Cost-Effective and Easily Configurable High Voltage Motor Controllers for Automotive Use

sdmay25-26 Bryce Rega, Marek Jablonski, Gavin Patel, Jonah Frosch, Long Yu

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Problem Statement

- There exists a market gap in lightweight EV motor controllers
  - Used in electric bikes and collegiate solar cars
- These unique applications have unique specs
  - Low RPM (0-1000)
  - High Torque (Direct Drive)
  - High/Medium Voltage (48-135V)
  - Medium Power (Peak ~7.5KW)
- Problem: Existing controllers
  - Are very expensive (~$5k each)
  - Black boxes to those who use them
  - Notorious for having issues.

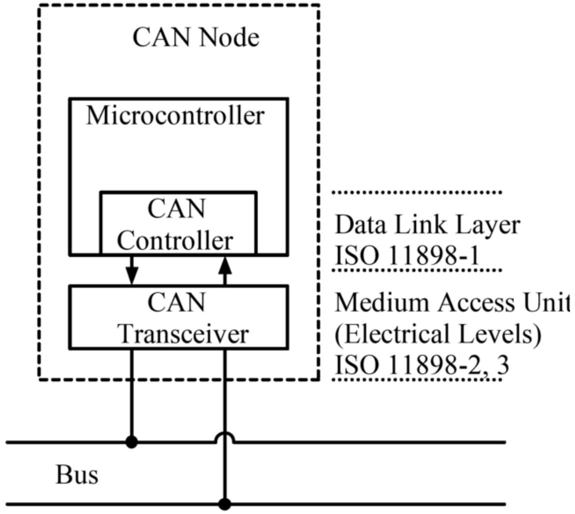
Electric bike in-hub motor
ebikeling.com

PRISUM's solar car, P15 Eliana
PRISUM Media Archive

Functional Requirements

- Operational
  - Spin Motor in either direction
  - Current and/or speed controlled
- Electrical
  - 0-25600rpm Electrical Rotation speed
  - 48-135VDC Power Input
  - 50A Bus Draw
  - 200A Peak Coil Current
    - High Torque Output
- Communication
  - CAN bus command/status IO
    - Used in large interconnected vehicles
  - GPIO interface
    - Simple Bare-bones operation

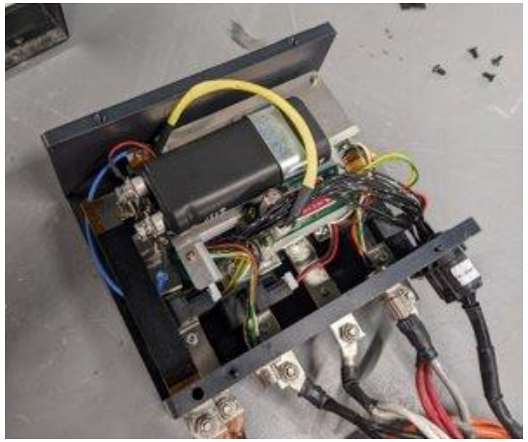
Mitsuba 2096-III Motor
Marek Jablonski



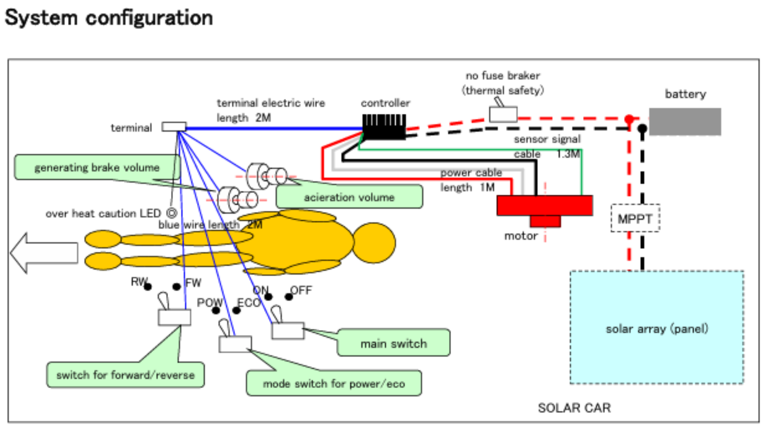
CAN Node Diagram
CAN bus - Wikipedia

Nonfunctional Requirements

- Compact and Lightweight
  - 200x200x100mm outer dimension
  - Less than 4kg
- Environmental Resistance
  - 0°-45°C Operating ambient
  - Water-resistant connectors
- Aesthetics
  - Useful Labeling
  - Professional Design
- User Experience
  - Comprehensive Documentation and Guides
  - External Configuration Utility



Mitsuba 2096C Controller
Marek Jablonski

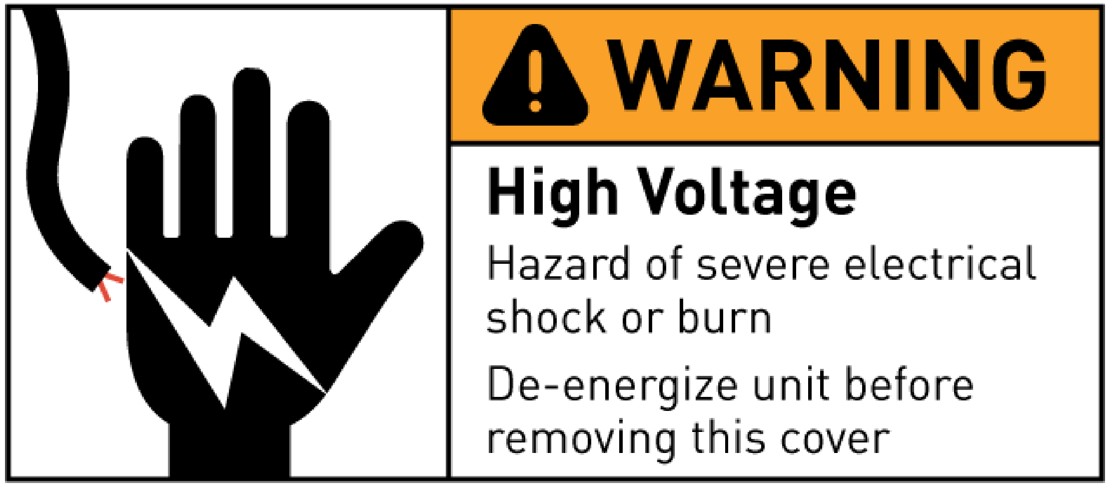


Existing hookup Diagram
Mitsuba M2096 Controller Manual

Other Considerations

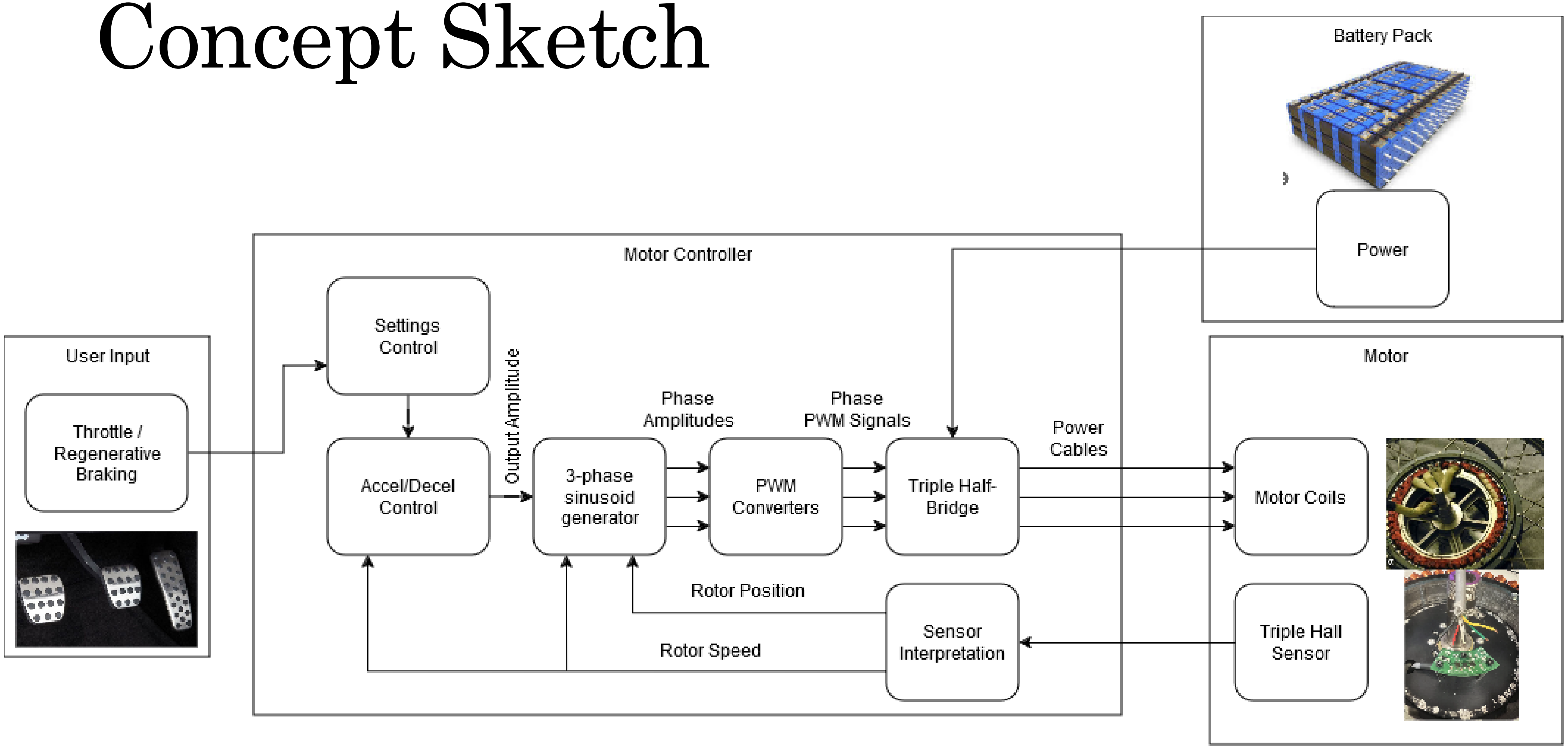
- Open-Source Design
  - Removes Overhead from User Cost
  - Enables Cost cuts for resourceful Users
- Safety
  - Dangerous Voltages/Energy
  - Electrical Isolation
  - Energy Dissipation
  - Cautions/Warnings

https://www.flickr.com/photos/lintmachine/2333562855



Example Hazard Label
Safety in Motor Maintenance and Troubleshooting – Monolithic Power System

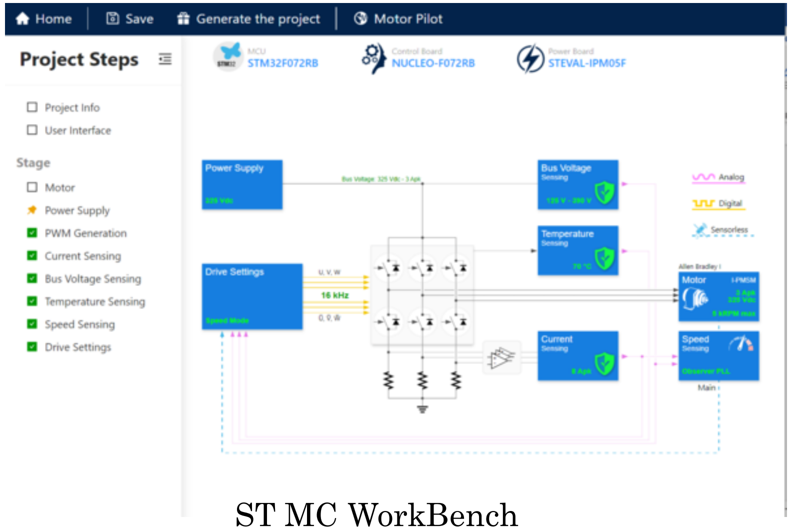
Concept Sketch



Project Overview

- Custom High Voltage Motor Controller
- Low Total cost for controller when compared to market options
- Develop a GUI for interfacing and configuring controller
- Compatible with many different applications

M2096 kit
Mitsuba M2096 Controller Manual



ST MC WorkBench
STMicro SDK Wiki

In-hub Bicycle Motor
LeafBike.com

Market Survey – Uniqueness

- Other options contain a few key flaws:
- Lack of proper documentation makes integrating motor controllers difficult
- Motor controllers for higher power applications have affordability issues
- Most motor controllers are either difficult to configure or do not allow for custom configuration

M2096 Motor and Controller
Micro Mobility Products

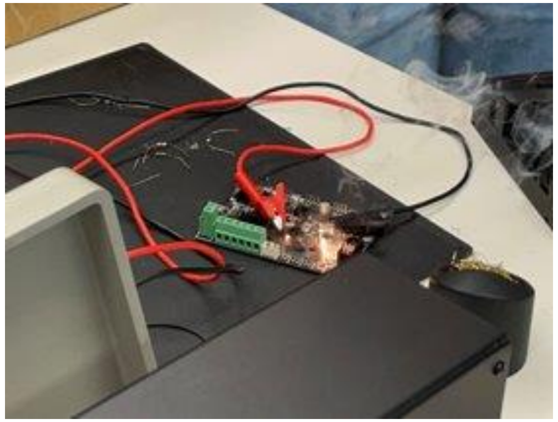
WaveSculptor22 Motor Inverter
Tritium Charging

48-72V Brushless Motor Speed Controller
DC 1500W Scooter Controller Replacement
for E-Bike Scooter Motor Controller

Potential Risks & Mitigation

- Prototyping Risks
  - Design Time Overruns
    - Setting aside additional time outside normal meeting hours to ensure work is being done
  - Test Motor Failure
    - We have backup hall sensors and additional motors and components for repairing damage
  - Development Board Damage
    - Incremental testing will be performed with proactive limits in place
- First Revision
  - Component Failure
    - Ensure most intensive use cases are properly simulated in LTSpice
  - Software Delay
    - Design multiple rev 1 prototypes to support our desired MCU and dev board
- Second Revision
  - Overspending Budget
    - Purchase components in the first revision in bulk

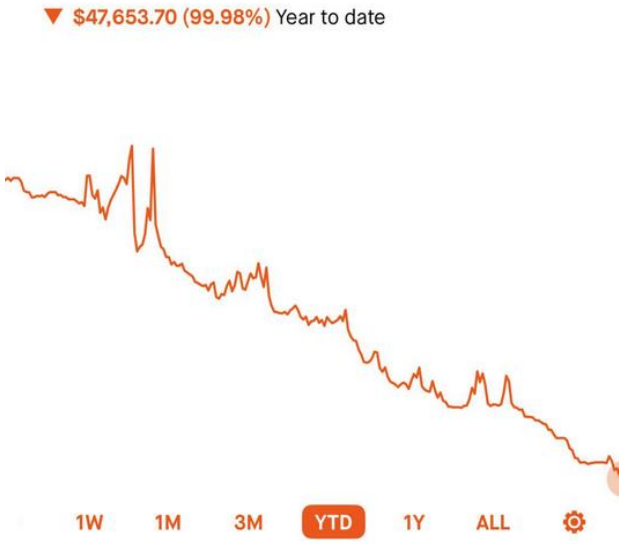
High voltage run through PCBs



Overvoltage Damage

Resource/Cost Estimate

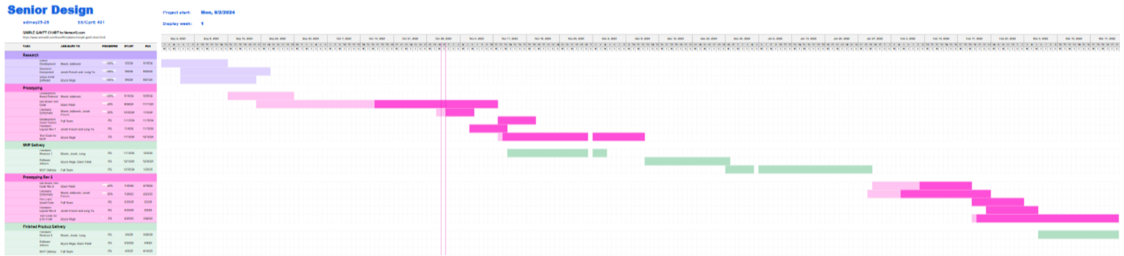
- Primary cost comes from the board and components
  - Plan to hand solder components to board
- Development board and ST-Link were purchased
- Open-Source software to run on the board
- Free documentation on how to properly use the board
- End cost to the user would only be the board + components
- Overall cost around $300 dollars



Reddit.com, u/Severe_Life1437

Project Milestones & Schedule

- Milestones
  - Development board drives the motor
  - Custom prototype drives motor with throttle and direction control
  - Motor reliably runs (no regular faults)
  - Motor controller meets requirements laid out by the client
- Project schedule
  - Milestone 1 was completed in the first week of November
  - Milestone 2 will be completed at the start of semester 2
  - Milestone 3 should be completed shortly after Milestone 2
  - Milestone 4 is planned to be complete in mid-March



Prototyping Phases

Development Board

- Get familiar with software via examples
- Setup hardware configurations

Revision 1

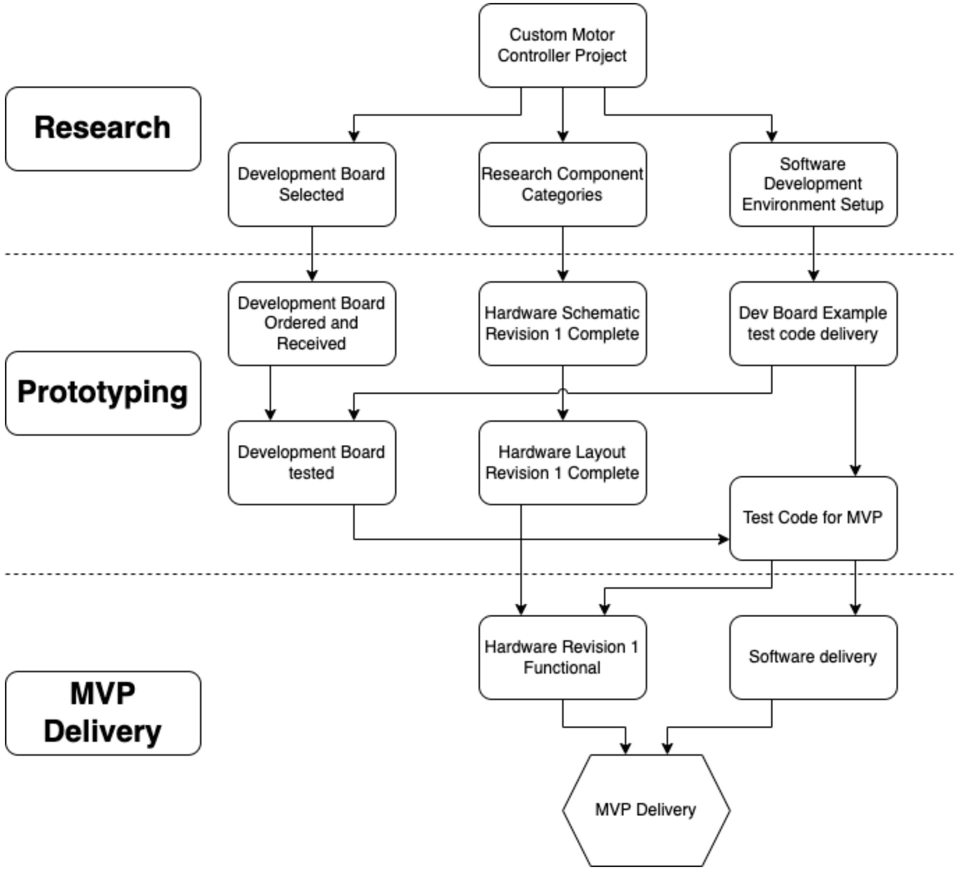
- Partially meet requirements
- Test hardware to learn for next revision
- Test basic custom software

Revision 2

- Completely meet requirements
- Final deliverable

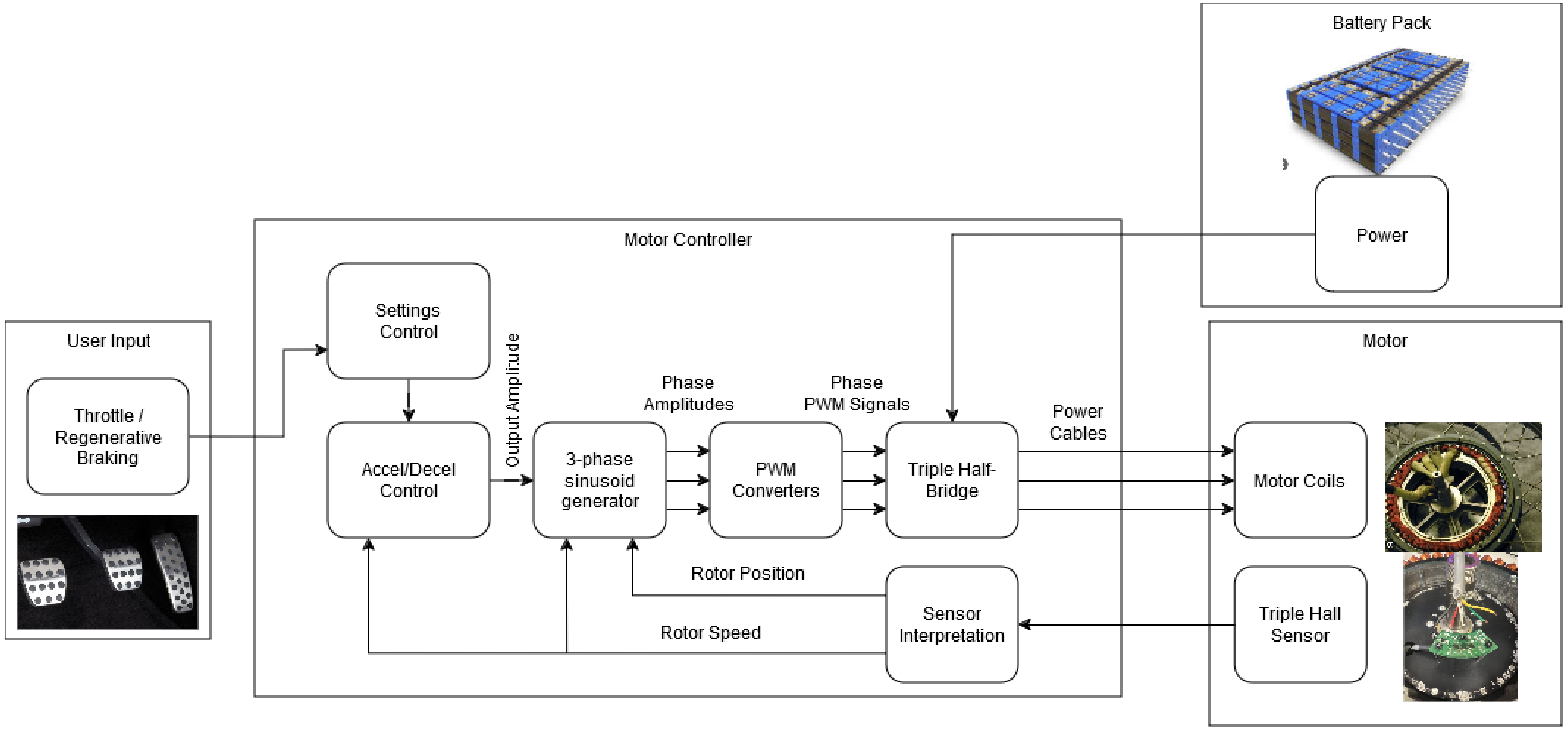
Functional Decomposition

- Research
  - Select dev board and software prep
  - Research components
- Prototyping
  - Develop and test software on dev board
  - Create schematic, then layout of PCB
  - Prototype software for custom PCB
- Minimum Viable Product (MVP)
  - Hardware is functional and tested
  - Software is functional and tested
  - Revision 1 (MVP) is complete
- Repeat for revision 2

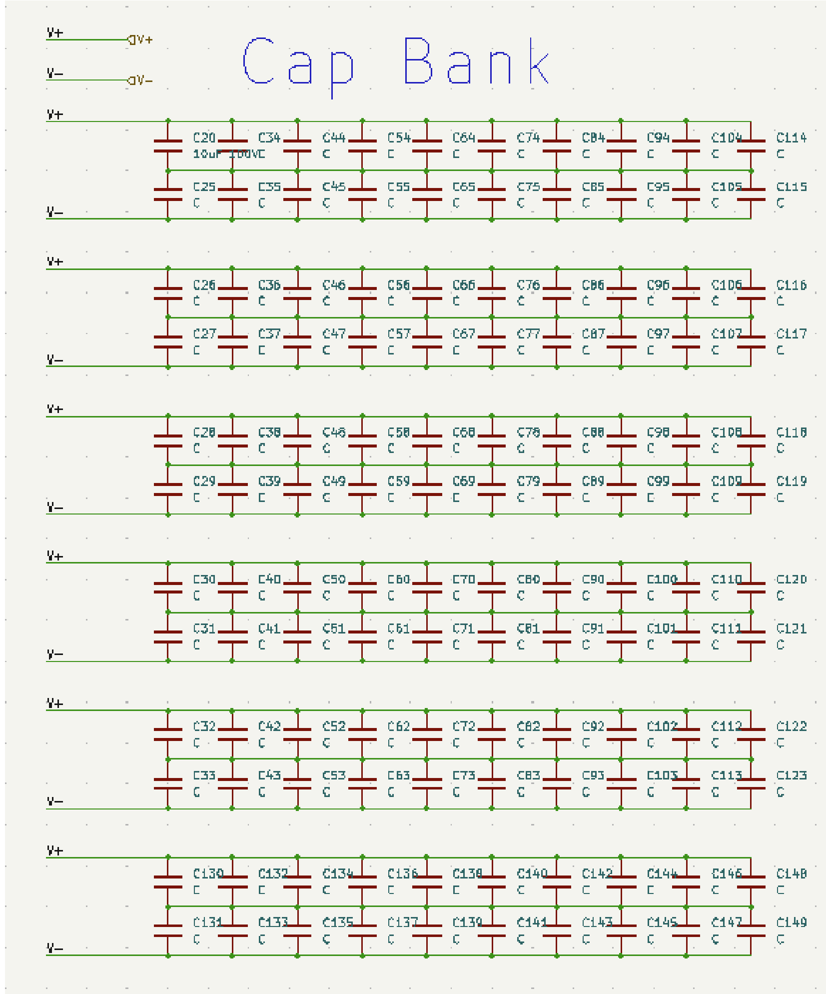


High Level Design

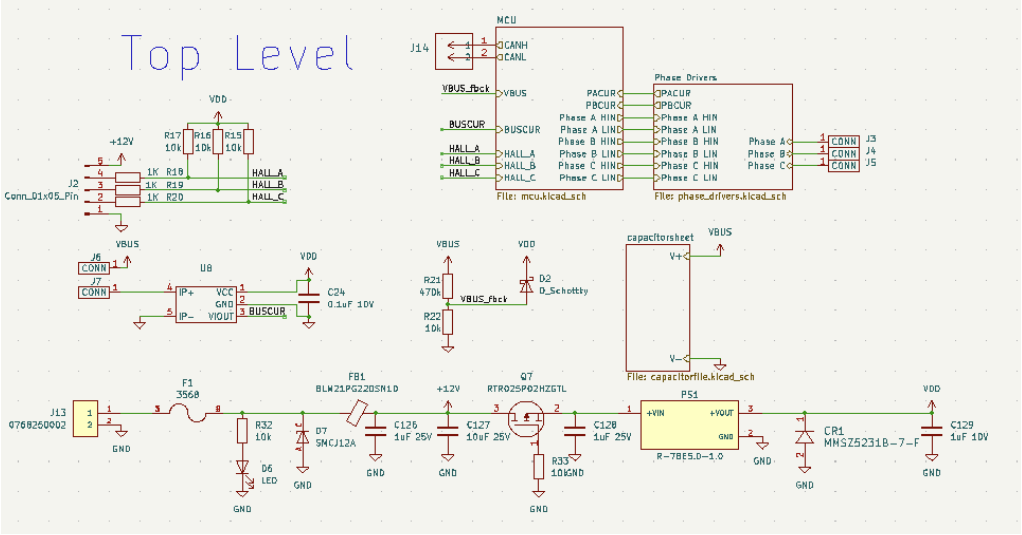
- Take inputs from a user throttle / braking and a DC voltage source for power
- Output a 3 phase sinusoidal waveform for driving motors
- Software drives the motor and receives data back through a HALL effect sensor in a feedback loop



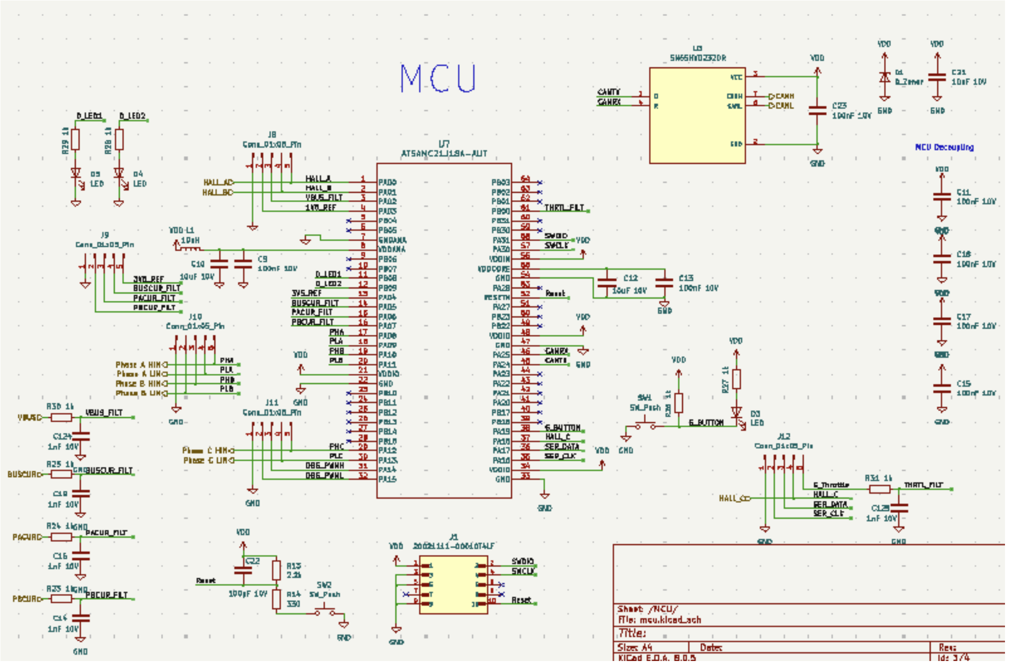
Schematic



High Voltage Capacitor Bank Sheet

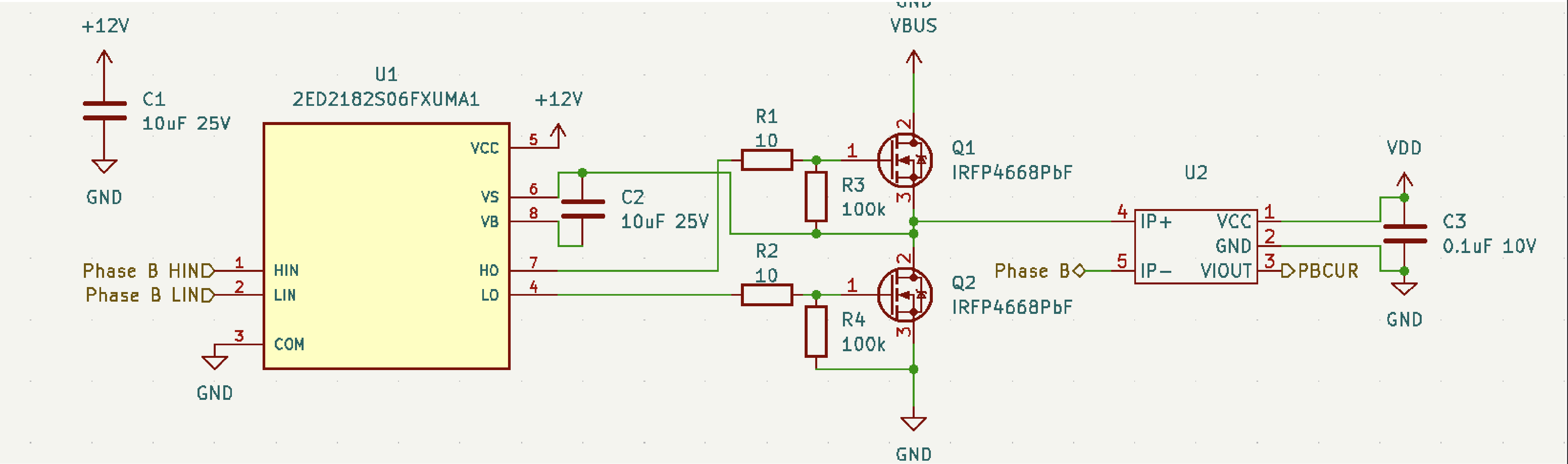


Top Level Schematic



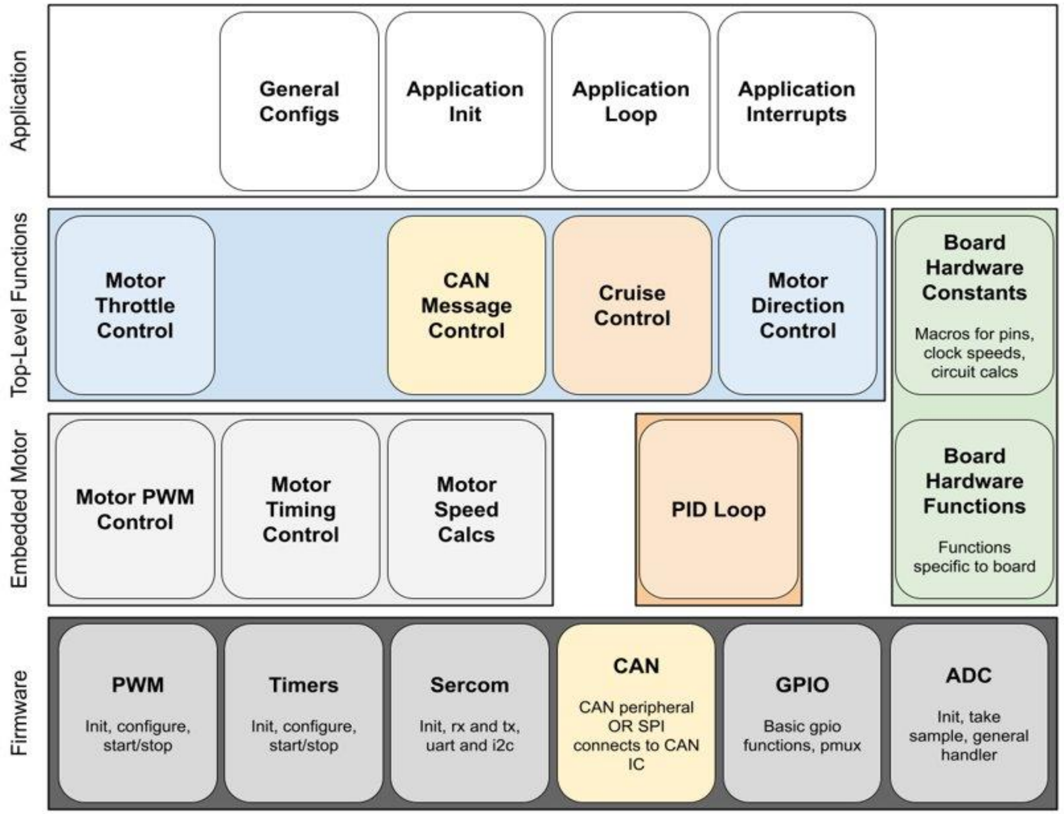
MCU Schematic Sheet

Gate Driver Design



Gate Driver

Detailed Design



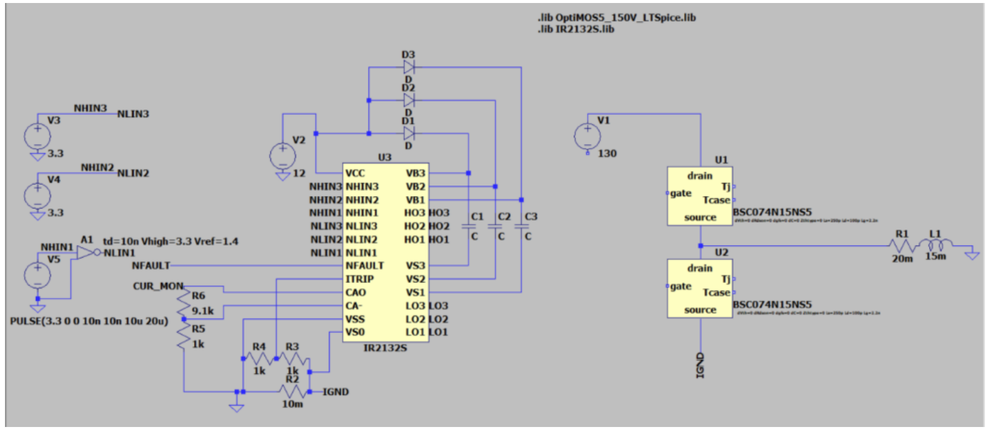
Software Design Diagram

AT SAM C21 J18	Primary		Secondary		Tertiary		
Function	Port & Pin	Peripheral	Port & Pin	Peripheral	Port & Pin	Peripheral	Debug?
Phase H	PA08	TCC0 [0]	PA16	TCC0/2	PB30	TCC1 [2]	Pin
Phase L	PA09	TCC0 [1]	PA17	TCC0/2	PB31	TCC1 [3]	Pin
Phase H	PA10	TCC1 [0]	PA30	TCC1 [0]	PB30	TCC1 [2]	Pin
Phase L	PA11	TCC1 [1]	PA31	TCC1 [1]	PB31	TCC1 [3]	Pin
Phase H	PA12	TCC2 [0]	PA16	TCC0/2	PB30	TCC1 [2]	Pin
Phase L	PA13	TCC2 [1]	PA17	TCC0/2	PB31	TCC1 [3]	Pin
Bus Voltage	PA02	AIN2	PB00	AIN0			Pin
Phase Current	PA05	AIN5	PB01	AIN1			Pin
Phase Current	PA06	AIN6	PB02	AIN2			Pin
Phase Current	PA07	AIN7	PB03	AIN3			Pin
1.5V Reference	PA03	VREFA					No
3.5V Reference	PA04	VREFB					No
HALL Sensor	PA00	EXTINT[0]	PA14	EXTINT[14]			Pin
HALL Sensor	PA01	EXTINT[1]	PA15	EXTINT[15]			Pin
HALL Sensor	PA18	EXTINT[2]	PA02	EXTINT[2]			Pin
CAN Tx	PA24	CAN0 TX	PB22	CAN0 TX	PB14	CAN1 TX	No
CAN Rx	PA25	CAN0 RX	PB23	CAN0 RX	PB15	CAN1 RX	No
DAC Analog Out	DNC		PA02	VOUT			N/A
Sercom Data	PA16	SERCOM 1/3	PA22	SERCOM 3/5			Pin
Sercom Clock	PA17	SERCOM 1/3	PA23	SERCOM 3/5			Pin
Throttle ADC	PB00	AIN0	PA08	AIN8	PB08	AIN2/4	Pin
Timer or PWM H	PA14	TC4 [0]	PA18	TC4 [0]	PB08	TC0 [0]	N/A
Timer or PWM L	PA15	TC4 [1]	PA19	TC4 [1]	PB09	TC0 [1]	N/A
Extra Button	PA19	EXTINT[3]	PA14	EXTINT[14]	PA15	EXTINT[15]	No
Extra LED	PA14	EXTINT[14]	PA15	EXTINT[15]	PA19	EXTINT[3]	No
Extra LED	PA15	EXTINT[15]	PA14	EXTINT[14]	PA19	EXTINT[3]	No
Extra GPIO	PA22	EXTINT[6]	PB22	EXTINT[6]	PB12	EXTINT[12]	Pin
Extra GPIO	PA23	EXTINT[7]	PB23	EXTINT[7]	PB13	EXTINT[13]	Pin

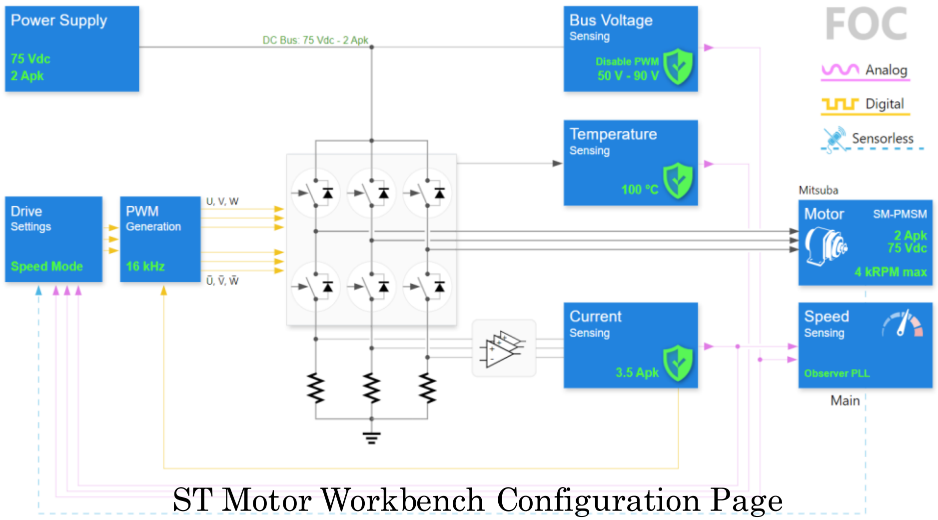
MCU Pinout

Technology Platforms

- LT Spice for circuit testing and development
  - Free usage and we have common familiarity
- ST Motor Workbench & Libraries
  - Good for initial development, lots of customizability
  - Often poor documentation
- VSCode and PRISUM's Software Environment
  - Client's software environment for MCUs
  - Reliable and easy to use



Example LTSpice Simulation Setup



ST Motor Workbench Configuration Page

Test Plan

- Development Board
  - Use to test motor parameters
  - Use to create testing plans
- LTSpice simulations of the gate driver
- Software Tests
  - Modularize code so it may be tested at every level
  - Include some unit testing to stress test
- Final Tests
  - Use power metrics on efficiency
  - Test system edge cases to ensure safety and reliability

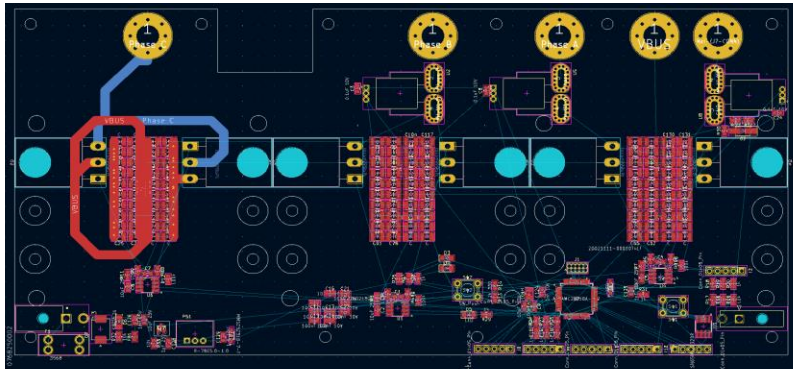
Prototype Results

- Determined test motor parameters
  - Coil Inductance
  - Internal Resistance
  - Winding and Pole/Pair Scheme
- Too Low Torque
  - Could barely spin up motor
  - Frequent OC faults
- Control Scheme Issues
  - Not configured for this motor type
- Prototype Failed
  - Gate Driver internal failure
  - Necessary information gained beforehand

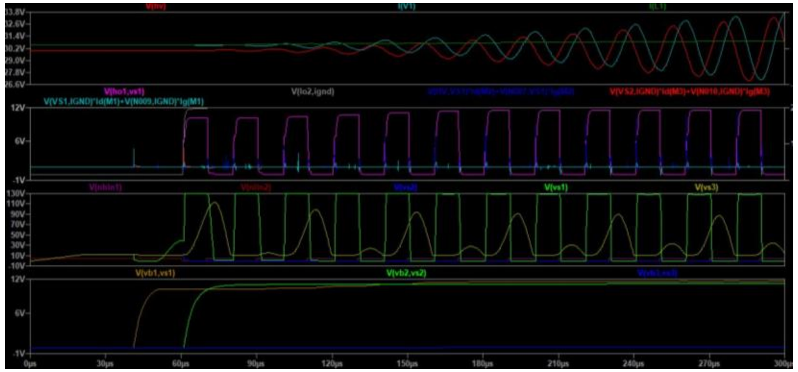
Current Status

- Software
  - Firmware layer implemented
  - High-level skeleton code written
  - Middle layers and implementing skeleton function in progress
- Hardware
  - Circuit level simulation compete, will run board level once layout is complete
  - Schematic completed, all components selected and footprints created.
  - Layout in progress

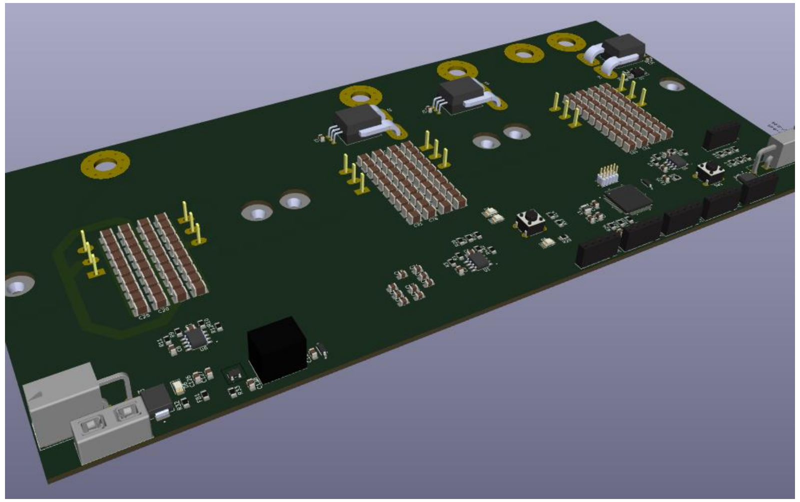
Revision 1 Status



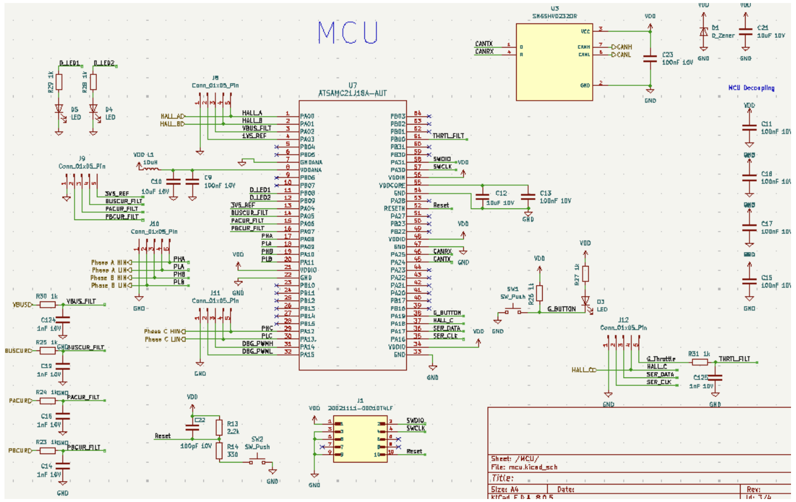
Current Layout of Rev 1



Switching Characteristics simulation

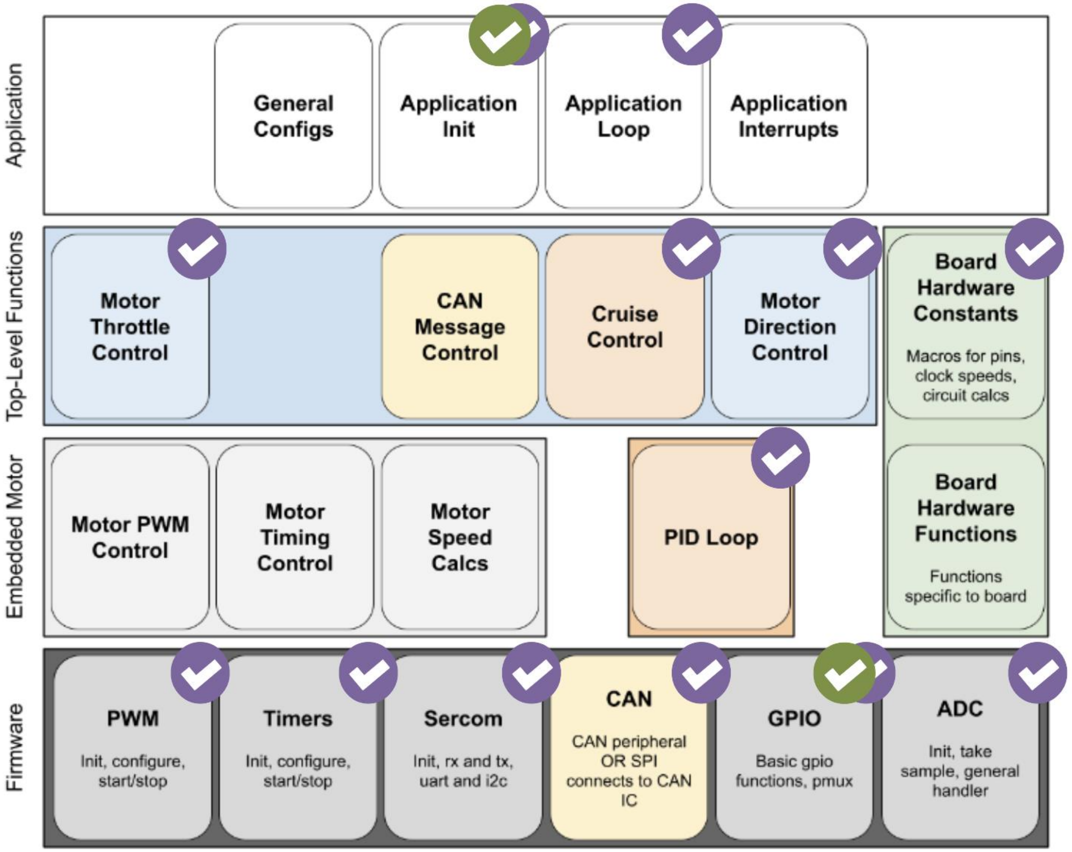


3D View of Rev 1 Layout



Schematic for the MCU in Rev 1

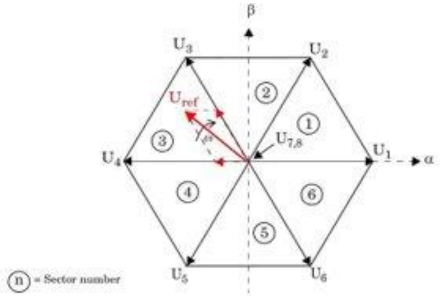
Revision 1 Status



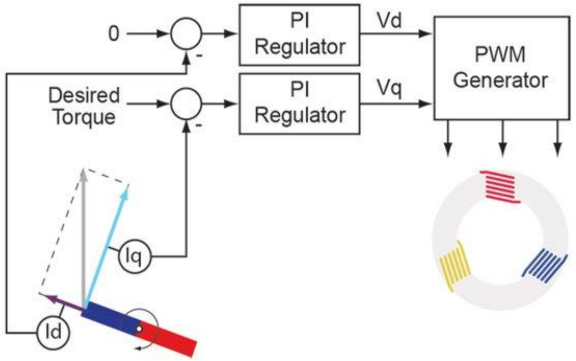
Software organization and status diagram

AT SAM C21 J18	Primary	
Function	Port & Pin	Peripheral
Phase H	PA08	TCC0 [0]
Phase L	PA09	TCC0 [1]
Phase H	PA10	TCC1 [0]
Phase L	PA11	TCC1 [1]
Phase H	PA12	TCC2 [0]
Phase L	PA13	TCC2 [1]
Bus Voltage	PA02	AIN2
Phase Current	PA05	AIN5
Phase Current	PA06	AIN6
Phase Current	PA07	AIN7
1.5V Reference	PA03	VREFA
3.5V Reference	PA04	VREFB
HALL Sensor	PA00	EXTINT[0]
HALL Sensor	PA01	EXTINT[1]
HALL Sensor	PA18	EXTINT[2]
CAN Tx	PA24	CAN0 TX
CAN Rx	PA25	CAN0 RX

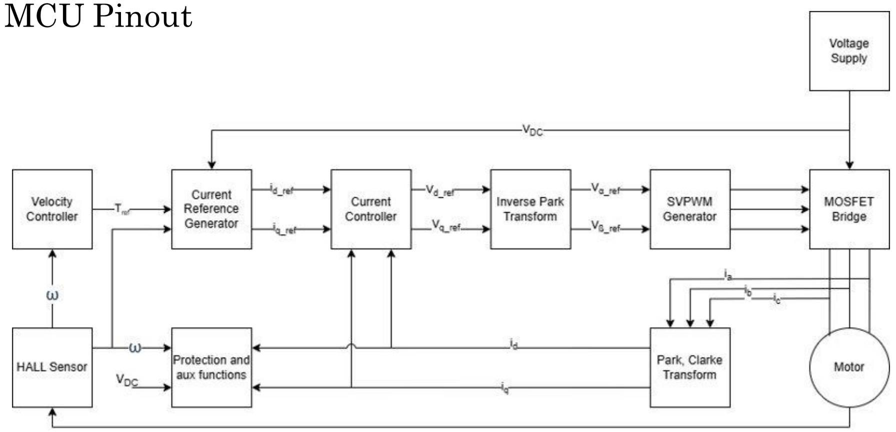
MCU Pinout



6-Step Phasor Diagram

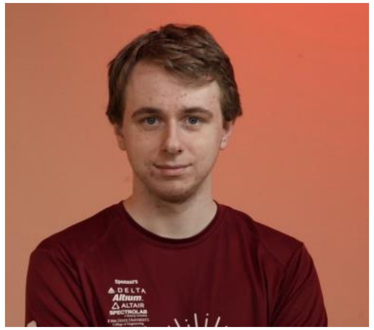


Simplified Control Diagram



Full FOC Control Implementation

Contributions



Marek

Simulations and applications expertise

Bryce

Fixed dev-board example code, developed firmware layer

Jonah

Component selection, Schematic design and Layout design

Gavin

Generated dev-board example code, research & design for FOC control

Long

Reasearch and order parts, updated documents and websites

Next Semester

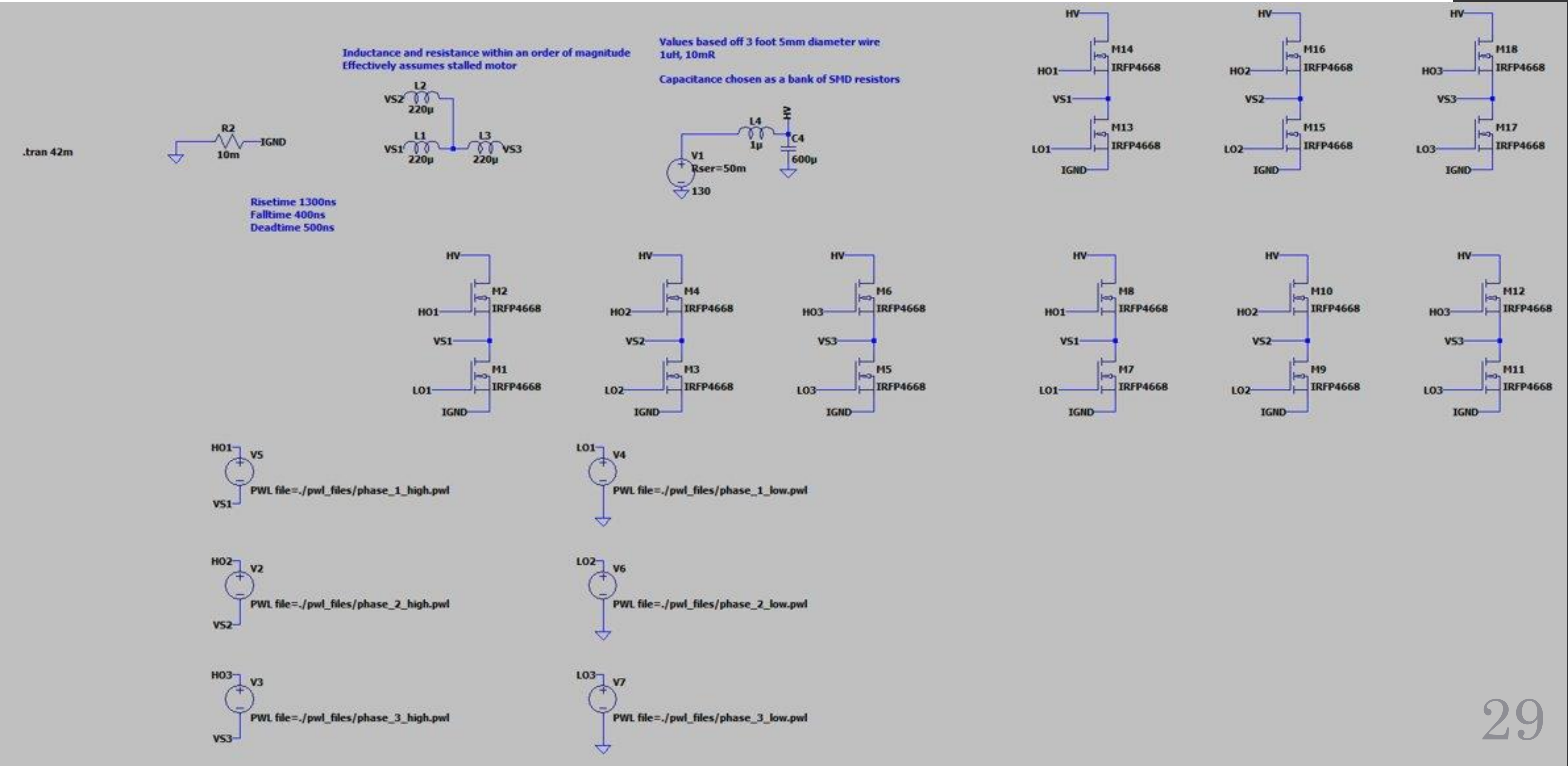
- Finish Revision 1
  - Finish the layout, order the board, and assemble the board
  - Implement the skeleton code and develop the "middle" motor layer of code
- Test Revision 1
  - Debug software and hardware
- Design Revision 2
  - Develop a schematic based on what was learned from revision 1
  - Scale everything up to meet requirements
- Assemble Revision 2
  - Assembled as a final deliverable
- Final Delivery
  - Documentation and software interfacing included

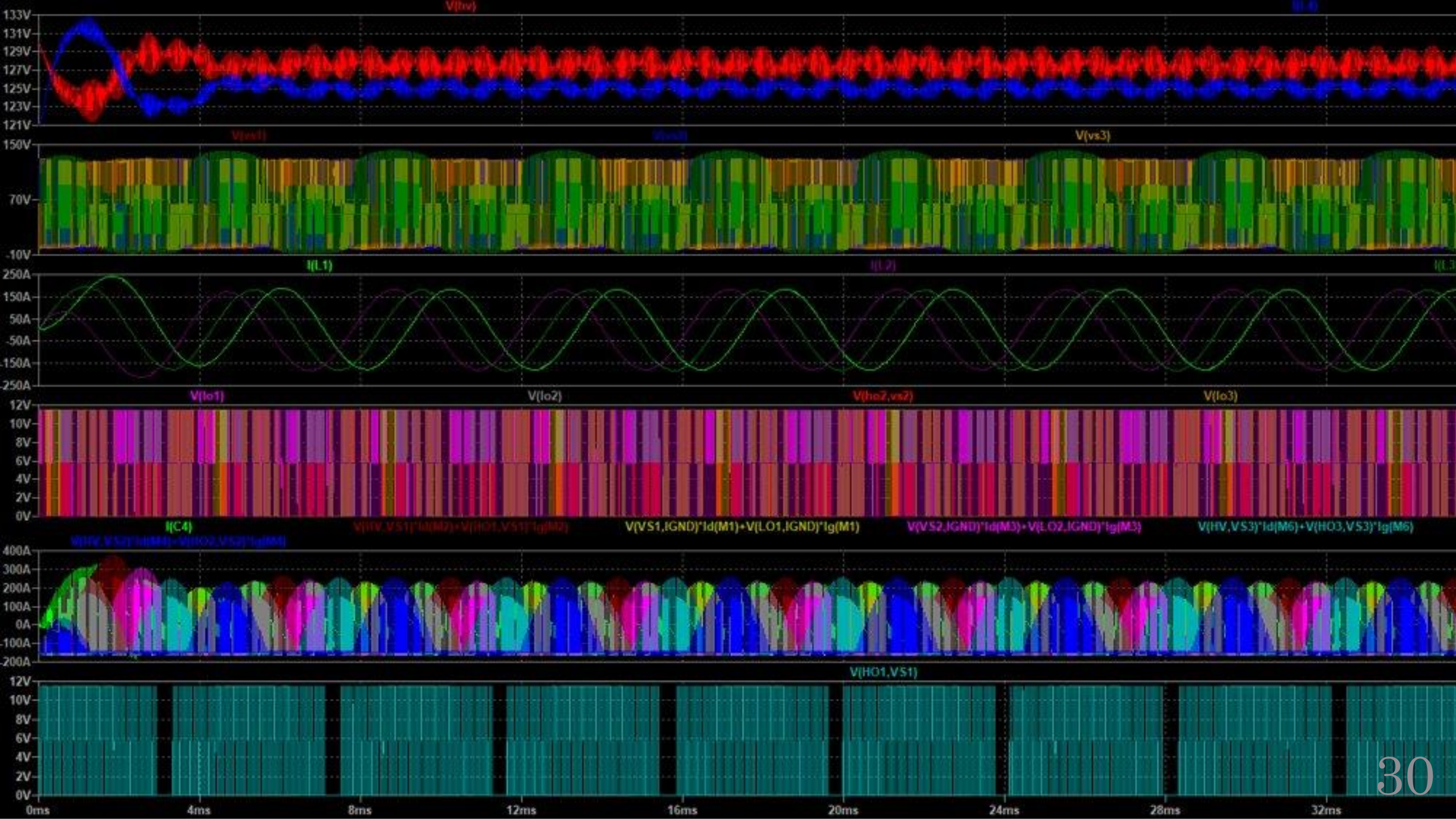
Questions?

Further Technical Details

Additional content to support what was covered in the high-level slides

Simulation schematic

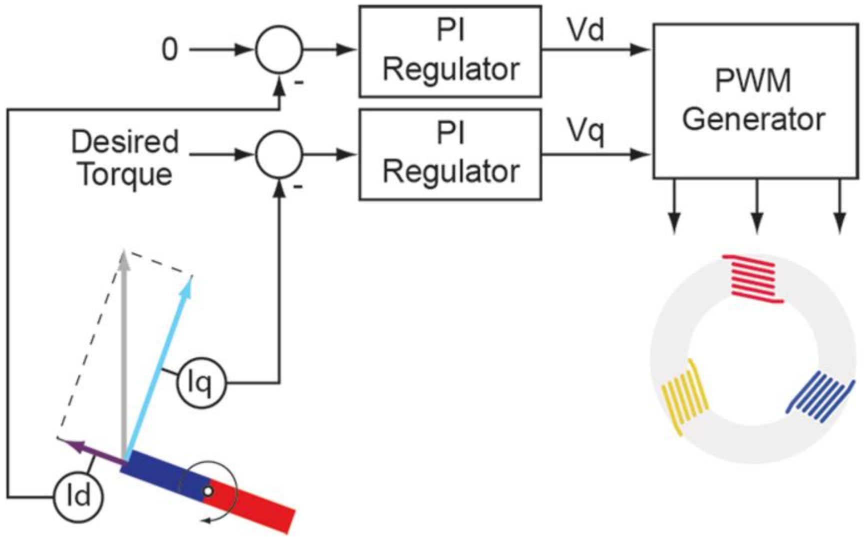


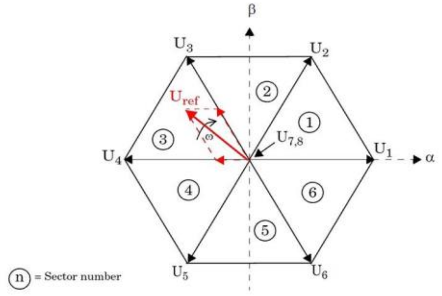

V(hv)
133V
131V
129V
127V
125V
123V
121V
V(vs3)
150V
70V
-10V
I(L1)
250A
150A
50A
-50A
-150A
-250A
V(lo1)
V(lo2)
V(ho2,vs2)
V(lo3)
12V
10V
8V
6V
4V
2V
0V
I(C4)
V(VS1,IGND)*Id(M1)+V(LO1,IGND)*Ig(M1)
V(VS2,IGND)*Id(M3)+V(LO2,IGND)*Ig(M3)
V(HV,VS3)*Id(M6)+V(HO3,VS3)*Ig(M6)
400A
300A
200A
100A
0A
-100A
-200A
V(HO1,VS1)
12V
10V
8V
6V
4V
2V
0V
0ms
4ms
8ms
12ms
16ms
20ms
24ms
28ms
32ms

SAM C21 J18 Pinout

AT SAM C21 J18	Primary		Secondary		Tertiary		
Function	Port & Pin	Peripheral	Port & Pin	Peripheral	Port & Pin	Peripheral	Debug?
Phase H	PA08	TCC0 [0]	PA16	TCC0/2	PB30	TCC1 [2]	Pin
Phase L	PA09	TCC0 [1]	PA17	TCC0/2	PB31	TCC1 [3]	Pin
Phase H	PA10	TCC1 [0]	PA30	TCC1 [0]	PB30	TCC1 [2]	Pin
Phase L	PA11	TCC1 [1]	PA31	TCC1 [1]	PB31	TCC1 [3]	Pin
Phase H	PA12	TCC2 [0]	PA16	TCC0/2	PB30	TCC1 [2]	Pin
Phase L	PA13	TCC2 [1]	PA17	TCC0/2	PB31	TCC1 [3]	Pin
Bus Voltage	PA02	AIN2	PB00	AIN0			Pin
Phase Current	PA05	AIN5	PB01	AIN1			Pin
Phase Current	PA06	AIN6	PB02	AIN2			Pin
Phase Current	PA07	AIN7	PB03	AIN3			Pin
1.5V Reference	PA03	VREFA					No
3.5V Reference	PA04	VREFB					No
HALL Sensor	PA00	EXTINT[0]	PA14	EXTINT[14]			Pin
HALL Sensor	PA01	EXTINT[1]	PA15	EXTINT[15]			Pin
HALL Sensor	PA18	EXTINT[2]	PA02	EXTINT[2]			Pin
CAN Tx	PA24	CAN0 TX	PB22	CAN0 TX	PB14	CAN1 TX	No
CAN Rx	PA25	CAN0 RX	PB23	CAN0 RX	PB15	CAN1 RX	No
DAC Analog Out	DNC		PA02	VOUT			N/A
Sercom Data	PA16	SERCOM 1/3	PA22	SERCOM 3/5			Pin
Sercom Clock	PA17	SERCOM 1/3	PA23	SERCOM 3/5			Pin
Throttle ADC	PB00	AIN0	PA08	AIN8	PB08	AIN2/4	Pin
Timer or PWM H	PA14	TC4 [0]	PA18	TC4 [0]	PB08	TC0 [0]	N/A
Timer or PWM L	PA15	TC4 [1]	PA19	TC4 [1]	PB09	TC0 [1]	N/A
Extra Button	PA19	EXTINT[3]	PA14	EXTINT[14]	PA15	EXTINT[15]	No
Extra LED	PA14	EXTINT[14]	PA15	EXTINT[15]	PA19	EXTINT[3]	No
Extra LED	PA15	EXTINT[15]	PA14	EXTINT[14]	PA19	EXTINT[3]	No
Extra GPIO	PA22	EXTINT[6]	PB22	EXTINT[6]	PB12	EXTINT[12]	Pin
Extra GPIO	PA23	EXTINT[7]	PB23	EXTINT[7]	PB13	EXTINT[13]	Pin

Field Oriented/Weakening Control





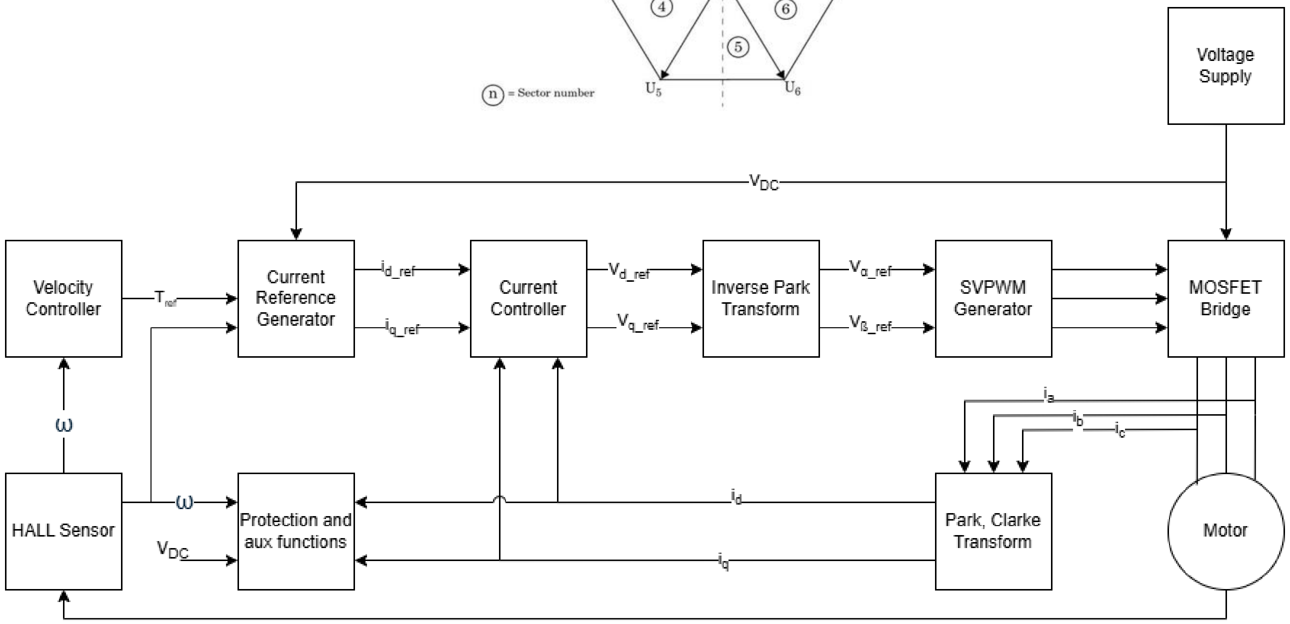
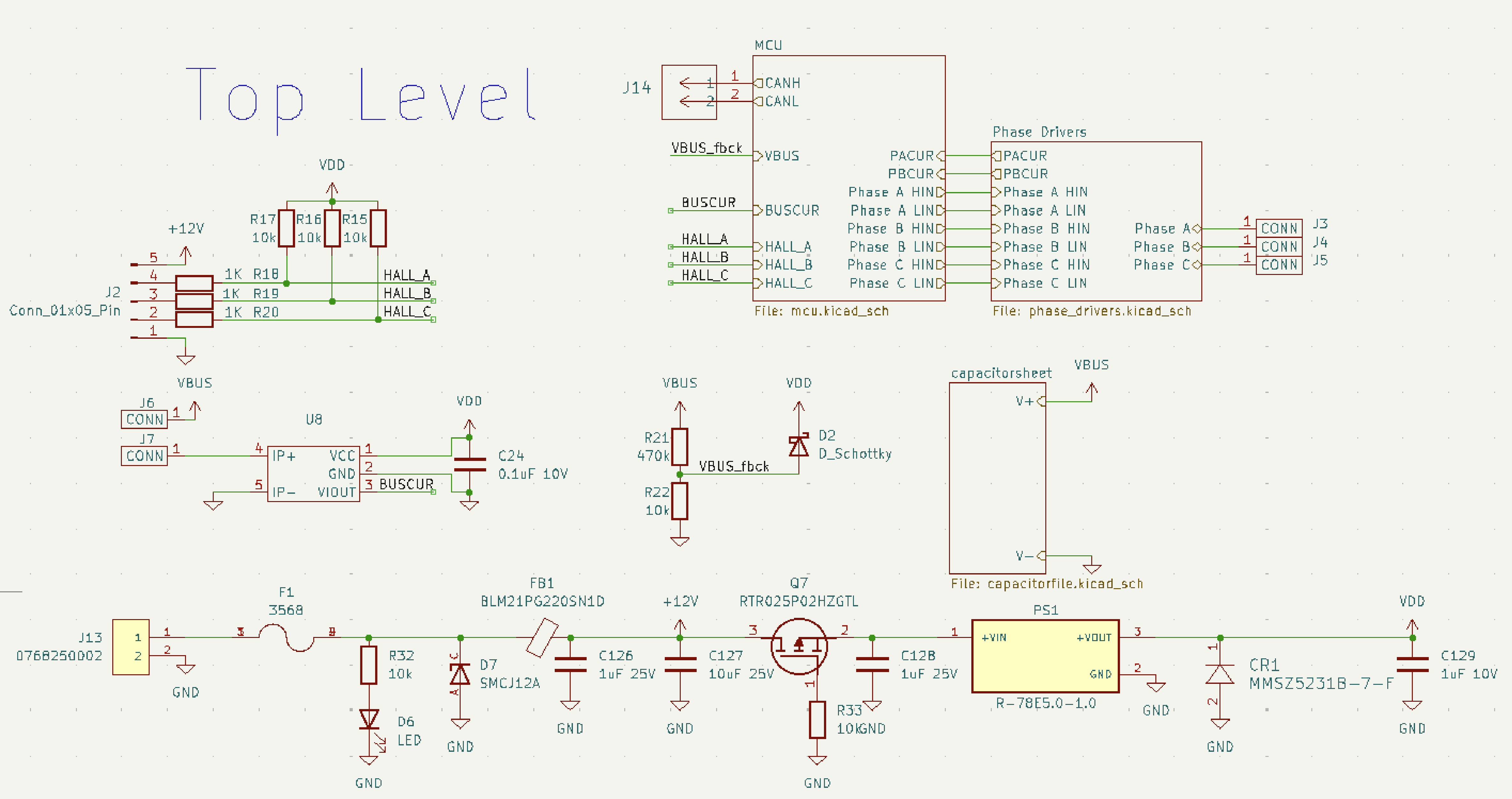
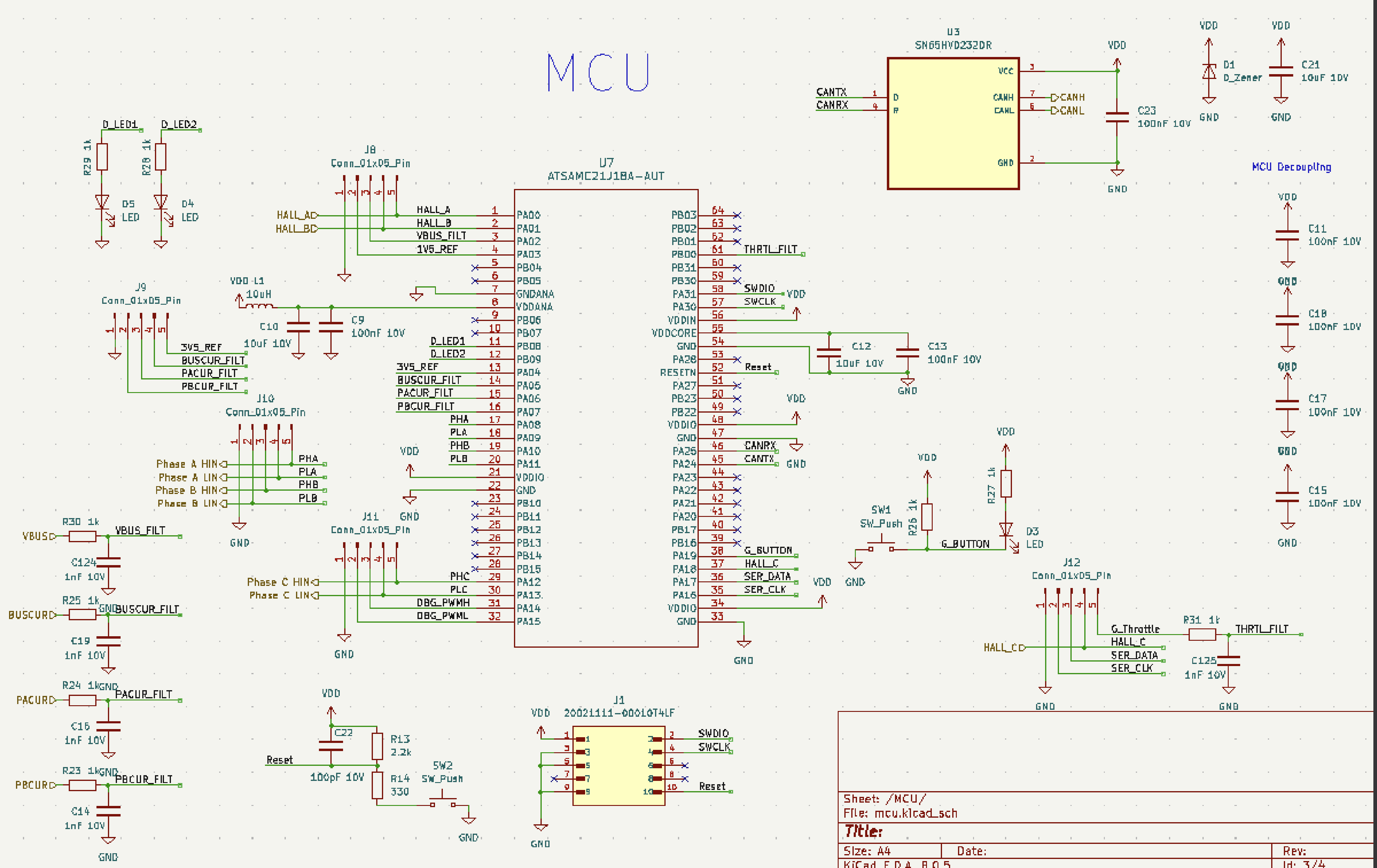


Figure out what this all means for our code

Schematic



Top Level
MCU
J14
CANH
CANL
VBUS_fbck
VBUS
BUSCUR
HALL_A
HALL_B
HALL_C
PACUR
PBCUR
Phase A HIN
Phase A LIN
Phase B HIN
Phase B LIN
Phase C HIN
Phase C LIN
File: mcu.kicad_sch
Phase Drivers
Phase A
Phase B
Phase C
CONN
J3
J4
J5
File: phase_drivers.kicad_sch
VDD
+12V
R17 10k
R16 10k
R15 10k
1K R18
1K R19
1K R20
J2
Conn_01x05_Pin
J6
J7
U8
IP+
IP−
VCC
GND
VIOUT
C24
0.1uF 10V
R21 470k
R22 10k
D2
D_Schottky
capacitorsheet
V+
V−
File: capacitorfile.kicad_sch
J13
0768250002
F1
3568
FB1
BLM21PG220SN1D
Q7
RTR025P02HZGTL
PS1
+VIN
+VOUT
R-78E5.0-1.0
R32 10k
D6 LED
D7 SMCJ12A
C126 1uF 25V
C127 10uF 25V
C128 1uF 25V
R33 10K
CR1
MMSZ5231B-7-F
C129 1uF 10V
GND



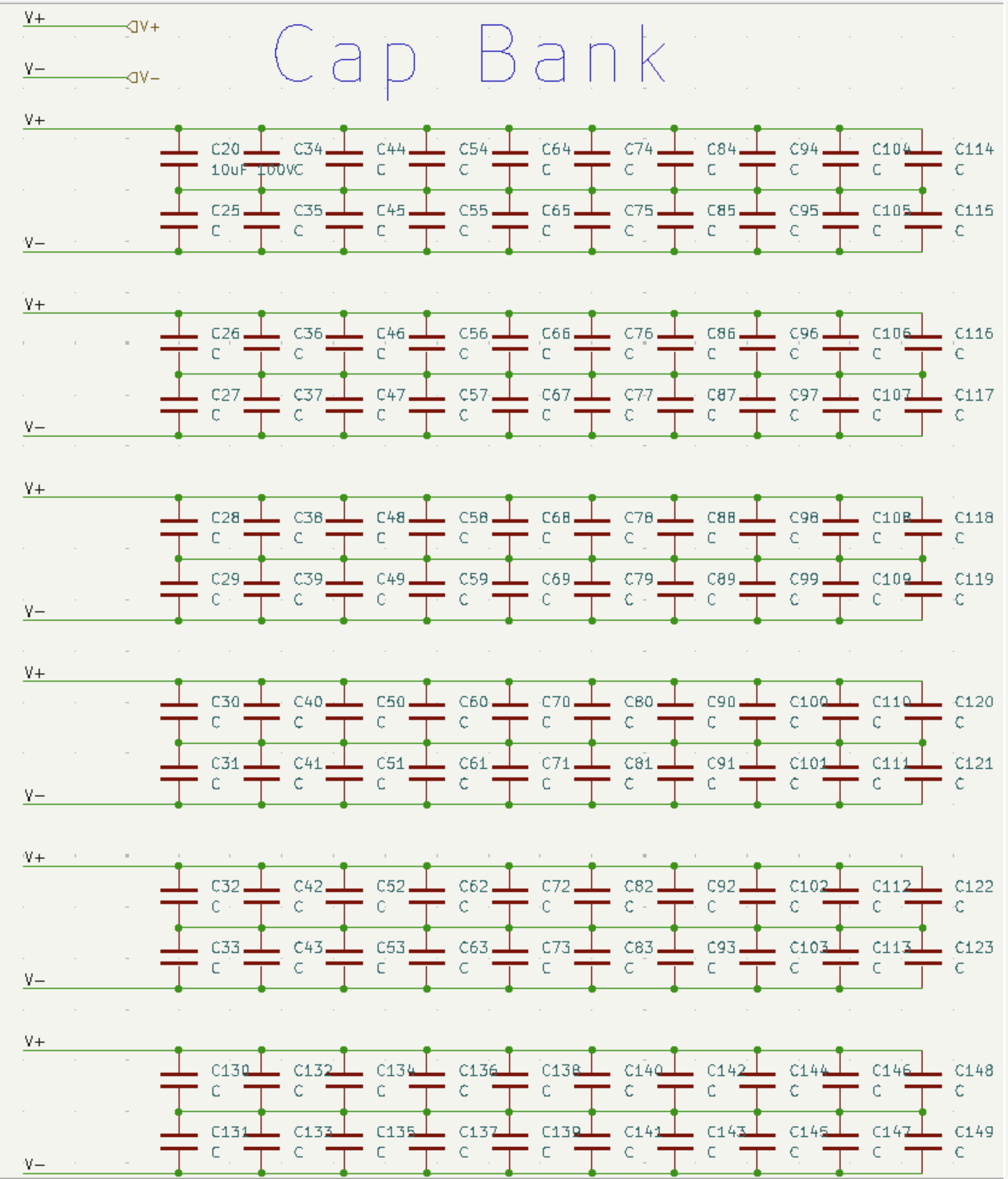
Sheet: /MCU/

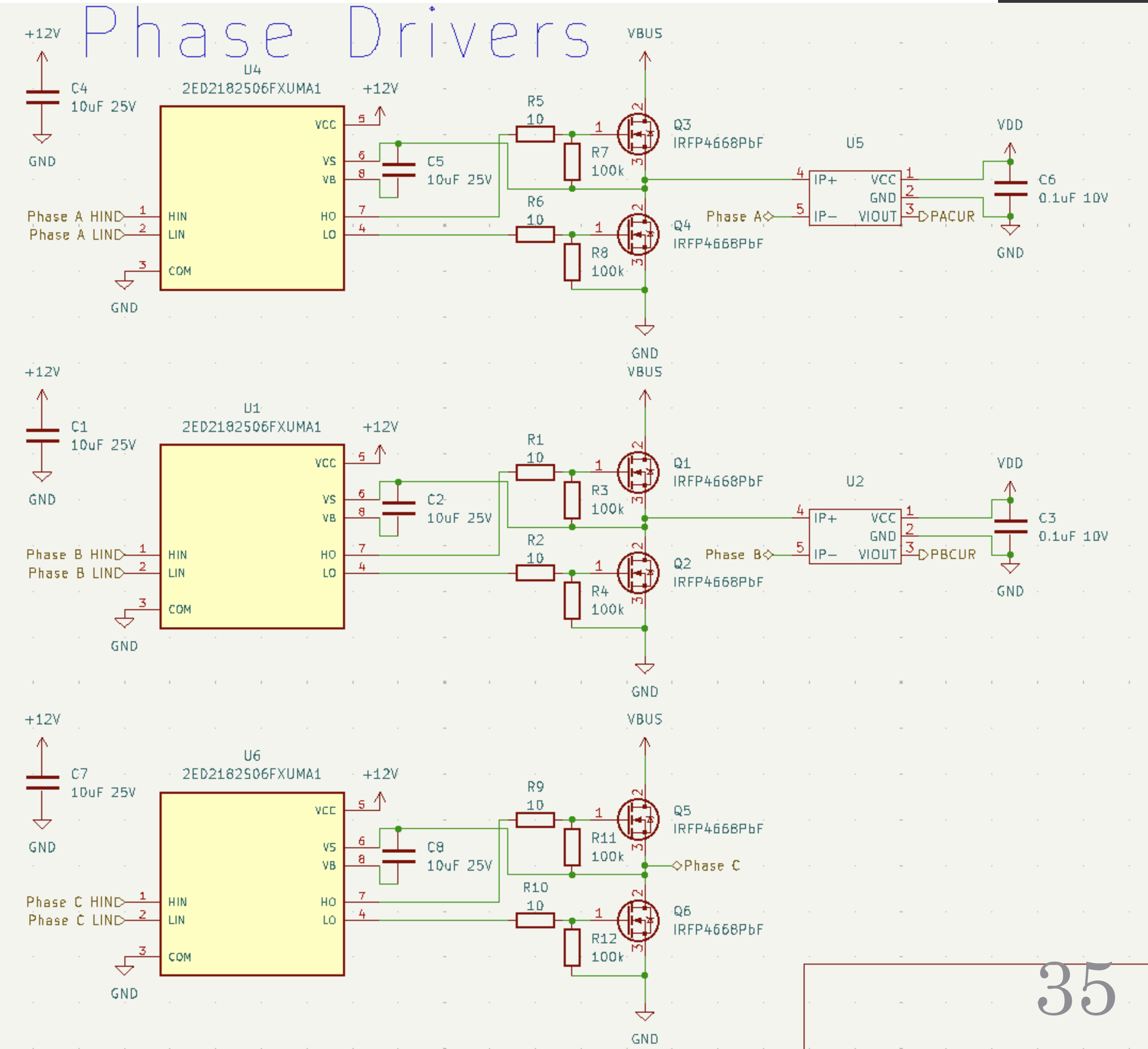
File: mcu.kicad_sch

Title:

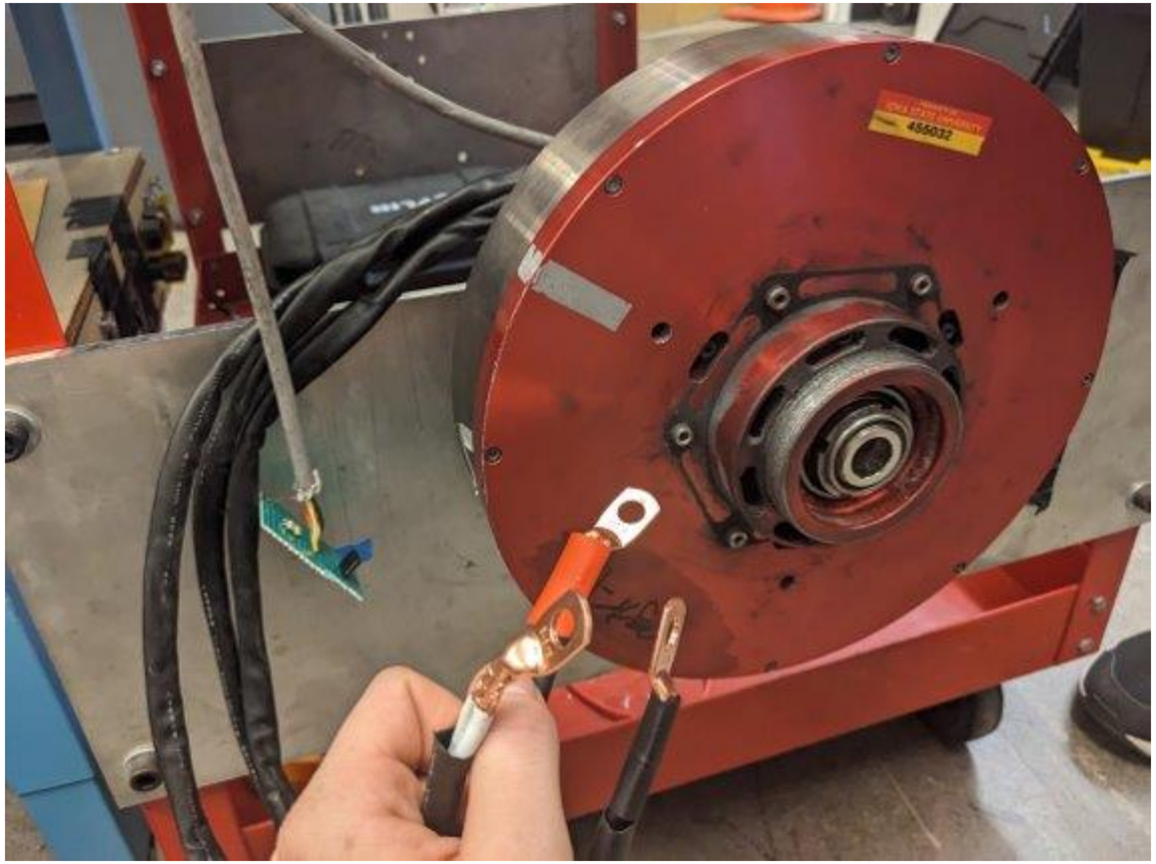
Size: A4 | Date: | Rev:

KiCad E.D.A. 8.0.5 | Id: 3/4

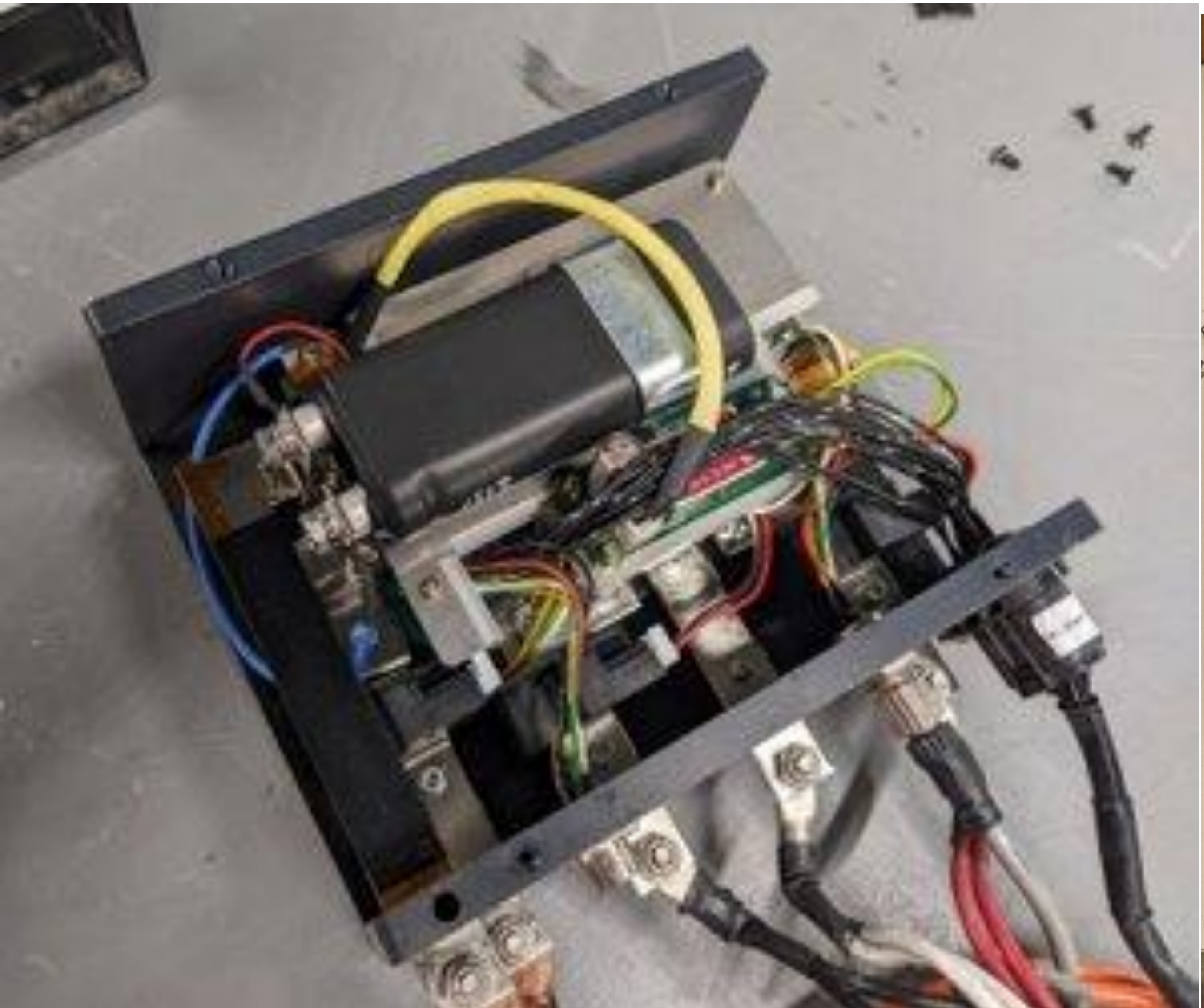

Cap Bank
V+
V−
10uF 100VC

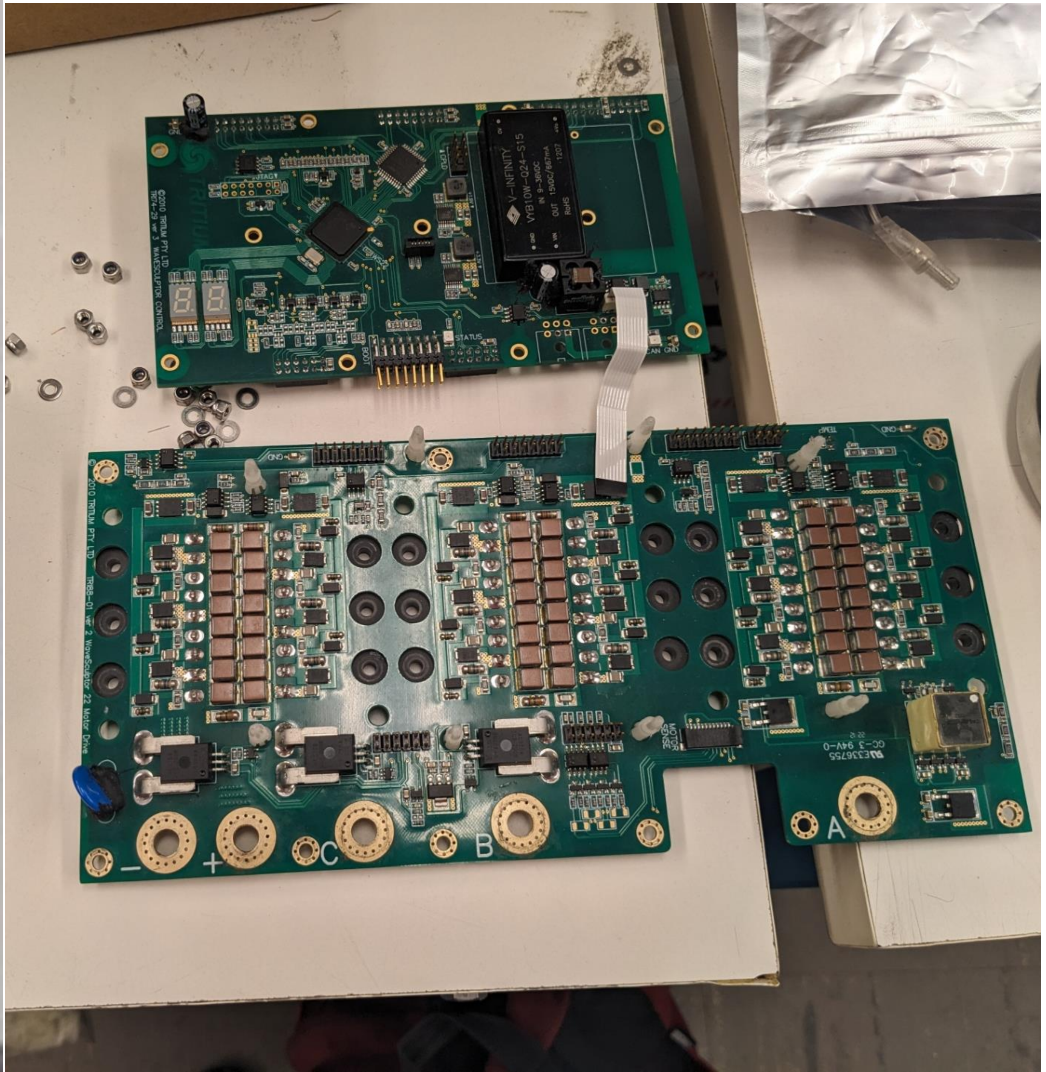

Phase Drivers
+12V
VBUS
GND
VDD
U4
U1
U6
2ED2182S06FXUMA1
U5
U2
IRFP4668PbF
Phase A HIN
Phase A LIN
Phase B HIN
Phase B LIN
Phase C HIN
Phase C LIN
Phase A
Phase B
Phase C
PACUR
PBCUR
10uF 25V
0.1uF 10V

Motor Reference Images



Controller Reference Images





Engineering Standards

- IEEE 1547 - Standard for Interconnecting Distributed Resources with Electric Power Systems
  - This standard outlines requirements for safely interconnecting distributed energy resources (like solar and wind) with electric power systems, focusing on performance, safety, and reliability.
- IEEE 1149.1 - Standard Test Access Port and Boundary-Scan Architecture
  - This standard defines a boundary-scan architecture for testing and debugging integrated circuits and circuit boards, allowing access to internal signals for easier diagnostics without physical probes.
- IEEE 1554 - Standard for Software Engineering in the Life Cycle of Digital Systems
  - This standard provides guidelines for software engineering throughout the life cycle of digital systems, emphasizing structured practices for development, Detroit testing, and maintenance to improve software quality and reliability.