Orbitool SO3 v1.4

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Should a tool-board *magic smoke* come out because of user error? Why?

Should a tool-board be destroyed by a fault in your 3D printer? Why?

My answer is NO! And this is what this tool-board is all about!

We are hobbyist and professionals, and let's face it, we make mistakes, and when the magic smoke shows up, everybody is disappointed, even if we know it's a user's fault. In this board, I promise you the *magic smoke* is kept inside extremely tight!

Smokeless Features

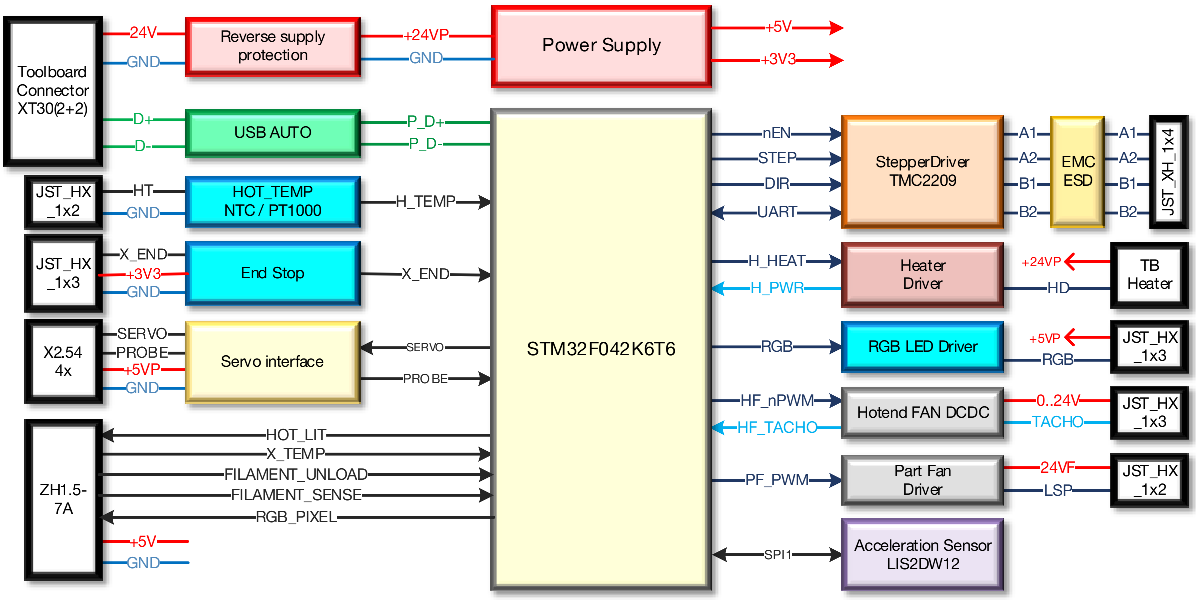
- Optimized for Smart Orbiter v3 shape and features
- STM32F042 microcontroller running at 48MHz
- Automotive USB communication with a Raspberry PI
- Onboard LIS2DW12 accelerometer
- TMC2209 extruder stepper driver
- Direct connection to SO3 integrated board
- 1x PWM controlled part fan outputs
- DC-DC converter based Hot-end fan driver, compatible with 12/24V fan types with RPM speed input signal
- Hot-end temperature sensor input compatible with standard NTC or PT1000 temperature sensor types
- I/O for bed level sensor
- X-Stop sensor input
- Onboard temperature sensor
- Advanced thermal management

Protection Features

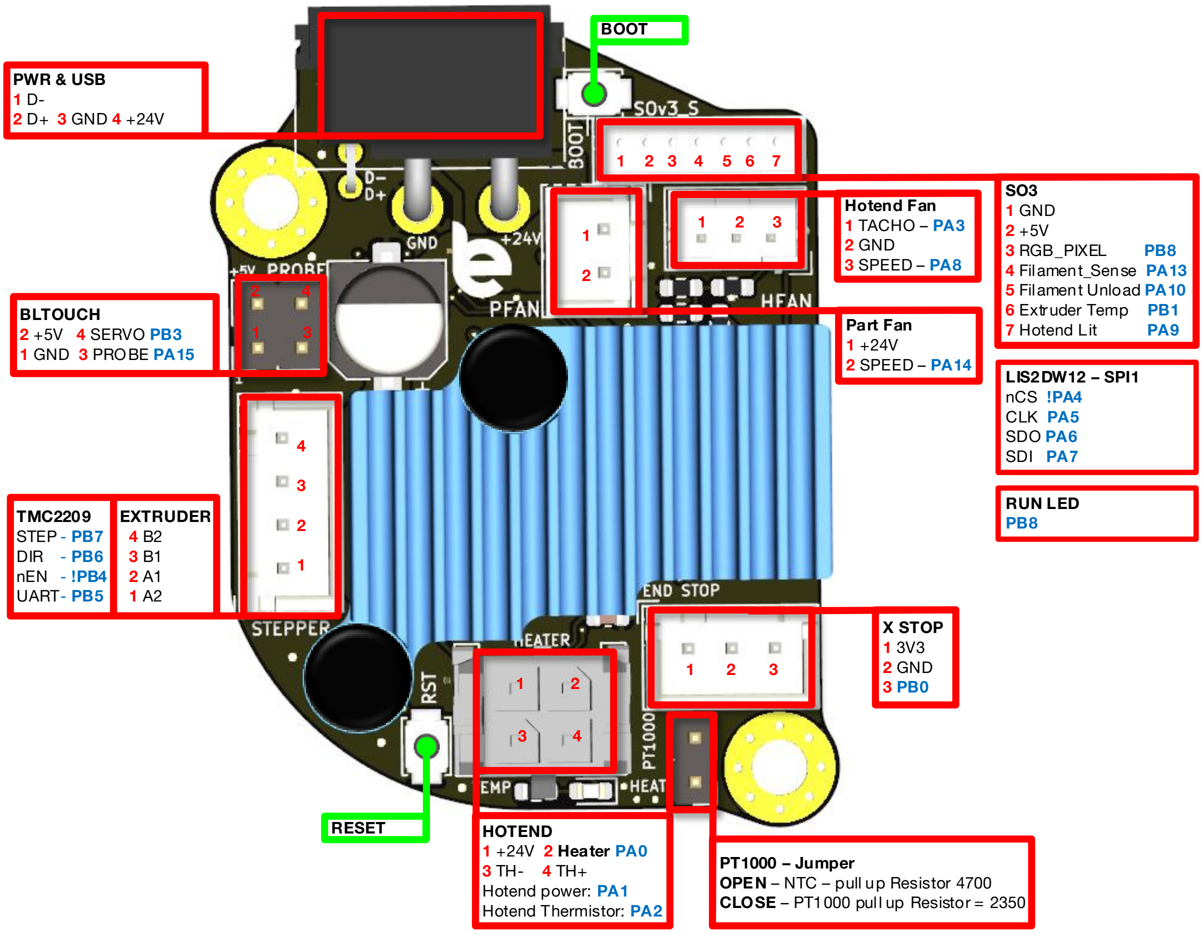
- Active short circuit protected Hot-end output
- Active short circuit protected fan driver outputs
- Active Protection circuit against reverse power supply connection
- Protection against loss of GND supply
- Analog and digital inputs protected against short to +24V supply voltage
- USB data lines are protected against short circuits to GND and +24V
- EMI interference and ESD protection on all inputs and outputs
- Heater thermal runaway protection in case of a short between heater and sense thermistor wires

1 Block Diagram

Block diagram for Orbitool SO3 v1.4.



2 Pinout definition



3 Features description

3.1 Introduction

For me, the electrical robustness of a design is part of the requirements. One of my main design goals was to integrate protection against common user errors and 3D printer defects.

In the end, nothing is more frustrating than powering up your new board and letting the *magic smoke* out. Even if it is due to user fault, the disappointment will still be present.

This design is based on automotive technology, where protection from all kinds of hazards is a state-of-the-art a long time ago.

This document describes the main specific features of the tool-board.

3.2 Power supply concept

The board is supplied via an XT30 (2+2) connector, which includes +24V, GND, USB_DATA+ and USB_DATA- signals.

From the connector, the board is supplied via a reverse power supply protection circuit. This prevents tool-board damage. In the event of an accidental reversed supply by user error, the board will not start up and will behave like it's not powered

The microcontroller is supplied from a 3.3V LDO supplied from the onboard 5V DC-DC buck converter for the highest power supply efficiency and lowest possible power consumption

3.3 USB communication interface

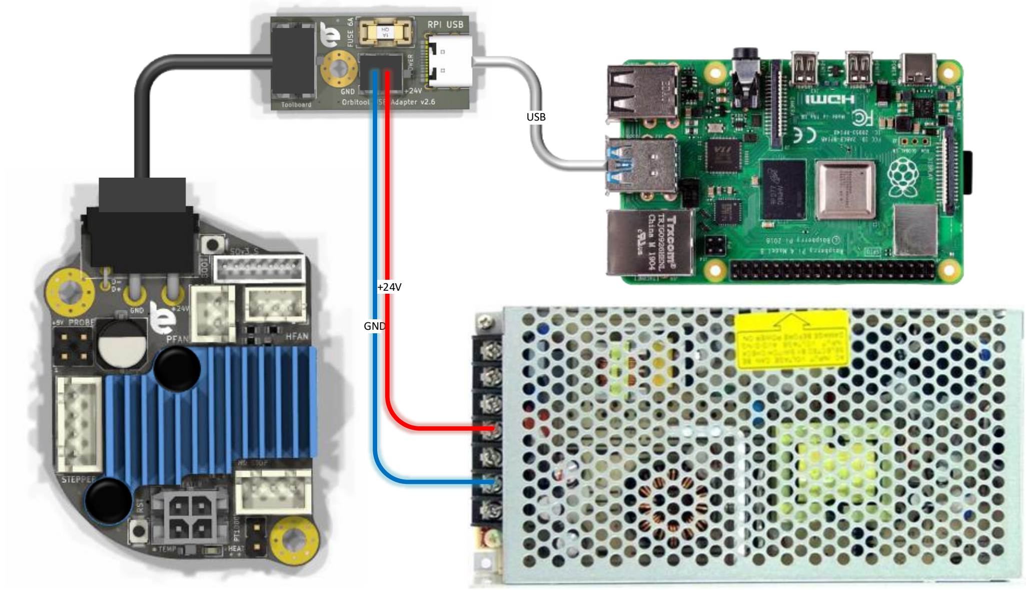
The tool-board is equipped with an automotive grade USB interface. The main difference is the higher electrical robustness of the automotive USB, still maintaining highest possible communication speed. Therefore, if the USB data lines are short-to-GND or up to +28V, it will not cause any destruction and will work properly after the short circuit is removed.

The same circuit offers protection in case of GND connection loss, which will lead to biasing all the communication signals to the supply positive line (in our case, +24V).

The USB interface of the Raspberry Pi is not robust against these electrical hazards that may occur in a 3D printer. Therefore, the tool-board shall be supplied and connected to the Raspberry Pi using the supplied adapter board, which has onboard protection circuits to protect the Raspberry Pi USB port.

The next picture presents the tool-board wiring connection principle.

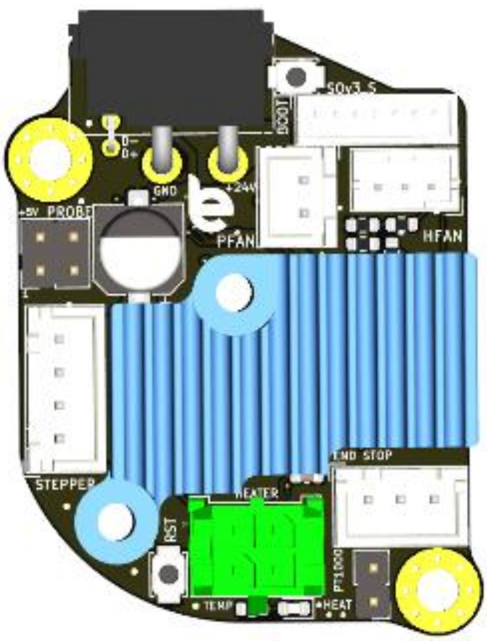
SO3 tool-board wiring diagram.



3.4 Hot-end & temperature sensor

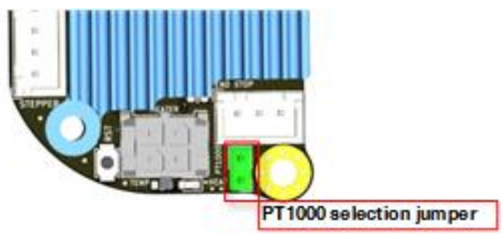
The hot-end temperature input circuit accepts two types of thermal sensor elements,

- **100k NTC** - ATC Semitec 104GT-2, included in the SO# hotend. Pull up resistor value 4700
- **PT1000** selectable via closing Jumper PT1000. Pull up resistor value 2350. Option for connecting custom hot ends to the SO3



The senor input is protected against short circuits to GND and to the 24V supply voltage.

The SO3 tool-board has a protection circuit against dangerous thermal runaway due to a short circuit between the hotend GND and the thermistor GND connection. Without this protection the hotend heater would turn on with 100% power and go into a dangerous thermal runaway, which of course represents a fire hazard condition, and Klipper can do nothing against it. The probability of this failure, of course, is small, but considering the severity of the outcome, this board is the first to implement a protection against this event.



Hotend heater driver circuit

The hot-end heater driver circuit is implemented with active protection against short circuits.

The circuit measures the heater current and in case the current rises over a predefined threshold i_{OC_HOT}, it switches off the heater MOSFET until the next PWM cycle to prevent damage.

The heater max power shall be limited to 99.5%, meaning max_power: 0.995 to avoid driver stuck in protection mode due to an unlikely event of a fake error detection.

```
max_power: 0.995
```

The heater current is fed to Klipper, which can calculate the actual power consumption of the heater element. This can be used to detect failures of the heater element, like a short circuit or a loss of heating power.

You may say yes; other boards also have protection with onboard fuses. Well, that is simply not enough to protect MOSFETs from being damaged because fuses have a long reaction time, about 1-2s range. Their mission is to protect the circuit from catching fire in case of a defect, but it cannot protect the heater driver MOSFET from getting destroyed. This active protection reacts within 10ms, ensuring the driver stage is switched off before it gets damaged due to a short circuit or overload event.

To display the actual power of the heater, include the following section:

```
[adc_temperature HOT_P]
#temperature1:5 # value in Ampere
temperature1:120 # value in Watts
#voltage1:1.32
voltage1:1.91
#temperature2:10 # value in Ampere
temperature2:240 # value in Watts
voltage2:3.82
#voltage2:2.64

[temperature_sensor Hotend_power]
sensor_pin: orbitool02:PA1
sensor_type: HOT_P
min_temp = -10
max_temp = 120
```

The hot-end power or current can be displayed based on preference. The power is calculated considering a 24V power supply.

To improve the heater power calculation accuracy, the heater PWM is forced to 100Hz (instead of the 10Hz default of Klipper).

```
max_power: 0.995 # limit heater power to 99.5% to enable autorecovery from short detection
pwm_cycle_time: 0.01
```

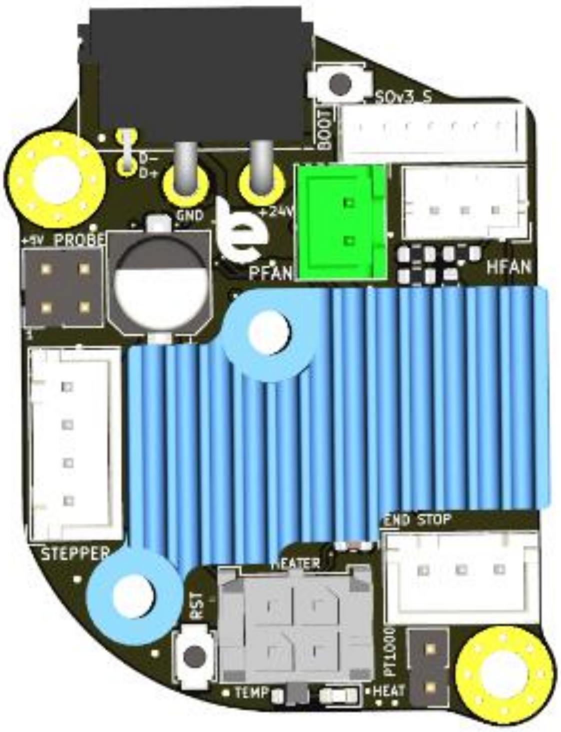
3.5 Fan driver outputs

The fan drivers (part fan and aux / tool-board fan) have a similar protection circuit to the hot-end driver; in case of overcurrent, the fan driver is switched off until the next PWM cycle.

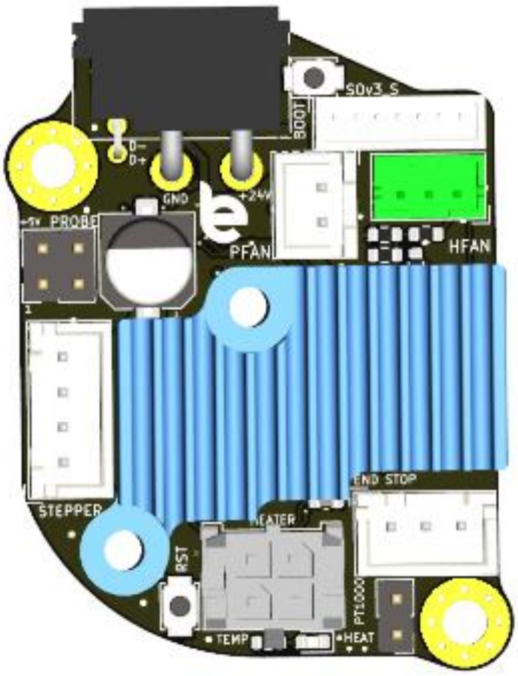
The PWM duty cycle of the fan driver shall be limited to 99.5%, meaning max_power: 0.995, to avoid the fan driver being stuck off due to an unlikely event of a fake error detection.

Suggested configuration of the part fan driver:

```
[fan]
pin: SO3:PA14
max_power: 0.995
shutdown_speed: 0.0
cycle_time: 0.02
kick_start_time: 0.2
hardware_pwm: False
```



3.6Hot-end fan output



The hot-end fan circuit is implemented using a microcontroller-controlled DC-DC converter.

PWM control of three wire fans will destroy the speed signal. PWM (Pulse Width Modulation) control means switching on and off the fan power supply several times every second. This means there are moments when the fan is actually not supplied with power. In those moments, the speed sensing electronic circuit is not supplied, therefore it cannot generate a reliable speed signal. Practically, the PWM signal will be superimposed over the speed signal.

Another advantage of this control circuit is the possibility of limiting the maximum voltage according to the fan type the user has.

This output supports 12V or 24V fan types configured by the max power value in the fan configuration section:

This output supports 12V or 24V fan types configured by the max power value in the fan configuration section:

- **12V** fan – max_power: 0.5
- **24V** fan – max_power: 1.0

The Smart Orbiter is equipped with a 24V fan type, so the default should be *max_power :1.0*.

To reduce hotend fan noise, its power can be reduced to 60%. In the case of clogs while printing very slowly, the fan speed needs to be increased.

Configuration of the Hotend fan driver:

```
[heater_fan hotend_Fan]
pin: !SO3:PA8
tachometer_pin: SO3:PA3
heater: extruder
cycle_time: 0.0001 #10KHz PWM frecvency
heater_temp: 75
fan_speed: 1.0
hardware_pwm: false
shutdown_speed: 0.0
max_power: 1.0
tachometer_ppr: 2
tachometer_poll_interval: 0.001
```

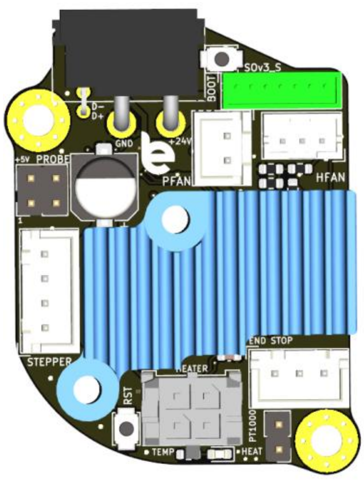
* Note the PWM control frequency of the circuit must be set to 10KHz, *cycle time: 0.0001*

Since the fan driver is based on a DC-DC converter, the PWM frequency required for correct operation is defined by the converter design, not by fan properties. Fan PWM speed control frequency shall be set to 10 Khz, cycle time = 0.0001 – do not change this to a lower frequency.

3.7 SO3 Extruder smart features connector

SO3 tool-board features a connection to the Smart Orbiter v3 internal electronics, fully supporting its features:

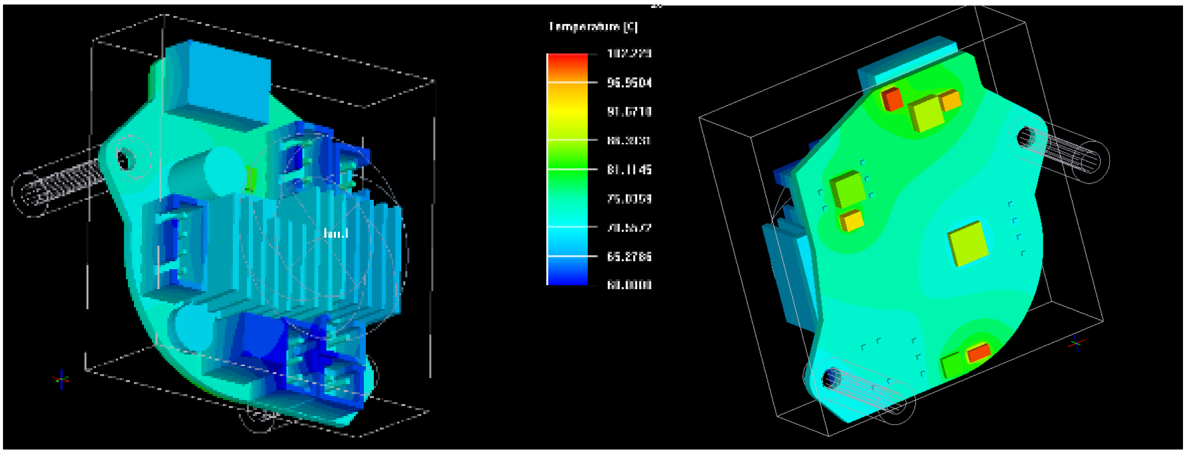
- Filament sensing and autoload
- Filament autounload
- RGB LED-lit filament input
- White LED hotend lit
- Extruder temperature sensor



3.8 Thermal considerations

Closed printer chamber requires tool-board operation in high ambient temperature conditions. In addition, this tool-board is mounted on the backside of the stepper motor, which transfers a considerable amount of heat. Therefore, the circuits of this tool-board are designed to have low temperature drift and efficient thermal management to make sure none of the components heat up over their maximum allowed operation temperature.

I performed lots of thermal simulations using finite element simulations and real-life measurements using a Flir thermal camera (simulation results from the Orbiter 2 SO2 tool-board but the basic design is the same with the SO3).



The simulation result show that in a 60°C chamber temperature environment, the tool-board components do not heat over their maximum junction temperature rating.

The SO3 tool-board is safe to operate in maximum **60°C** ambient (printer chamber) conditions.

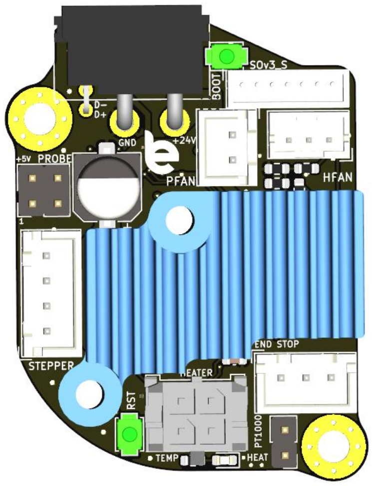
To reduce heat transfer from the stepper towards the tool-board a minimum distance of 4-5 mm shall be maintained. This is ensured by using the supplied standoffs.

The toolboard is designed for passive cooling, but even with the most optimized thermal design, stepper current derating over temperature still applies. This is mainly because there is simply not enough space for a bigger heatsink. Even if the heatsink size were doubled, it would still not be enough.

However, it is possible to use the SO3 tool-board in closed chamber temperatures over **60°C** up to **75°C** with additional measures:

- Reduce stepper current from 0.85A to 0.55A
- Use active cooling by adding a small 20x20mm or 25x25mm fan to the back of the tool-board which blows a small amount of air toward the SO3 tool-board heatsink. The power supply lines of the fan can be connected in parallel with the hotend fan.

4 Microcontroller programming



1. Connect the board to the host Raspberry Pi via a USB adapter cable.
2. This step depends on whether your board has firmware on it or not:
   a) If your board is pre-flashed with Klipper, first must enter DFU mode as follows:
      - press the BOOT and RESET buttons,
      - release the RESET while keeping the BOOT button pressed,
      - release the BOOT button after about three seconds.
      - The buttons might be a little tricky to access. Hint, use some ceramic screwdriver or simple toothpicks to push the buttons and avoid creating any short over the board with metal tools

   b) If your board is a new, un-flashed board:
   - The MCU is already in DFU mode; confirm this at step 4

3. Connect to your host raspberry pi via SSH
4. Run lsusb from the command prompt
   - Make sure you see an STM32 in DFU mode listed
5. Run dfu-util --list from the command prompt
   - note the text inside the [xxxx:yyyy] (default is -> 0483:df11)
6. Run cd ~/klipper from the command line to enter the Klipper directory
7. Run make menuconfig settings should be:
   - Cristal oscillator – 8Mhz

```
(Top)
                          Klipper Firmware Configuration
[*] Enable extra low-level configuration options
    Micro-controller Architecture (STMicroelectronics STM32)  --->
    Processor model (STM32F042)  --->
    Bootloader offset (No bootloader)  --->
    Clock Reference (8 MHz crystal)  --->
    Communication interface (USB (on PA11/PA12))  --->
    USB ids  --->
    Optional features (to reduce code size)  --->
()  GPIO pins to set at micro-controller startup
```

- Set custom USB ID to *SO3Tool*

```
(Top) → USB ids
                    Klipper Firmware Configuration
(0x1d50) USB vendor ID
(0x614e) USB device ID
[ ] USB serial number from CHIPID
(SO3Tool) USB serial number
```

- Optional features (to reduce code size):

```
(Top) → Optional features (to reduce code size)
                    Klipper Firmware Configuration
[*] Support GPIO "bit-banging" devices
[ ] Support LCD devices
[*] Support external sensor devices
[*] Support lis2dw 3-axis accelerometer
[ ] Support ldc1612 eddy current sensor
[ ] Support HX711 and HX717 ADC chips
[ ] Support ADS 1220 ADC chip
[ ] Support software based I2C "bit-banging"
[ ] Support software based SPI "bit-banging"
```

- Hit Q to Exit and Save

8. Run make clean to clean up the make environment
9. Run make flash FLASH_DEVICE=0483:df11
10. In case you encounter some errors but still having the message of File downloaded successfully than you are good to proceed to the next step.

```
DFU mode device DFU version 011a
Device returned transfer size 2048
DfuSe interface name: "Internal Flash  "
Downloading to address = 0x08000000, size = 23004
Download        [=========================] 100%        23004 bytes
Download done.
File downloaded successfully
Transitioning to dfuMANIFEST state
dfu-util: can't detach
Resetting USB to switch back to runtime mode
roby@Machcube:~/klipper $
```

11. Press the RESET button to restart the MCU and enter normal operating mode
12. Run ls /dev/serial/by-id/* should return a device beginning with:
    /dev/serial/by-id/usb-Klipper_stm32f042x6_SO3Tool-if00
13. Copy this virtual serial port name to the SO3.cfg config file MCU section

```
[mcu SO3]
serial: /dev/serial/by-id/usb-Klipper_stm32f042x6_SO3Tool-if00
restart_method: command
```

Manual definition of USB ID, flashing the MCU with Klipper will always result in the same serial ID.

Your tool-board should now be usable with Klipper. Use the example config file to get started. The best option is to copy the config file into the same directory as printer.cfg.
Add [include SO3.cfg] to the beginning of your printer.cfg to include the file.

5 Assembly instructions

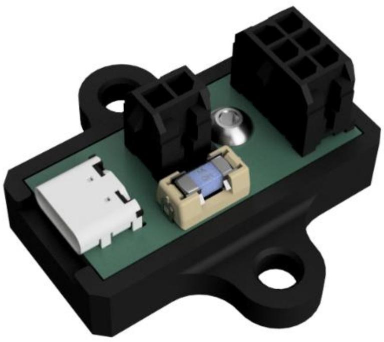
Based on the user setup, we can have several assembly combinations, as described below. As a recommendation, some kind of bracket with strain release for the USB cable is a must. Fixing the cable is necessary to prevent constant bending forces over the PCB during printhead movements. Even if the forces are not very high, it still stresses the PCB, and it could develop component or solder cracks. A well-designed strain release will avoid this issue.
Mount the two M3 L=18mm standoffs to the Orbiter v2 stepper's backside.

Print the braket and the wire lock (downloadable from GitHub).

Insert the toolboard into the bracket, and using the two M3 L=8 mm and two washers fix it to the two standoffs.

Insert the USB cable and fix it into place using the printed wire lock.

To fix the small USB adapter board to the printer frame, you may use my simple mount, as shown in the next picture. All you need is to print the mount, an M3 heat insert (L = 4~5 mm), and an M3 screw (L = 6 mm). The PCB mount can be fixed to the printer frame using two M3 screws and nuts, or attach it simply using strong foam tape.



Tool-board pack list

Orbiter v2 Toolboard pack list				
Item	**Description**	**Nr pieces / length**	**Type**	**LCSC**
1	Orbitool v1.4	1	v2.72	
2	USB adapter board v2.6	1	v2.6	
3	24V USB cable	150cm		
4	24V power supply cable	50cm		
5	Short USB A to USB C cable	30cm		
6	1 pin Dupont female connector housing	4		
7	Dupont connector pins	6	A2541-TB	C339354
8	XH-2 pin connector housing	1	XH-2	C144401
9	XH-3 pin connector housing	1	XH-3	C144402
10	XH crimp pins	10	SXH-001T-P0.6N	C385122
11	M3 threaded aluminum spacer **L=20mm**	2	M3 L20	
12	M3 screw L = 8mm	2	M3x8	
13	Me screw L = 25	2	M3x25	
14	M3 washers	2	M3	
15	2.54mm Jumper	2		

6 Tips and tricks

Correct operation of the toolboards and basically any 3D printer electronics depends on the environment they are used. Even if these toolboards have lots of protection circuits, it does not mean that improper installation or usage cannot cause damage or malfunction.

Below is a list of recommendations when wiring DIY 3D printers:

1. The printer frame must be connected to mains earth and GND.

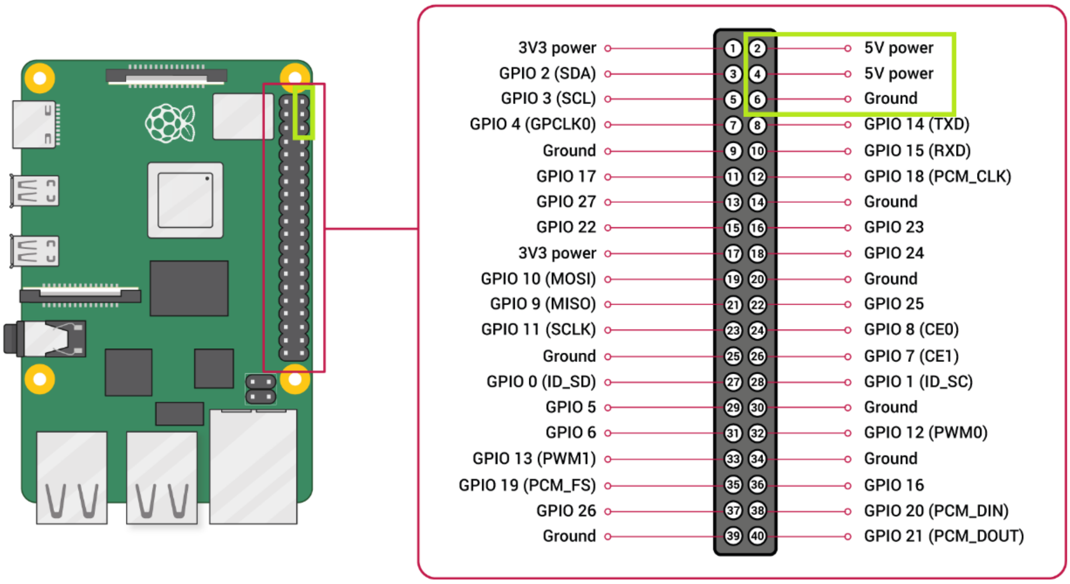
2. Aluminum bed shall be connected to frame and GND. A severe crash of the toolhead into the bed or print piece causing the toolhead to brake may cause short circuits between the bed and any input or output of the toolboard (like heater, fan outputs or end-stop, temperature sensor inputs, etc.). If the bed is not connected to GND, then it can have any voltage potential level even in the range where the toolboard protection circuit is not effective anymore, leading to loss of functions or total damage.

3. Toolhead made with metal parts shall be connected to GND with extra wire using proper electrical connection washer (washer with ribs or teeth, and hole for wire soldering). Not grounded toolheads will build up static charge, eventually, this will arc over the toolhead which may cause electrical damage to the toolboard (less likely) or disturb communication between the toolboard and RPI causing disconnection errors (very likely scenario).
4. When connecting wires to printer frame or any aluminum parts, special washers with toots or ribs shall be used! Aluminum oxide is very good electrical insulator, therefore using only a flat washer connector will not ensure proper electrical contact.



5. The small adapter board must be supplied with 5V, not less! The adapter board version v2.xx is taking the 5V supply from the USB-C connector. This voltage is used to supply the onboard USB protection circuit. If this voltage is less than 5V, the protection circuit may disturb the USB communication, causing toolboard disconnection failures. Note that using an improper power supply for the RPI (especially RPI 3 & 4) will lead to a lower USB voltage than 5V. The original power supplies of these PRI boards are actually providing 5.5V to compensate for the voltage loss over the internal voltage regulator and protection circuits of the RPI.

6. <u>USB cables are not the best choice to supply the RPI</u> due to high drop voltage over them. The best is to supply the RPI with 5V via the GPIO pin header pins with a proper cable. This ensures the supply voltage of the RPI is stable during sudden current load increases. Remember that when the adapter board is connected to the RPI, the supply voltage of the USB protection circuit is taken from the RPI, any disturbance in that is a potential communication disturber.



7 Electrical characteristics

7.1 Absolute maximum ratings

Important Note: The Orbitool SO3 board can withstand these limits without electrical damage; however, long-term exposure to these limits is not recommended. The absolute maximum rating is not the same as the functional range.

The maximum ratings may not be exceeded under any circumstances!

Table 1 Orbitool SO3 absolute maximum ratings

Nr.	Parameter	Min	Max	Unit
A1	Ambient temperature range	-20	85	°C
A2	Supply voltage	-30	30	V
A3	Extruder stepper current		1	A
A4	Hot-end heater current		6.8	A
A5	Part fan output current		1	A
A6	Hot-end Fan		0.5	A
A7	USB Data lines	-1	28*	V
A8	Hot-end temperature sensor input	-1	28*	V
A9	End stop input	-1	28*	V
A10	Z sensor I/O interface	-1	+15	V
A11	ESD-Protection level for handling (Human Body Model, HMB)	-8	8	kV

*Should not exceed the power supply voltage

7.2 Full Operational limits

Table 2 Orbitool SO3 electrical characteristics

Nr.	Parameter	Symbol	Min	Typ	Max	Unit
	General					
P1	Operating temperature range	t_o	-20		60	°C
P2	Max ambient temperature with active cooling	t_{o_cooled}			80	°C
P3	Power supply voltage	v_{PWR}	20		28	V
P4	Power supply voltage measurement accuracy	a_{PWR}	-3		3	%
	Extruder stepper					
P5	Extruder stepper current (max 60°C chamber temp)	i_{MOT_60}			0.85*	A
P6	Extruder stepper current (max 80°C chamber temp)	i_{MOT_80}	0.5		0.6	A
	Hot-end heater					
P7	Hot-end heater nominal current	i_{HEATER}			5	A
P8	Hot-end heater overcurrent switch OFF threshold	i_{OV_HOT}	5.9	6.8	7.2	A
P9	Hot-end overcurrent detection time	t_{OV_HOT}			10	ms
P10	Hot-end power measurement accuracy	a_{P_HOT}	-6		6	%
	Part Fan					
P11	Part fan output nominal current	i_{PART_FAN}			1	A
P12	Part fan overcurrent switch OFF threshold	i_{OC_PART}	1.2	2	2.5	A
P13	Part fan overcurrent detection time	t_{OC_PART}			5	ms
P15	Part fan PWM frequency	f_{PART_FAN}		100		Hz
	Hot-end Cooling fan					
P16	Hot-end fan output nominal current	i_{HOT_FAN}			0.4	A
P17	Hot-end fan current limitation	$i_{CL\_HOT\_FAN}$	2	3	3.9	A
P18	Hot-end fan PWM frequency	f_{HOT_FAN}	9	10	20	Khz
	Internal supplies					
P19	Internal 5V supply protection current limitation	i_{SC_5V}	2	3	3.9	A
P20	Internal 3.3V supply protection current limitation	i_{SC_3V3}	220	350	550	mA
P21	Weight			18		g

*Parameter derating with ambient temperature