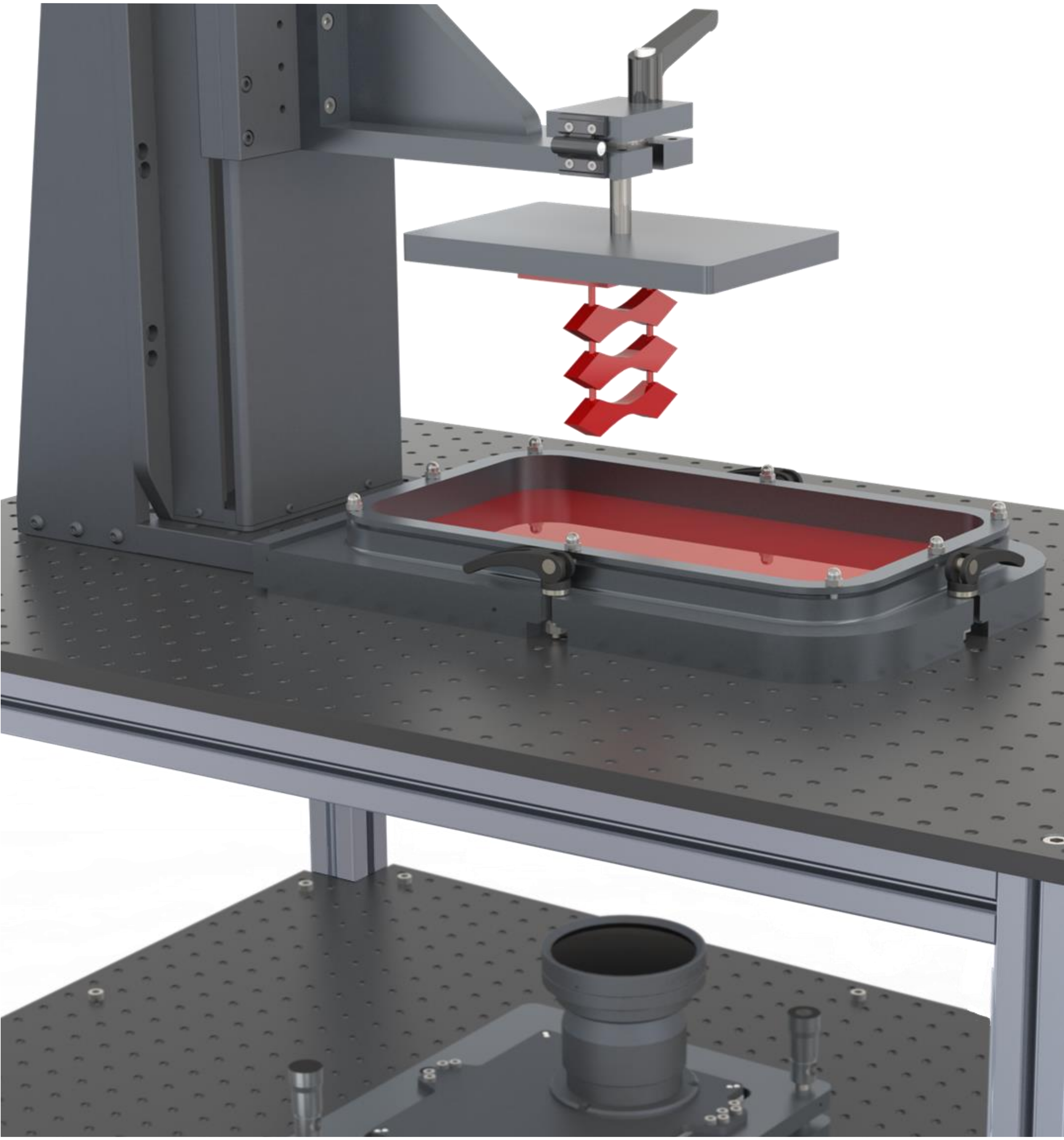
Technical Guide of a High-Resolution Vat-Photopolymerization setup



By Macarena Mendez Ribo, June 2020

Preface

Vat photopolymerization (VP) is a game changer technology capable of fabricating high-resolution, intricated geometries. The accuracy and repeatability achieved with VP is unmatched by any other additive manufacturing strategy.

Due to its popularity, there is a myriad of VP units on the market ranging from \$200 - \$15,000 for desktop machines, and \$15,000 to \$500,000 for industrial machines. The common denominator among these machines is that they fall under proprietary technologies, meaning that at higher or lower level they are protected by patents or copyrights. Although profitable for businesses, locking this intellectual property limits researchers to unravel the physics, optimization and all the possibilities that this technology has to offer.

This guide provides all the necessary documentation to machine, purchase and build a high-resolution vat photopolymerization machine with mask projection (MP). By opening our technology, the DTU AM laboratory team foresees to further develop VP in collaboration with worldwide researchers.

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1 Basic information

DEFINITION

Vat phoptopolymerization (VP) is an additive manufacturing (AM) technology which uses a light source to crosslink a light-sensitive material (i.e. photopolymer or resin)[1]. The working principle of VP is represented in Figure 1.

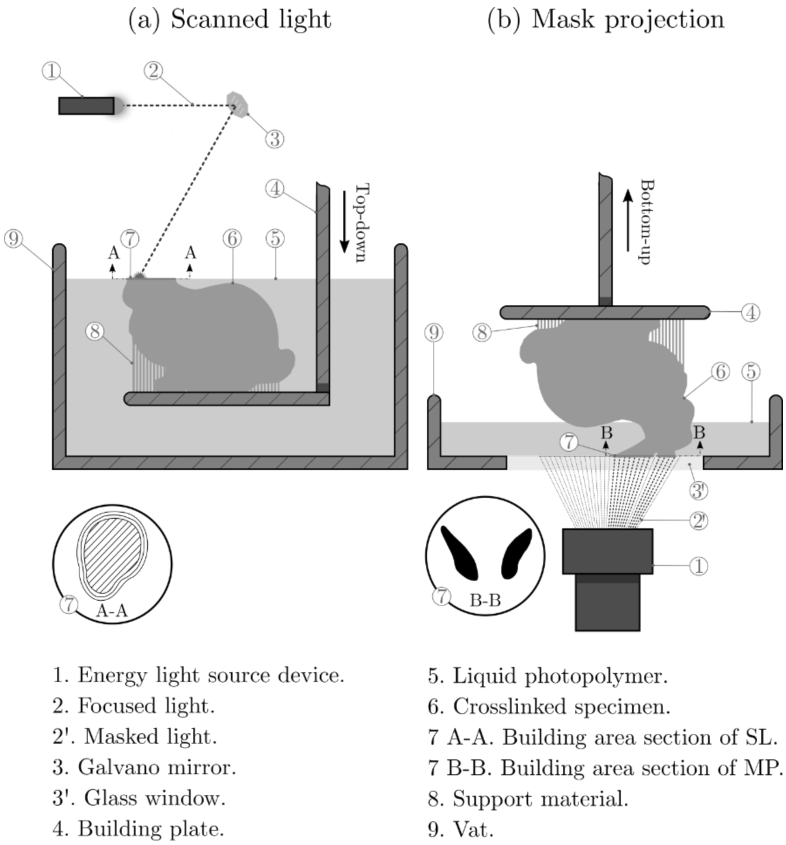


Figure 1 Two alternative approaches of VP AM, (a) scanned light (SL) and (b) mask projection (MP), the latter is the technology used for the machine described in this document.

The unit described called DLP V2 (or Giant Unit to Manufacture Big Objects uses a Digital Light Processing (DLP) projector, thus falling in the category of mask projection (MP). MP crosslinks each layer by sequentially casting the cross section of the sliced geometry over the building area. Advantages of this VP alternative are the speed, high resolution (defined by the pixel size) and layer control due to the bottom-up machine configuration.

SOFTWARE

As an open source machine, the operating software is also open source. Developed by Andrea Luongo, all the documentation can be found at his GitHub repository.

This software allows the user to:

- Configure the building area with one or multiple geometries.
- Slice geometry with a minimum layer thickness of 0.625 nm.
- Adjust machine parameters such as speed, acceleration, greyscale values[2], and more.
- Control building parameters such as exposure time, irradiance, layer thickness.
- Advance features options with incremental amplitude, exposure, and greyscale correction.

MATERIALS

The machine described in this document is a powerful research tool that allows any material that can be crosslinked at a wavelength of 380 nm. With the right upgrades and add-ons, it is possible to mix resins with metal or ceramic powders.

The user might need several iteration before obtaining optimal parameters if the material is unknown. It is recommended to tune the material using a checkerboard pattern and the advance incremental software features.

From the beginning the DTU AM lab team has been collecting data from a smaller DLP unit but with many similarities. This logbook collects parameters for different materials, and observations helpful for other researchers.

Post-processing of fabricated parts requires a solvent such as isopropyl alcohol (IPA) or tripropylene glycol monomethyl ether (TPM) to wash the liquid photopolymer away before drying and curing, respectively.

SAFETY

The toxic nature of most photopolymers in its liquid form, dealing with highly volatile solvents and being in contact with ultraviolet (UV) light calls for several safety precautions:

- Use nitrile gloves when handling any un-cured photopolymer work or touching any contaminated area. Avoid using nitrile gloves around clean areas to avoid contamination.
- In case of contamination, thoroughly wash the skin with soap and water.
- Use a laboratory coat to prevent splashes over skin or clothes.
- Place machine in a ventilated area or use a filtered mask.
- Clean the fabricated parts in a fume hood.
- Store volatiles in a safe environment.
- De-contaminate and clean possible splashes and work-area after use.
- UV protective googles are recommended if the user is going to work calibrating the projector or looking directly into the UV.

2 Machine components and specifications

The DLP machine is composed of three main building blocks (Figure 2), (1) the *projector*, this component joins the other blocks together and houses the projector, backbone of this technology; (2) the *drum vat*, which contains the liquid photopolymer; and (3) the *stage,* in control of the vertical motion and hosting the workpiece . Each of these blocks is accountable for the final quality of the manufactured part. The specifications and purpose of these parts are explained in this section.

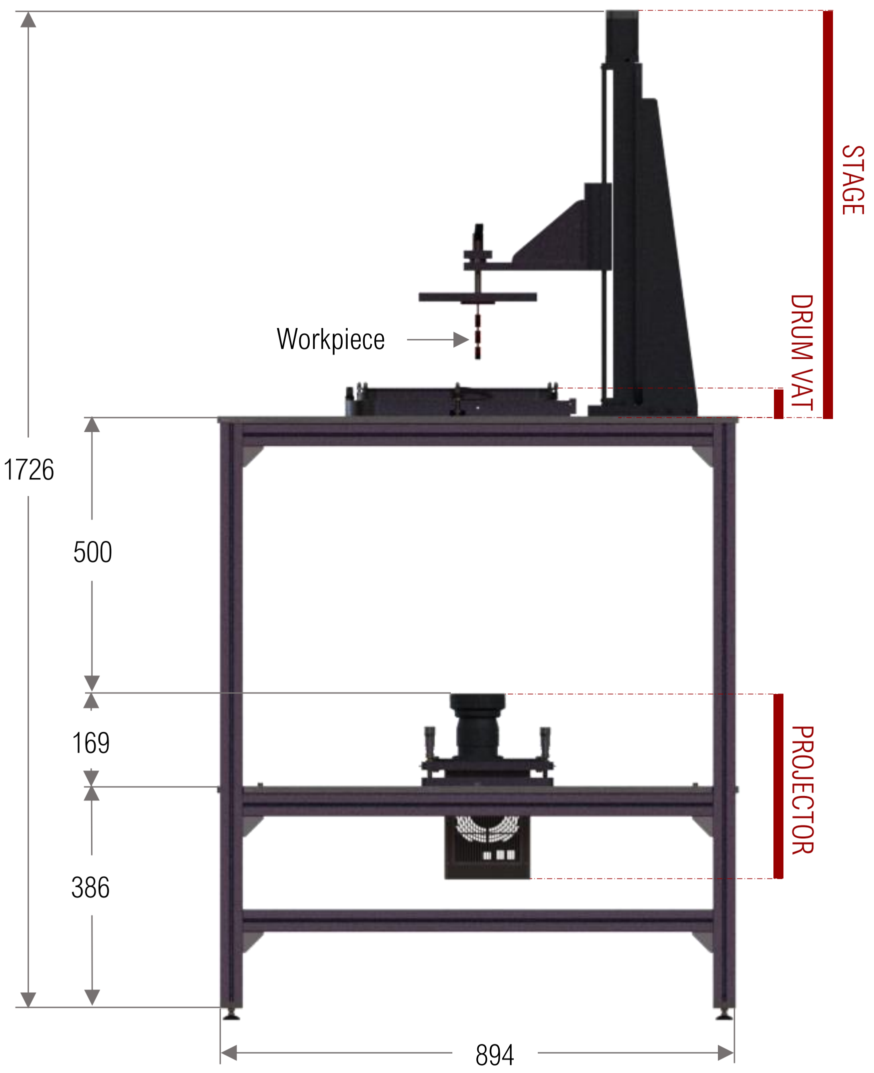


Figure 2 Overall dimensions and building blocks of the DLP machine DLP V2. Note that these are approximate measurements, which will vary depending on the table height or the projector lens. The 500 mm distance correspond to the nominal working distance with the LRS+4KA 14x lens. All units are in mm.

PROJECTOR

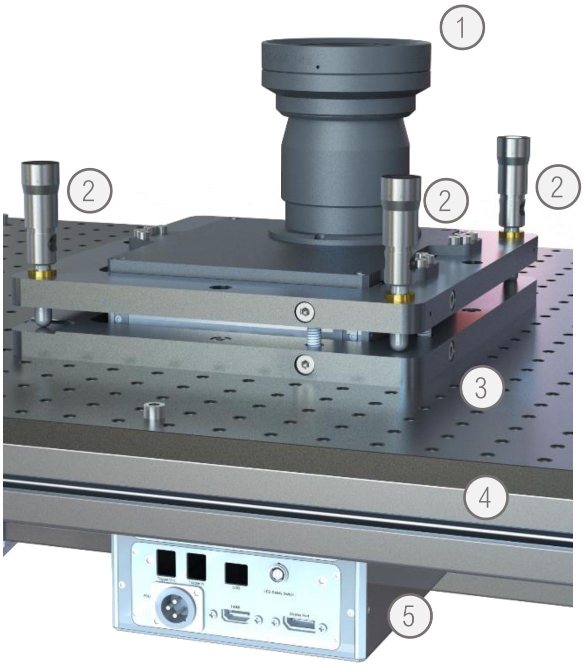


Figure 3 Parts of the DLP projector. (1) Lens, (2) micrometers, (3) kinematic mount, (4) breadboard, (5) projector.

The device used to project each layer is a DLP projector from Visitech Engineering. The model is a Light Engine LUXBEAM LRS-4KA-405P/N 7000290-380, equipped with a projection lens LRS-4KA LRS 14x P/N 6502850 (Figure 3). A DLP projector is equipped with a micro-electro-mechanical component known as digital micromirror device, developed by Texas Instruments[3]. This projector is also equipped with a controller that avoids re-sampling errors using the exact native resolution of the DMD, this is referred as Full Pixel Sequence Control (FPSC). As seen in Figure 2, the projector is located at its working distance, 500 mm below the top of the glass installed in the vat (as we will see in the VAT section), which is where the focus plane is located. The projector is installed on a kinematic mount. The purpose of this assembly is to finely align parallel the vat glass with the DMD chipset. The mount is adjusted using the Kelvin kinematic coupling with three micrometers with a ball end, one of them is resting on a flat plane, another on a vee-shaped groove and the last one on a trihedral socket.

Specifications

Projector	LUXBEAM LRS-4KA-405P/N 7000290-380
Power supply/output/consumption	12 V DC / 4.5 W / 200 W
Size w/o lens	190 x 150 x 228 mm^3 (4 kg)
DMD Type	DLP660TE (2716 x 1528 Pixels) / 5.4-Micron micromirror pitch
Resolution	8,3 million addressable pixels (UHD-4k images with optical actuator)
LED	380 nm
Lens	LRS-4KA LRS 14x P/N 6502850
Native pixel pitch in image	75 µm
Feature size in FPSC / XPR™ mode	37.5 µm
Build size	204 x 115 mm^2
Working distance	500 mm

DRUM VAT

Figure 4 Drum vat used in DLP V2. The bracket shape allows an easy FEP film change and the drum mechanism ensures an even stretch. The offset glass helps the flow recoating for each layer and an easy layer peel. (1) Glass plate, (2) bracket, (3) top and bottom bracket plates, (4) drum frame and (5) cam handles.

The vat (or resin tank), as the name of this technology indicates, is the backbone of vat photopolymerization. It contains the liquid photopolymer, and it is the nexus between the projected light and the building plate, thus allowing the workpiece fabrication. There are many different shapes a vat can take, from a simple shallow container with a PDMS bottom (seen in the Peopoly Moai[4] or Form 1 and 2[5]), to the vat used in the DLP V2 with a drum mechanism. Both have the same challenge, prevent the workpiece from attaching to the bottom of the vat. One of the challenges of the bottom-up configuration, is that as a layer is being cured, it attaches to the building plate and the glass. To overcome the adhesive forces from the bottom of the vat, we use a FEP film as release layer due to its anti-stick and low frictional properties. It also adds flexibility to gently self-peel the parts from the film[6,7]. The drum frame evenly stretches the film, making the film change task easier and quicker (Figure 5).

Figure 5 FEP film placement on the drum vat. An O-ring located on the base of the top bracket frame and the three cam handles keep the film in place under the drum vat stretch.

STAGE

Figure 6 Stage, which encompasses three parts, (1) building plate, (2) linear slide, and (3) servo motor.

The stage (Figure 6) is the main moving part of the whole system. During fabrication, the servo motor precisely locates the building plate above the FEP film leaving a gap equal to the desired layer thickness. After a layer is cured, the building plate is lifted enough so the liquid resin recoats the empty area left after the previous layer. Then, the building plate is relocated over the FEP film leaving again the layer thickness gap (Figure 7). These motions require precision and accuracy to achieve repeatable, high resolution parts.

The building plate is attached to a ball joint which is fixed by a hatch-lock. This assembly allows a manual but precise parallel alignment between the film and the building plate.

The linear slide NLS8 is a heavy-duty precision linear stage customized with a hybrid motor Clearpath with in integrated servo system to precisely control position. The combination of the stage and the motor allow the machine a resolution of 0.625 μm and an accuracy of ±2 μm. Higher accuracy could be achieved if the machine is placed in a temperature and atmosphere-controlled environment, on an isolated optical table.

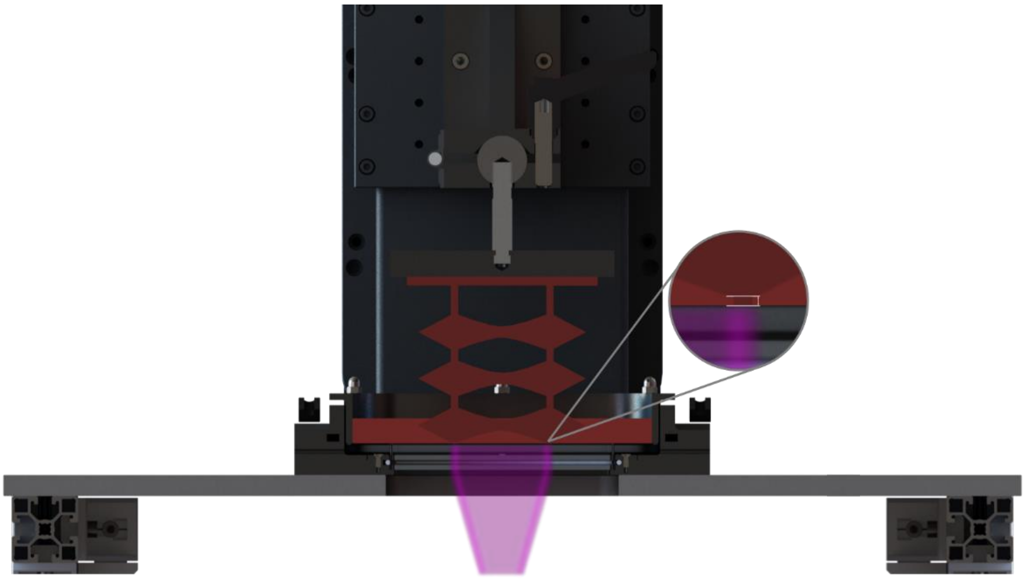


Figure 7 Cross section of the machine during the fabrication process. After a layer has been fabricated, the building plate lifts, the resin recoats the empty area left by the recently solidified layer and the building plate is relocated over the film, ready to cure the next layer.

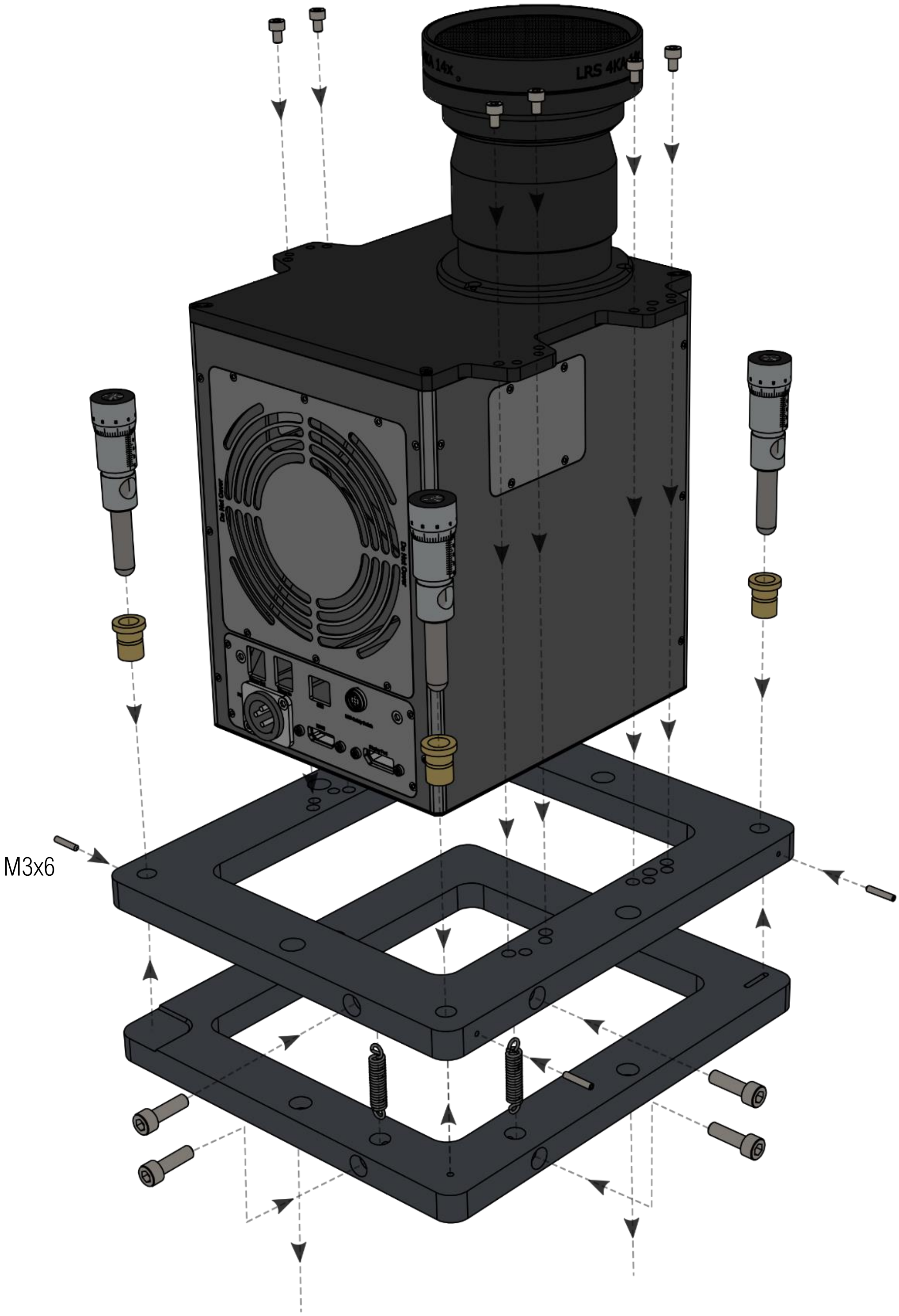
Specifications

Linear slide	Newmark NLS8-400-102
Travel range	400 mm
Dimension/weight	592 x 178 x 72 mm^3 / 12 kg
Load	36.3 kg
Limit/home switches	Optical switches, normally closed. Hard stop possibility with Clearpath
Lead Screw Pitch	4 mm
Operating Temperature	0°C to 50°C
Servo motor	Clearpath CPM-SCSK-2310S-EQNA
Power supply / Peak power	75VDC / 100W
Motor size	NEMA 23 / 1/4" (6.35 mm) shaft diameter (0.6 kg)
Positioning resolution	6400 cts/rev (i.e. 0.625 μm layer thickness)
Achievable resolution	0.057°
Repeatability	0.03°
Peak torque (@75 VDC)	1.6 N-m
Maximum radial Load	111.2 N
Maximum thrust Load	22.2 N
Cont. (RMS) torque	0.3 N-m
Maximum speed	4000 RPM*
Maximum acceleration	TBA*

*Speed and acceleration can be modified with our software, the optimal values for the whole system are currently investigation.

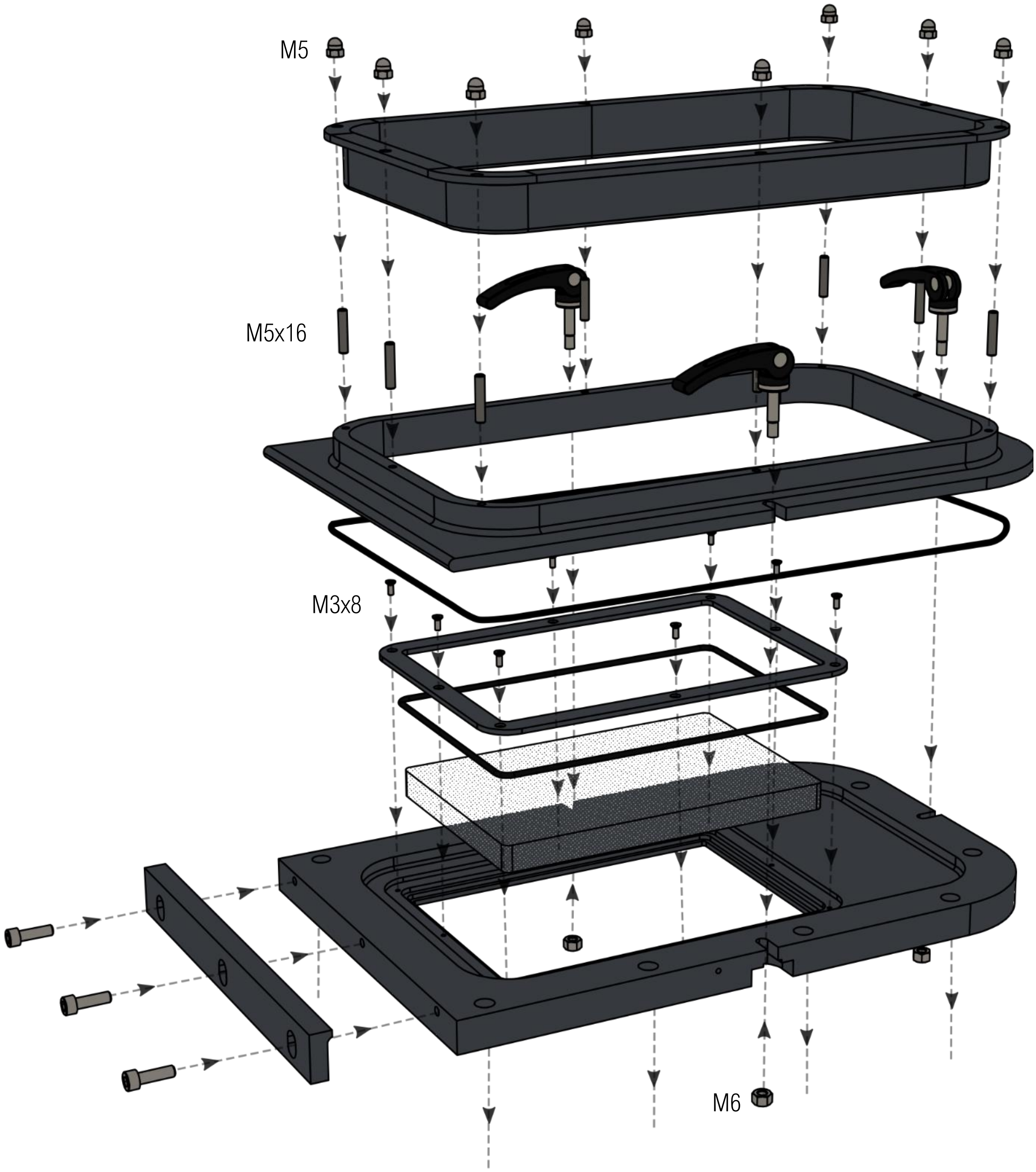
3 Assembly

PROJECTOR



Attach to the breadboard with 4 M6x20 screws. Unless otherwise specified, the rest of the screws are also M6x16.

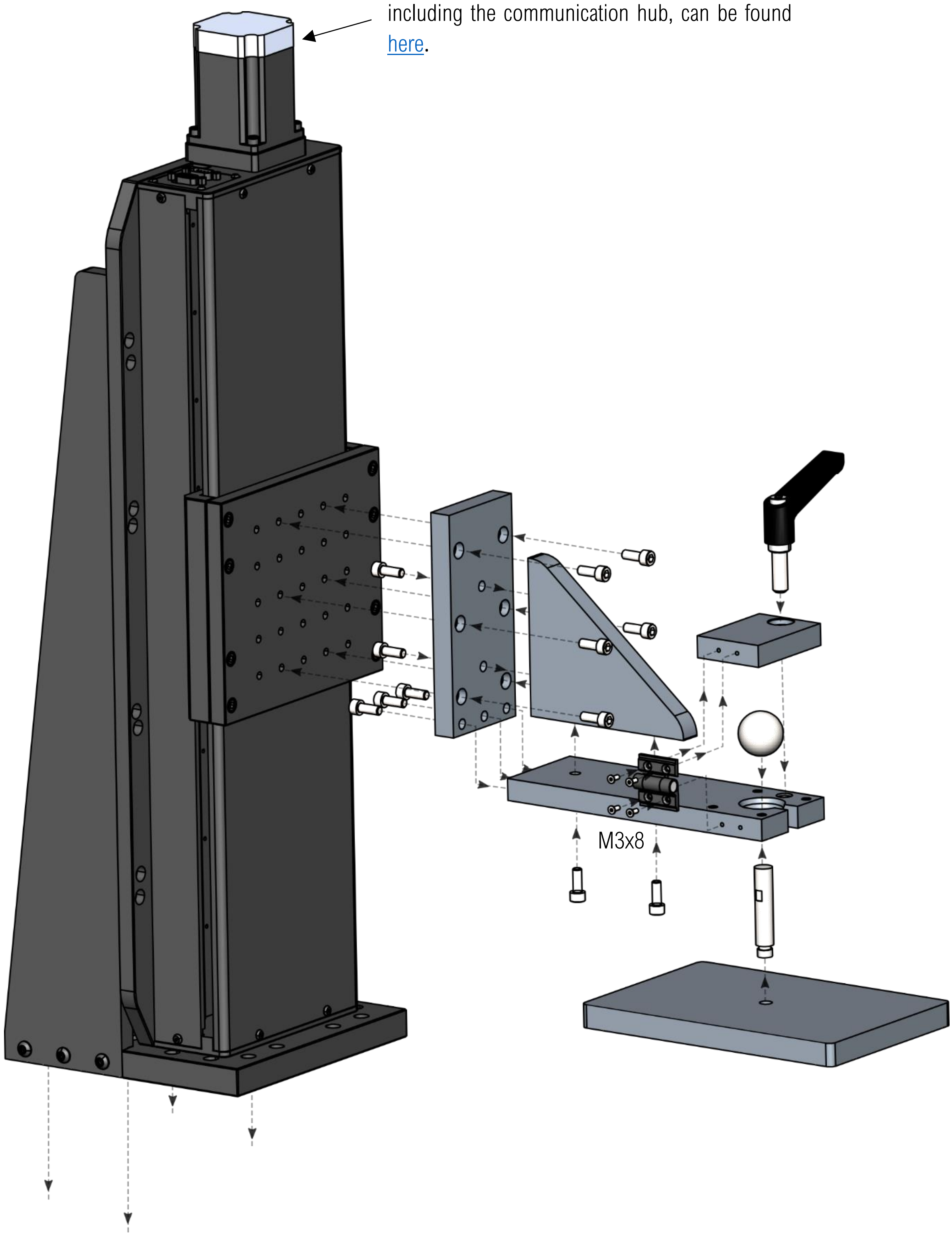
VAT



Attach to the breadboard with 8 M6x20 screws. Unless otherwise specified, the rest of the screws are also M6x16.

STAGE

Assembly of the servo-motor accessories including the communication hub, can be found [here](#).



Attach to the breadboard with 4 M6x20 screws. Unless otherwise specified, the rest of the screws are also M6x20.

4 Bill of materials

VAT						
ITEM	COMPANY	ID	COMMENTS	UNIT PRICE [DKK]	QTY	TOTAL [DKK]
O Ring Top plate	M Seals	201267	Inner 319.30, outer 330.7, thick 5.7	38,34	2	76.68
O Ring bottom plate	M Seals	202791	Inner 214, outer 222, thick 4	30,44	2	60.88
Glass	Mirit glass		135 x 205 15±0,4 mm Borofloa, tempered 4 x R=4,5	1.878,00	1	1 878.00
M3 x 8 ISO 10642	RS Components	304-4918	Countersunk Screws ISO 10642 (8 stk)	67,31	8	538.48
Grub screw M5 x 16	RS Components	124-7393	Grub screw (8 stk)	97,73	8	781.84
M5 nut	RS Components	293-072	DIN 1587 Domed cap nut (8 stk)	120,22	8	961.76
M6 nut	RS Components	525-919	Thick nut M6 ISO 4034 (3 stk)	64,43	3	193.29
M6 x 20	RS Components	468-0105	Hex socket screw ISO 4762 (13 stk)	222,21	13	2 888.73
Quick Release	RS Components	42-316	45mm. ø6mm	25,00	3	75.00
Bottom plate	Workshop		3DHubs estimate, Al 1060	2684,48	1	2 684.48
Top plate	Workshop		3Dhubs estimate, Al 1060	2493,22	1	2 493.22
Drum plate	Workshop		3Dhubs estimate, Al 1060	2518,76	1	2 518.76
Bracket	Workshop		3Dhubs estimate, Al 1060	731.78	1	731.78
Glass fixture	Workshop		3Dhubs estimate, Al 1060	928,98	1	928.98
VAT TOTAL [DKK]						16 999.72

PROJECTOR AND TABLE						
ITEM	COMPANY	ID	COMMENTS	UNIT PRICE [DKK]	QTY	TOTAL [DKK]
Projector 4KA	Visitech	7000290-405	380 nm, 3840 x 2160 FPSC mode, DLP660TE	59 093.41	1	59 093.41
Projection Lens	Visitech	502850	LRS 14x P/N 6502850 37.5 (nominal) in FPSC mode	30 218.22	1	30 218.22
Breadboard	Thorlabs	MB6090/M	600 mm x 900 mm x 12.7 mm, M6 Taps	4 369.05	2	8 738.10
Strut	RS Components	459-7211	40x40 mm, 10mm Groove, L: 3000 Bosch Rexroth	435.87	4	1 743.48
Strut slider	RS Components	390-0408	10 mm groove M6 bag of 10	75.40	8	603.20
Adjustable foot	RS Components	331-4166	M8	41.64	4	166.56
Angle bracket	RS Components	523-370	10mm groove M6 screws	57.70	36	2 077.20
M8 x 16 mm	RS Components	529-703	ISO 4762	136.60	1	136.60
M4 x 25 mm	RS Components	467-9919	ISO 4762	186.31	1	186.31
M6 X 20 mm	RS Components	468-0076	ISO 4762	216.03	1	216.03
Tension spring	RS Components	751-916	59mm x Ø 8.5mm, pack of 10, (2 stk)	90.12	1	90.12
Micrometer	Thorlabs	DM12	Ø9.5 barrel pitch 25 µm with 0.5 µm Graduations	1 079.19	3	3 219.57
Setscrew M3x6	Thorlabs	SS3M6	Screw for the adjuster barrel SS3M6,Pack of 50 (1 stk)	69.88	1	69.88
Top frame	Workshop		3Dhubs estimate, Al 1060	1 850.17	1	1 850.17
Bottom frame	Workshop		3Dhubs estimate, Al 1060	1 662.94	1	1 662.94
PROJECTOR AND TABLE TOTAL [DKK]						110 291.67

Z STAGE AND BUILDPLATE						
ITEM	COMPANY	ID	COMMENTS	UNIT PRICE [DKK]	QTY	TOTAL [DKK]
Stage	Newmark	NLS8-400-102	Travel 400 mm, 4 mm pitch	30 362.59	1	30 362.59
Z stage fix	Newmark	250016	Bracket for stage clamped with 4 screws	3 415.36	1	3 415.36
Clearpath servo motor	Teknic	CPM-SCSK-2310S-EQNA	NEMA 23 - Peak torque: 1.6 N-m	2 547.86	1	2 547.86
Clearpath power supply	Teknic	IPC35-CABLE110	Clearpath and hub accessories	1666.06	1	1666.06
AC Power Cable for IPC-3 and IPC-5	Teknic	SC4-HUB	Clearpath and hub accessories	94.05	1	94.05
Communication Hub for ClearPath-SC Series	Teknic	CPM-CABLE-M2P2P-120	Clearpath and hub accessories	329.97	1	329.97
24 Volt Power, 2-Pin Molex Cable	Teknic	CPM-CABLE-M4P4P-120	Clearpath and hub accessories	87,54	1	87,54
I/O Cable, 4-Pin Molex	Teknic	CPM-CABLE-PWR-MS120	Clearpath and hub accessories	94.28	1	94.28
DC Power Cable, IPC to ClearPath, 10 ft	Teknic	CPM-CABLE-CTRL-MU120	Clearpath and hub accessories	127.95	1	127.95
Controller Cable, 10 ft	Teknic	CPM-CABLE-USB-120AB	Clearpath and hub accessories	154.88	1	154.88
USB Cable, for SC4-HUB to USB Port	Teknic	CPM-CABLE-USB-120	Clearpath and hub accessories	60.64	1	60.64
USB Cable, for ClearPath Rear USB Port	Teknic	917-4573	Clearpath and hub accessories	60.64	1	60.64
Male Die Cast Zinc Indexed Clamping Handle	RS Components	468-0105	M10 x 20 (2 stk)	117.92	1	117.92
M6 x 20 ISO 4762	RS Components	304-4918	Hex socket screw ISO 4762, pack of 200	222.21	1	222.21
M3 x 8 ISO 10642	RS Components	918-5346	Countersunk Screws ISO 10642, pack of 50 (4 stk)	67.31	1	67.31
Lock hinge	RS Components	917-4573	Spring loaded, 30mm x 35mm x 3.3mm M3	73.32	1	73.32
Ball	KJV		30 mm M12 machined hole		1	
Stage	Workshop		3DHubs estimate, Al 1060	790.79	1	790.79
Ball joint lock	Workshop		3DHubs estimate, Al 1060	606.64	1	606.64
Stage holder	Workshop		3DHubs estimate, Al 1060	971.26	1	971.26
Wedge	Workshop		3DHubs estimate, Al 1060	811.22	1	811.22
Rod	Workshop		3DHubs estimate, Stainless steel 304	598.65	1	598.65
Side	Workshop		3DHubs estimate, Al 1060	720.23	1	720.23
Z STAGE AND BUILDING PLATE TOTAL [DKK]						43 480.95

MACHINE TOTAL COST [DKK]	170 772.34*

*Costs may vary due to inflation, workshop rates, resourced components and/or conversion rates.

5 References

1. Jacobs, P. F. & Reid, D. T. *Rapid prototyping & manufacturing : fundamentals of stereolithography*. (Society of Manufacturing Engineers in cooperation with the Computer and Automated Systems Association of SME, 1992).

2. Luongo, A. *et al.* Microstructure Control in 3D Printing with Digital Light Processing. *Comput. Graph. Forum* **39**, 347–359 (2020).

3. Dudley, D. *et al*. Emerging digital micromirror device (DMD) applications. in (ed. Urey, H.) **4985**, 14 (International Society for Optics and Photonics, 2003).

4. Resin vat for Moai – Peopoly. Available at: https://peopoly.net/collections/frontpage/products/resin-vat-for-moai. (Accessed: 20th May 2020)

5. Standard Resin Tank: Maintenance and care. Available at: https://support.formlabs.com/s/article/Standard-Resin-Tank-Maintenance-and-Care?language=en_US. (Accessed: 20th May 2020)

6. Pedersen, D. B. *et al*. A self-peeling vat for improved release capabilities during DLP materials processing. in *2nd International Conference on Progress in Additive Manufacturing (Pro-AM 2016)* (2016).

7. Ribo, M. *et al.* Optimization of a self-peeling vat for precision vat photopolymerization setups Optimization of a self-peeling vat for precision vat photopolymerization setups. in *Proceedings of the 19th International Conference and Exhibition (EUSPEN 2019)* (Euspen, 2019).