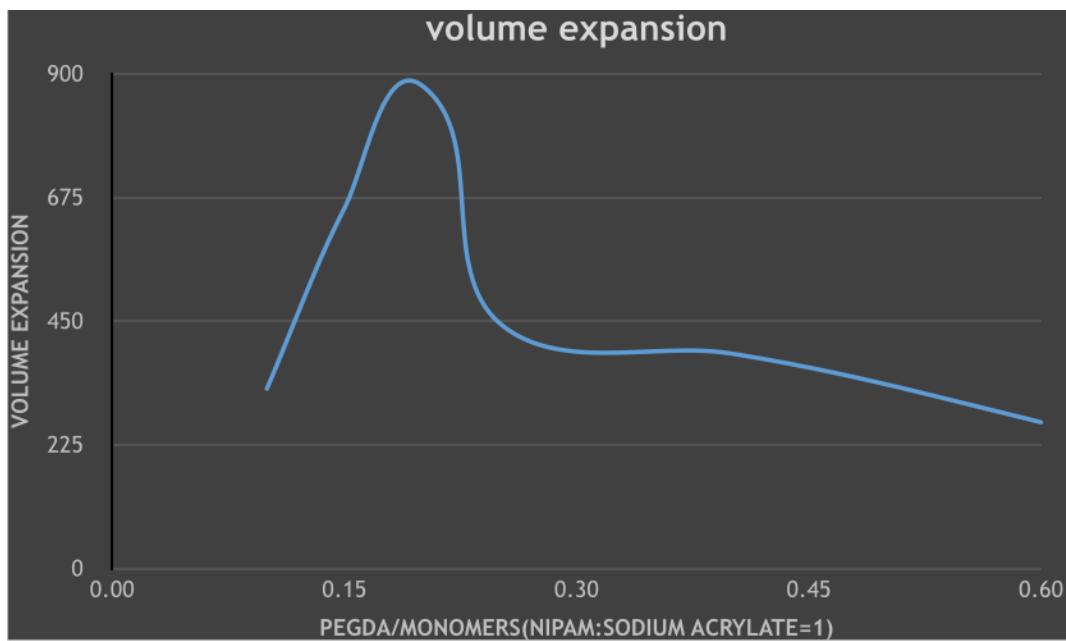


Figure 4: The volume expansion ratio of the hydrogels with different proportion of PEGDA

name	content	company	catalog number	comments
Poly(ethylene glycol) diacrylate(Mw 575)	7.7%	Sigma-Aldrich	437442	Hydrogel backbone
Sodium acrylate	25.7%	Sigma-Aldrich	408220	To increase swelling ratio
N-Isopropylacrylamide	5.1%	Sigma-Aldrich	415324	To increase the toughness.
phenylbis(2,4,6-trimethylbenzoyl) phosphine oxide	0.154%	Sigma-Aldrich	511447	photo-initiator(PI)
Isopropyl alcohol	9.9%	Sigma-Aldrich	W292907	To dissolve PI
Sudan I	0.1%	Sigma-Aldrich	103624	photo-absorber

Table 7: Nipam/Sodium acrylate/PEGDA SYSTEM RECIPE

A.4 Hydrogels preparation: Pre-printing test of the material

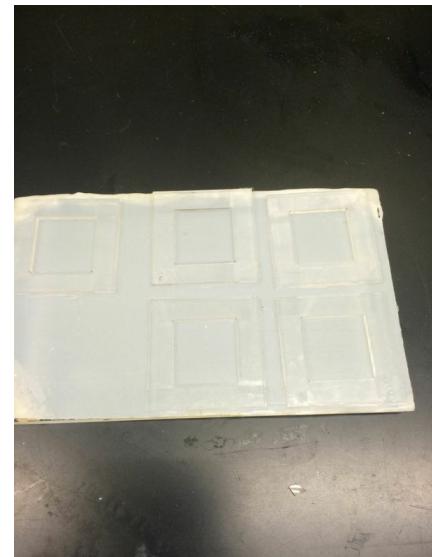
Swellable Sodium Acrylate/NIPAM/PEGDA system

Generally in a hydrogel system, its free-swelling ratio in the water is **positively** correlated with the ionic concentration. *In a material point of view*, using monomers with ionic property(Such as Sodium Acrylate or acrylic acid) can greatly increase the free-swelling ratio of the hydrogels in water. It is largely because that the ions can lower the chemical-potential within the hydrogel system thus creating the chemical gradient for the surrounding water to flow in. If you want to test the swelling performance of the hydrogels before 3d-printing, following the steps below:

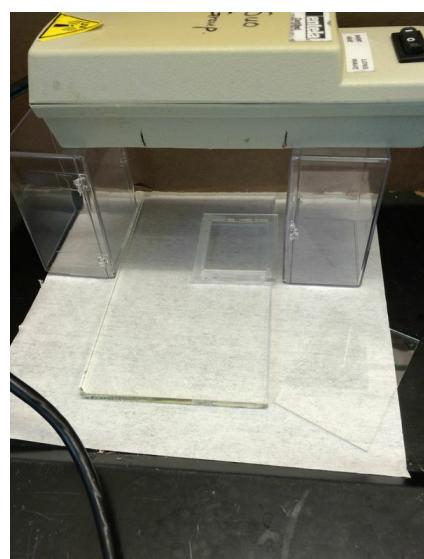
- **Solution preparation:** Sodium acrylate:NIPAM:DI water=1:1:5 by weight solution was **prepared** after 20-min vigorous stirring. Stir the PEGDA:photo-initiator=49:1 mixture in a light-proof brown bottle for 2-3h. **Make sure** there are no visible green particles interspersed in the PEGDA:PI mixture.



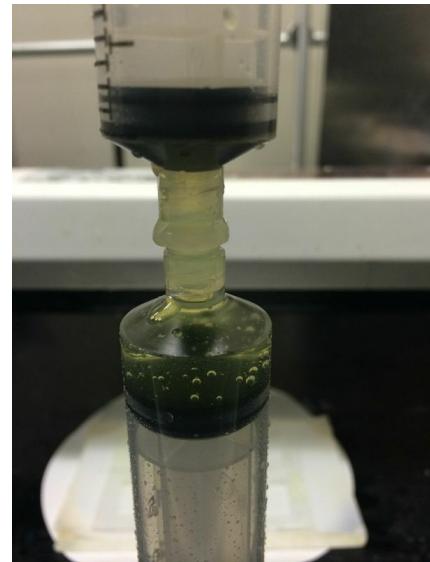
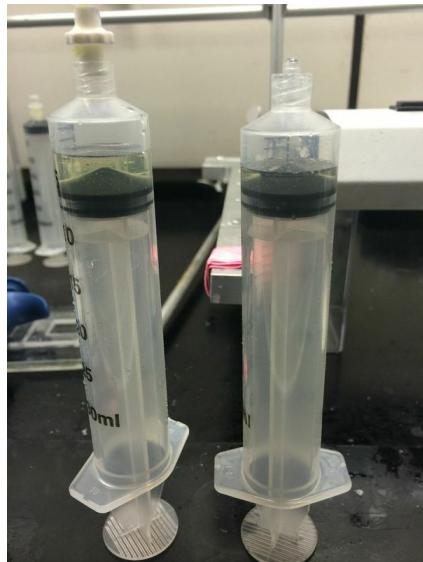
- **Mold preparation:** Stick the *plastic mold* onto the *teflone plate* using *3M-Scotch*.



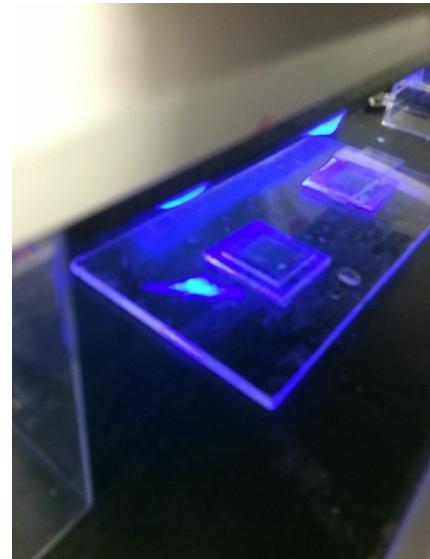
- **UV-LAMP preparation:** Hang the UV-Lamp on two vertically placed Acrylic box. Put the Teflone plate with *plastic mold* on it right under the *UV-LAMP*.



- **Syringe blending:** Two *Luer-lok syringes* were used in this step together with a *connector* to ensure the oxygen-free and homogeneous blending of the pre-polymer solution. Draw certain amount of Sodium acrylate/NIPAM solution into one *syringe* and PEGDA/PI mixture into another.⁵ Carefully **push** the air out of both *syringes* and **use** *connectors* to vertically bond them. Then begin **mixing**.



- **UV-curing:** Push the mixed solution into one syringe and Quick **transfer** it into the mold. **Cover** the *mold* with *micro-slides*. Carefully **Set up** plastic boards around the UV-Lamp to prevent UV-light leakage. **Shine** the pre-polymer solution in the *tex-titmold* **using** 365nm wavelength⁶.



- **Hydrogel swelling test:** Turn off the *UV-LAMP* and Remove the cured sample from the *mold* using a **razer-blade**. **measure** the initial weight of the sample on the *balance* and **put** it directly into a *beaker* with water.⁷ After 12 h, **Take** the sample out and **wipe** the water on the surface. **Measure** the weight and volume of the hydrogels in swollen state individually using a *balance* and a *vernier scale*.



⁵the amount of two should be calculated according to the PEGDA/monomer(NIPAM:sodium acrylate ratio) you need

⁶365nm is the peak adsorption wavelength of the PI in our system

⁷the initial volume of the sample is determined by the mold you use

- **Cleaning:** Wash the *plastic mold* with acetone and scratch off the scotch residue using a blade. Then wash the *mold* again using water. Teflone plate should also be wahsed with water to wipe off the residue on its surface. If you want to test the bonding of two hydrogels with different recipes, you should prepare the *solution A and B, mold and UV-LAMP* as stated before. However in the UV-curing section, **Do not use a slide to cover the mold.** Use a pipete to add a layer of solution A and shine immediately with *UV-Lamp* to **cure** it. After **curing** several layers of solution A hydrogels, **repeat** the previous steps and **cure** another few layers of solution B hydrogels. **Remove** the sample from the *mold* carefully to see if they can be bonded together.

