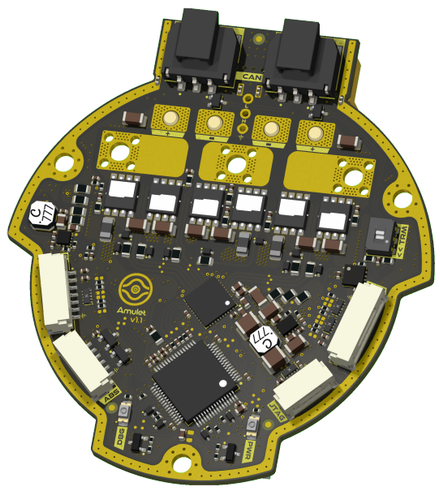
Amulet Motion Controller

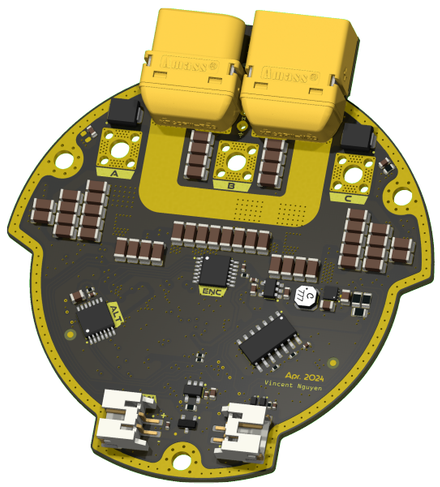
Variant: RELEASED

2025-01-18
Rev 1.1.1

TOP VIEW



BOTTOM VIEW



NOTES

Schematic based off Josh Pieper's moteus controllers.

Not fitted components are marked as X

DRAFT - Very early stage of schematic, ignore details.
PRELIMINARY - Close to final schematic.
CHECKED - There shouldn't be any mistakes. Contact the engineer if you find any.
RELEASED - A board with this schematic has been sent to production.

Date: 18-Jan-2025

DESIGN CONSIDERATIONS

DESIGN NOTE: Example text for informational design notes.

DESIGN NOTE: Example text for debug notes.

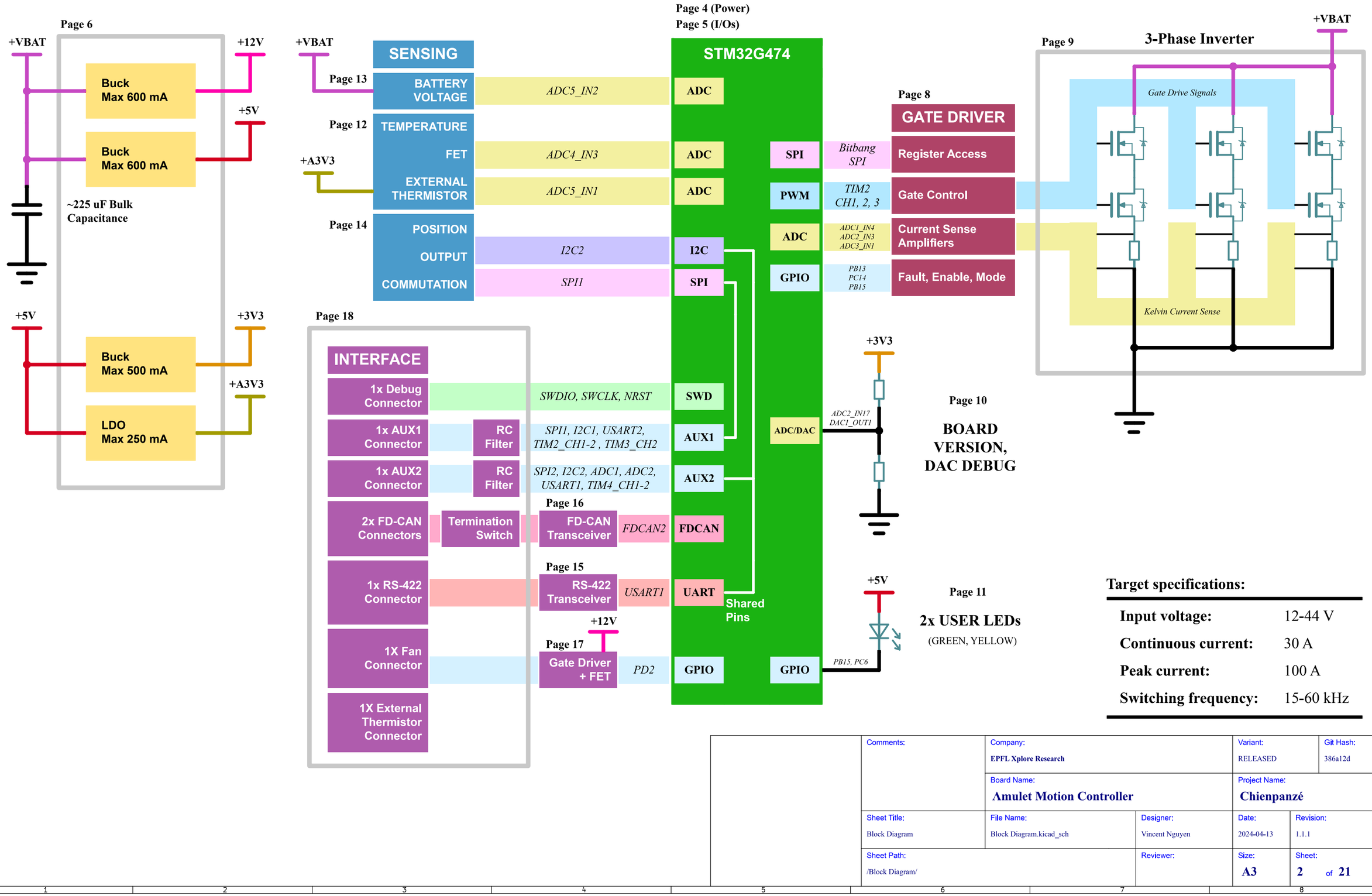
DESIGN NOTE: Example text for cautionary design notes.

DESIGN NOTE: Example text for critical design notes.

LAYOUT NOTE: Example text for critical layout guidelines.

Comments:	Company: EPFL Xplore Research		Variant: RELEASED	Git Hash: 386a12d
	Board Name: Amulet Motion Controller		Project Name: Chienpanzé	
Sheet Title: Cover Page	File Name: amulet_controller.kicad_sch	Designer: Vincent Nguyen	Date: 2024-04-13	Revision: 1.1.1
Sheet Path: /		Reviewer:	Size: A3	Sheet: 1 of 21

[2] Block Diagram

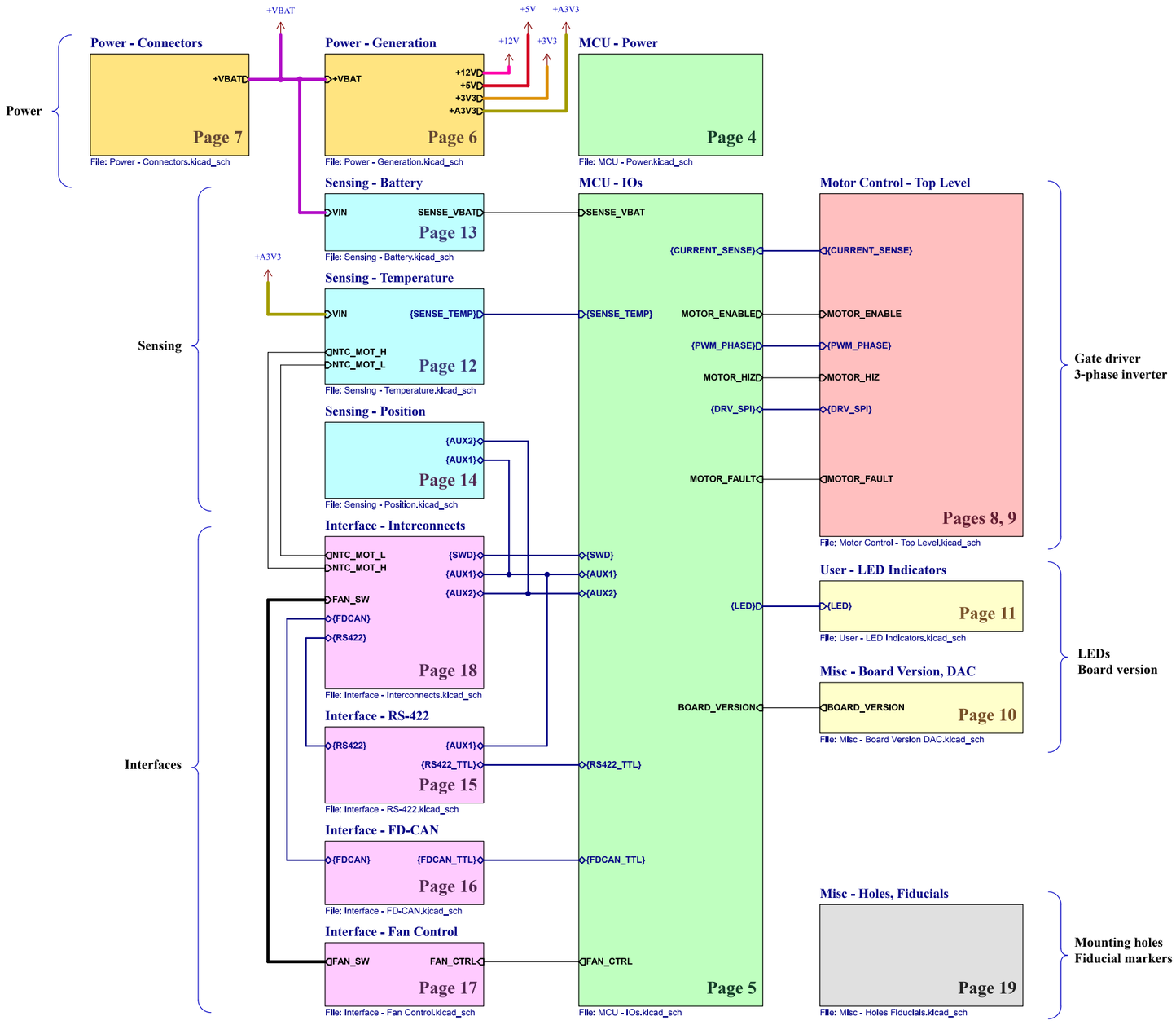


Target specifications:

Input voltage:	12-44 V
Continuous current:	30 A
Peak current:	100 A
Switching frequency:	15-60 kHz

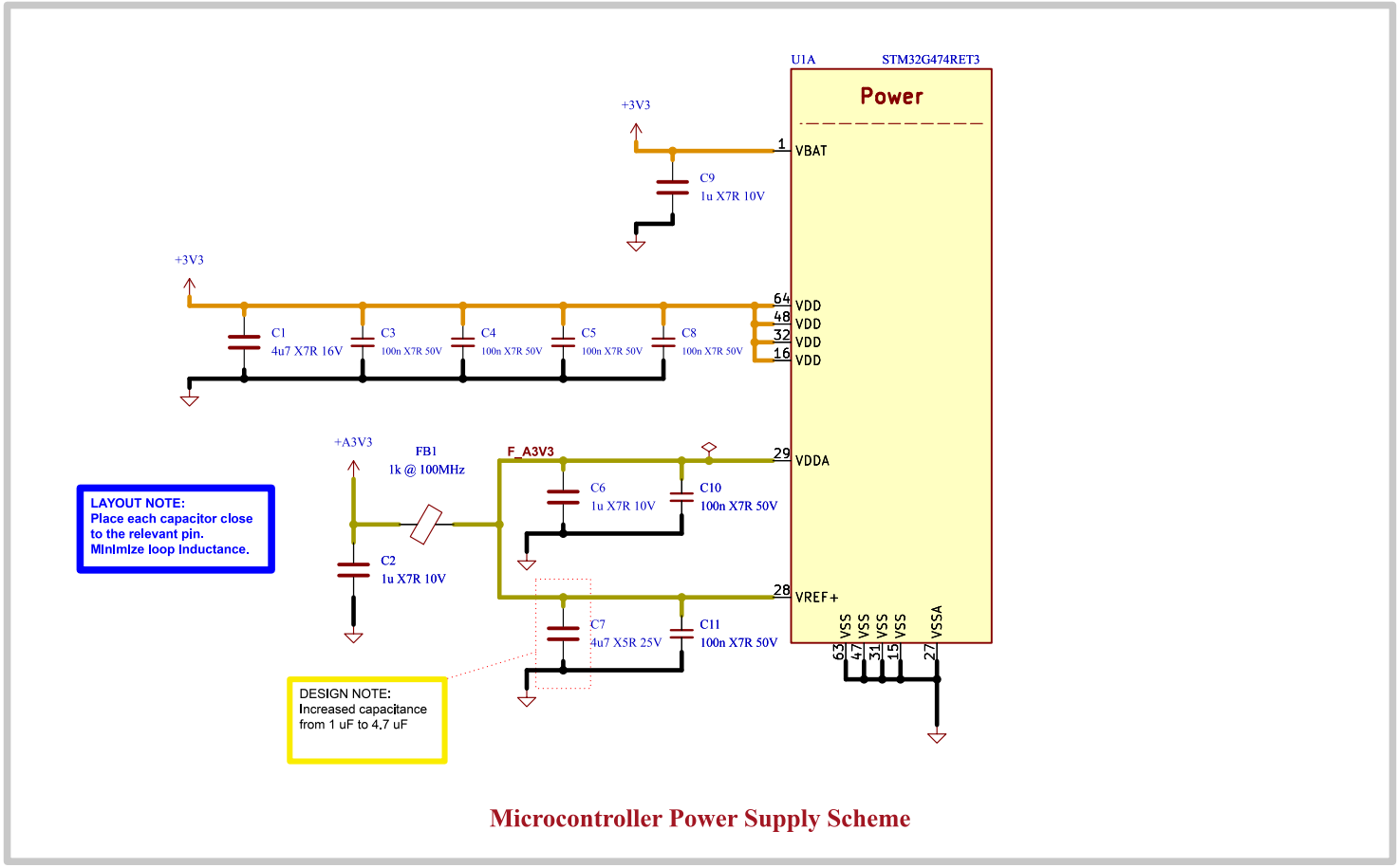
Comments:	Company: EPFL Xplore Research		Variant: RELEASED	Git Hash: 386a12d
	Board Name: Amulet Motion Controller		Project Name: Chienpanzé	
Sheet Title: Block Diagram	File Name: Block Diagram.kicad_sch	Designer: Vincent Nguyen	Date: 2024-04-13	Revision: 1.1.1
Sheet Path: /Block Diagram/		Reviewer:	Size: A3	Sheet: 2 of 21

[3] Project Architecture



Comments:	Company: EPFL Xplore Research		Variant: RELEASED	Git Hash: 386a12d
	Board Name: Amulet Motion Controller		Project Name: Chienpanzé	
Sheet Title: Project Architecture	File Name: Project Architecture.kicad_sch	Designer: Vincent Nguyen	Date: 2023-12-22	Revision: 1.1.1
Sheet Path: /Project Architecture/		Reviewer:	Size: A3	Sheet: 3 of 21

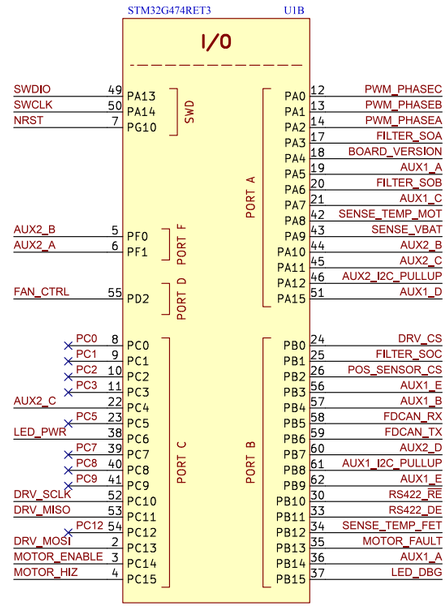
[4] MCU - Power



Microcontroller Power Supply Scheme

Comments: AN5346; STM32G474 Datasheet p.81; J. Pieper ADC investigation	Company: EPFL Xplore Research		Variant: RELEASED	Git Hash: 386a12d
	Board Name: Amulet Motion Controller		Project Name: Chienpanzé	
Sheet Title: MCU - Power	File Name: MCU - Power.kicad_sch	Designer: Vincent Nguyen	Date: 2023-12-18	Revision: 1.1.1
Sheet Path: /Project Architecture/MCU - Power/		Reviewer:	Size: A4	Sheet: 4 of 21

[5] MCU - I/Os

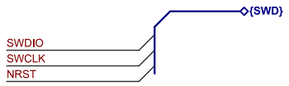


DESIGN NOTE:
We use the LQFP64 version to have extra pins for controlling an external fan.

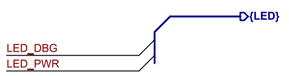
DESIGN NOTE:
Do not forget to flash option bytes when flashing for the first time.

LAYOUT NOTE:
Footprint devlates from datasheet and IPC7351 to allow for soldermask sliver between pads according to PCBWay design rules.

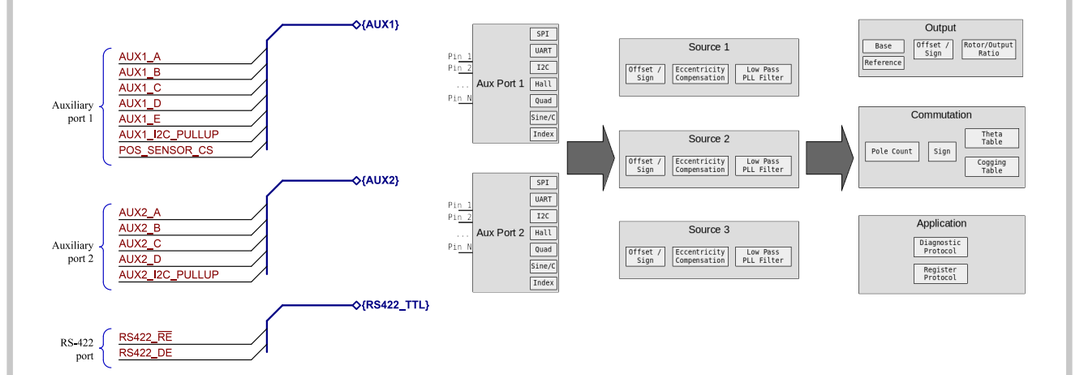
Microcontroller I/O Domain



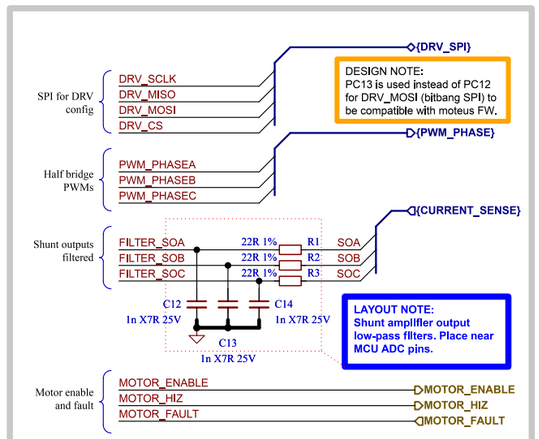
SWD (Debug) Port



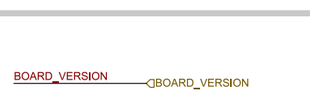
User LEDs



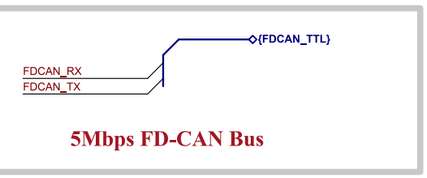
Auxiliary Ports



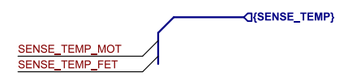
Connection to Gate Driver



Board Version Selection



5Mbps FD-CAN Bus



Temperature Sense

Battery Voltage Sense

Low-Side Fan Control

Gate Driver

MOTOR_ENABLE	TP1	MOTOR_ENABLE
MOTOR_HIZ	TP2	MOTOR_HIZ
MOTOR_FAULT	TP3	MOTOR_FAULT
DRV_SCLK	TP4	DRV_SCLK
DRV_MISO	TP5	DRV_MISO
DRV_MOSI	TP6	DRV_MOSI
DRV_CS	TP7	DRV_CS
PWM_PHASEA	TP8	PWM_PHASEA
PWM_PHASEB	TP9	PWM_PHASEB
PWM_PHASEC	TP10	PWM_PHASEC
SOA	TP11	SOA
SOB	TP12	SOB
SOC	TP13	SOC

Debug

SWDIO	TP14	SWDIO
SWCLK	TP15	SWCLK
NRST	TP16	NRST

Auxiliary pins 1

AUX1_A	TP17	AUX1_A
AUX1_B	TP18	AUX1_B
AUX1_C	TP19	AUX1_C
AUX1_D	TP20	AUX1_D
AUX1_E	TP21	AUX1_E
AUX1_I2C_PULLUP	TP22	AUX1_I2C_PULLUP
POS_SENSOR_CS	TP23	POS_SENSOR_CS

Auxiliary pins 2

AUX2_A	TP24	AUX2_A
AUX2_B	TP25	AUX2_B
AUX2_C	TP26	AUX2_C
AUX2_D	TP27	AUX2_D
AUX2_I2C_PULLUP	TP28	AUX2_I2C_PULLUP

RS-422

RS422_RE	TP29	RS422_RE
RS422_DE	TP30	RS422_DE

LEDs

LED_DBG	TP31	LED_DBG
LED_PWR	TP32	LED_PWR

FD-CAN

FDCAN_RX	TP33	FD_CAN_RX
FDCAN_TX	TP34	FDCAN_TX

Fan

FAN_CTRL	TP35	FAN_CTRL

Sense

SENSE_TEMP_MOT	TP36	SENSE_TEMP_MOT
SENSE_TEMP_FET	TP37	SENSE_TEMP_FET
SENSE_VBAT	TP38	SENSE_VBAT

Test Points

Comments:
References:
Flexible I/O worked examples
Flexible I/O source configuration

Company: **EPFL Xplore Research**

Variant: RELEASED

Git Hash: 386a12d

Board Name: **Amulet Motion Controller**

Project Name: **Chienpanzé**

Sheet Title:	File Name:	Designer:	Date:	Revision:
MCU - I/Os	MCU - IOs.kicad_sch	Vincent Nguyen	2023-12-20	1.1.1

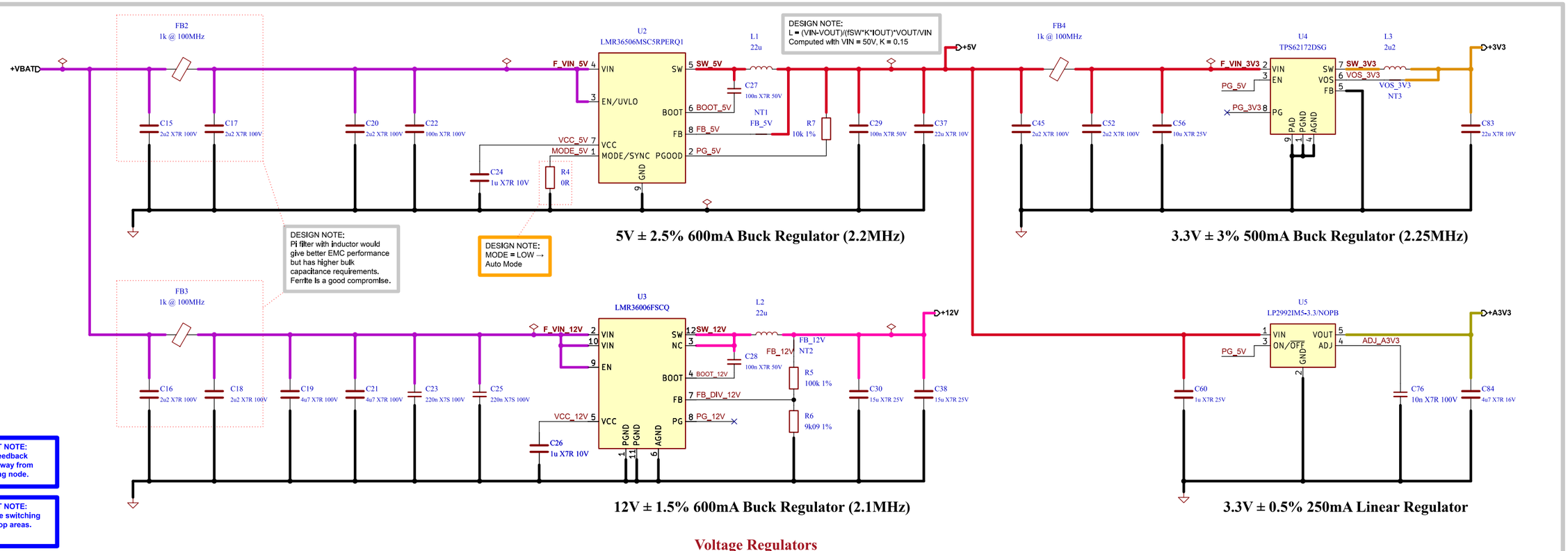
Sheet Path: /Project Architecture/MCU - IOs/

Reviewer:

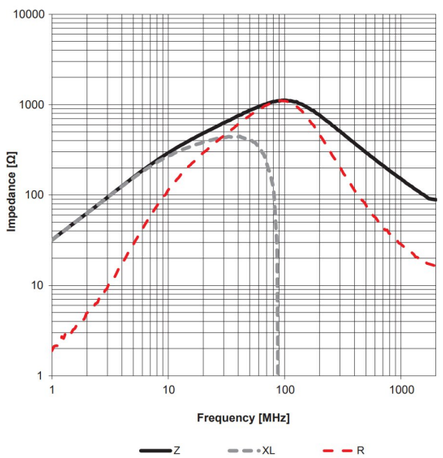
Size: **A3**

Sheet: **5** of **21**

[6] Power - Generation

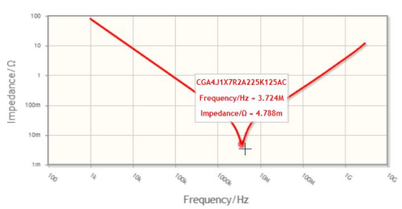


Ferrite bead Impedance vs Frequency curve



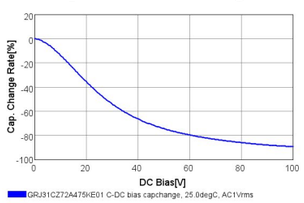
DESIGN NOTE:
XL drops around 45th harmonic.

Pi filter capacitor Impedance vs Frequency curve



CGA4J1X7R2A225K125AC

Bulk capacitance Derating curve



DESIGN NOTE:
Effective capacitance at 33V is approximately 2.1 uF

Capacitor and Ferrite Bead Parameters

Battery

+VBAT	TP39	+VBAT
+VBAT	TP40	+VBAT
+VBAT	TP41	+VBAT

Filtered Power Rails

F_VIN_12V	TP42	F_VIN_12V
F_VIN_5V	TP43	F_VIN_5V
F_VIN_3V3	TP44	F_VIN_3V3

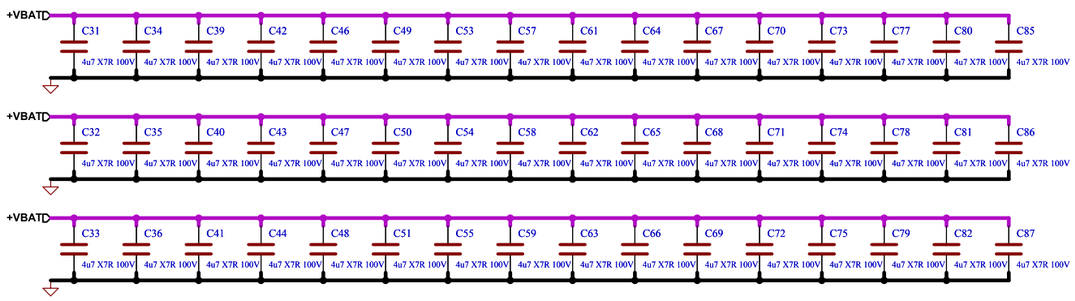
Power Rails

+12V	TP45	+12V
+5V	TP46	+5V
+5V	TP47	+5V
+3V3	TP48	+3V3
+3V3	TP49	+3V3
+3V3	TP50	+3V3
+A3V3	TP51	+A3V3

Ground

GND	TP52	GND
GND	TP53	GND
GND	TP54	GND
GND	TP55	GND
GND	TP56	GND
GND	TP57	GND
GND	TP58	GND

Test Points



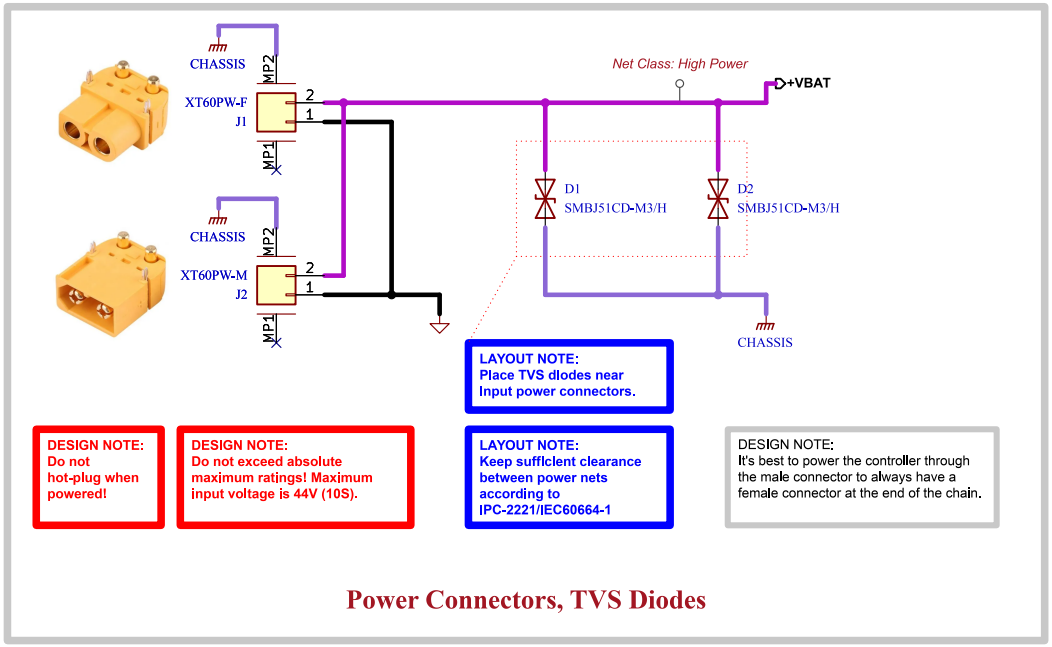
DESIGN NOTE:
An external precharge circuit is advised to charge the bulk capacitors if multiple boards are connected.

DC-Link Bulk Capacitors. 48 x 4.7 uF = 225.6 uF (100.8 uF at 33V)

DESIGN NOTE:
X6S 10uF is marginally better (but worse DC bias derating) at a higher price.

Comments: +12V (600 mA): Fan power +5V (600 mA): Gate Driver, LEDs +3V3 (500 mA): digital 3.3V +3V3A (250 mA): analog 3.3V	Company: **EPFL Xplore Research**	Variant: RELEASED	Git Hash: 386a12d
	Board Name: **Amulet Motion Controller**	Project Name: **Chienpanzé**	
Sheet Title: Power - Generation	File Name: Power - Generation.kicad_sch	Designer: Vincent Nguyen	Date: 2024-04-13 / Revision: 1.1.1
Sheet Path: /Project Architecture/Power - Generation/		Reviewer:	Size: **A3** / Sheet: **6** of **21**

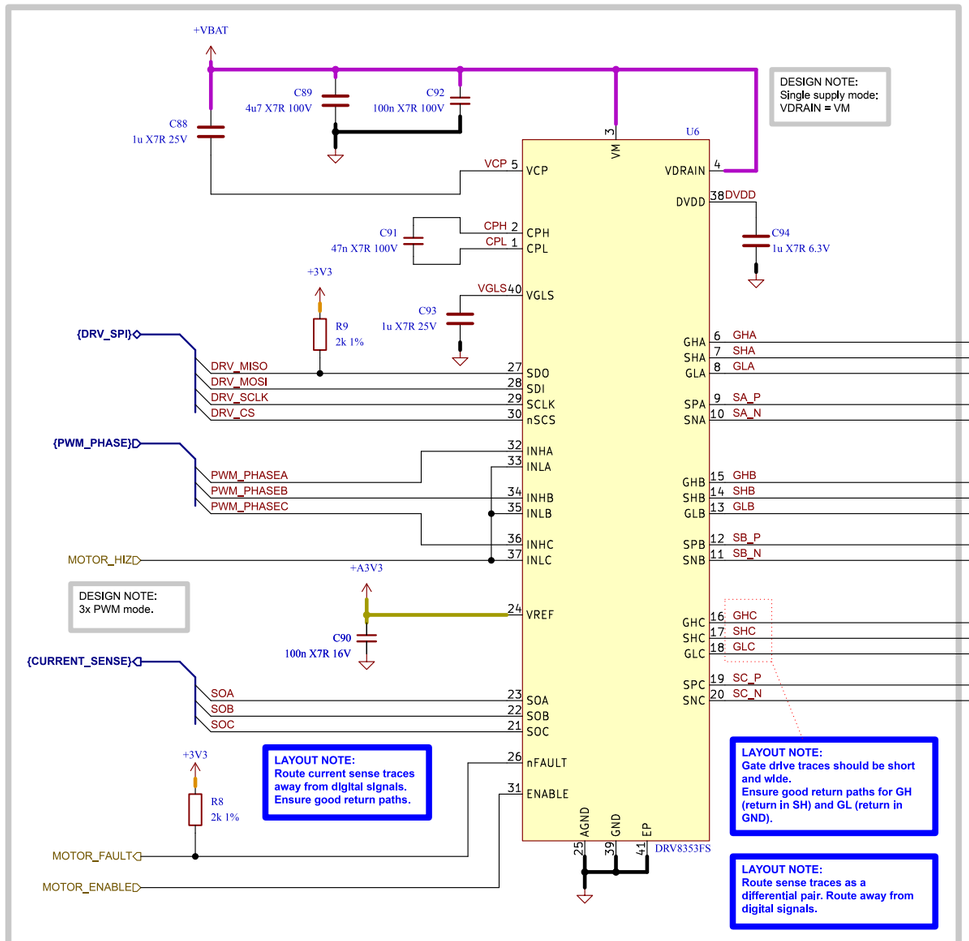
[7] Power - Connectors



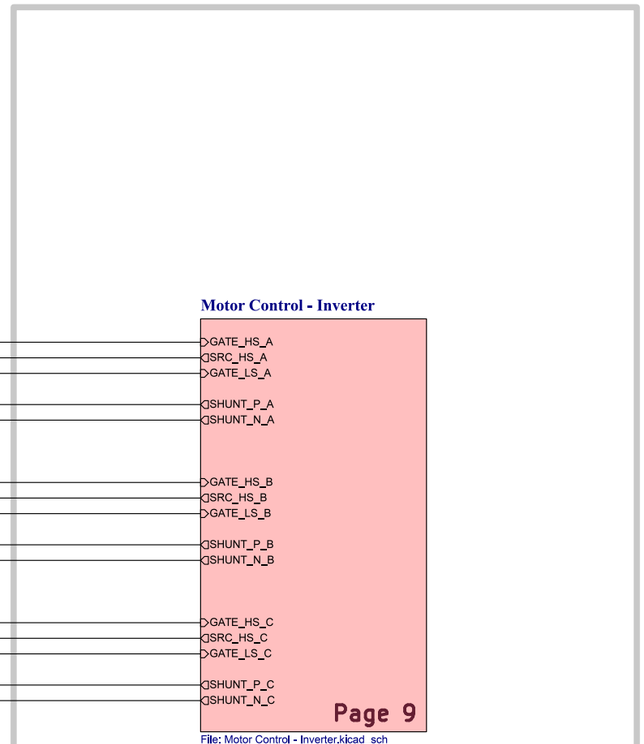
Power Connectors, TVS Diodes

Comments:	Company: EPFL Xplore Research		Variant: RELEASED	Git Hash: 386a12d
	Board Name: Amulet Motion Controller		Project Name: Chienpanzé	
Sheet Title: Power - Connectors	File Name: Power - Connectors.kicad_sch	Designer: Vincent Nguyen	Date: 2023-12-31	Revision: 1.1.1
Sheet Path: /Project Architecture/Power - Connectors/		Reviewer:	Size: A4	Sheet: 7 of 21

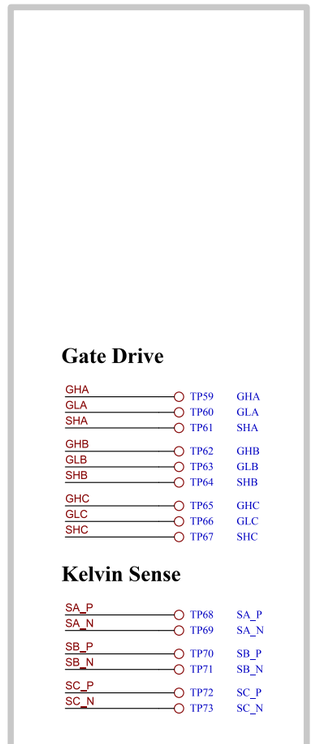
[8] Motor Control - Top Level



100-V Three-Phase Smart Gate Driver



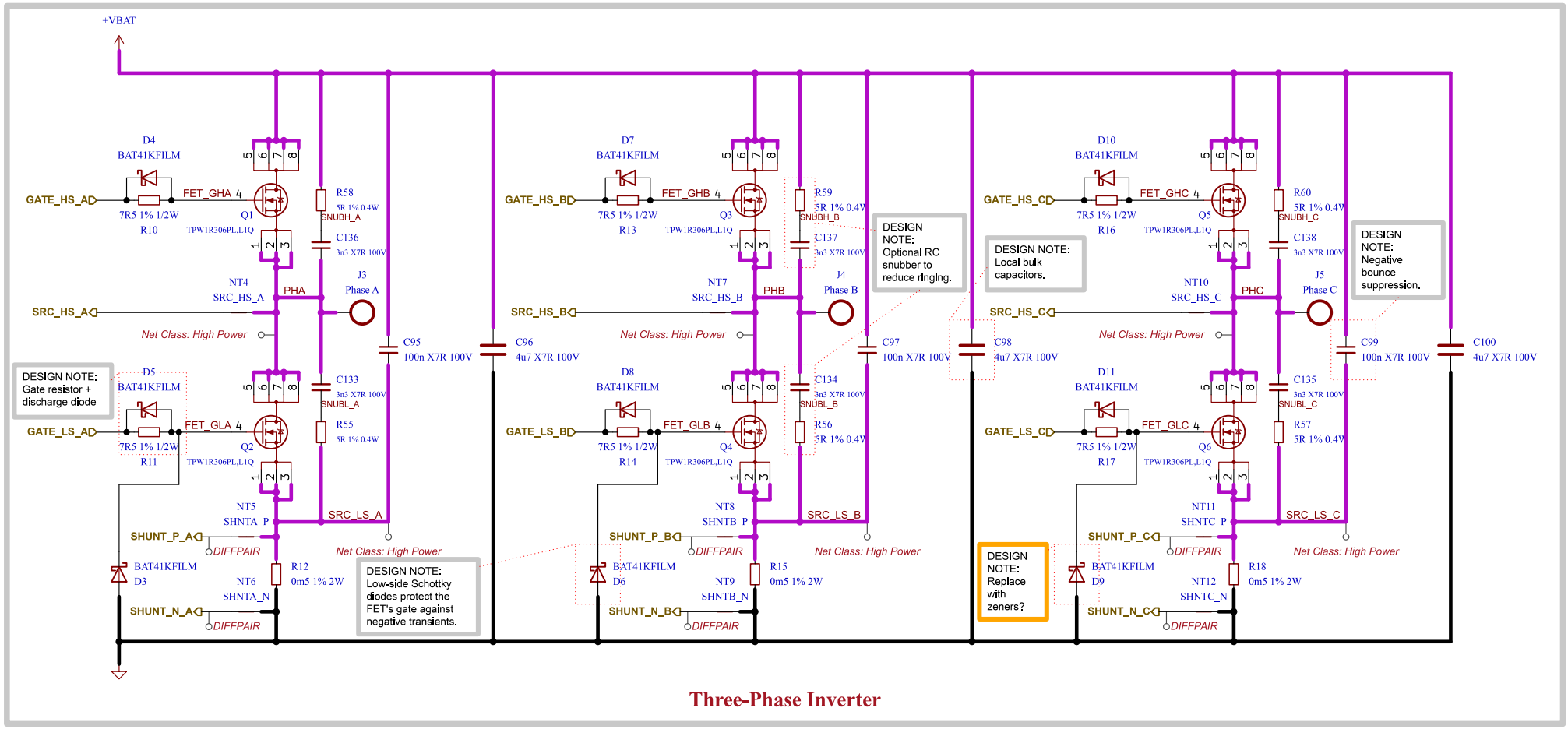
Three-Phase Inverter



Test Points

Comments:	Company: EPFL Xplore Research		Variant: RELEASED	Git Hash: 386a12d
	Board Name: Amulet Motion Controller		Project Name: Chienpanzé	
Sheet Title: Motor Control - Top Level	File Name: Motor Control - Top Level.kicad_sch	Designer: Vincent Nguyen	Date: 2023-12-20	Revision: 1.1.1
Sheet Path: /Project Architecture/Motor Control - Top Level/		Reviewer:	Size: A3	Sheet: 8 of 21

[9] Motor Control - Inverter



Three-Phase Inverter

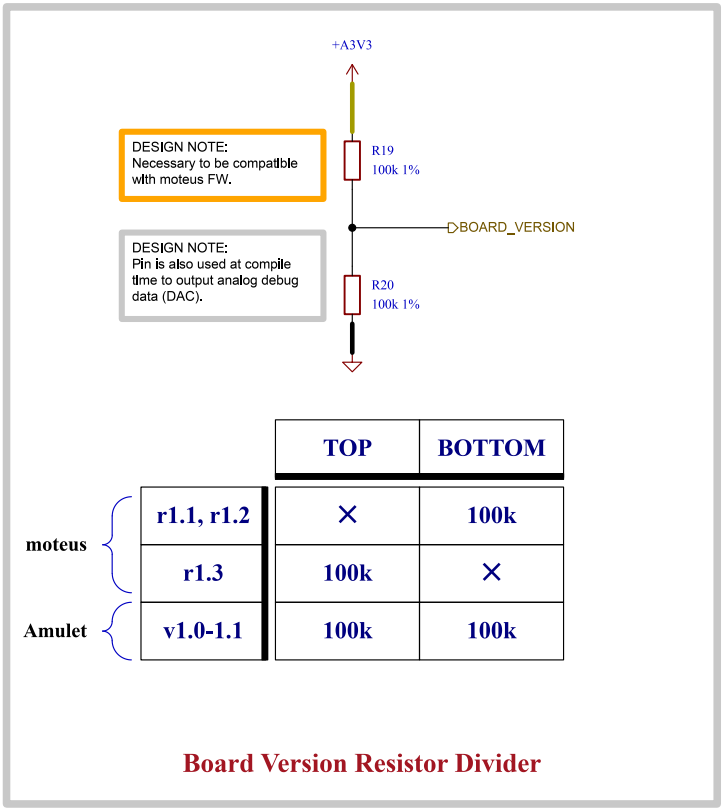
LAYOUT NOTE:
High current traces must be carefully designed. Ensure ground return path does not cross sensitive parts of the board. Use multiple planes for higher current carrying capacity.

LAYOUT NOTE:
Keep sufficient clearance between power nets according to IPC-2221/IEC60664-1.

DESIGN NOTE:
A gate drive current that is too large can damage the FETs!

Comments: System Design Considerations for High-Power Motor Driver Applications; Best Practices for Board Layout of Motor Drivers; Proper RC Snubber Design for Motor Drivers	Company: EPFL Xplore Research		Variant: RELEASED	Git Hash: 386a12d
	Board Name: **Amulet Motion Controller**		Project Name: **Chienpanzé**	
Sheet Title: Motor Control - Inverter	File Name: Motor Control - Inverter.kicad_sch	Designer: Vincent Nguyen	Date: 2024-01-25	Revision: 1.1.1
Sheet Path: /Project Architecture/Motor Control - Top Level/Motor Control - Inverter/		Reviewer:	Size: **A4**	Sheet: **9** of **21**

[10] Misc - Board Version, DAC

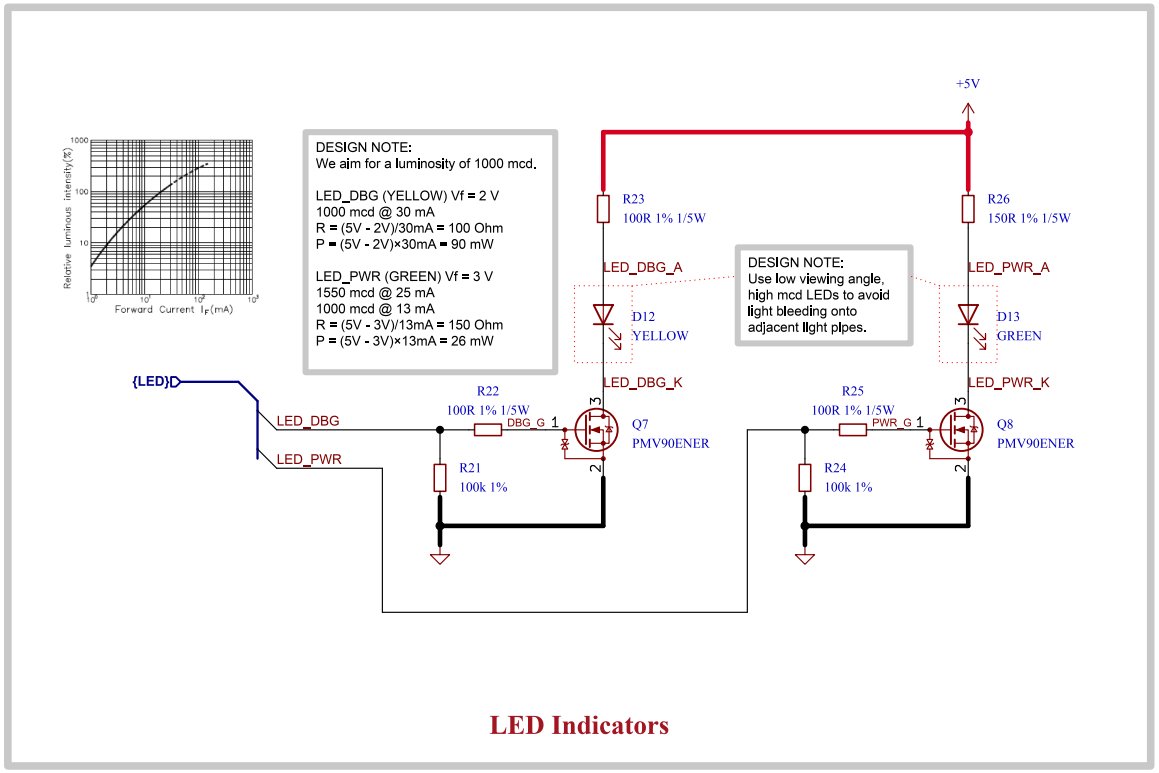


		TOP	BOTTOM
moteus	r1.1, r1.2	×	100k
	r1.3	100k	×
Amulet	v1.0-1.1	100k	100k

Board Version Resistor Divider

Comments:	Company: EPFL Xplore Research		Variant: RELEASED	Git Hash: 386a12d
	Board Name: Amulet Motion Controller		Project Name: Chienpanzé	
Sheet Title: Misc - Board Version, DAC	File Name: Misc - Board Version DAC.kicad_sch	Designer: Vincent Nguyen	Date: 2024-04-13	Revision: 1.1.1
Sheet Path: /Project Architecture/Misc - Board Version, DAC/		Reviewer:	Size: A4	Sheet: 10 of 21

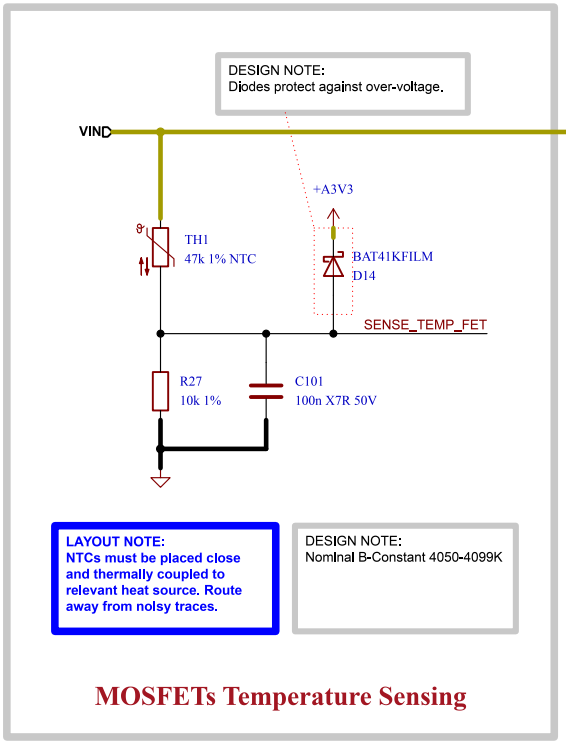
[11] User - LED Indicators

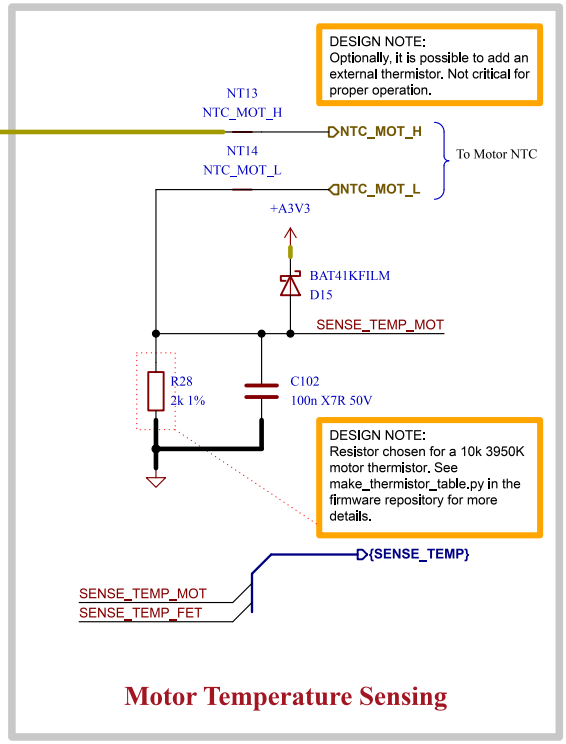


LED Indicators

	Comments:	Company: **EPFL Xplore Research**	Variant: RELEASED	Git Hash: 386a12d
		Board Name: **Amulet Motion Controller**	Project Name: **Chienpanzé**	
	Sheet Title: User - LED Indicators	File Name: User - LED Indicators.kicad_sch	Designer: Vincent Nguyen	Date: 2023-12-19 / Revision: 1.1.1
	Sheet Path: /Project Architecture/User - LED Indicators/		Reviewer:	Size: **A4** / Sheet: **11** of **21**

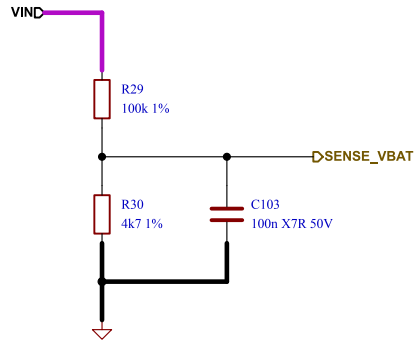
[12] Sensing - Temperature





Comments:	Company: EPFL Xplore Research		Variant: RELEASED	Git Hash: 386a12d
	Board Name: Amulet Motion Controller		Project Name: Chienpanzé	
Sheet Title: Sensing - Temperature	File Name: Sensing - Temperature.kicad_sch	Designer: Vincent Nguyen	Date: 2024-04-13	Revision: 1.1.1
Sheet Path: /Project Architecture/Sensing - Temperature/		Reviewer:	Size: A4	Sheet: 12 of 21

[13] Sensing - Battery



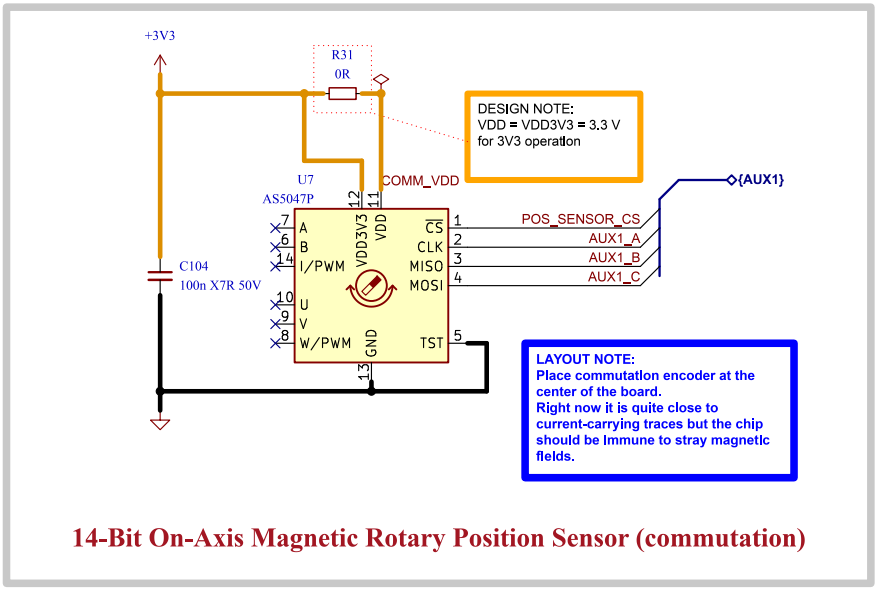
DESIGN NOTE:
1/23 temperature stable voltage divider. Use low ppm resistors.

12S: max voltage: 2.19 V
8S: max voltage: 1.95 V
6S: max voltage: 1.46 V

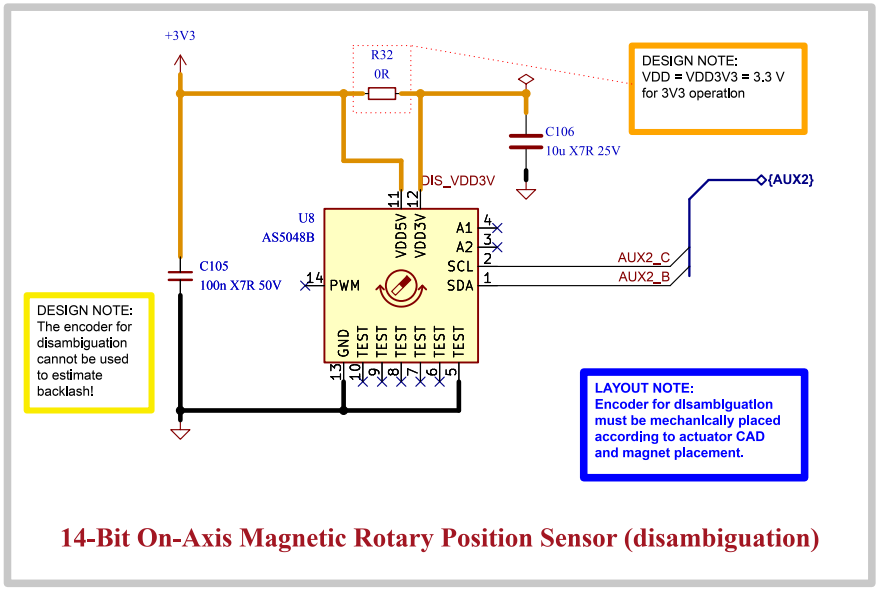
Battery Voltage Sensing

Comments:	Company: EPFL Xplore Research		Variant: RELEASED	Git Hash: 386a12d
	Board Name: Amulet Motion Controller		Project Name: Chienpanzé	
Sheet Title: Sensing - Battery	File Name: Sensing - Battery.kicad_sch	Designer: Vincent Nguyen	Date: 2023-10-14	Revision: 1.1.1
Sheet Path: /Project Architecture/Sensing - Battery/		Reviewer:	Size: A4	Sheet: 13 of 21

[14] Sensing - Position



14-Bit On-Axis Magnetic Rotary Position Sensor (commutation)

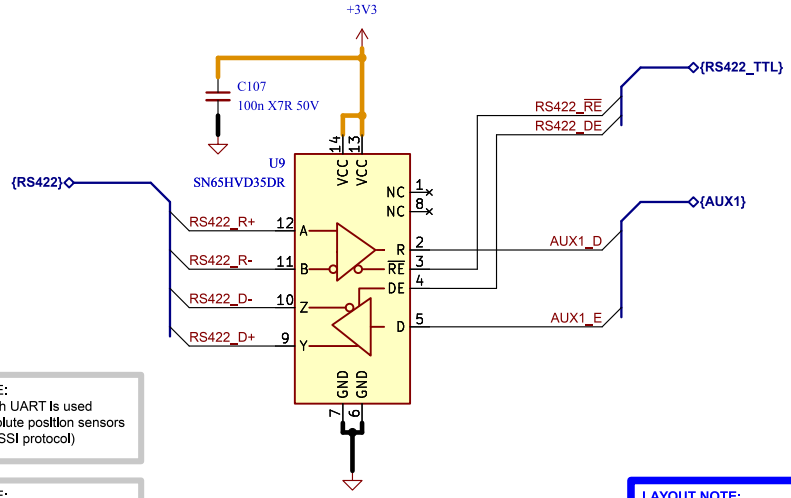


14-Bit On-Axis Magnetic Rotary Position Sensor (disambiguation)

DESIGN NOTE:
AS5047P senses magnet mounted on planetary sun gear, for commutation.
AS5048B senses magnet mounted on shaft with same reduction factor as planetary gearbox for disambiguation.

Comments:	Company: EPFL Xplore Research		Variant: RELEASED	Git Hash: 386a12d
	Board Name: Amulet Motion Controller		Project Name: Chienpanzé	
Sheet Title: Sensing - Position	File Name: Sensing - Position.kicad_sch	Designer: Vincent Nguyen	Date: 2023-10-14	Revision: 1.1.1
Sheet Path: /Project Architecture/Sensing - Position/		Reviewer:	Size: A4	Sheet: 14 of 21

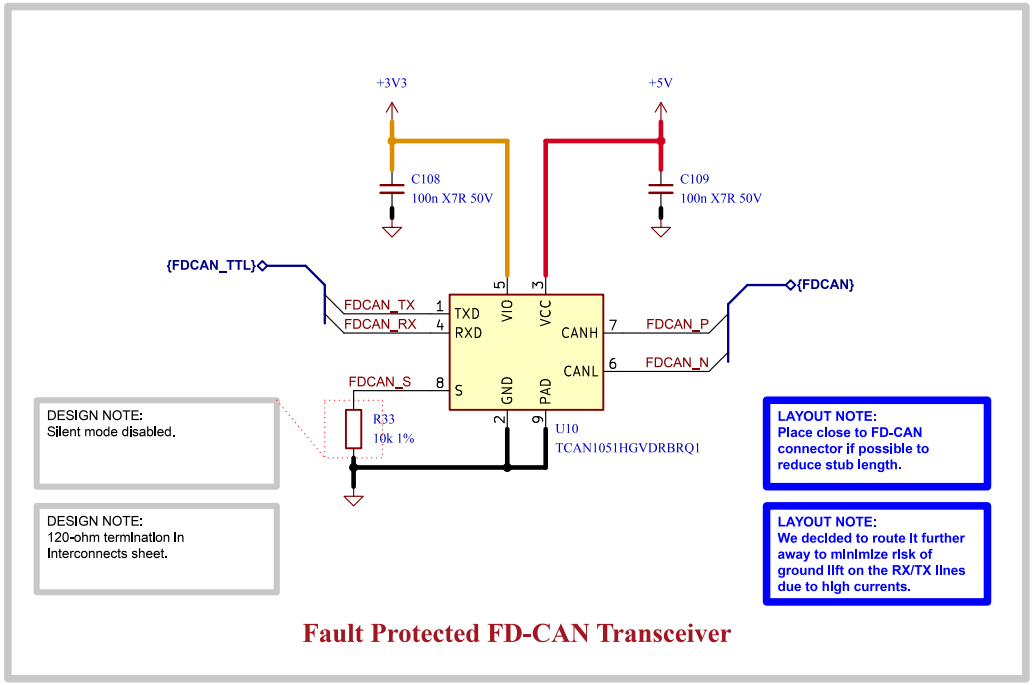
[15] Interface - RS-422



3.3-V Full-Duplex RS-422 Interface

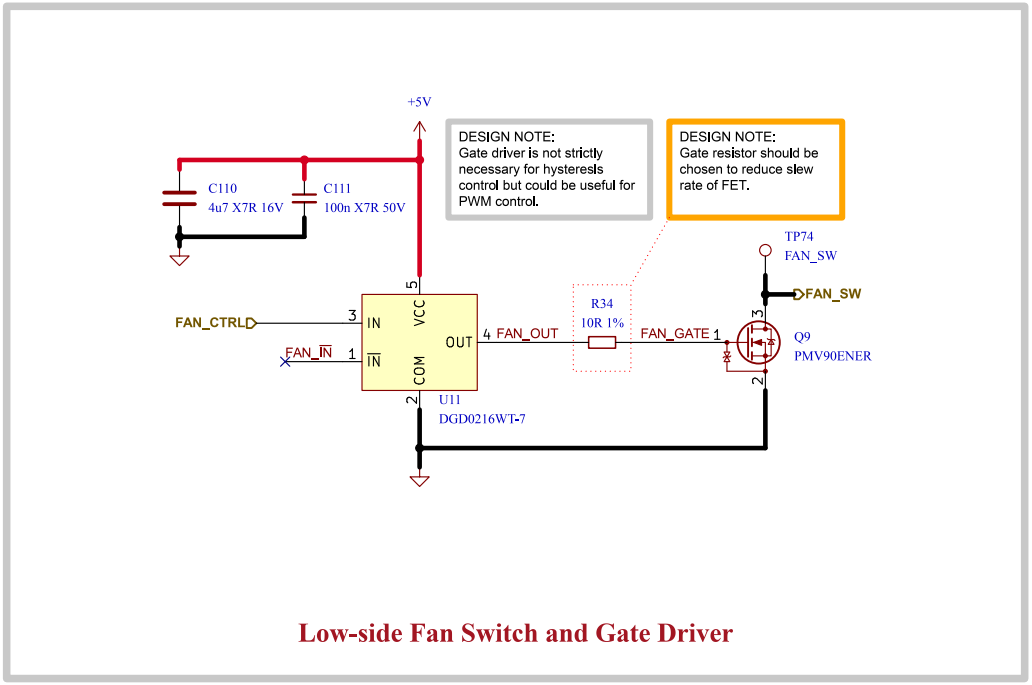
Comments:	Company: EPFL Xplore Research		Variant: RELEASED	Git Hash: 386a12d
	Board Name: Amulet Motion Controller		Project Name: Chienpanzé	
Sheet Title: Interface - RS-422	File Name: Interface - RS-422.kicad_sch	Designer: Vincent Nguyen	Date: 2023-10-15	Revision: 1.1.1
Sheet Path: /Project Architecture/Interface - RS-422/		Reviewer:	Size: A4	Sheet: 15 of 21

[16] Interface - FD-CAN



	Comments:	Company: EPFL Xplore Research		Variant: RELEASED	Git Hash: 386a12d
		Board Name: Amulet Motion Controller		Project Name: Chienpanzé	
	Sheet Title: Interface - FD-CAN	File Name: Interface - FD-CAN.kicad_sch	Designer: Vincent Nguyen	Date: 2023-10-15	Revision: 1.1.1
	Sheet Path: /Project Architecture/Interface - FD-CAN/		Reviewer:	Size: A4	Sheet: 16 of 21

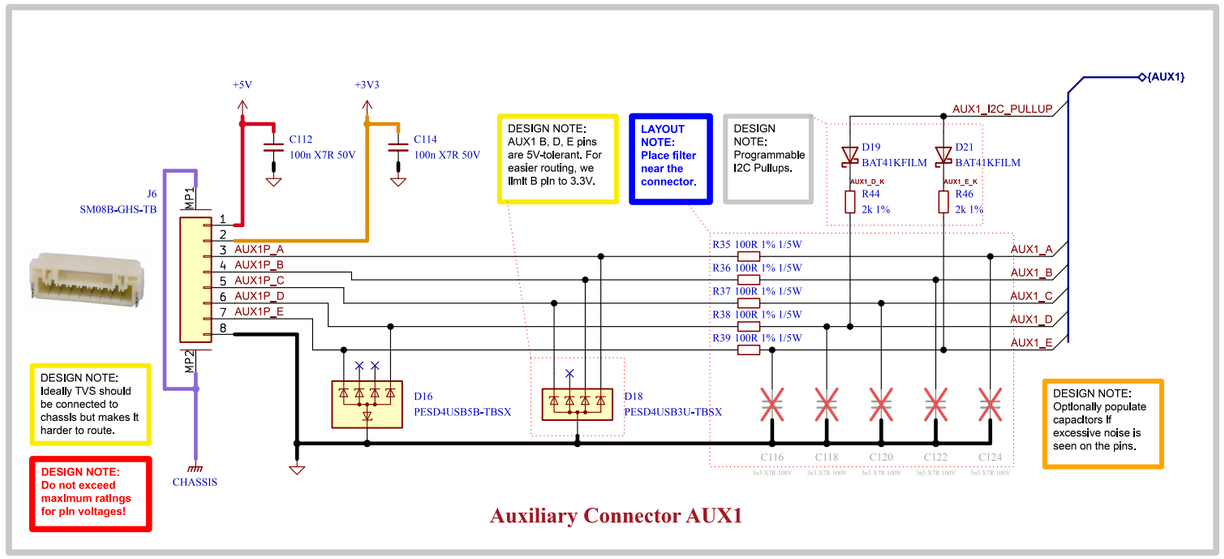
[17] Interface - Fan Control



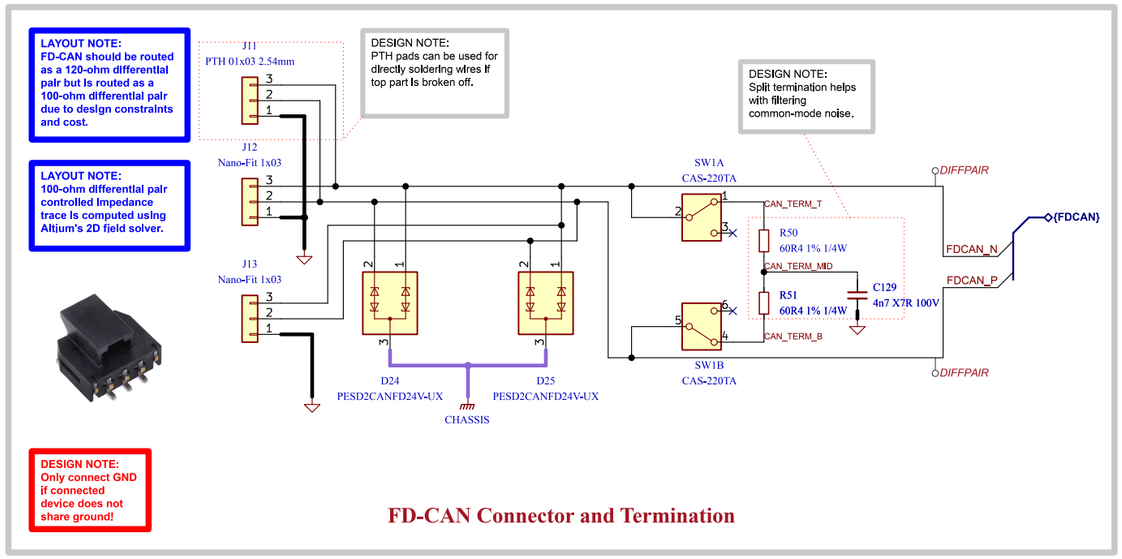
Low-side Fan Switch and Gate Driver

Comments:	Company: **EPFL Xplore Research**		Variant: RELEASED	Git Hash: 386a12d
	Board Name: **Amulet Motion Controller**		Project Name: **Chienpanzé**	
Sheet Title: Interface - Fan Control	File Name: Interface - Fan Control.kicad_sch	Designer: Vincent Nguyen	Date: 2023-11-19	Revision: 1.1.1
	Sheet Path: /Project Architecture/Interface - Fan Control/	Reviewer:	Size: **A4**	Sheet: **17** of **21**

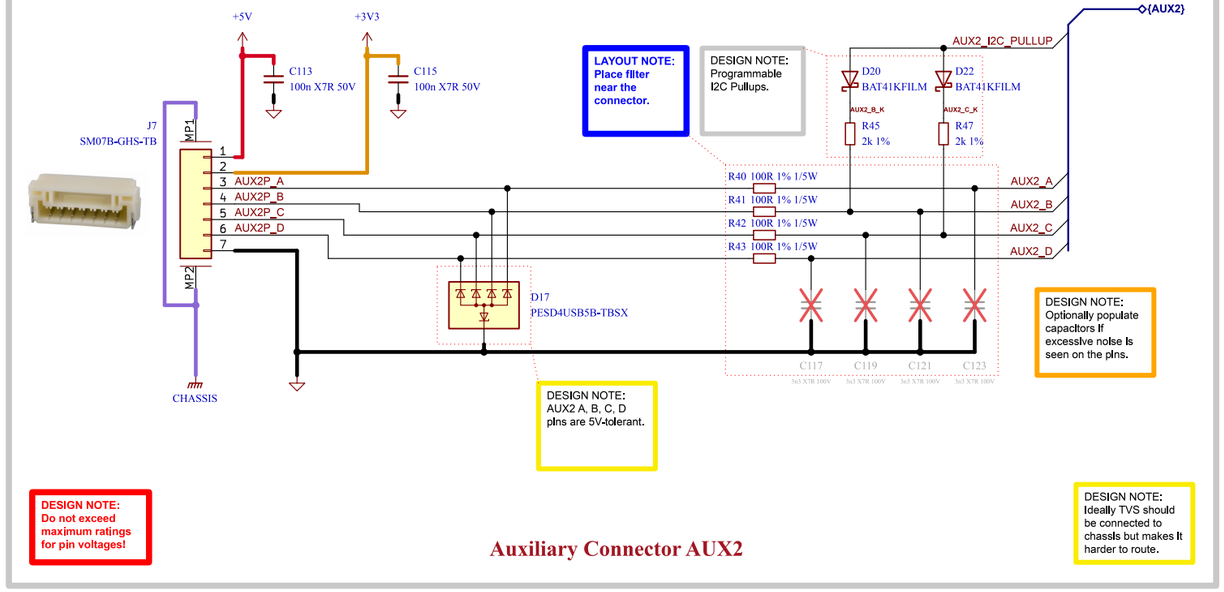
[18] Interface - Interconnects



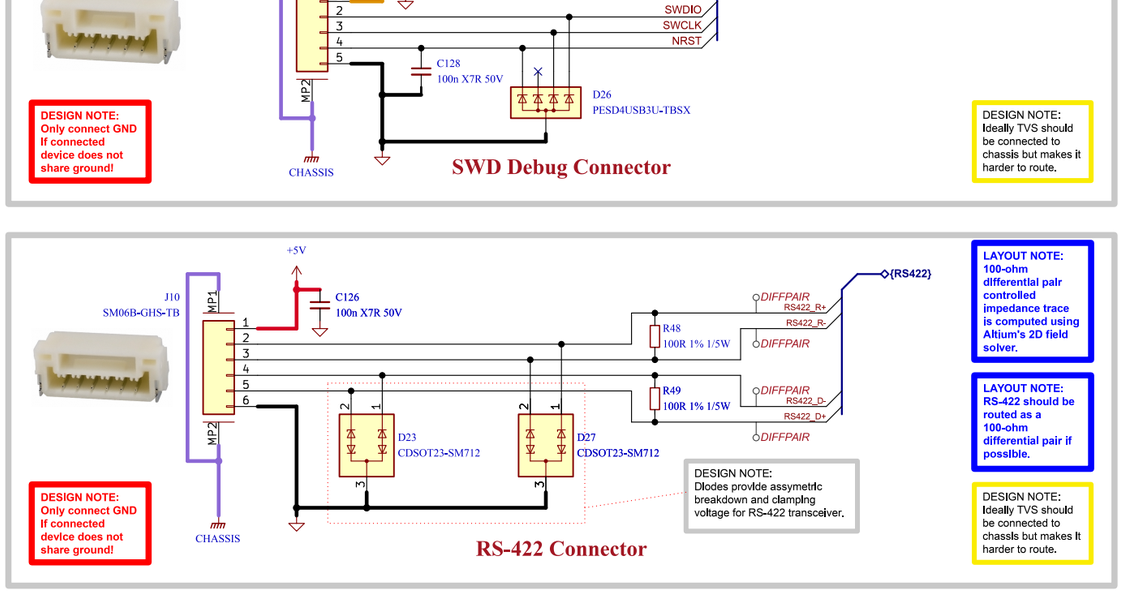
Auxiliary Connector AUX1



FD-CAN Connector and Termination

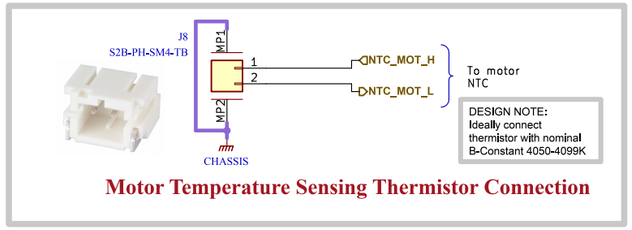


Auxiliary Connector AUX2

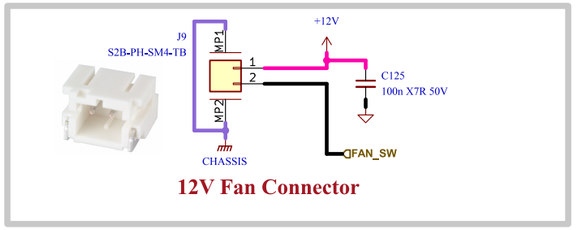


SWD Debug Connector

RS-422 Connector



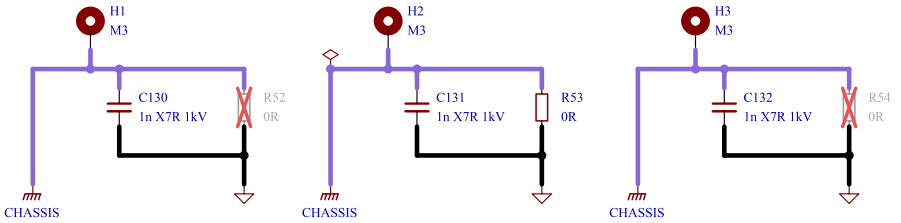
Motor Temperature Sensing Thermistor Connection



12V Fan Connector

Comments: **Reference:** Flexible I/O worked examples	Company: **EPFL Xplore Research**	Variant: RELEASED	Git Hash: 386a12d
	Board Name: **Amulet Motion Controller**	Project Name: **Chienpanzé**	
Sheet Title: Interface - Interconnects	File Name: Interface - Interconnects.kicad_sch	Designer: Vincent Nguyen	Date: 2023-12-31 / Revision: 1.1.1
Sheet Path: /Project Architecture/Interface - Interconnects/		Reviewer:	Size: **A3** / Sheet: **18** of **21**

[19] Misc - Holes, Fiducials



DESIGN NOTE:
Optional RC filter for chassis grounding. Capacitors offer multi-point low-impedance connections at high-frequencies.

DESIGN NOTE:
0-Ohm resistor provides low-impedance bond between chassis and signal GND. Be aware of ground loops through cable shield.

Mounting Holes and Chassis Connection

Front

FM1 FM3 FM5

Back

FM2 FM4 FM6

Fiducial Markers

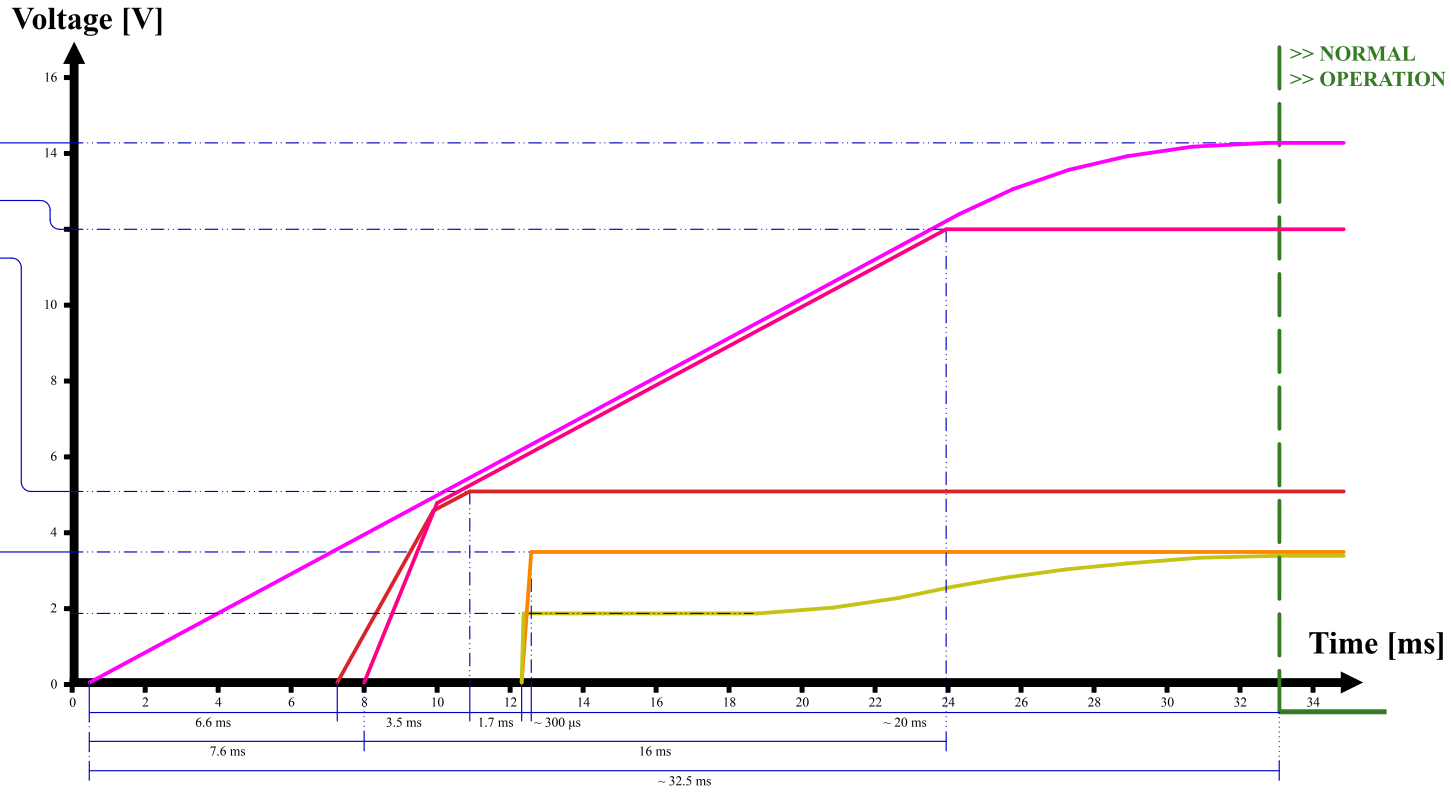
Comments:	Company: EPFL Xplore Research		Variant: RELEASED	Git Hash: 386a12d
	Board Name: Amulet Motion Controller		Project Name: Chienpanzé	
Sheet Title: Misc - Holes, Fiducials	File Name: Misc - Holes Fiducials.kicad_sch	Designer: Vincent Nguyen	Date: 2023-10-22	Revision: 1.1.1
Sheet Path: /Project Architecture/Misc - Holes, Fiducials/		Reviewer:	Size: A4	Sheet: 19 of 21

[20] Power - Sequencing

NAME	SOURCE	LEVEL
+VBAT	BATTERY	12 - 44V
+12V	LMR36006	12V ± 1.5%
+5V	LMR36506	5V ± 1.5%
+3V3	TPS62172	3.3V ± 3%
+A3V3	LP2992	3.3V ± 0.5%

DESIGN NOTE:
Power sequencing graph measured experimentally.

DESIGN NOTE:
Start-up time of 12V rail depends on +VBAT charging time, which itself depends on the precharge circuit.



Comments:	Company: EPFL Xplore Research		Variant: RELEASED	Git Hash: 386a12d
	Board Name: Amulet Motion Controller		Project Name: Chienpanzé	
Sheet Title: Power - Sequencing	File Name: Power - Sequencing.kicad_sch	Designer: Vincent Nguyen	Date: 2024-03-12	Revision: 1.1.1
Sheet Path: /Power - Sequencing/		Reviewer:	Size: A4	Sheet: 20 of 21

[21] Revision History

Version 1.0.0 - 2023-12-12

Added

- TVS protection and termination switch to FD-CAN.
- Low-side switched 12V 600 mA source for external fan.
- LDO for analog supply.
- One TVS diode per power connector.
- Second on-board I2C magnetic encoder for disambiguation.
- ESD protection to all interfaces.
- Over-voltage protection on thermistor ADC inputs.
- Pi filters to inputs of buck regulators and MCU analog supply.
- Decoupling caps next to power pins of connectors.

Changed

- CPH-CPL capacitor to 47 nF (gate driver).
- FD-CAN transceiver IC.
- FETs for top cooled variant.
- Input power TVS diode to bidirectional.
- Moved SOx low-pass filter to MCU section.
- PWM_PHASEA with PWM_PHASEC on STM32G474 pinout for easier routing.
- RS422 pinout on connector.
- Buck regulators to optimize for low noise.

Version 1.0.1 - 2024-01-25

Added

- Controller target specifications.
- Credits to moteus on cover page.
- Optional RC-Snubber to power stage.

Fixed

- Chassis guard ring to go around the board.
- CAN and power TVS diodes now go to chassis.
- Clearance between nets to respect IEC60664-1 where possible.
- Comment on precharge.
- Power TVS diode reference designator from "U" to "D".

Changed

- 5V 300 mA buck converter with 600 mA version.
- Chassis-GND capacitor by 1nF 1kV.

Version 1.0.2 - 2024-03-12

Changed

- Power sequencing graph according to experimental data.

Version 1.1.0 - 2024-04-13

Added

- RC snubber passive values.

Fixed

- More vias for VBUS and LMR36006 GND pads.
- Board version voltage reference from +3V3 to +A3V3.

Changed

- Motor thermistor resistor divider to 2kOhm for a 10k 3950K thermistor.

Version 1.1.1 not found.

Version 1.1.1 not found.

Comments:	Company: EPFL Xplore Research		Variant: RELEASED	Git Hash: 386a12d
	Board Name: Amulet Motion Controller		Project Name: Chienpanzé	
Sheet Title: Revision History	File Name: Revision History.kicad_sch	Designer: Vincent Nguyen	Date: 2024-01-03	Revision: 1.1.1
Sheet Path: /Revision History/		Reviewer:	Size: A4	Sheet: 21 of 21