The journey of Fabulaser Mini: designing, making and documenting of an open source, Fablab produced, laser cutter

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Abstract

With the ability to quickly create prototypes and being necessary to run Fab Academy, laser cutters are the workhorse in every Fablab. Furthermore, because of their ease of usage, they are often the most used machines and the first to be approached by inexperienced makers. However, laser cutters are currently an expensive purchase for Fablabs, usually being the most expensive machine in their inventory and mainly available as commercial closed source products. In the concept of Fablab 2.0, the machines used in the lab are replicated by the machines present in it, allowing the "transition from buying a Lab to making a Lab" (Neil Gershenfeld, 2022). The making of machines instead of buying, implies several advantages beyond the machine capabilities itself, such as open source inclusiveness, distributed development, the learning of the processes for hardware replication, the understanding of how the machine works, customization and more. To jointly address laser cutting needs of Fablabs and Fablabs 2.0 research, Fabulaser Mini was developed by Daniele Ingrassia in 2021 at InMachines Ingrassia GmbH (Germany). It has been conceptualised as a small format laser cutter, prioritising open source design, replicability, affordability, performance and safety. To fulfil the purpose of the machine replication, Liane Sayuri Honda and Marc Kohlen joined the team to develop the assembly manual of Fabulaser Mini. With a BOM (Bill Of Materials) of about 2000€ at the time of writing, Fabulaser Mini has been replicated in more than 7 machine-building workshops and can be produced using standard Fablab equipment. It is the first open source laser cutter in the Fablab inventory, and has been used by Fab Academy students. Derived from Fabulaser Mini, OSLK Small Laser, is currently part of the Open Lab Starter Kit, an open source set of machines developed within the project Fab City Hamburg, in cooperation with the Helmut Schmidt University (Germany). In this paper, the authors will describe the processes behind the development of Fabulaser Mini. The machine design will be discussed considering fabrication, performance, usability and safety. The production process will be explained, including the required machines, materials and recommendations. Information about the structuring, creation and visualisation of the assembly steps will be given, addressing the making of the assembly manual. Current achievements and facts will be used to evaluate the results.

Keywords

Fabulaser, Open Source Hardware, machine building, Fab Lab 2.0, laser cutter, machine design, documentation, Fab City, OLSK, inventory, workshop

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1 Introduction

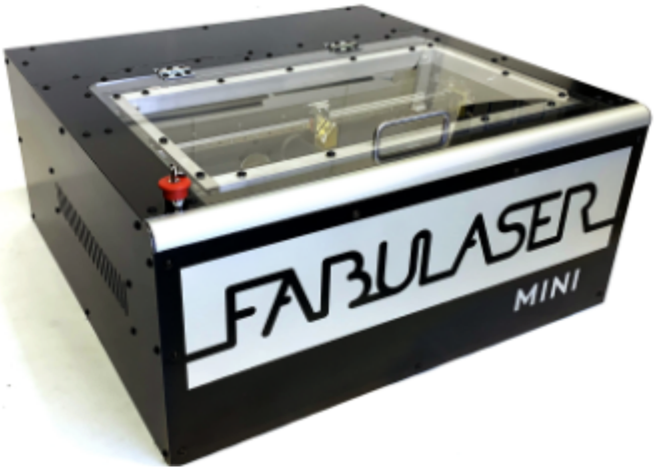


Figure 1: Fabulaser Mini V2

Fabulaser Mini is an affordable desktop format laser cutter, developed as an open source machine and to be assembled as a kit by Daniele Ingrassia.

The initial idea was triggered by the need of local schools (in North Rhine Westphalia, Germany), to have a cheap laser cutter that can be assembled together with high-school students. These schools often have a small budget to purchase digital machines, in comparison with the typical high price of laser cutters, being a limiting factor in spreading Fab Labs in a scholastic environment.

The idea of having it as open source was supported by our Fab Lab roots, where we believe that sharing knowledge is an enabling key asset for others. Especially when thinking about the several skills needed to build a machine and how they could be used to develop other projects or to find a job. Furthermore the user will be able to know how to fix/repair/modify the machine. The open sourceness of the machines was also crucial to schools, where workshops are supposed to have learning content for the students. Fabulaser Mini has been released under CERN Open Hardware Licence Version 2 Weakly Reciprocal (CERN-OHL-W).

If one part of the motivation was to support local schools, the other was given by the Fab Lab 2.0 concept, where Fab Labs are supposed to be able to replicate Fab Labs. In this concept, existing Fab Labs should use their own knowledge, equipment and machines, to fabricate further knowledge, equipment and machines for new Fab Labs. And being one of the most used machines in Fab Labs, a laser cutter can be considered as one of the key machines to be replicated. For the above mentioned reasons, Fabulaser Mini has therefore been designed not only to be open source, but also reproducible with the standard Fab Lab machines. The decision to make Fabulaser Mini was also supported by the previous experience of Daniele Ingrassia in building a large format laser called Laserduo in 2017.

Figure 2: LaserDuo

The current version of Fabulaser Mini has the following specifications:

Laser source	CO_2 40 W continuous Wave 10.6 µm
Cutting area	600 x 400 mm
Precision	up to 0.05 mm
Speed	up to 400 mm/s
Frame	Aluminium profiles
Housing	Aluminium composite
Controller	NXP LPC1768 Arm Cortex M3
Firmware	grbl-LPC
Cutting thickness	up to: 10 mm acrylic, 6 mm MDF, about 15 mm poplar wood
Dimensions	870 x 810 x 380 mm (W x D x H)

Table 1: Fabulaser Mini V2 specifications

2 Machine Design

Differently from LaserDuo, where the machine has been conceptualised following a bottom-up approach (where the “center” of the machine was developed first and all the rest as a consequence of it), Fabulaser Mini was designed using a top-down approach: the frame was designed first and later its interior.

The main idea behind the frame of the first 2 versions, was to use aluminium profiles as the main frame of the machine. This component was selected as a main building element to flexibly adjust the machine dimensions and to provide support to all the machine parts. These types of aluminium profiles are compatible with different, and modular systems to join them in many configurations and also for attaching standard or custom parts. The shape of the profiles also allows robust structures, compared to weight and amount of aluminium used in them.

The aluminium profiles allowed to quickly sketch the machine frame, and to later design and attach parts that were not considered initially. This way the initial design did not have to consider many of the small details that were needed later on, allowing us an easy start. The aluminium profiles used are of 30 x 30 mm and 20 x 20 mm, mainly of the BOSCH type. The frame consists of an outer box completed in the front with a filletted profile, with additional inner profile bridges to hold the internal structures.

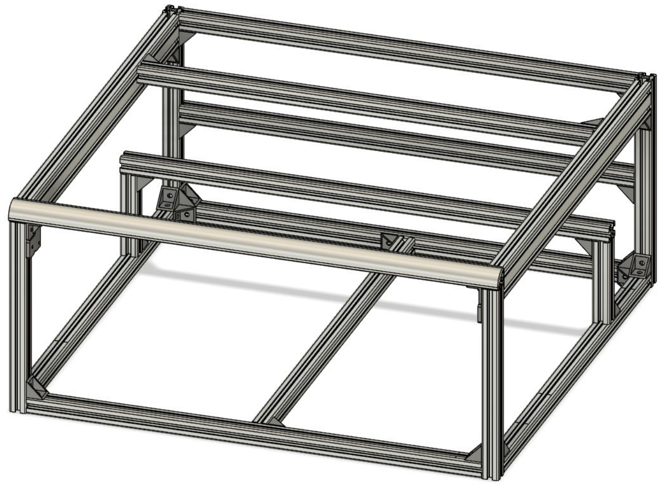


Figure 3: Fabulaser Mini V2 frame

The housing (including internal surfaces) is currently fabricated using CNC milled sandwich panels with a thickness of 3 mm. Aluminium sandwich panels consist of 2 thin layers of aluminium (between 0.2 and 0.3 mm) and of an inner layer of polyethylene. Because of the aluminium layers, these panels can resist unfocused CO2 laser beams. Furthermore they can be easily cut with a lightweight CNC milling machine or hand tools, and are available in standard colours and finishings. Mainly the panels are fastened to the frame with screws and nuts, but some of them were designed with joints for the correct positioning.

Figure 4: Fabulaser Mini V2 housing and inner panels

Fabulaser Mini implements motion using Nema 17 motors, GT2 belts (10 mm) and 12 mm linear rails. Normally, laser cutters are fast moving machines, therefore the choice to use linear rails and belts. The Y motor is positioned centrally in the back of the machine, and actuates the motion via couplers using 2 shafts and 4 pulleys placed at the edge of the rectangle constituting the Y axis. The Y axis moves 2 belts, one on each side, that are sliding centrally 5 mm below the 12 mm linear rails. To save space, the Y rails are attached directly to the aluminium profiles, also used as top sides of the frame. The X axis is attached to the Y axis using CNC milled aluminium plates, which in turn are moved back and forth with the belts. The X motor is directly driving a pulley to move the X belt, which is in its turn, moving the laser head.

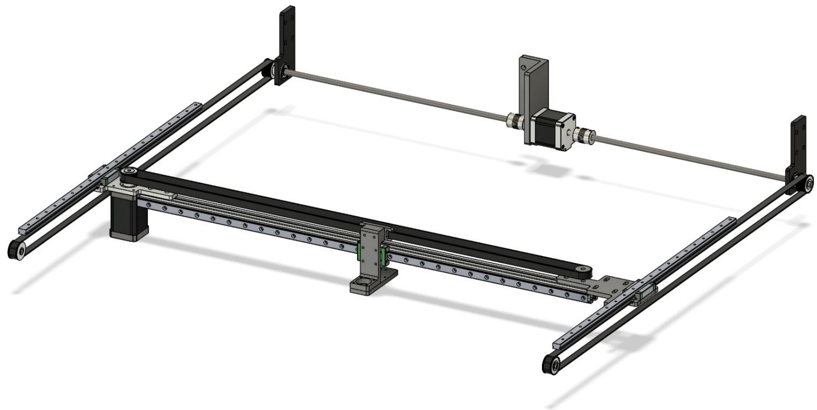


Figure 5: Fabulaser Mini V2 motion axes

The laser source is CO2 water cooled laser tube, 720 mm long. The laser path consists of 3 mirrors and a lens, in a configuration where the first mirror (25 mm) is stationary while second and third mirrors (both 20 mm) move along the X and the Y axis. The laser lens (18 mm) has a focal length of 50.2 mm. The design of the laser path makes use of the existing structures, with some spacers and adjustments to be able to be in the same plane. The position of the mirror holders has been determined by using fictitious solids in the CAD (Autodesk Fusion 360). The short path and focal distance, combined with the built-in air assist, allows it to cut up to 10 mm acrylic without burns.

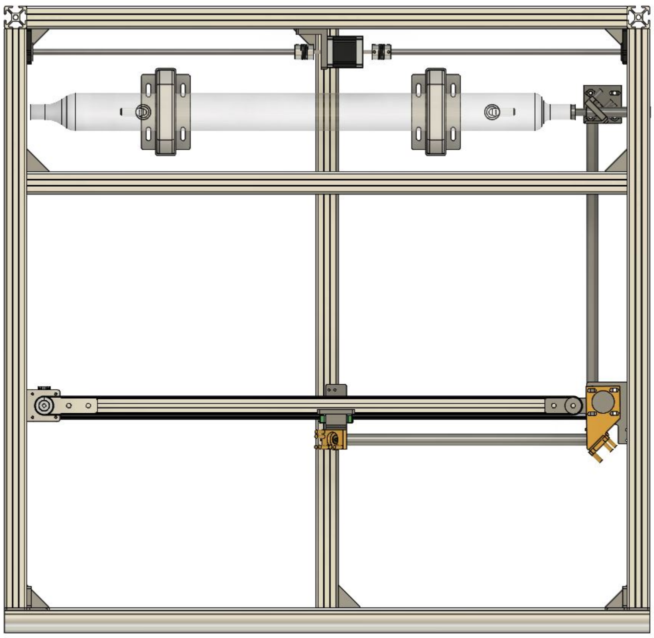


Figure 6: Fabulaser Mini V2 laser path

In order to be able to execute engraving at sustained speed (about 200 mm/s), Fabulaser Mini currently uses as firmware grbl-LPC, a port of grbl. While grbl is commonly used on different kinds of CNC machines running on the Atmega328p, grbl-LPC is a 32 bit port running on the LPC1768 Cortex M3 microcontroller, that acquired notoriety for its use in laser cutters. Fabulaser Mini uses the MKS SBASE controller board together with a custom PCB. The custom PCB integrates an Attiny45 and takes care of the logic signal conversion for the laser signal (from 3.3 v to 5 v) and the controlling of a relay. The relay is used to disconnect the laser signal between the laser controller and the laser power supply during the booting of the MKS SBASE or its resetting, avoiding unwanted laser firing.

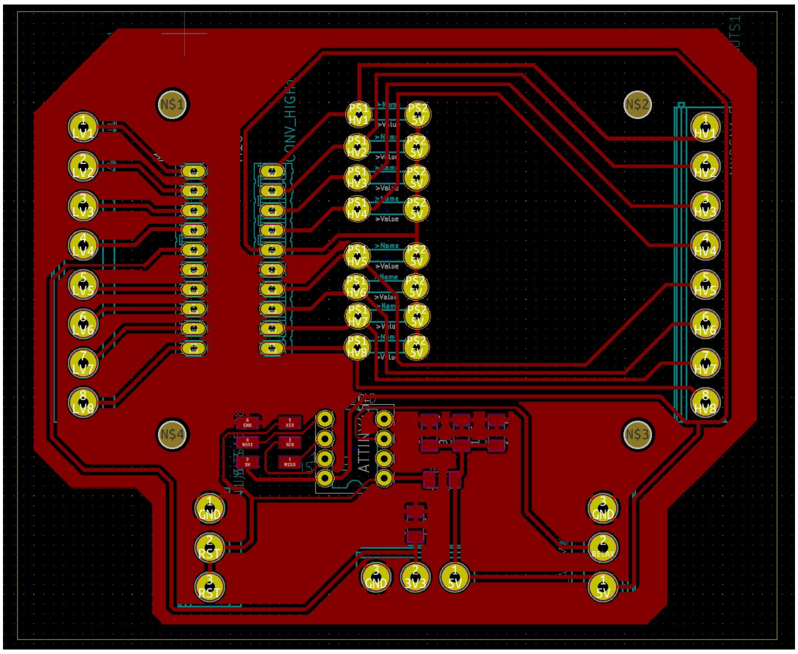


Figure 7: Fabulaser Mini V2 converter PCB

Fabulaser Mini uses magnetic sensors as endstops. The window uses a combination of mechanical and magnetic sensors to shut the laser off whenever it is open. A water flow sensor is used to determine if the water is flowing into the laser tube, stopping the laser from firing when the water is not circulating. The safety is completed with a lockable emergency button, and fully enclosed housing.

Fabulaser Mini uses a membrane air pump and PVC tubing to implement air-assist, and hydraulic connectors together with silicon pipes for the water cooling system. An external chiller takes care of cooling the water that flows inside the laser tube. Fabulaser Mini also comes with a radial fan and a 3-stage filter.

2.1 2.1 Design iterations

Fabulaser Mini has been going through 2 main design milestones: V1 and V2. Currently the first prototype of V3 is in the assembling and testing stage at InMachines Ingrassia GmbH. At each design milestone, several improvements have been implemented.

Only 3 Fabulaser Mini V1 have been produced. The V1 served the purpose to implement the basic machine functionalities and to test the main ideas about the design. At that time the machine was still called "Fab Laser". As typical with first versions, improvements and mistakes were identified quickly by showing the machines to colleagues and users. Main limitations were the lack of gas springs for the windows, the usage of an Arduino UNO as controller which limited engraving performance, the usage of plastics for many parts that could collide with the beam, etc.

Fabulaser Mini V2 brought many modifications collected from usage feedback, workshops and other Fab Lab experts. It was the first Fabulaser Mini version able to engrave at reasonable speed, thanks to the new controller and different firmware. Furthermore, it added gas springs to the window, redundant window sensors, magnetic endstops, and led strips. The laser path was redesigned adding a 25 mm mirror and a different mirror holder. V2 received a refresh with V2.1 fixing some minor problems in the electronics, and had good success with more than 20 machines built, mostly in schools.

Fabulaser Mini V3 is currently being assembled as a prototype, bringing a completely different frame that can be produced both in Fab Labs and industrially. Also, parts count has been reduced consistently. Below is a comparison among the Fabulaser Mini different versions:

	V1	V2	V3
Frame	Aluminium profiles	Aluminium profiles	Interlocked aluminium plates
Housing	Sandwich panel	Sandwich panel	
Controller	Atmega328p (Arduino UNO)	LPC1768 (MKS SBASE) and custom PCB	iMXRT1062 (Teensy 4.1) and custom PCB
Motors	Nema 17		Nema 23/24
Linear guides	Linear rails		Linear rails (X) linear shafts (Y)
Speed	400 mm/s		1000 mm/s
Belts	GT2 10 mm		HTD 5M, self tightening, closed loop
Laser Path	20 mm mirrors, 18 mm lens	25 mm and 20 mm mirrors, 18 mm lens	25 mm mirrors, 20 mm lens
Safety	Mechanical window sensors, water flow sensor, mechanical endstops	Mechanical and magnetic window sensors, waterflow sensor, magnetic endstops, safety stickers	Magnetic window sensors, waterflow sensor in the chiller, full aluminium body, inductive endstops, safety stickers
Size(WxDxH)	863 x 806 x 353 mm	870 x 810 x 380 mm	1150 x 808 x 400 mm
Part count	About 150	About 200	About 60
Additional features	Air-assist, modular bed lamella	Air-assist, modular bed lamella, led lights	Air-assist, touchscreen, coaxial laser pointer, ethernet, WiFi, Web gui, modular bed lamella, led lights
Assembly	3 - 4 days, frame alignment, manual laser calibration		1 - 2 days, aided laser calibration (pointer)
Documentation	PDF assembly manual		Web based 3D assembly manual
Production	Fab Labs		Fab Labs and industry

Table 2: Comparison of the the Fabulaser Mini versions

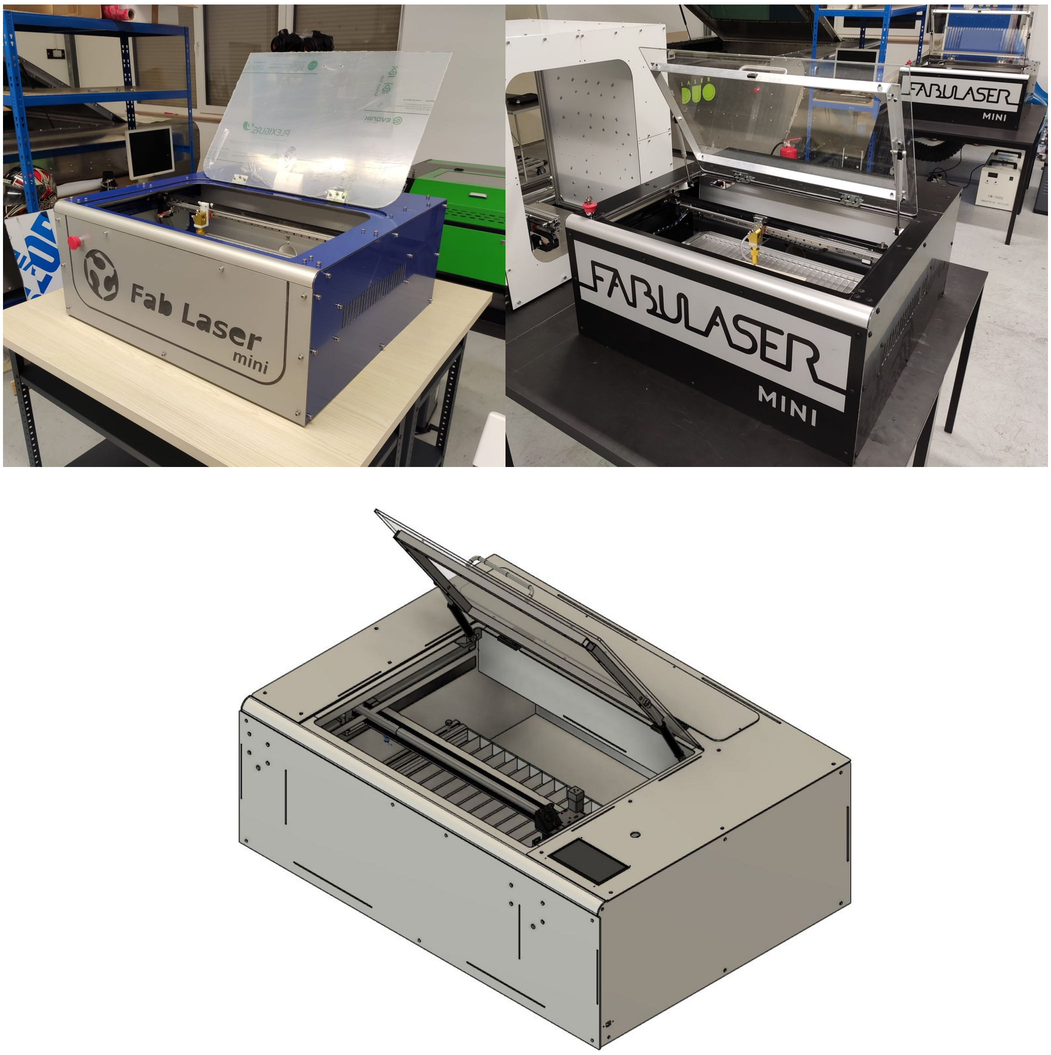


Figure 8: Fabulaser Mini versions; top left V1, top right V2, bottom V3

3 Procuring and production

The current list of required parts and materials to produce Fabulaser Mini consist of about 200 different elements. Fabulaser Mini is made with a mix of parts categorised as follows:

- Premade parts (ready made)
- Manually fabricated parts
- 3D printed parts
- CNC milled parts
- Laser cut parts

The parts are procured from different vendors and sellers, with about 90% of them being located in Germany, and about 10% in China. About 60% of the sellers are established and have their own shops, while about 40% change and must be researched between purchases. Fabulaser Mini V2 took advantage of the German market because of the local production of sandwich panels, screws and aluminium profiles. Regardless of this fact, these parts are quite standard nowadays and sourceable in many countries.

The following machines are required to produce Fabulaser Mini:

Machine	Working area	Parts
CNC milling machine	Minimum 1000 x 1000 mm	Sandwich panels, aluminium parts
Laser cutter	Minimum 800 x 600 mm	Window and other parts
PCB milling machine	Minimum 100 x 100 mm	Converter PCB
3D printer	Minimum 200 x 200 x 300 mm	3D printed parts (e.g. exhaust)
Drill press	-	Laser head

Table 3: Machines required to produce Fabulaser Mini V2

Other standard Fab Lab or workshop equipment is required to produce the parts manually, which are mostly about the wiring:

- Soldering station
- Wire tools
- Filers
- Deburring tool

A Gitlab wiki has been used to document the preparation of the kit and the manual production of parts. The wiki describes the type of cable required, the cable length and the used connectors. Cables are tested before being included in the kit.

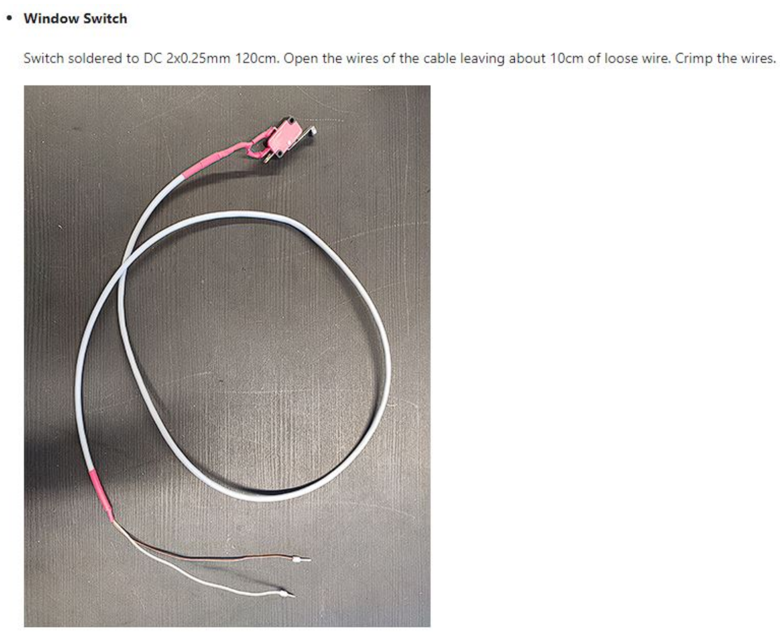


Figure 9: Snapshot of the wiki

4 Preparation of the Kit

As a strategy to enable learning and knowledge development, Fabulaser Mini is delivered as a kit, often accompanied by the machine building workshop.

- The preparation of the kit involves several steps that can be summarised as:
- Storage picking up
- Labelling, sleeving and boxing
- Quality control
- Intermediate and final checks

The kit consists of market-available parts and produced parts (as discussed in the previous section). All the parts are listed in a modified Bill of Material (table for the preparation of the kit, Fig.10), which contains:

- Production name: the name used to recognised the part during production
- Specification: a brief description of the part
- Quantity: the amount needed for one kit
- Label name: the name used in the assembly manual; often production name and label name coincide, except when the kit part consists of the combination of more than one part (for example, electronic parts and their cables)
- Checks: aspects to check in order to deliver a complete and functioning kit

Electronics								
Production Name	Specification		Label Name	Checks				
Emergency Button	Emergency button with key AS22-B142	1	Emergency Button	-	☐	☐	☐	☐
USB Cable Inside	Panel mount USB B	1	USB Cable Inside	Insert 2x P-screw M3-8.	☐	☐	☐	☐
USB Cable	3m shielded, 90 connector	1	USB Cable	-	☐	☐	☐	☐
Laser Power Supply	40W CO2 Power Supply	1	Laser Power Supply	Test if it turns on. Remove the last right terminal. Crimp the Laser (+) cable. Test if it was well crimped.	☐	☐	☐	☐
Laser Controller	MKS Sbase	1	Laser Controller	Must be programmed.	☐	☐	☐	☐
Motor Driver	TB6600	2	Motor Driver	Test if it turns on.	☐	☐	☐	☐
Relay	single channel	1	Relay	Test if it turns on.	☐	☐	☐	☐
Motor Power Supply	24V 15A	1	Motor Power Supply	Test if it turns on.	☐	☐	☐	☐
Window Switch	V-156-1C25	1	Window Switch	Needs to be prepared with the Switch Cable and crimped. Check if the loose wires arre at least 10 cm long. Test if it was well crimped.	☐	☐	☐	☐
Window Sensor	PS-3150		Window Sensor	Needs to be prepared with the Window Sensor Cable and crimped. Check if the loose wires arre at least 10 cm long. Test if it was well crimped.	☐	☐	☐	☐
Window Magnet	PS-3150		Window Magnet	-	☐	☐	☐	☐
Y-endstop Sensor	PS-3150		Y-endstop Sensor + X-endstop Sensor + Endstop Cable	Needs to be prepared with the Endstop Cable (cable with 3 ends) and crimped. Test if it was well crimped. Sensors must be labeled (Y and X).	☐	☐	☐	☐
X-endstop Sensor	PS-3150							
X-endstop Magnet	PS-3150		X-endstop Magnet	-	☐	☐	☐	☐
Y-endstop Magnet	PS-3150	3	Y-endstop Magnet	-	☐	☐	☐	☐
Cable Wrapper	1m 4mm+	1	Cable Wrapper	Needs to be cut in the right length.	☐	☐	☐	☐
Foot Switch	240V Eco Line Comfort Switch Adapter	1	Foot Switch	-	☐	☐	☐	☐
Terminal Block	4 Positions, minimum 1.5-2.5mm2	2	Terminal Block	Check if it fits to the Bottom Panel holes and if the Mains Cable fits in it.	☐	☐	☐	☐
Laser Attachments	2 Terminal Block + 2 heat shrinking tubes	2	Laser Attachments	Check if the Terminal Blocks can be fixed in the Laser Tube connections. Check if the shrinking tubes are big enough to cover the Terminal Block.	☐	☐	☐	☐
Power Cable	PC Power Cable	1	Power Cable	-	☐	☐	☐	☐
Power Plug	Main Power Plug Inlet+Power switch, 1.5 or 2mm panel spacing	1	Power Plug + Mains Cable + Earth Cable	Test the Power Plug. Check if the Fuse holder is in it with Fuse. Must be prepared with the Mains Cable	☐	☐	☐	☐
Chain	Cable Chain 8x8-R18 1000mm	1	Chain	-	☐	☐	☐	☐
Fuse	6.3A 5x20mm	2	Fuse	-	☐	☐	☐	☐
Resistor	1K resistor 1/4W trough hole	1	-	-	-	-	-	-
LED Strip	2 x 30cm 5730, meters	2	LED Strip	Must be prepared with the LED Cable and tested. Test if it was well crimped.	☐	☐	☐	☐

Figure 10: Table for the preparation of the kit

There are five categories of parts:

- Mechanics
- Fasteners
- Electronics
- Laser accessories
- Hydraulics

After printing the labels, each part is taken from the storage and placed in a bag of the adequate size. The bag is labelled (Fig. 11). The parts that don't fit in a bag are labelled directly on their surface (for example, the panels) or, if they come in a box, on their box (for example, the laser tube).

The panels and the window are also labelled with their assembly direction, to facilitate machine building and avoid mistakes.

The part is marked on the table in fig. 10 to indicate it was inserted in a bag and labelled and it is then placed in the box according to its category.

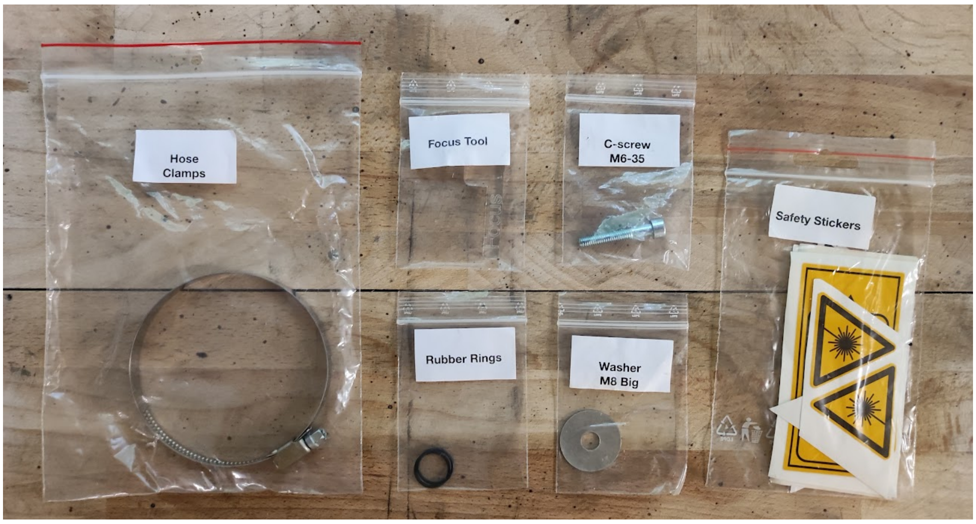


Figure 11: Example of labelled bags

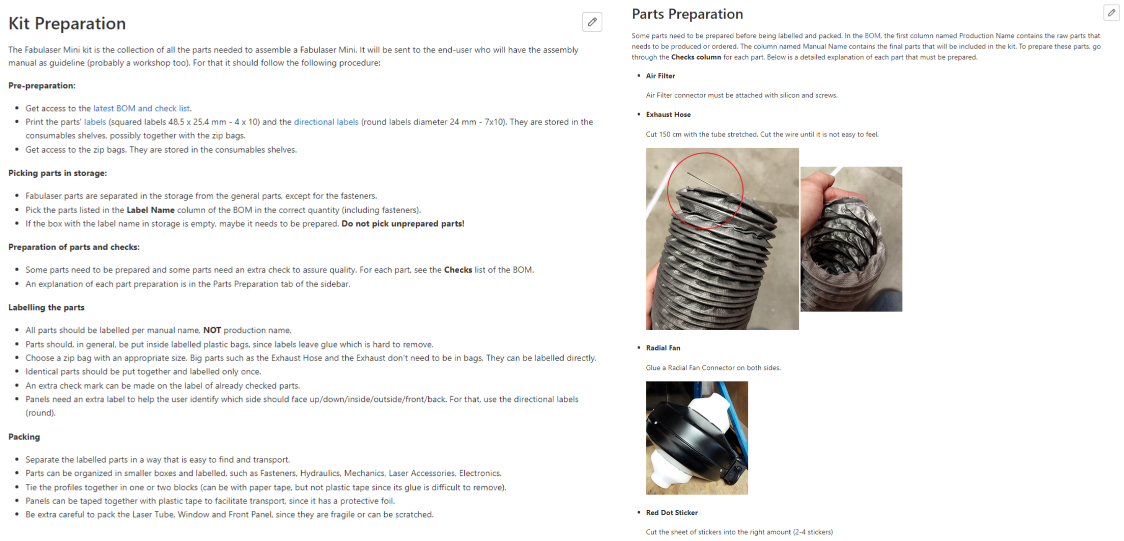
During this step, quality control and checks take place; each part is investigated for defects and damages. Electricity activated parts are turned on. Tubes and panels are cleaned if needed. Furthermore, specific parts have specific checks: for example, checking that the laser tube holders hold the laser tube stably.

As further aid for the kit preparation, in wiki the post processing steps (such as applying the logo on the Front Panel, Fig. 12) and the checks are explained in detail (Fig. 13).

Figure 12: Example of post processing steps; the logo is applied to the Front Panel

Once labelled and placed in the boxes, a second member of the team checks that all the parts have been packed and the quality and functionality are satisfied. The parts which passed the control are marked a second time on the kit preparation spreadsheet.

A third check to ensure that all the parts have been packed is performed before the boxes are closed to be delivered.


Kit Preparation

The Fabulaser Mini kit is the collection of all the parts needed to assemble a Fabulaser Mini. It will be sent to the end-user who will have the assembly manual as guideline (probably a workshop too). For that it should follow the following procedure:

Pre-preparation:

- Get access to the latest BOM and check list.
- Print the parts' labels (squared labels 48,5 x 25,4 mm - 4 x 10) and the directional labels (round labels diameter 24 mm - 7x10). They are stored in the consumables shelves, possibly together with the zip bags.
- Get access to the zip bags. They are stored in the consumables shelves.

Picking parts in storage:

- Fabulaser parts are separated in the storage from the general parts, except for the fasteners.
- Pick the parts listed in the **Label Name** column of the BOM in the correct quantity (including fasteners).
- If the box with the label name in storage is empty, maybe it needs to be prepared. **Do not pick unprepared parts!**

Preparation of parts and checks:

- Some parts need to be prepared and some parts need an extra check to assure quality. For each part, see the **Checks** list of the BOM.
- An explanation of each part preparation is in the Parts Preparation tab of the sidebar.

Labelling the parts

- All parts should be labelled per manual name, **NOT** production name.
- Parts should, in general, be put inside labelled plastic bags, since labels leave glue which is hard to remove.
- Choose a zip bag with an appropriate size. Big parts such as the Exhaust Hose and the Exhaust don't need to be in bags. They can be labelled directly.
- Identical parts should be put together and labelled only once.
- An extra check mark can be made on the label of already checked parts.
- Panels need an extra label to help the user identify which side should face up/down/inside/outside/front/back. For that, use the directional labels (round).

Packing

- Separate the labelled parts in a way that is easy to find and transport.
- Parts can be organized in smaller boxes and labelled, such as Fasteners, Hydraulics, Mechanics, Laser Accessories, Electronics.
- Tie the profiles together in one or two blocks (can be with paper tape, but not plastic tape since its glue is difficult to remove).
- Panels can be taped together with plastic tape to facilitate transport, since it has a protective foil.
- Be extra careful to pack the Laser Tube, Window and Front Panel, since they are fragile or can be scratched.

Parts Preparation

Some parts need to be prepared before being labelled and packed. In the BOM, the first column named Production Name contains the raw parts that needs to be produced or ordered. The column named Manual Name contains the final parts that will be included in the kit. To prepare these parts, go through the **Checks column** for each part. Below is a detailed explanation of each part that must be prepared.

- **Air Filter**

  Air Filter connector must be attached with silicon and screws.

- **Exhaust Hose**

  Cut 150 cm with the tube stretched. Cut the wire until it is not easy to feel.

- **Radial Fan**

  Glue a Radial Fan Connector on both sides.

- **Red Dot Sticker**

  Cut the sheet of stickers into the right amount (2-4 stickers)

Figure 13: GitLab wiki page to aid the preparation of the kit

5 Documentation and knowledge transfer

5.1 Assembly Manual

The creation of the assembly manual had two goals: to offer the machine as an independent assembly kit and to assist the machine building workshops for teenagers and adults. Having that in mind, the manual aimed at being self-explanatory for users who have no knowledge or experience in machine building. While Daniele Ingrassia designed the machine, another part of the team composed of Marc Kohlen and Liane Sayuri Honda, was responsible for developing the manual independently.

Planning

The first step was the planning; strategic decisions were made regarding its structure, content, version tracking and visuals. Based on a research of references and the personal experience of the team (whose professions are educational leader and designer), the following guidelines were defined for the manual:

- The instructions should be, as much as possible, visual, prioritising images over text.
- The illustrations should be in a perspective view of the machine, with simple 2D lines, as in the IKEA assembly manuals, to not overwhelm the user with visual information.
- Assembly steps that need an extra explanation should include a “magnifying glass” with detailed illustrations to support the main image.
- Each page should contain a title and step number in order to allow the splitting of the manual in separate steps without confusion.
- Each step should display the list of parts and tools needed with illustrations.
- Each step should display the time necessary to complete it.
- The manual should be written in common language and avoid technical terms and DIN names of the parts to be accessible for users with no technical knowledge.
- The assembly manual should be offered as a downloadable DIN A4 format pdf file since it is easy to distribute online, offline and printed, if necessary.

Assembling and documenting

The second step was to build the machine together with the creator, in order to understand the assembly process and define the steps and their optimal order for an easy and smooth assembling experience for the user. This first assembly with the participation of the entire team also brought discussions of improvements on the first version of the machine, such as the creation of the template tools to support the user with the spacing and alignment of parts and the addition of the red dot sticker to mark the front of the machine.

Throughout this assembly, the process was documented, taking notes of the parts, tools, time and assembly observations. This information was then structured in a shared online workbook where the team could visualize and organize the content of the assembly manual before the layout.

Through this workbook it was also possible to note that some steps, which were more complex and/or demanded more explanation, needed to be divided into sub-steps. This became crucial to not overwhelm the user with excessive information in one page, which brings confusion and possible mistakes in the assembly.

In addition, the division of the assembly into steps was already taking into consideration that the machine can be built by groups of people working independently in parallel. For example, the bed, Y-axis, X-axis and top panel can be pre-assembled by one group before being attached to the machine main frame, built by another group. Photos of the entire process were also taken for further consultation, and shared in a Google Drive folder.

Step 1

Building the Bottom Frame

Time: 15 min.

Parts	Tools
3 x Aluminum Profile 30 740mm	Allen Key 5
2 x Aluminum Profile 30 800mm	Allen Key 1,5
6 x Bracket 30 Big	
12 x T-Nut 6 M6	
12 x Cap Screw M6 12mm	
12 x Washer M6	
Dot sticker to mark the front	

Remarks used in manual

Don´t tighten the screws and bolt yet. They will be tighten in the next step. Use your fingers to tighten it slightly.

Details

Detail view on one bracket with screw, washer & T-nut

Figure 14: Workbook page of step 1

In parallel to the assembly of the machine, the team proceeded with the following steps: splitting the 3D CAD file of the machine into the defined assembly steps of the workbook, defining and producing the illustrations and designing the manual.

Organising the 3D CAD file and producing the illustrations

Rhino3D Version 6 was used to create the assembly illustrations. Although open source alternatives exist and would be ideal considering the concept of the project, the team's expertise with this software made it possible to achieve faster results, and no time was wasted in learning a new one. As well, Rhino3D has rendering features which are very useful for this project.

From Fusion 360 , a STEP file could be exported and imported in Rhino3D. In this conversion, most of the objects are imported as “Blocks”, which, in Rhino3D, is a link to one original object file. In Rhino3D these “Blocks” cannot be properly used in layers; they need to be “exploded”, in other words, split into solids, polysurfaces or surfaces. After they are “exploded,” all the objects will be in one layer.

In sequence, all the parts had to be manually distributed in separate layers as listed in the workbook´s steps.

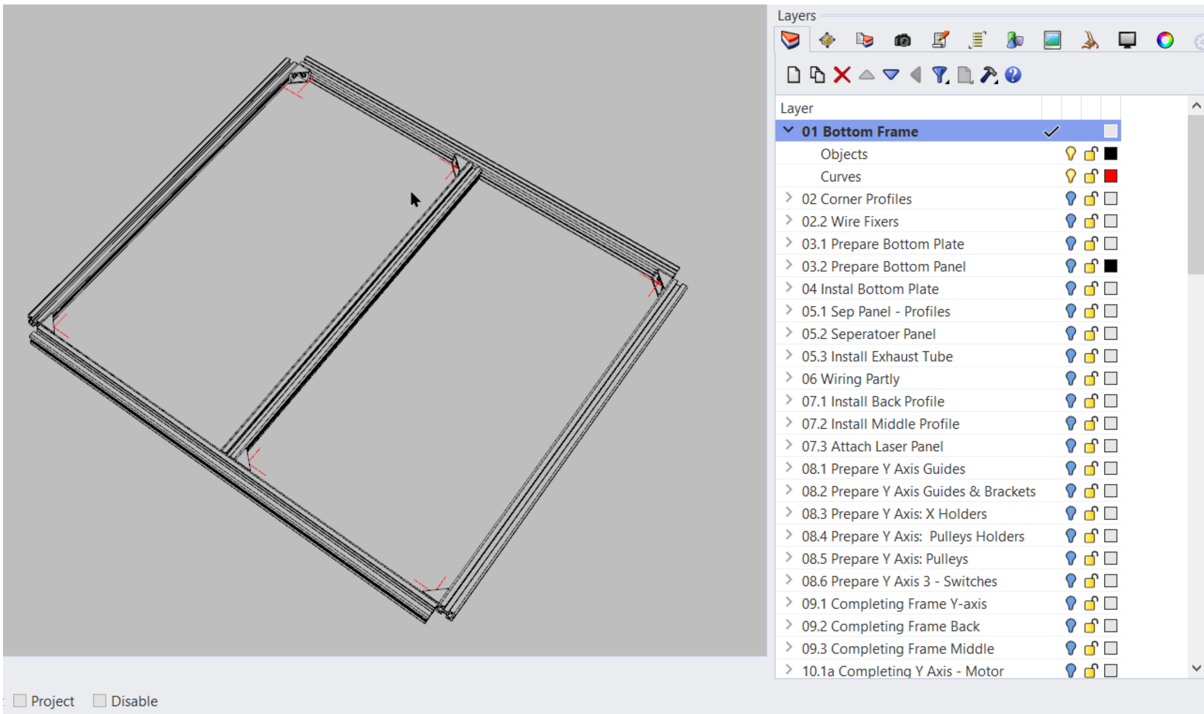


Figure 15: Layers as steps in Rhino 6

After the 3D file was separated into steps, the content of the main illustration and the detailed illustration to be displayed in each step was discussed, defined and documented in the workbook. To illustrate the actions in every step, such as inserting screws and adding parts, the parts in the CAD file were moved and the motion was represented by a red line. To save this “motion”, Rhino3D has the “Named Position” function.

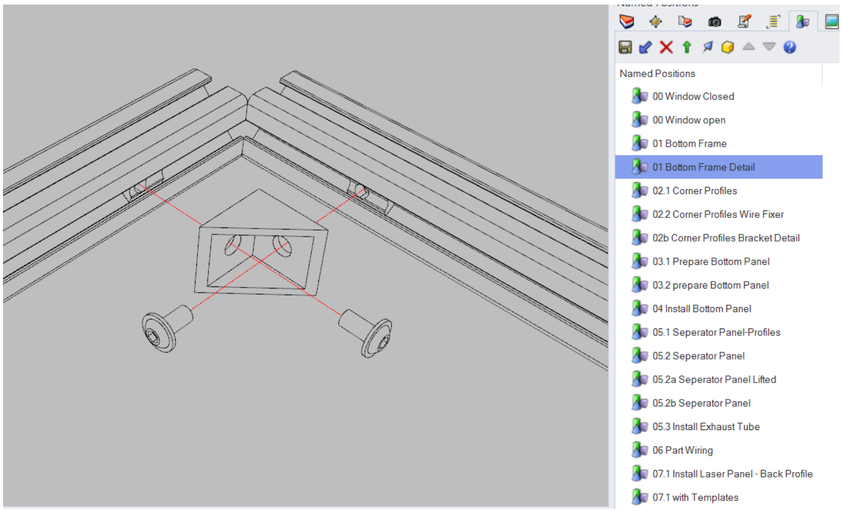


Figure 16: Named Positions in Rhino 6

Each step needed its own perspective view in which the position and angle of the geometries required a clear understanding of the 3D parts in 2D lines and their position in the machine, and considering the overlapping of geometry, sizing of the details and the fitting of the image in the page layout. The chosen perspective needed to be saved in order to be allowed to retrieve it, if anything needed to be added or changed. For that purpose Rhino3D offers the “Named Views” function.

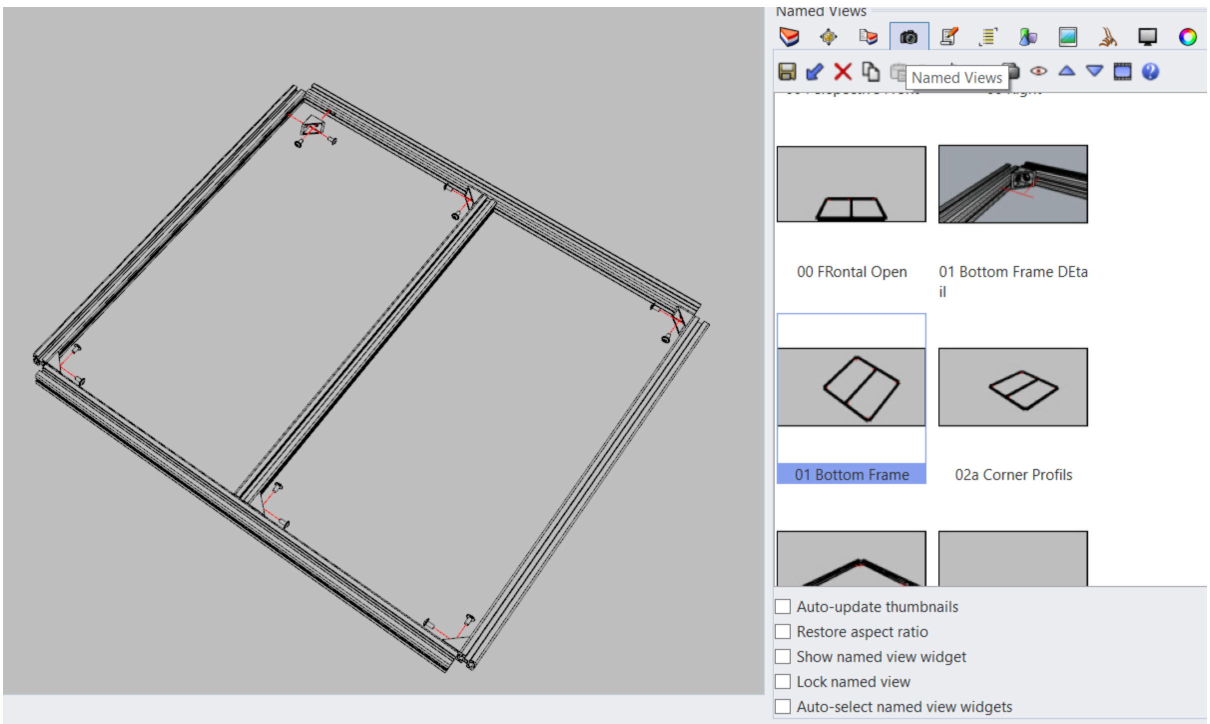


Figure 17: Named Views in Rhino 6

It was also important to show in the manual the chronology of steps to be taken. To emphasise the new parts to be added in each step, the parts from previous steps are colored grey and the new parts kept black. However, to do this for every step is a laborious task. For this reason, “Layer States” were used to have this semi-automated.

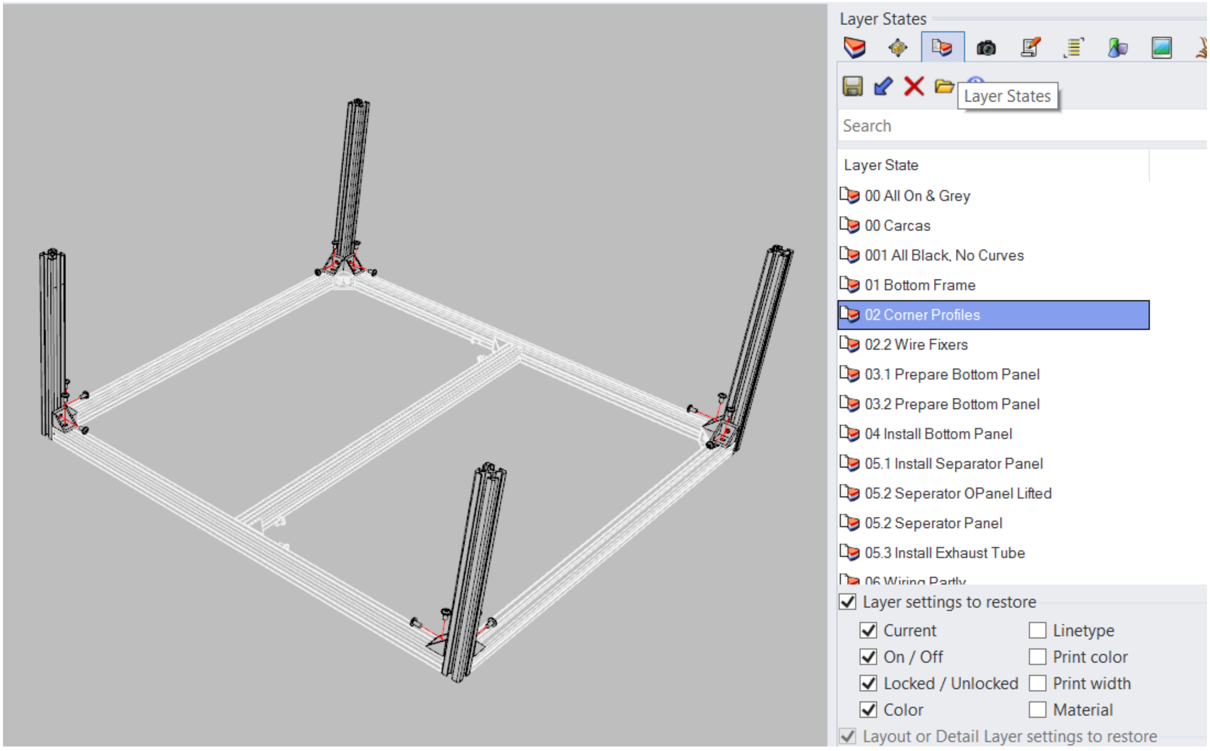


Figure 18: Layer States in Rhino 6

To create the illustration, 2D screenshots of each step were taken and exported into a vector illustration. Rhino 6 had a "Snapshot" function which combined all the previously mentioned functions (Layers, Layer States, Named Views, Named Positions) but, because of a bug, this function increased the file enormously with each change, making it unusable. Fortunately, Rhino3D version 7 has eliminated this bug, enabling the snapshot function, which was of great help.

The rendering of the illustrations was also customised to the desired outcome; Rhino3D has the possibility to create your own rendering settings. To have the image as clear as possible, all the unnecessary lines were removed in the rendering before exporting it as a vector screenshot. Edges appear whenever parts have fillets and chamfer; these were removed according to our purpose.

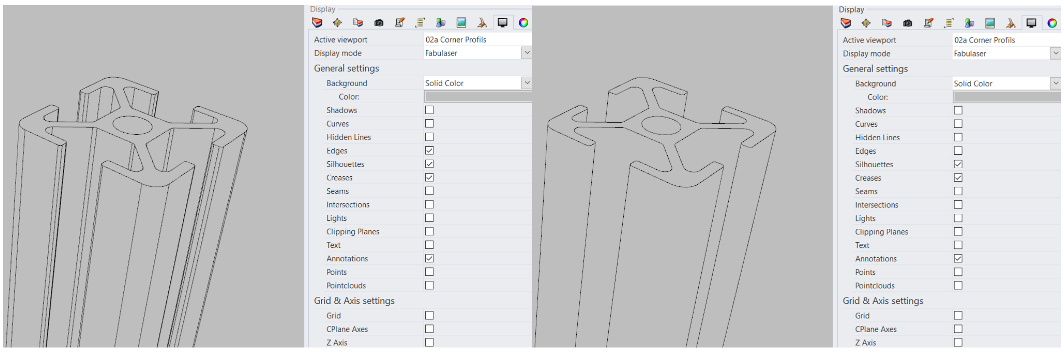


Figure 19: Detail on the rendering settings in Rhino 6 showing illustrations with (left) and without (right) the edges rendering lines

Designing the manual

The information that could not be illustrated were added to the step page in text format in a list of remarks. There were basic instructions and tips that were needed in more than one step, such as inserting T-nuts and inserting the mirrors in the mirror holders. To cover these, it was decided to add a "how-to" section to the manual, to avoid repetition of information and provide better support to beginner users.

The step page layout was designed considering all the requirements mentioned previously: inclusion of title, step number, list of parts, tools, time, version, main view, detailed view, remarks and how-tos. After some design iterations, the final layout can be seen in figure 20.

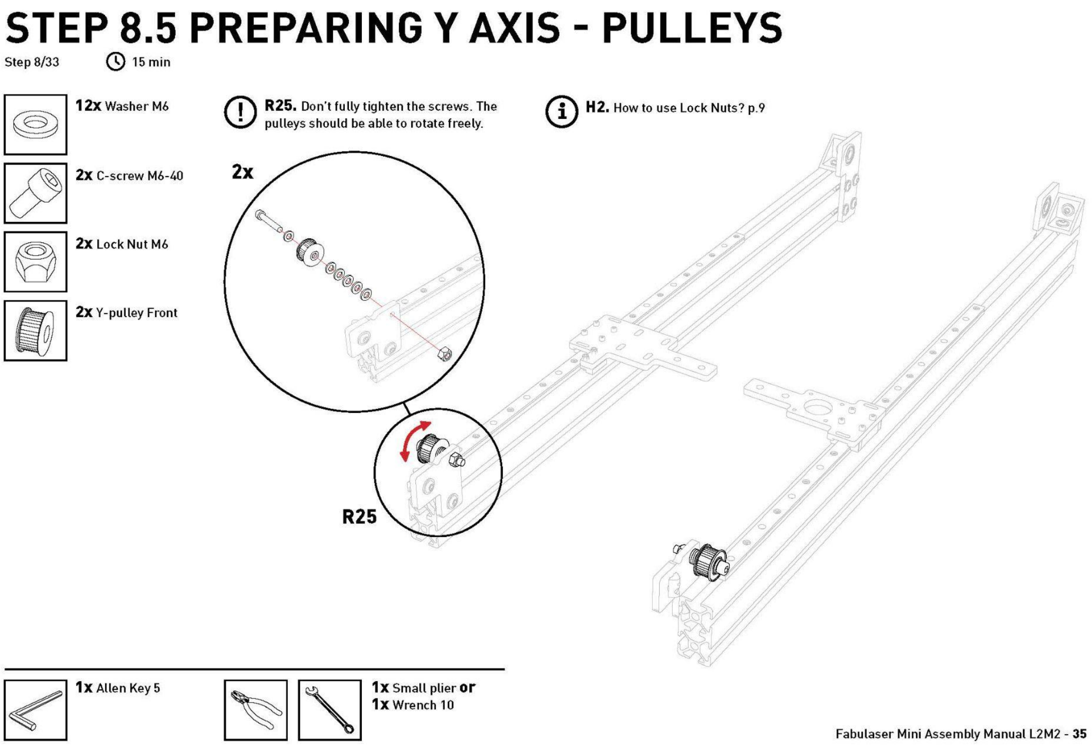


Figure 20: Example of a step page of the Fabulaser assembly manual

The software used were Adobe InDesign and Adobe Illustrator, which are professional tools to create editorial design and vector images, respectively. As mentioned previously, similarly the use of Rhino3D, this software choice was made due to time-efficiency,

Through the creation of a page layout template in InDesign, all components of the page had a pre-defined space, which facilitates the creation and consistency of the manual.

On the left side of the page, the list of parts includes the parts name, the necessary quantity for the step and icons, which facilitates its identification among more than a hundred other parts. The remarks have codes which can be referred to in the illustrations, and the how-tos refer to their respective page number. The diagram below explains the general structure of the manual (Figure 21).

Unfortunately, the vector images exported from the Rhino3D could not be directly used in the manual layout, since they had to be exported in a bigger size to keep the rendering of the details sharp and accurate. For this reason, each illustration needed to be resized, recolored and have its line width adjusted in Adobe Illustrator before being inserted in the manual layout.

The use of colours in the design is functional to help identify parts and highlight information. As mentioned previously, while the already assembled parts fade to a dark grey colour, the parts to be assembled are displayed in black. Red lines represent motion and help the user understand the direction and position of the parts to be assembled. Template tools are also illustrated in a different colour to highlight that they are special tools and not machine parts.

The explanation of the electronic wiring also uses colours to visually aid the user to achieve a successful connection. Although the colours of the jumper cables, for example, are not relevant for the function of the machine, having defined colours helps the checking of the connections when working in a group.

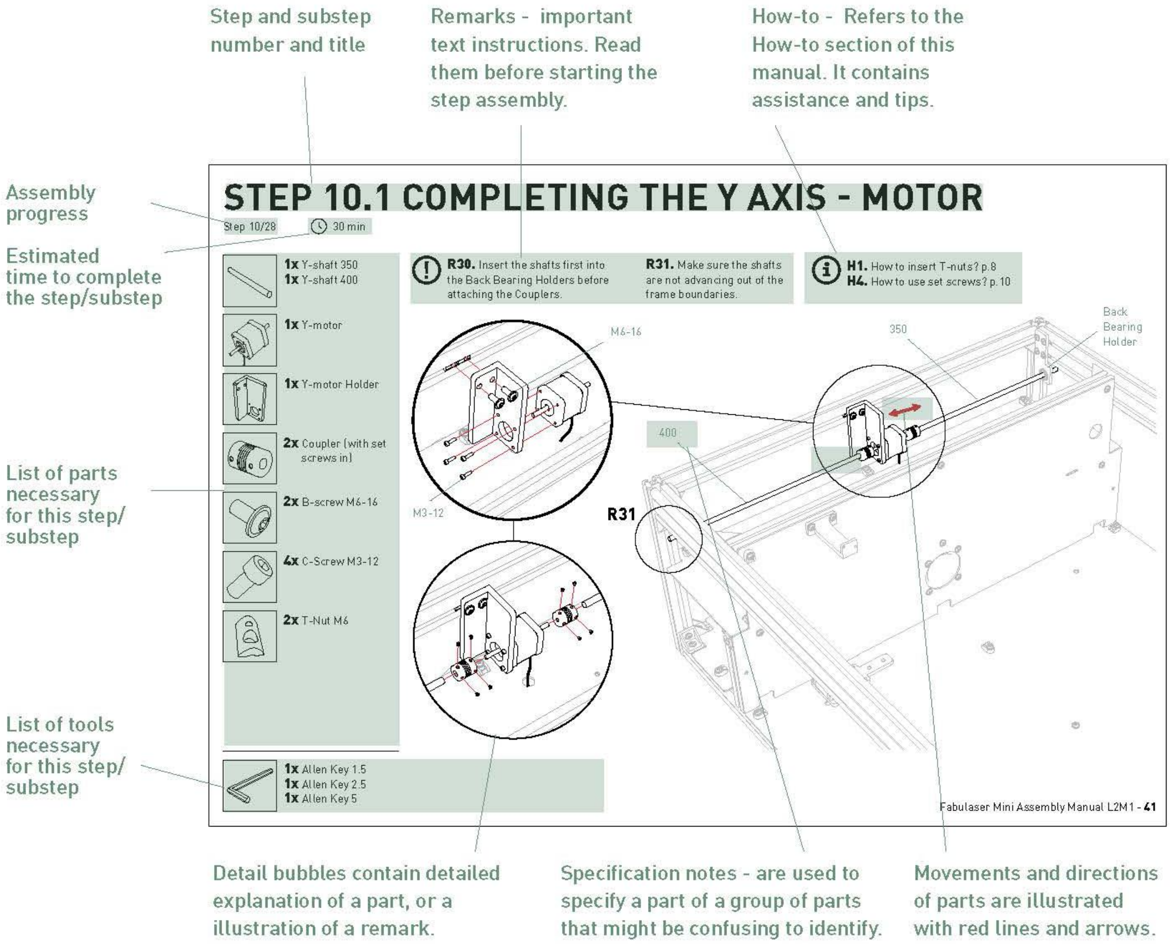


Figure 21: Structure of the assembly manual step page

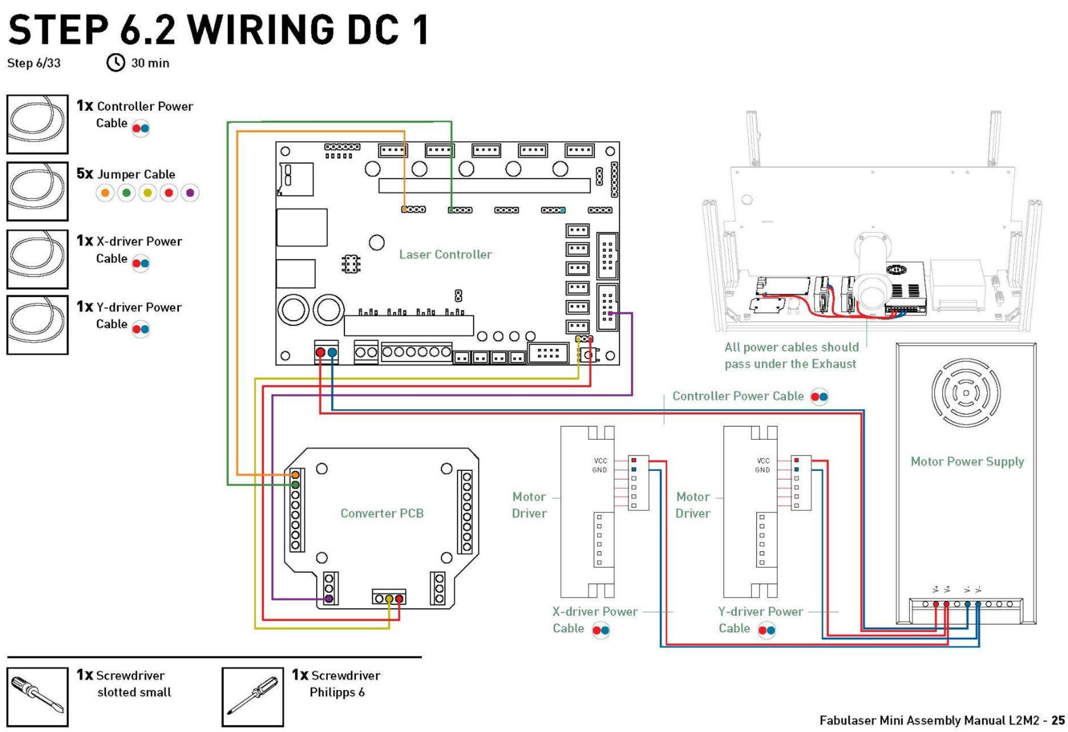


Figure 22: Example of the assembly manual instructing part of the wiring

5.2 Workshops

Building the machine is the best way to have a deeper understanding of how it works and the purpose of each part. While the assembly manual was still in its initial state, the Fabulaser Mini assembly kit could only be purchased with a machine building workshop. The first 3 workshops were essential to the development of the manual; through these workshops the assembly manual could be tested by observing in which points the participants were having difficulty. Every workshop provided valuable feedback, exposing corrections to be made and possible improvements, not only in the manual but also in the machine design and production of the kit, which were considered and implemented in the next productions.

Workshop structure and process

In the beginning of the workshop, after the introduction, the workshop environment needs to be set up. Apart from defining the workspace for the groups and placement of parts and tools, the Fabulaser Mini needs to be built on top of a very flat surface to guarantee the frame assembly precision

The participants are asked to open the boxes of the kit and organise all the parts on a surface to facilitate the finding of the parts and tools. The assembly of the machine is mostly linear but some steps can be done in parallel, as mentioned previously. This was done to optimise the time of the workshop and have parallel groups building the machine at the same time, depending on the number of participants.

Once the groups are defined, the participants can start the assembly of the steps instructed by the workshop leader. During the assembly, the leader needs to observe closely, intervene whenever the participants are stuck or going in the wrong direction, and take notes of the observations. In order to test the usability of the manual, participants were left as independent as possible, using it as a reference.

Figure 23: Fabulaser Mini workshop.Two groups are working in parallel using the assembly manual

After the workshop, the observations are discussed and the team evaluates if an action needs to be taken or not. This experience with the workshops has shown that, once the manual had passed through several iterations and improvements of the steps order, illustrations and texts, the interference of the team in the assembly process during the workshops became minimal, proving its efficiency.

		Actions required in:										
		Workbook	Illustrations	Manual	Icons.PDF	Discussion	Action	Packing	Rhino	BOM	Fusion 360	Production
General	https://jamboard.google.com/d/1FZmjTwAhK3Uuwe7yvf_aojpql1jz6CdSgzLvEhCwK_U/viewer?f=2											
	Label the "extra" bag of fasteners differently...like "Reserve" ?					Talk - name it extra parts		☐				
	For my school workshops: Need more Tools when working in parallel groups: 4 sets of inbuss											
	They mistakenly swapped the corner profiles so a Red Dot Sticker is a necessity							☐				
	Measuring band / long ruler in list of Tools		☐	☐	☐	Talk - recommended to use a 1m ruler.			☐			
	For my school Workshops: Zollstock needed											
	We need the red dot sticker	☐	☐	☑	☐		Only visible untill step 5	☐		☐		
	I need better set of screwdriver for the schools											
	The Middle profile Align Template needs two notches to rest on the profiles while adjusting the distance between the profiles		☑	☑	☑	Liane will redesign the templates	Make 3D Files of the Vector files		☐			☐
	Labels on the Bags are not the same as in the manual							☐				☐
	Template Nr 1 must be redesigned							☐				
	is there a way to make the holes in the Laser Panel more smooth for the wires ???					Talk - Daniele will smooth them						
1. bottom frame												
	They did not know how to position the midlle profile...should we make that clear ?	☐	☐	☐		Talk	move middle profile to step 3.1? We ignore. It is too complicated to change for now.		☑			

Figure 24: Example of an organisational action table created to analyse the observations of a workshop

6 Safety aspects

Because the Fabulaser Mini was developed and created in Germany, all remarks about CE and safety aspects are related to European law and regulations.

6.1 CE Certification

As a producer of machines, it is necessary to have the CE mark on the machine, in order to sell it. This mark affirms the machine's conformity with health and safety standards. The CE certification process consists of testing and checking the machine according to various directives. In case of the Fabulaser Mini, that would be the Machinery Directive, Directive 2006/42/EC for machines in general, and specifically for laser cutters, the iec 60825 Standard. The whole process needs to be documented well.

Since many of the assembly kits were built by novices there was no possibility to go through the elaborate process of checking the conformity to health and safety standards, making it not possible to add a CE certification on the machine. This is a common global practice with every assembly kit.

However, the health and safety aspects were taken seriously; the iec 60825 standard was checked for safety of Laser Cutters and all the requirements for a Class 1 Laser Cutter needed were used. Some are mentioned below:

- Apply safety stickers according to iec 60825 standard on the proper positions
- The lid, when opened, should have a double safety switch to shut off the laser
- The window should withstand a laser beam for 10 seconds
- It should have an emergency button, well visible and reachable

6.2 Schools

When building a machine, schools need extra attention, since the children and teenagers have little or no understanding of building, constructing, tools and materials. Building a laser cutter is quite a challenge, which needs to be done precisely otherwise the laser cutter will not function properly. In addition, there are various safety aspects regarding the tools and materials used. For this reason, teaching and instructing the students on safety is a constant measure taken by the team.

Once the building of the machine is finished, a Safety Instruction on how to use the Fabulaser Mini is provided to the team of young makers. For the teacher or responsible person, a different safety instruction is given. A mandatory Safety Instruction sheet is also made available.

Furthermore a checklist is used together with the teacher to confirm the status of the machine on the last day of the workshop, making sure all the risks are checked, taken away and problems are solved. This document is stamped and signed. The schools who have built a Fabulaser Mini can also make use of an explanatory online board, created with the Miro platform, which is updated regularly.

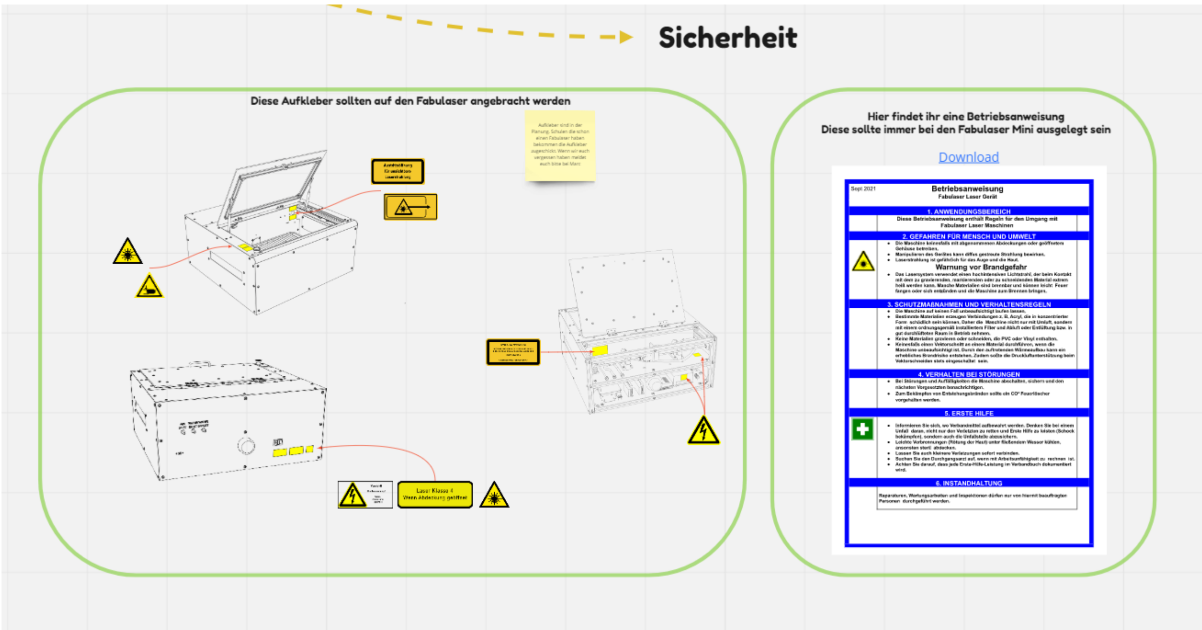


Figure 25: Example of the Safety Instruction sheet on the Fabulaser Miro Board

7 Conclusion and future work

The main hardware problems of Fabulaser Mini V1 and V2 are relative to the complexity of the construction of the frame, the laser calibration and the electric noise.

A single corner of the frame that joins 3 profiles, for example, requires 3 brackets, 6 screws and 6 nuts for a total of 15 pieces; only in the bottom section of the frame there are 4 corners for a total of 60 parts. In addition to the long time required for the assembly, the procurement of such parts also demands a long process. Furthermore, the more the joints assembled manually, the more difficult it is to align the frame properly, resulting in a skewed Y axis and a challenging if not impossible laser calibration.

The laser calibration requires precision in positioning the mirror holder, the laser tube and in adjusting the mirrors. A slight push of the laser mirror holder in the wrong direction may require several minutes to recover the correct position; every step must be done thoughtfully.

Combining the precision required to assemble the frame and to execute the laser calibration, the machine building requires constant focus, making it hard for inexperienced users. The time record of building a Fabulaser Mini is about 20 hours from 2 expert makers (including the inventor), which is a long time considering the small size of the machine.

Because of the high voltage of the laser tube used (maximum 23KV), Fabulaser Mini V1 had stability problems caused by electric noise. To tackle this, Fabulaser Mini V2 used shielded cables and a different wiring arrangement to increase stability. It is still possible, in case the user does not follow the manual, that V2 still suffers from resets during laser firing.

Fabulaser Mini V3 has been developed keeping the above issues in mind: it has implemented a completely redesigned frame which uses machined surfaces to easily square the machine, and uses a coaxial laser pointer to help calibration. With the pointer, there is no need to shoot the laser every time, reducing risk. Furthermore, the second mirror holder of the V3 has a fixed position, reducing the adjustment needed for the laser calibration.

The production of the parts and preparation of the kit also suffered major improvements. For example, some cables were combined to avoid mistakes in the connections, and some parts were pre-attached to facilitate the assembly, in case the participants did not have the correct tools, such as soldered parts (e.g. power plug and mains cable) or parts that need to be pushed with considerate force (e.g. Y-bearing Back and Back bearing holder).

Regarding the assembly manual, it is considered by experts state-of-the-art in open source assembly documentation, the process to achieve the current result was challenging and still needs improvements.Through the workshop's experience, the team agrees that only experts can build the machine relying solely on the manual with the team availability to offer support when needed.

Although the manual emphasises the importance of the assembly precision in text, usually the participants of the workshops do not fully understand and, for this reason, do not give enough attention and importance to it. The laser calibration also requires some level of explanation and expertise, which is hard to achieve using only the current manual. If the user does not have the understanding of what needs to be adjusted and when, the process of calibration can be extremely daunting and frustrating.

In addition, the efficiency of the manual depends on the attention and carefulness of the user to read it. The experience has shown that many participants do not read the manual, even though the amount of text is very minimal. Furthermore, they do not pay attention to the details of the images, attaching a part upside down, for example. It could be a further improvement of the manual to avoid that such details are not missed, by, for example, reducing the information on a single page. However, as with all manuals, it is not fully guaranteed that the user will follow the instructions presented.

Another documentation issue the team encountered is the difficulty in updating the manual. Since the illustrations are done through snapshots of the 3D file, once one step has a modification, all following illustrations that display this modification need to be remade.

This process is unfortunately not efficient and needs to be addressed in the future. Currently, the updating of the machine documentation is slower than the hardware development, making it unsustainable.

In addition, the manual versioning planned was not entirely followed, since small changes and corrections were often made without creating a new version. This lack of tracking is also confusing for the team and the users and needs to be addressed and improved.

The translation of the manual to other languages demands a long process because of the software choice, which requires Adobe licence to modify the file, making it difficult for other people to access.

The synchronisation of the manual, the BOM (Bill of Material) and the kit preparation was also a point that took some iterations of workshops to establish. The naming of the parts was one of the first issues that the team encountered since the labels of the kit contained the production name and were not matching with the name in the manual, making it difficult or sometimes impossible for the workshop participants to find the correct part. Also some parts names were confusing or too long and had to be modified to provide more information on the part or to simplify it.

Developing Fabulaser Mini has been a long journey of learning about making an open source laser cutter in Fab Labs, and helping others replicate it with the documentation. It has been keeping into account Fab Lab capabilities and limitations, open sourceness of design and knowledge transfer. We are happy to have made a laser cutter that has been used for the Computer Controlled Cutting Assignment in Fab Academy and that about 20 schools are now using in their activities nowadays. A Fabulaser Mini was also built with a remote workshop, where instructions and support was entirely given via videoconferencing. Lastly, Fabulaser Mini has been added to the Fab Lab Inventory in April 2022.

A fork or Fabulaser Mini V2 is currently part of the Open Lab Starter Kit (OLSK), a research project within Fab City Hamburg and in cooperation with the Helmut Schmidt University. The goal of the OLSK is to develop a set of open source digital fabrication machines to be used in Fab Labs. The machines of the OLSK are:

- large format CNC milling machine (2500 x 1250 x 300 mm)
- small format CNC milling machine (600 x 400 x 100 mm)
- large format laser cutter (1000 x 700 mm)
- small format laser cutter (600 x 400 mm)
- large format 3D printer (1000 x 1000 x 1000 mm)
- small format 3D printer (200 x 200 x 200 mm)
- vinyl cutter
- 3D scanner

The research program is structured in a 3 years timeframe, with each machine released in 3 different versions, counting a total of 8 machines per year and 24 machine versions. Fabulaser Mini V3 has been taking inspiration from the design of the large format laser V1.

Figure 26: OLSK large format laser cutter

The assembly documentation for these machines will also have major improvements based on the previous learnings. It is intended to have all manuals for the OLSK machines available as a web page and generated semi-automatically to facilitate distribution and updates. The documentation process will also be simplified by substituting the creation of the 2D illustrations by an online 3D viewer, which will reduce considerably the time needed.

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References

https://github.com/fab-machines/LaserDuo

https://github.com/fab-machines/Fabulaser-Mini

https://www.inmachines.net/open-lab-starter-kit

https://www.fabcity.hamburg

https://dtecbw.de/home

https://github.com/cprezzi/grbl-LPC

https://github.com/grbl/grbl

https://fabacademy.org/

https://ohwr.org/cern_ohl_w_v2.pdf

https://miro.com/app/board/o9J_l1vaKqQ=/?share_link_id=718372924635

http://inventory.fabcloud.io/

https://github.com/makerbase-mks/MKS-SBASE

https://www.pjrc.com/store/teensy41.html