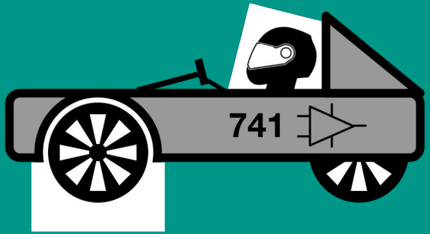
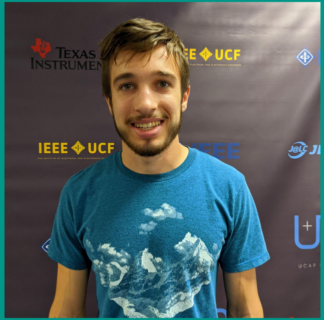


Rebuilt Electric Go-kart

Group 27

Our Team



Grace Tuomala

Computer Engineering

Julian Yerger

Electrical Engineering

Abdullah Arshad Choudhry

Electrical Engineering

Fouad Braimoh

Computer Engineering

Motivation and Background: **Electrathon**

- Electrathon is a race for electric go-karts in which individuals or teams compete to complete as many laps as possible on a **closed-loop track** during a **1-hour** period using at most **1kWh** of energy
- Nationwide organization with an active league in Tampa Bay
- Races throughout the year, typically hosted by high schools
- Four classes for scoring based on education level - high school or "open" - and battery type - lead-acid or lithium-ion
- This project: an electric go-kart to race in Electrathon's **open/lithium-ion class,** designed for performance and efficiency, paired with a driver assistance app to display vital information during the race

Goals and Objectives

	Hardware	Software
Basic	Build custom DC-DC converters to supply power from battery pack to 15V, -15V, 5.5V, and 3.3V rails	In-car Bluetooth display including lap counter, temperature monitor, time left in race, and button to start/stop race, easy to use & visually appealing user interface
Advanced	Motor controller with greater efficiency than typical RC controller, finish at least one Electrathon race	Send race statistics from car to subscribing spectators; measure and display speed, current, and voltage; display compatibility with varying device screen sizes
Stretch	Win a Tampa Bay Electrathon race, Custom 1800W DC fast charger to recharge battery between races	Graphs showing energy budget and/or voltage & current over time, iOS compatibility

Engineering Specifications

Powertrain	Battery Capacity (0.1C)	1000Wh, +/- 5%
	Battery Weight (cells)	< 15lbs
	Motor Controller Peak Efficiency	> 90%
User Interface	Current & Voltage Measurement Accuracy	+/- 5%
	Lap Counter Accuracy	+/- 10%
	Display Response Time	1 second
Battery Charger	Maximum Voltage	63V +/- 5%
	Maximum Current	36A +/- 5%

Hardware Technology Comparison: Motor

	Brushed DC Motor	Brushless DC Motor
Cost	Lower initial, higher maintenance	Pricier, low maintenance
Efficiency	Low	High
Lifespan	Low	High

Most Electrathon teams use a brushed motor, which is notably simpler to design and implement, but less efficient

Hardware Technology Comparison: Battery

Types of Battery Packs	Description
Alkaline	Cheaper option which is decent for every application but are not rechargeable
Nickel Metal Hydride (NIMH)	Reusable and more environmentally friendly but they are heavy and have a low nominal voltage
Lithium Ion	High cost and sub-optimal performance at extreme temperatures but offer higher voltage and are lighter

Hardware Technology Comparison: Semiconductor Material

	Si	SiC	GaN
Band Gap (eV)	**1.1**	**3.2**	**3.4**
Critical Field (10^6 V/cm)	**0.3**	**3**	**3.5**
Electron Mobility	**1450**	**900**	**2000**
Electron Saturation Velocity (10^6 cm/sec)	**10**	**22**	**25**
Thermal Conductivity (Watts/cm^2 K)	**1.5**	**5**	**1.3**

Hardware Comparison

	Relative Permittivity	Dielectric Str. (V/µm)	Typical Value (µF)	Dissipation Factor x10^-4
Ceramic Class 1	12 to 90	< 100	10^-6 to 1	10 at 1-MHz
Ceramic Class 2	200 to 14,000	< 35	10^-6 to 1	251 at 1-MHz
Electrolytic	9.6	710	1 to 47,000	100 at 120-Hz
Tantalum	26	625	1 to 100	600 at 120-Hz
Mica	5 to 8	118	10^-6 to 3*10^-3	4 at 1-MHz
Polyester Film	3.3	470/220	10^-4 to 10	170 to 300 at 100-kHz
Polypropylene Film	2.2	650/450	10^-4 to 102	2 to 25 at 1-MHz

Hardware Part Selection: Motor

- Main goal is maximum efficiency, but need to calculate
- Electrical resistance losses
  - Ohmic in motor windings, $P_{R\text{-}Loss} = I^2R$
- Frictional losses
  - Bearing resistance and air resistance, hard to calculate but small
- Hysteresis losses
  - Rotating permanent magnets drag against stationary iron in the core
  - Minimized with thinner laminations (reduce eddy currents) and efficient magnetic design
  - Magnet strength proportional to both hysteresis losses and torque constant

Hardware Part Selection: Motor

- Ohmic losses are winding resistance (R_M) times current squared
- No-load current (I_0) shows frictional and hysteresis losses, multiply by the voltage for the power loss
- For simplicity, assume that I_0 is constant with RPM, so we can define a watts/RPM loss
- Velocity constant (kV) and torque constant (K_T) show relationship to RPM
  - In SI units, $K_T = 60/(2*3.14*kV)$
- Can estimate motor efficiency curves from only R_M, I_0, and kV, which are the only commonly given BLDC motor specifications

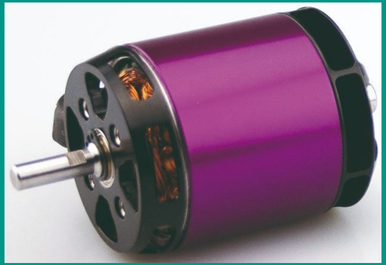
Hardware Part Selection: Motor

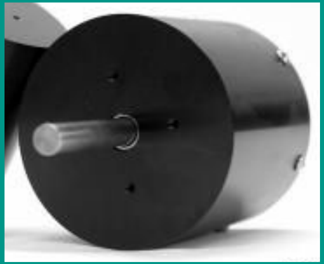
- $P = 0.105 * (Nm) * (rpm)$
- $(Nm) = P/(rpm*0.105) = K_T*(A)$
- $(A) = P/(rpm*0.105*K_T)$
- $Losses = A^2*R + L*(rpm)$
- $\eta = (P - [Losses])/P$
- $\eta (P, rpm) = (P - [(P/(rpm*0.105*K_T))^2*R + L*(rpm)])/P$
- May underestimate hysteresis loss

Hardware Part Selection: Motor

Table 3.5 - Motor Performance Parameters

	Rotomax 150cc	Astro 3220	KDE7 215XF	CA120	Hacker A50-16L	Hacker Q100	Hacker A60-18L
kV (RPM/V)	150	137	135	150	265	110	149
R_M (ohms)	0.011	0.05	0.057	0.005	0.031	0.0106	0.02
I_0 (amps)	5.2 at 51.8V	1 at 50V	0.5 at 10V	13 at 20V	0.95 at 8.4V	1.86 at 8.4V	1.6 at 8.4V
Loss (W/RPM)	0.035	.0073	0.0037	0.087	0.0036	0.0169	0.0107
Weight (kg)	2.53	1.8	0.56	2.73	0.45	1.83	0.91
Peak Efficiency	93.1	94.8	95.7	90.8	94.3	96.1	94.9

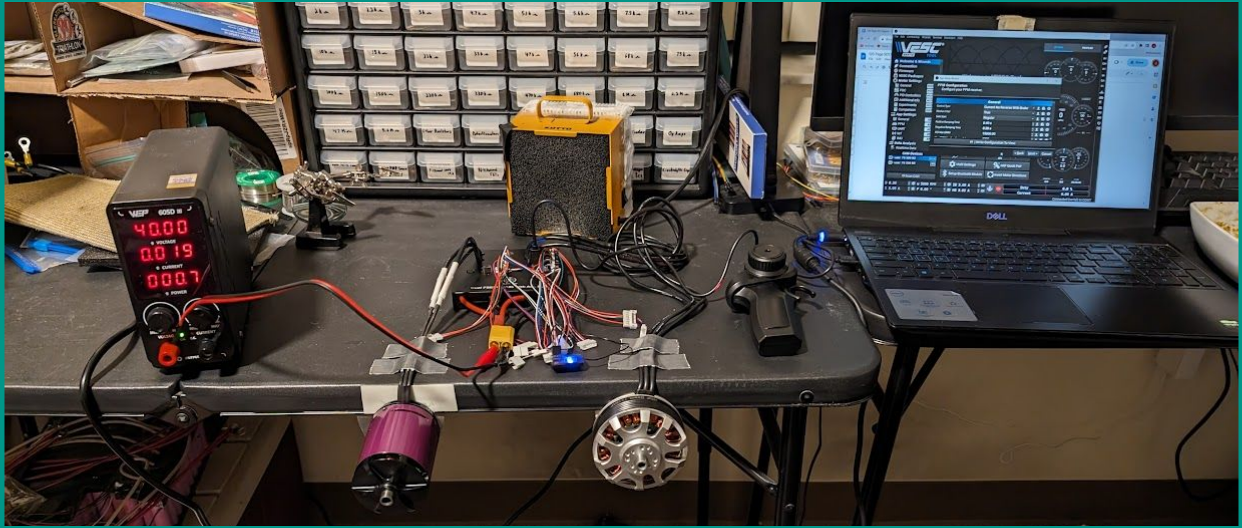




Hardware Part Selection: Motor

Table 3.6 - Motor Efficiency Curves							
	Rotomax 150cc	Astro 3220	KDE7 215XF	CA120	Hacker A50-16L	Hacker Q100	Hacker A60-18L
η at 500W	84.1	91.3	94.5	78.9	92.8	92.1	91.5
η at 1000W	87.4	93.1	95.4	83.2	94.2	93.7	93
η at 1500W	89	94	95.7	85.3	94.2	94.5	93.9
η at 2000W	90	94.5	95.4	86.7	–	95	94.4
η at 2500W	90.7	94.8	94.9	87.6	–	95.4	94.8
η at 3000W	91.2	94.8	94.4	88.4	–	95.7	–
η at 4000W	92	94.5	93.1	89.4	–	96.1	–
η at 5000W	92.6	94	–	90.2	–	–	–
η at 6000W	93.1	93.3	–	90.8	–	–	–

Hardware Part Selection: Motor



- At 40V, I_0 was 1.7A for the A60 and 1.73A for the KDE
- Datasheet not necessarily wrong, just measured at a lower voltage
- Winding resistance was 33.6 for A60 vs 76.8 mohms for KDE
- Used a 4-wire Kelvin method, but still has resistance in connectors

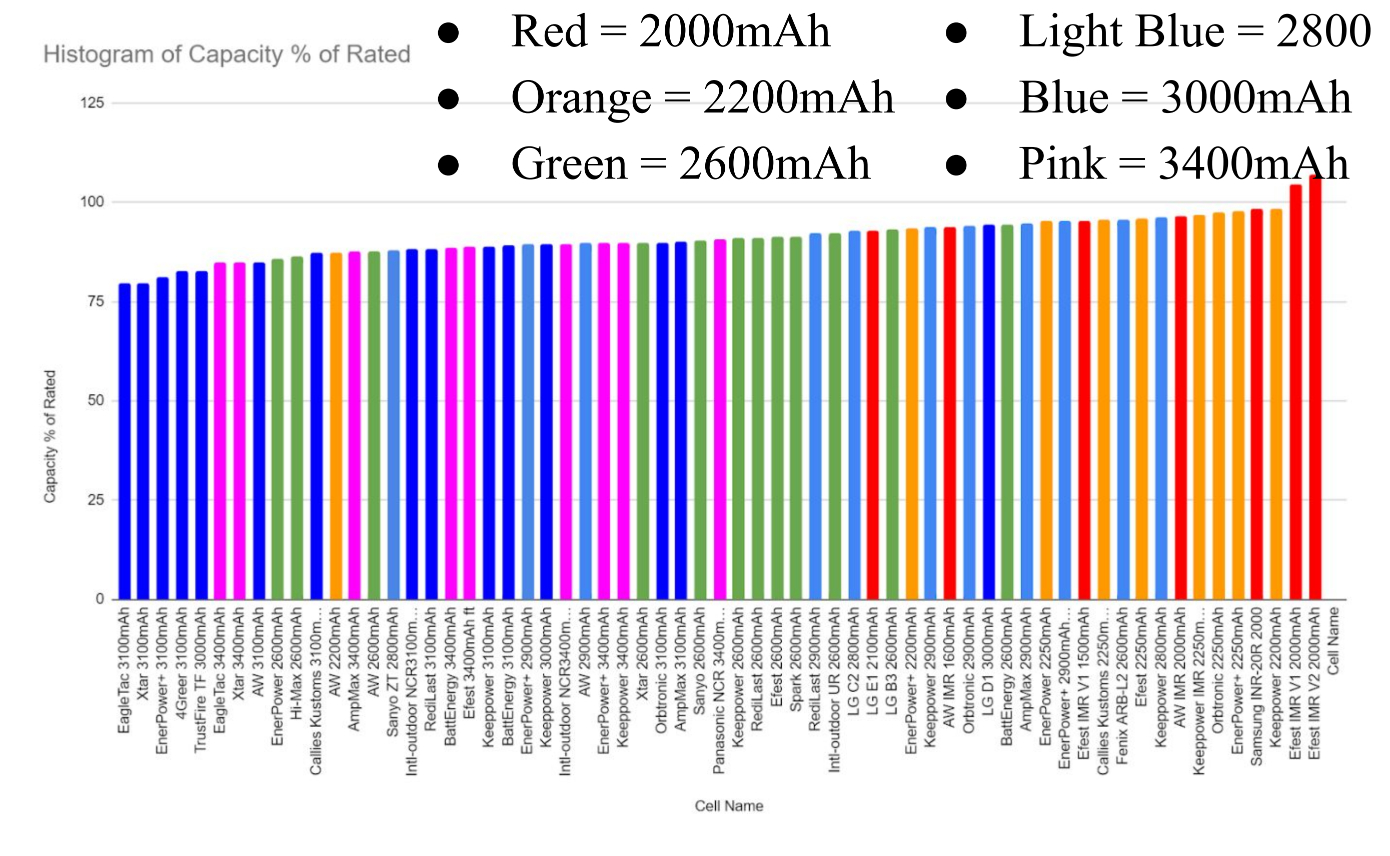
Hardware Part Selection: Battery

18650 case size

5A discharge

Smaller cells have lower resistance and higher percent of rated capacity

Will use 2Ah cells in 15S x 9P config.

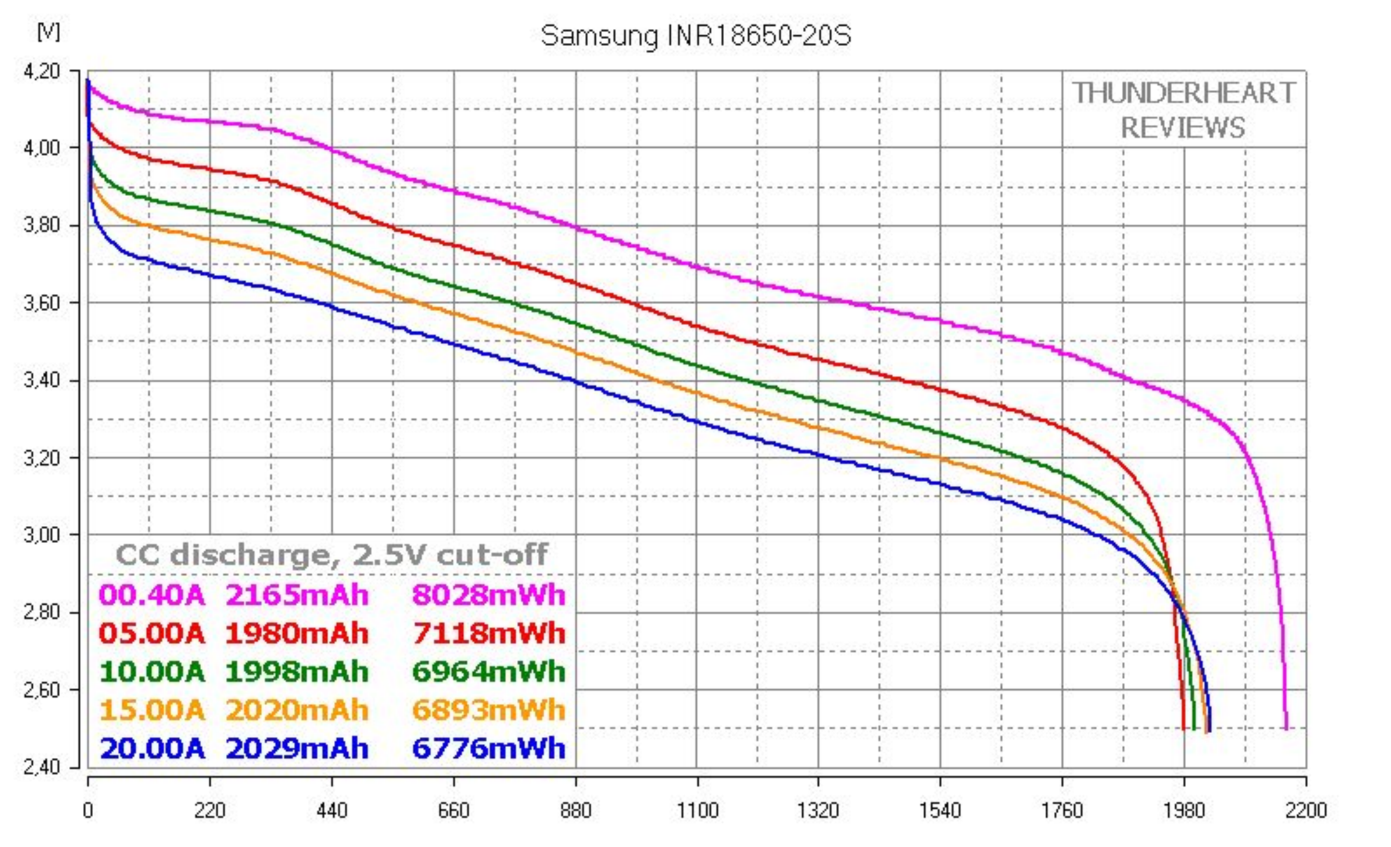


Hardware Part Selection: Battery

Selected the Samsung 20S

Tested very well

Rated for 30A per cell, will only see 2500/(135*3)= 6A



Hardware Part Selection: Transistors

Model Name	Maximum Voltage (V)	$R_{DS\text{-}On}$ (milli-ohms)	Gate Charge (nC)	Price (x12)
GS61004B	100	22	3.3	$6.64
GS61008T	100	9.5	8	$11.09
GAN3R2-100C	100	3.2	12	$3.68
GAN7R0-150L	150	7	7.6	$2.76

- 70 options for GaN FETs, all but 4 intended for 600V
- At low frequency $R_{DS\text{-}On}$ is more important than gate charge

Hardware Part Selection: Capacitors

- Design Conditions: 55.5V average, $10V_{Pk\text{-}Pk}$ ripple, 50A, 10 kHz
  - $R_{Load} = 55.5/50 = 1.11$ ohms
  - $V_{Ripple} = V_{Peak} / (f*R*C)$
  - $C = V_{Peak} / (f*R*V_{Ripple}) = 55.5/(10000*1.11*10) = 500\ \mu F$
- Use two 260 µF polypropylene capacitors each rated to 23A ripple current

Software Comparison: Display Options

	LCD With Dedicated MCU	LCD Connected to Central MCU	Smartphone App
Number of Microcontrollers	3	2	2
Languages Used	C only	C only	C, along with a development language such as JavaScript, Dart, or Kotlin
Number of IDEs	1-3	1-2	2-3
Learning Opportunities	Embedded programming only; display interfacing	Embedded programming only; display interfacing	Embedded programming and app development

Software Comparison: Motor Control Options

	Trapezoidal Control	Field Oriented Control
Implementation	“Six-step” block communication with 6 inverter states, algorithmically simpler than FOC	More mathematically complex, using Park and Clark transformations
Efficiency	Less Efficient	Up to 97% more efficient than Trapezoidal Control [29]
Maximum Power Generation	5330W at 1074rpm	5330W at 862rpm
Maximum Torque Generation	67Nm at 300rpm	78Nm at 324rpm
Development Support Available	Six-step firmware library for STM32, TrapeZoid Arduino library	InstaSPIN-FOC for select TI C2000 products, SimpleFOC for Arduino
Cost	None*	$10-$15 microcontroller, plus $35-$50 development board (optional, but useful for prototyping)

*Trapezoidal control does not have extensive requirements, so most general purpose microcontrollers could be used

Software Selection: Display MCU

	Operating Voltage	Clock Speed	Memory	Useful Features	Price
Arduino Uno	5V	16 MHz	32 KB Flash, 2 KB SRAM	USB connection, Power jack	$27.60
Arduino Mega	5V	16 MHz	256 KB Flash, 8 KB SRAM	USB connection, Power jack	$48.40
ESP 32 WROOM	3.3V	240 MHz	448 KB ROM, 520 KB SRAM	Low power options, Bluetooth connection, Wi-Fi, USB connection	$8.00
STM 32	1.8-3.6V	120 MHz	1 MB Flash, 128 KB SRAM	Low power options	$13.52
MSP 430	1.8 – 3.6V	25 MHz	512 KB Flash, 32 KB SRAM	Ultra-low power mode	$7.93

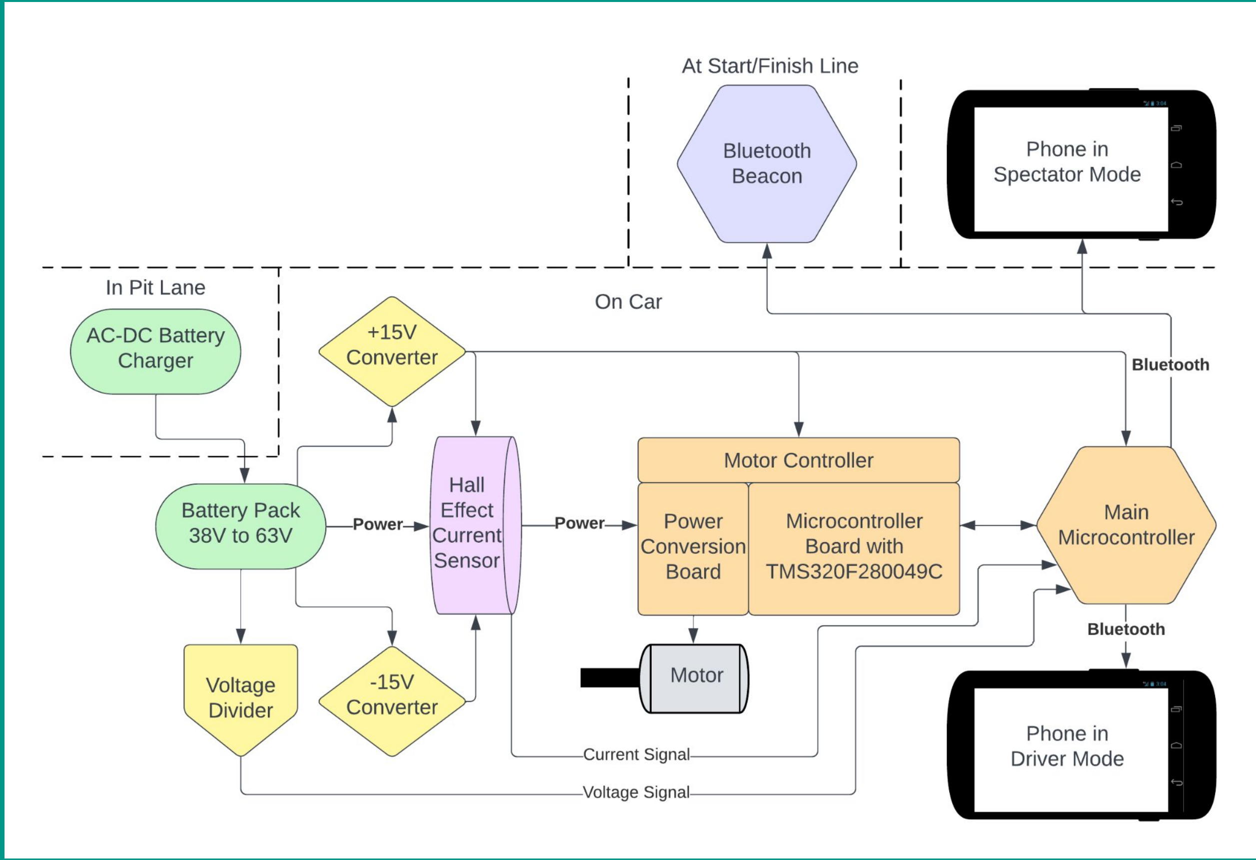
Software Selection: Development Platform

	Flutter	Thunkable	React Native
Language	Dart	Codeless	JavaScript
Support Community	Support groups on Discord, Slack, Stack Overflow, Reddit, and Google Developer	Thunkable Community Forum with about 20 posts/day	Multiple Discord groups, Slack; tagged content on Medium, Hacker News, and Reddit
Industry Relevance	Some skills may be applicable to industry	Little to none	Highly applicable to industry (JavaScript/frontend development)
Setup Requirements	Need separate IDE and Android Studio; multi-step installation process	Online interface and live testing app downloaded to phone	Need separate IDE
Limitations to free access	N/A (Open-source)	100MB storage and 2 download/month limit	N/A (Open-source)

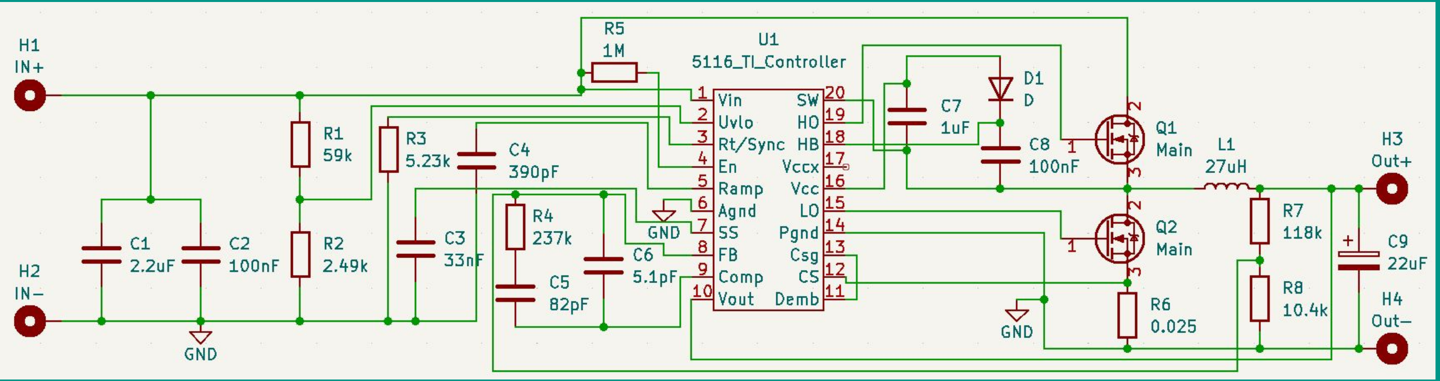
Software Selection: Motor Controller MCU

Model	TMS320F28335	TMS320F28034PNTR	TMS320F280049C
Clock Frequency	150MHz	60MHz	100MHz
Flash Memory	512KB	128KB	256KB
RAM	68KB	20KB	100KB
Processing (MIPS)	150	60	200
Notable Features	FPU (floating point unit)	CLA (control law accelerator)	CLA, FPU, TMU (trigonometric accelerator), InstaSPIN-FOC
Unit Price	$29.53	$8.86	$10.17

Hardware Design: Block Diagram

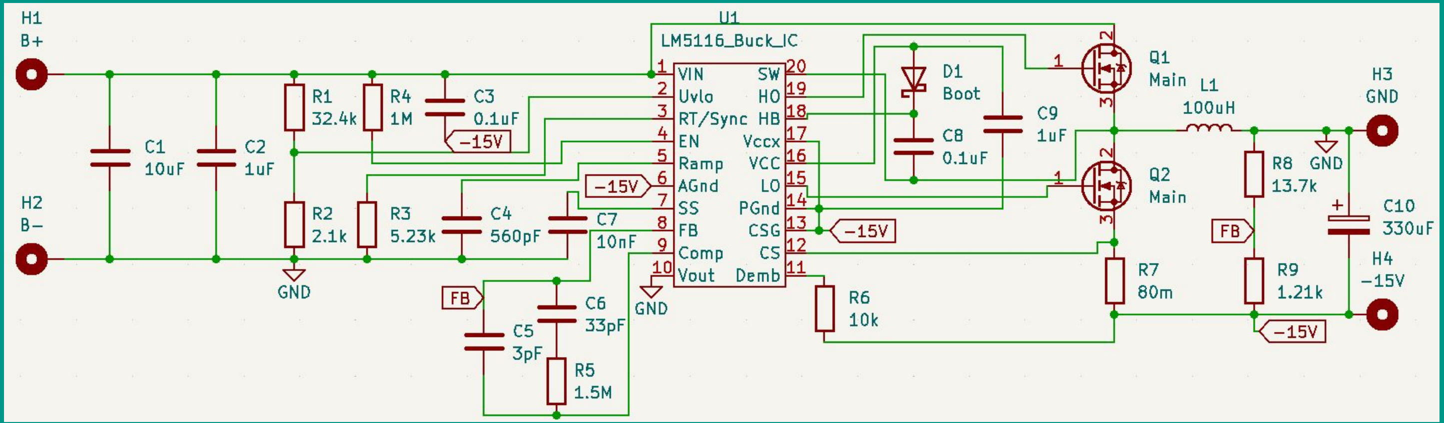


Hardware Design: Schematics



+15V Regulator

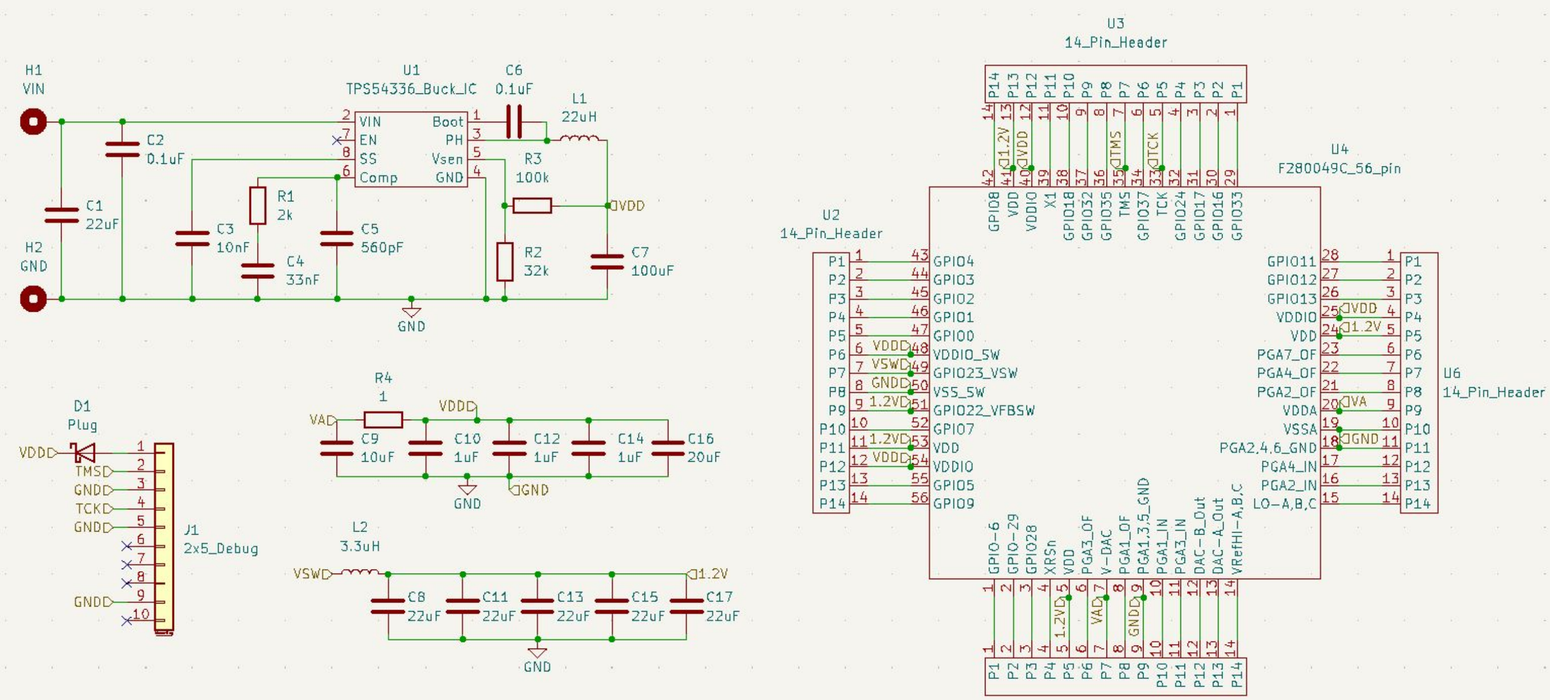
$I_{Out} = 2A$ max



-15V Regulator

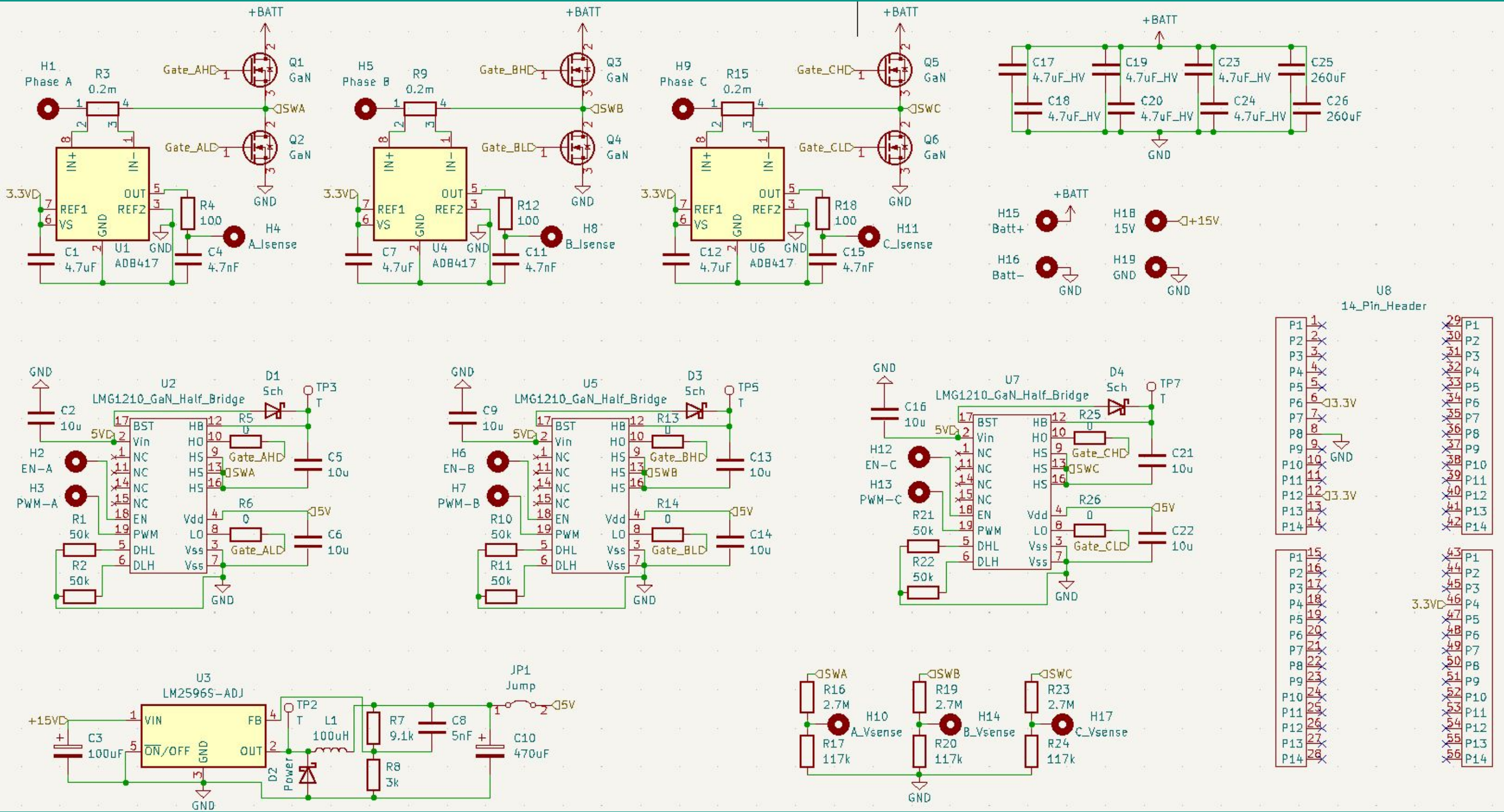
$I_{Out} = 0.5A$ max

Hardware Design: Schematics



- Motor controller MCU on a daughterboard for easy replacement
- F280049 is nominally 3.3V, but the core runs on 1.2V

Hardware Design: Schematics



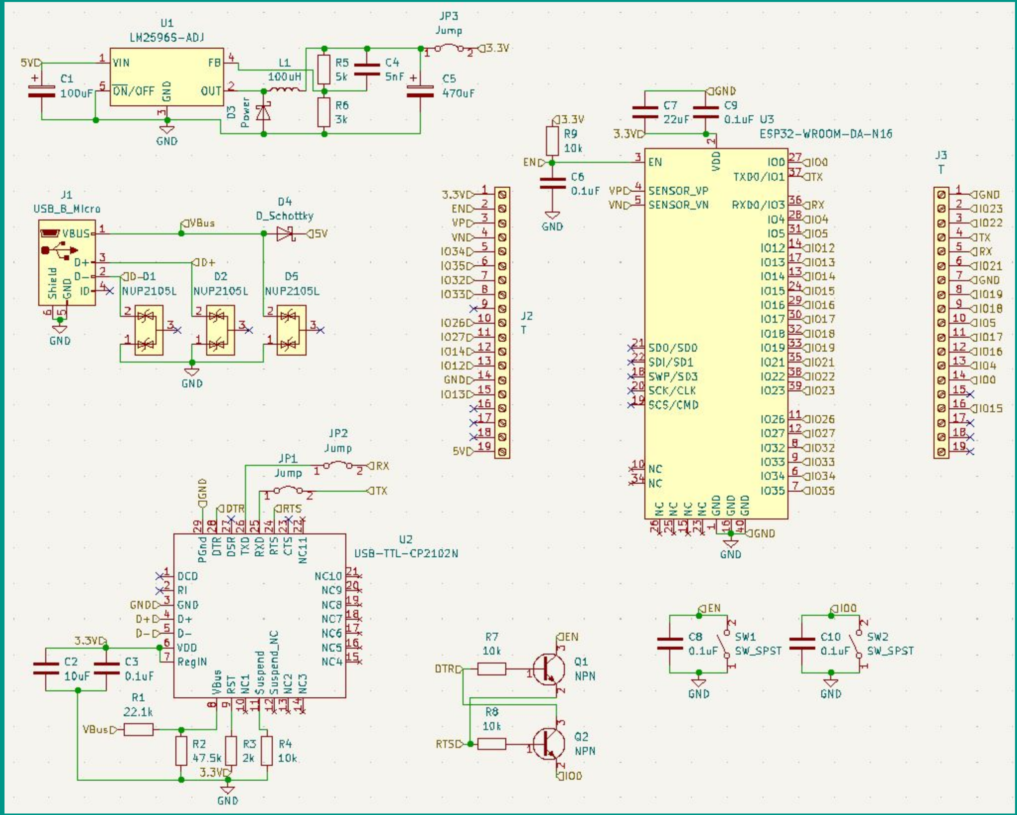
GaN instead of Si power FETs

Replaced single EDN7116 drivers with LMG1210 half bridge driver

Replaced buck IC LMQ61460 with LM2596 due to footprint and startup problems

Hardware Design: Schematics

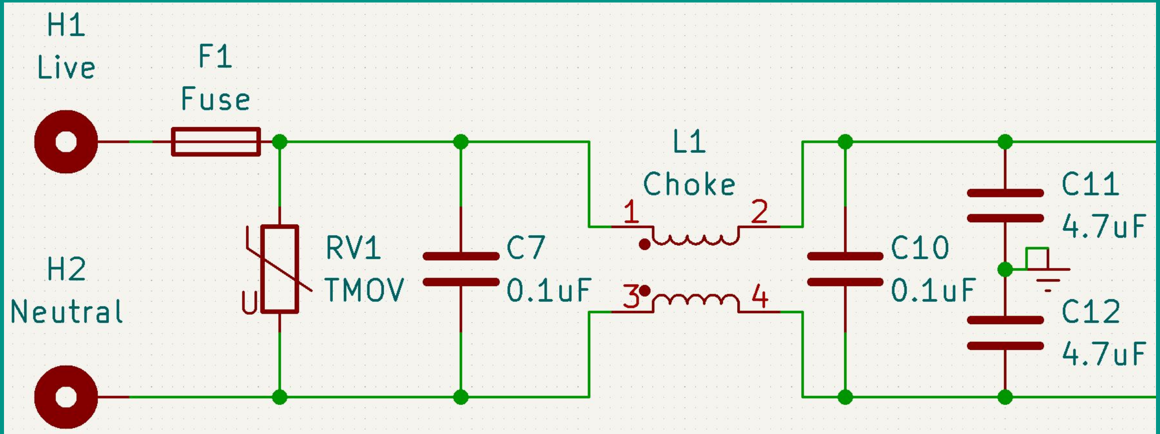
- Main microcontroller board, contains ESP32 in same form factor and pinout as V3 Devkit
- Plugs into female header pins in perfboard, then 22 gauge wires go to throttle, speed, and current sensors
- All pins broken out for maximum software flexibility



Hardware Design: AC-DC Converter

EMI Filter

- EN55032 limits differential & common mode noise from 150 kHz to 30 MHz
- Low pass filter, so the binding limit is 60 dBµV at 150 kHz
- Common mode choke and capacitors form a common mode LC filter and a differential mode PI filter



- Capacitors to ground are X2 safety, so more likely to fail open than short
- TMOV clamps voltage spikes (MOV) and thermal protection prevents overheating when clamped

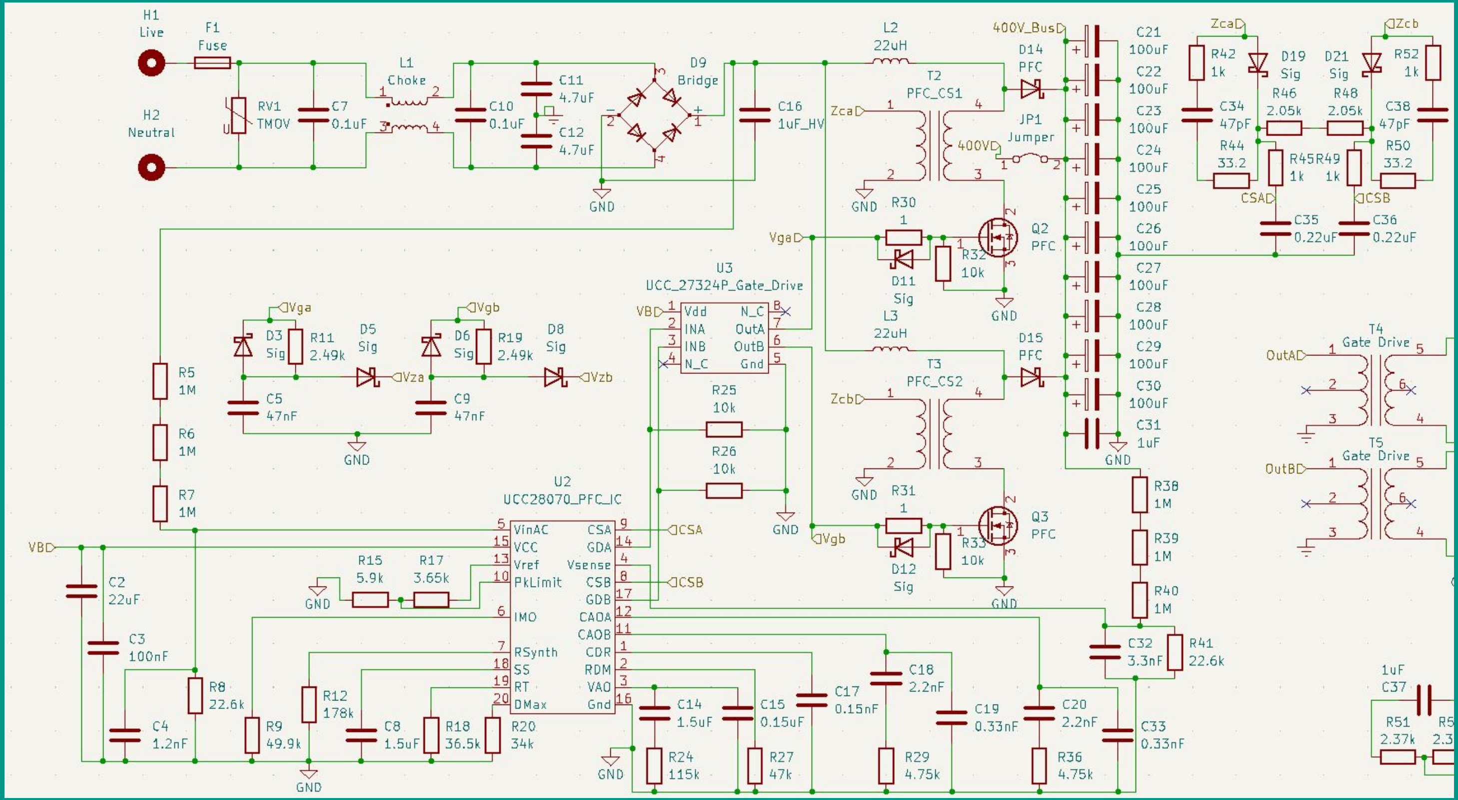
Hardware Design: AC-DC Converter

Power Factor Correction (PFC) Circuit

Rectifies AC-DC with PF ~ 1

Two phase interleaved boost converter for higher power

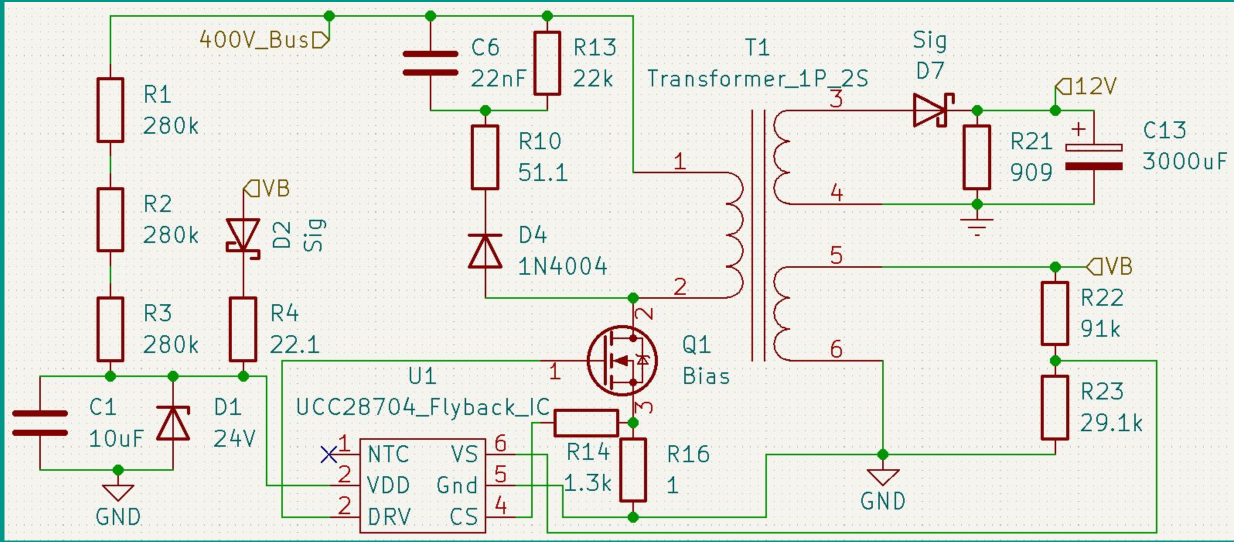
Peak current mode control through current transformers



Hardware Design: AC-DC Converter

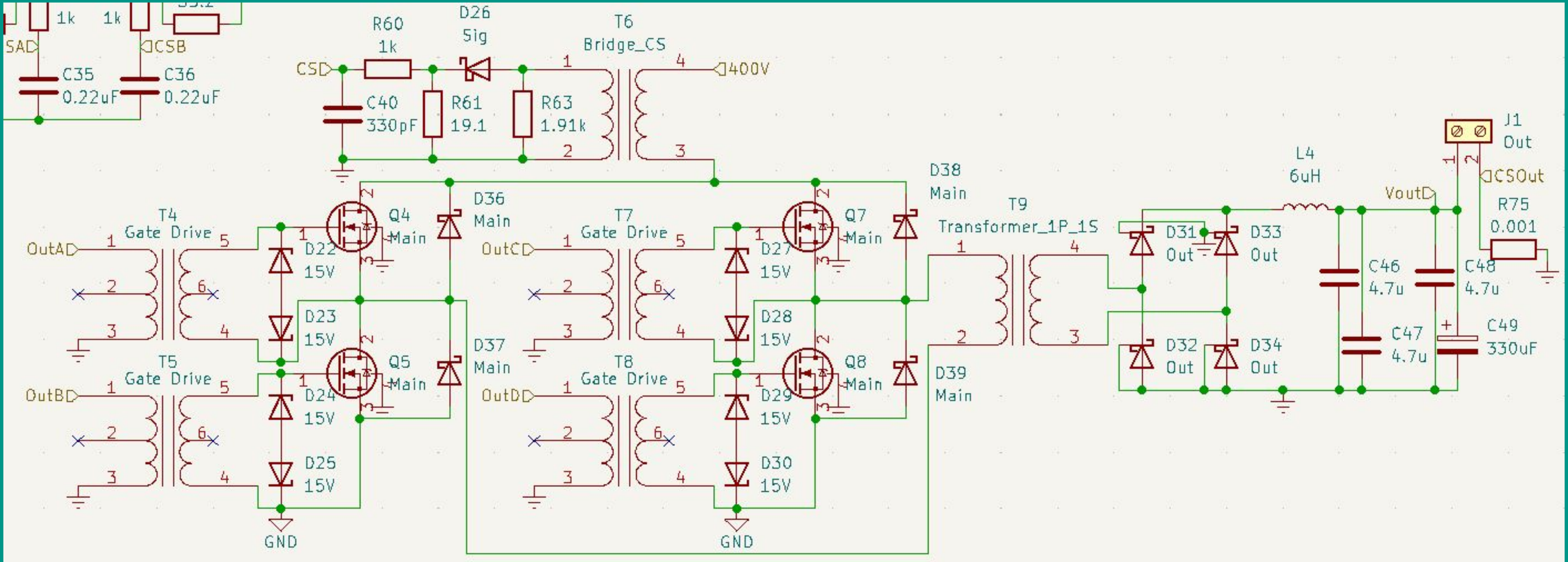
12V & 16V Bias Supply

- Powers the gate drive and control circuits within the power supply
- Flyback converter for simplicity
- Non-isolated 16V powers flyback and PFC, isolated 12V powers full bridge IC, gate drivers, and output sensing



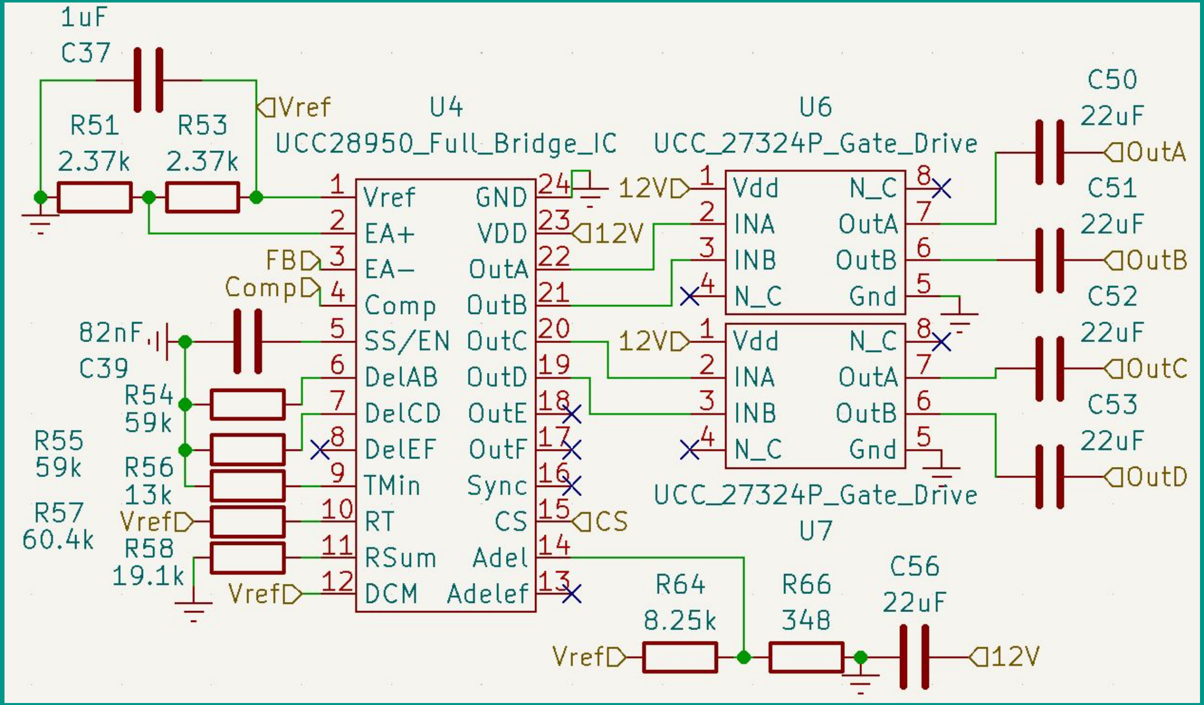
Hardware Design: AC-DC Converter

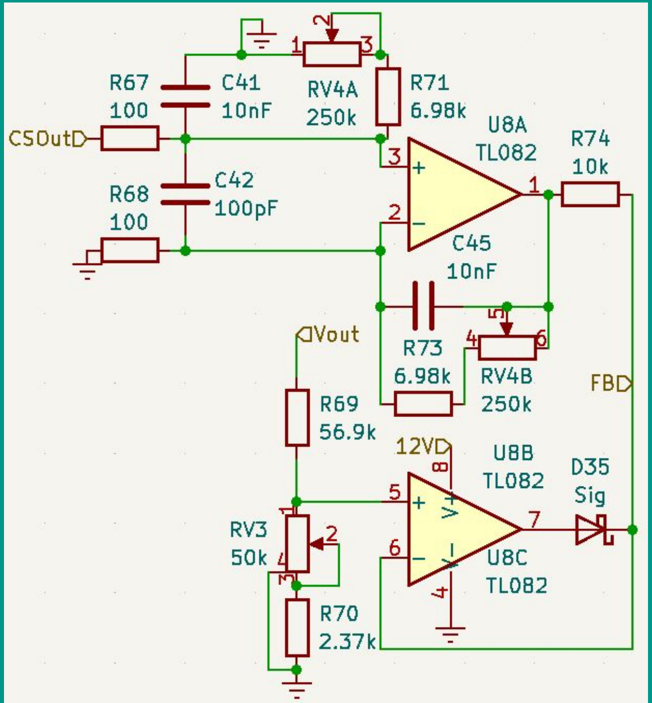
Phase-Shifted Full Bridge Converter



Hardware Design: AC-DC Converter

UCC27324 Controller IC and CC/CV Regulation



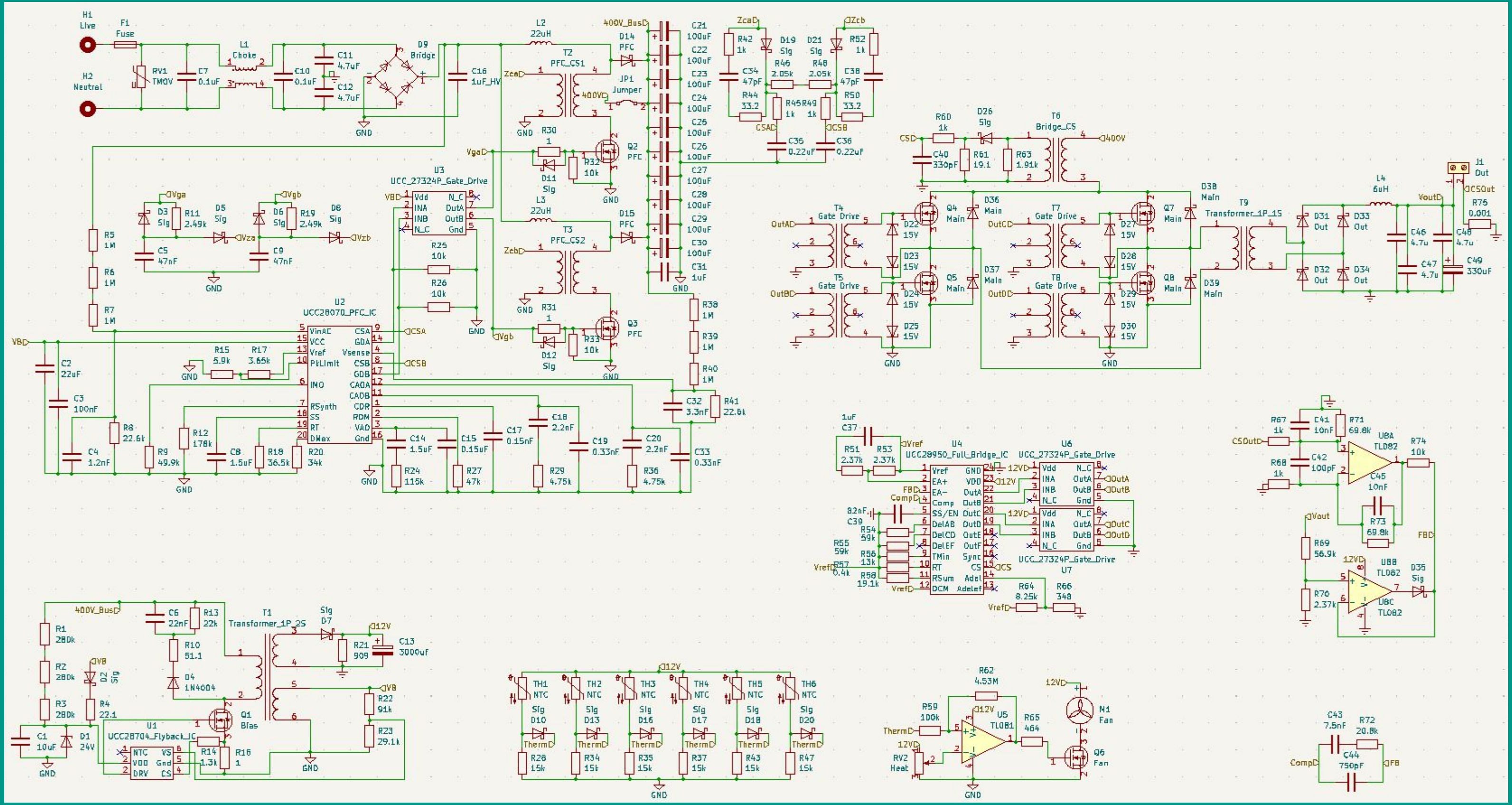


Hardware Design: AC-DC Converter

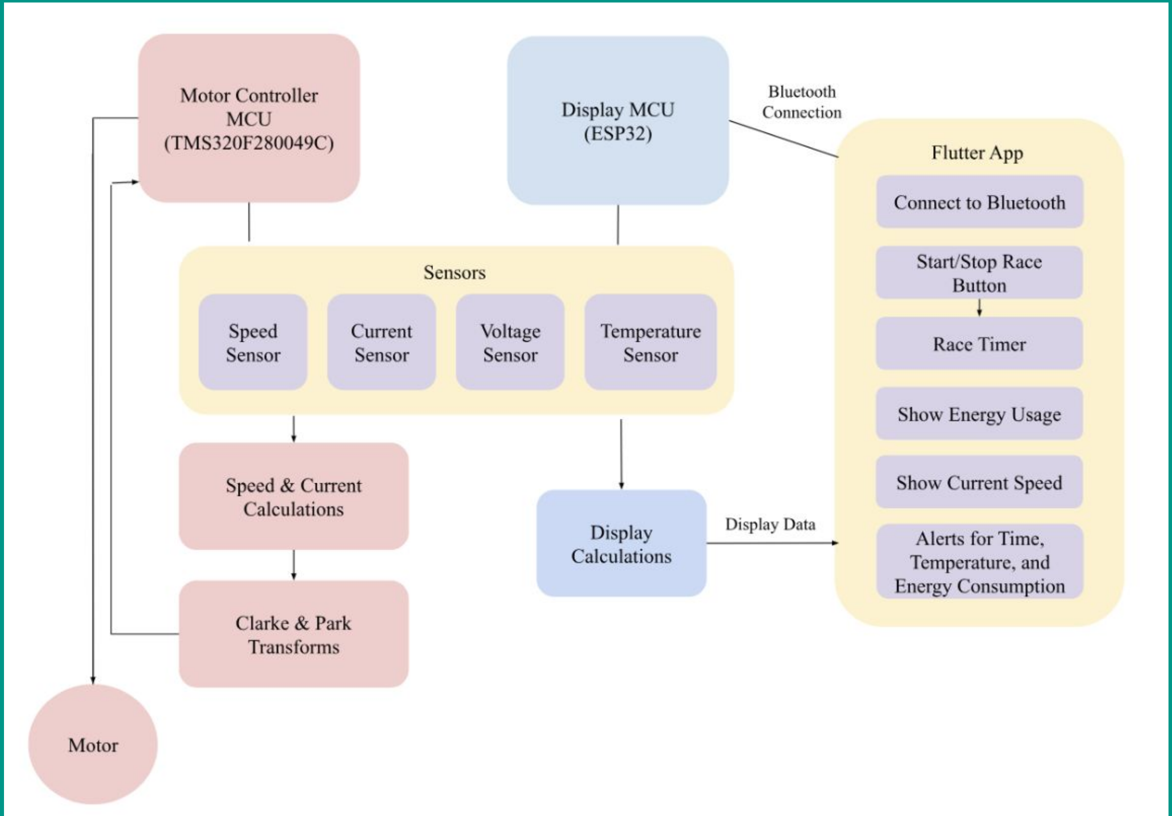
Output:
5.2V to 63V
1A to 36A

Input:
15A x 120V
= 1800W
max power

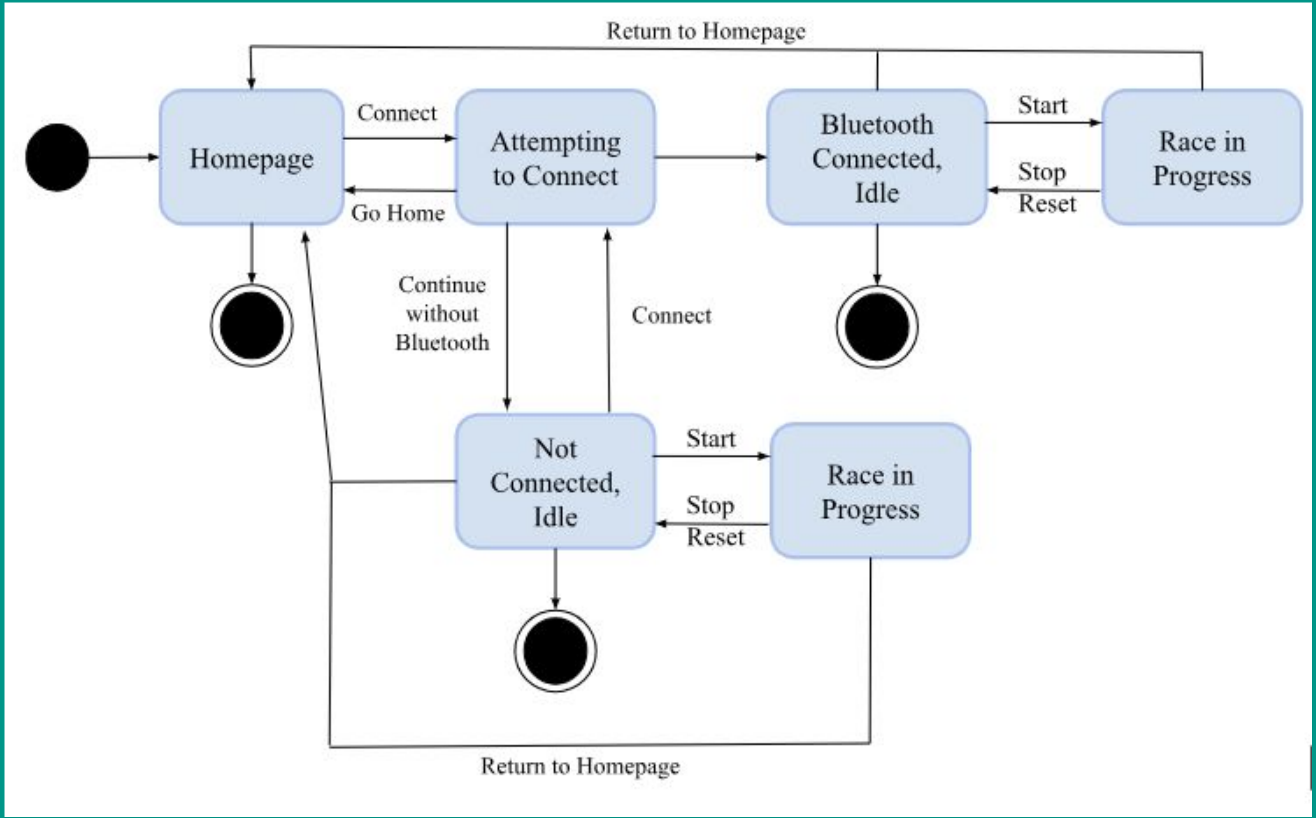
Designed
for 15S
lithium-ion
battery pack



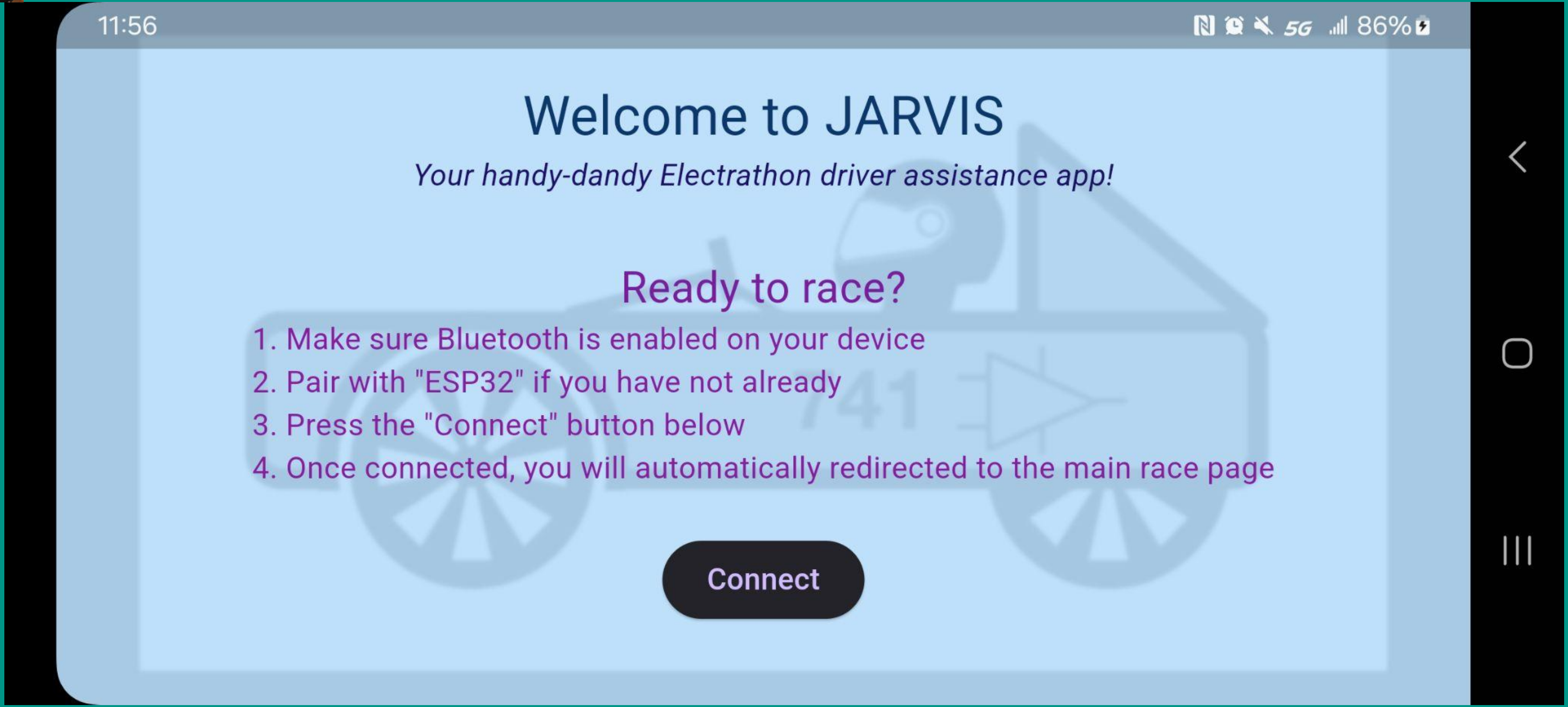
Software Design: Overall Flowchart



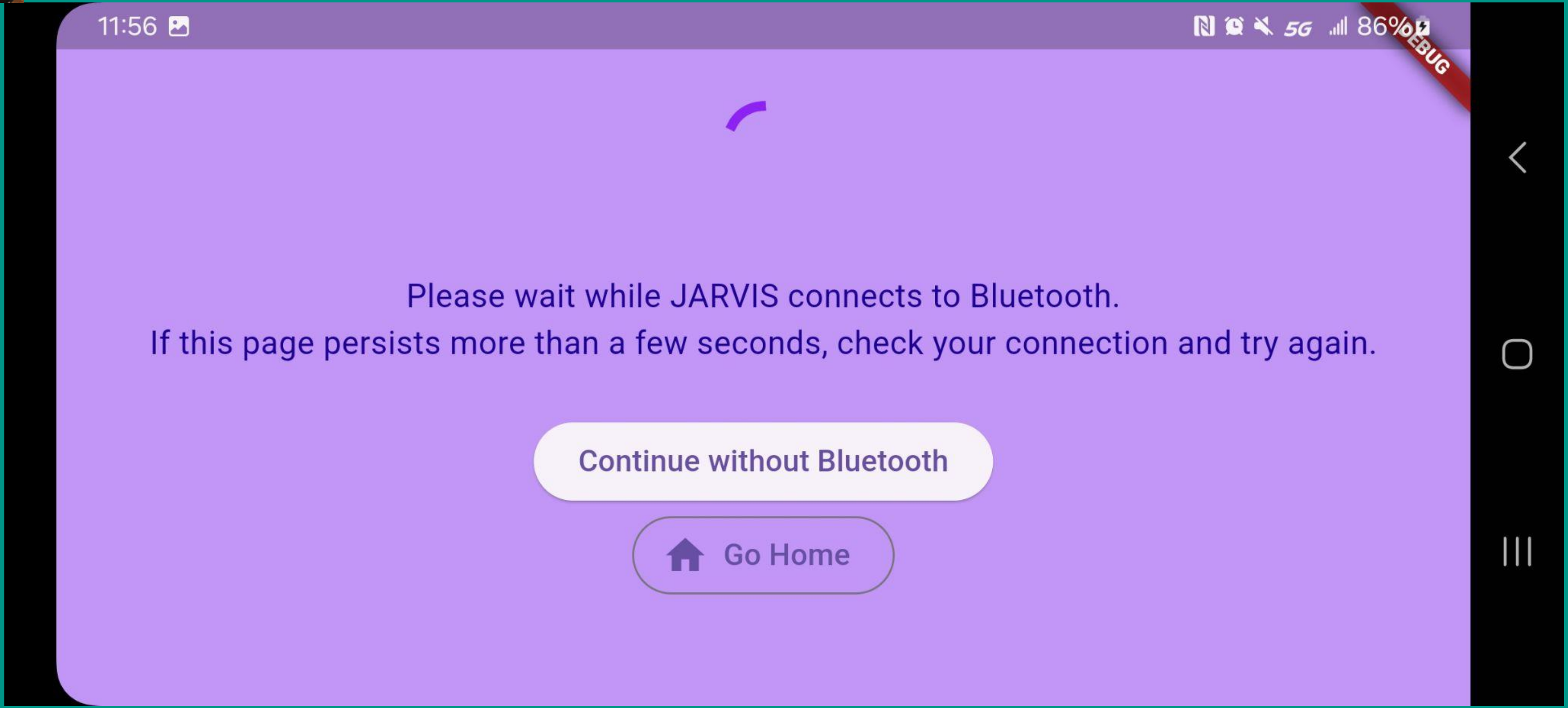
Software Design: Display App State Diagram



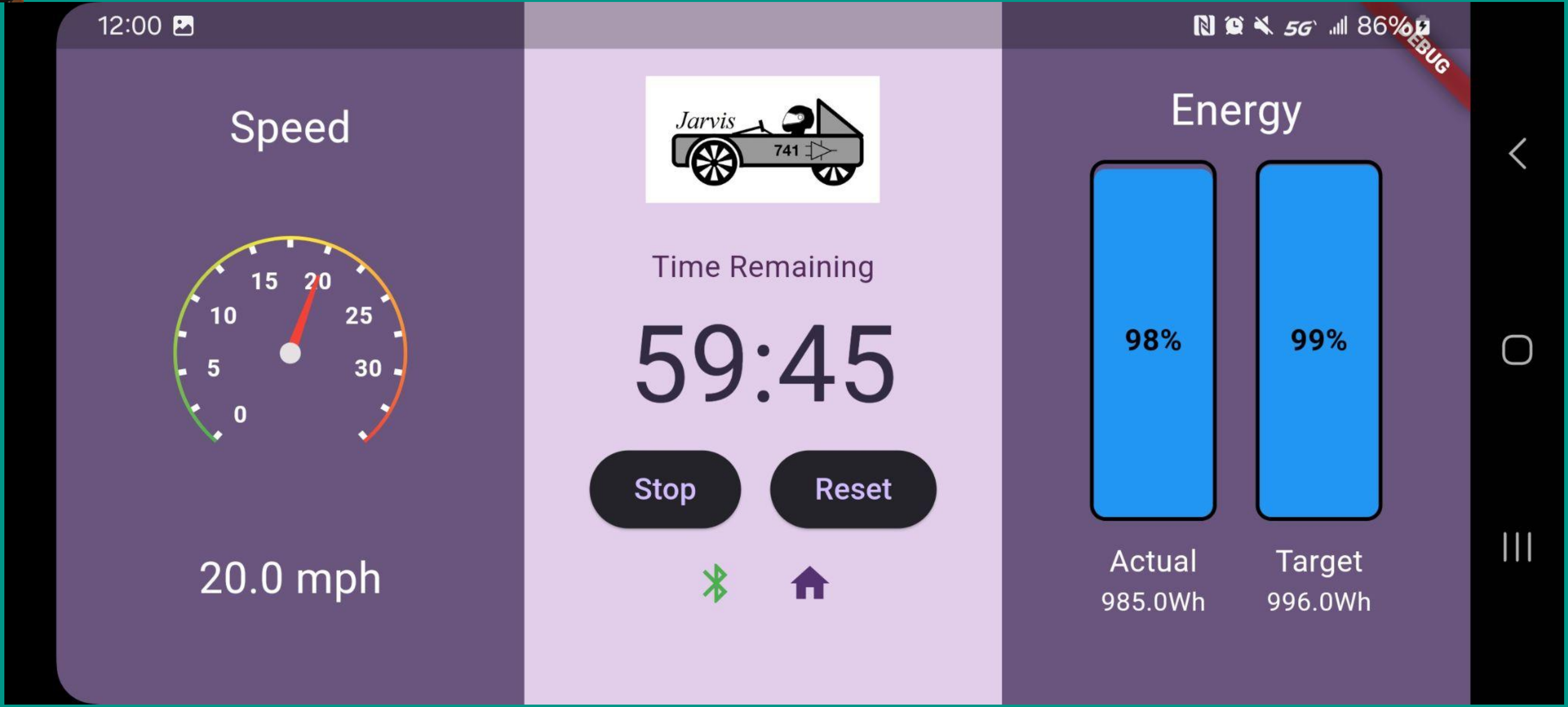
Homepage: Instructs User on How to Connect



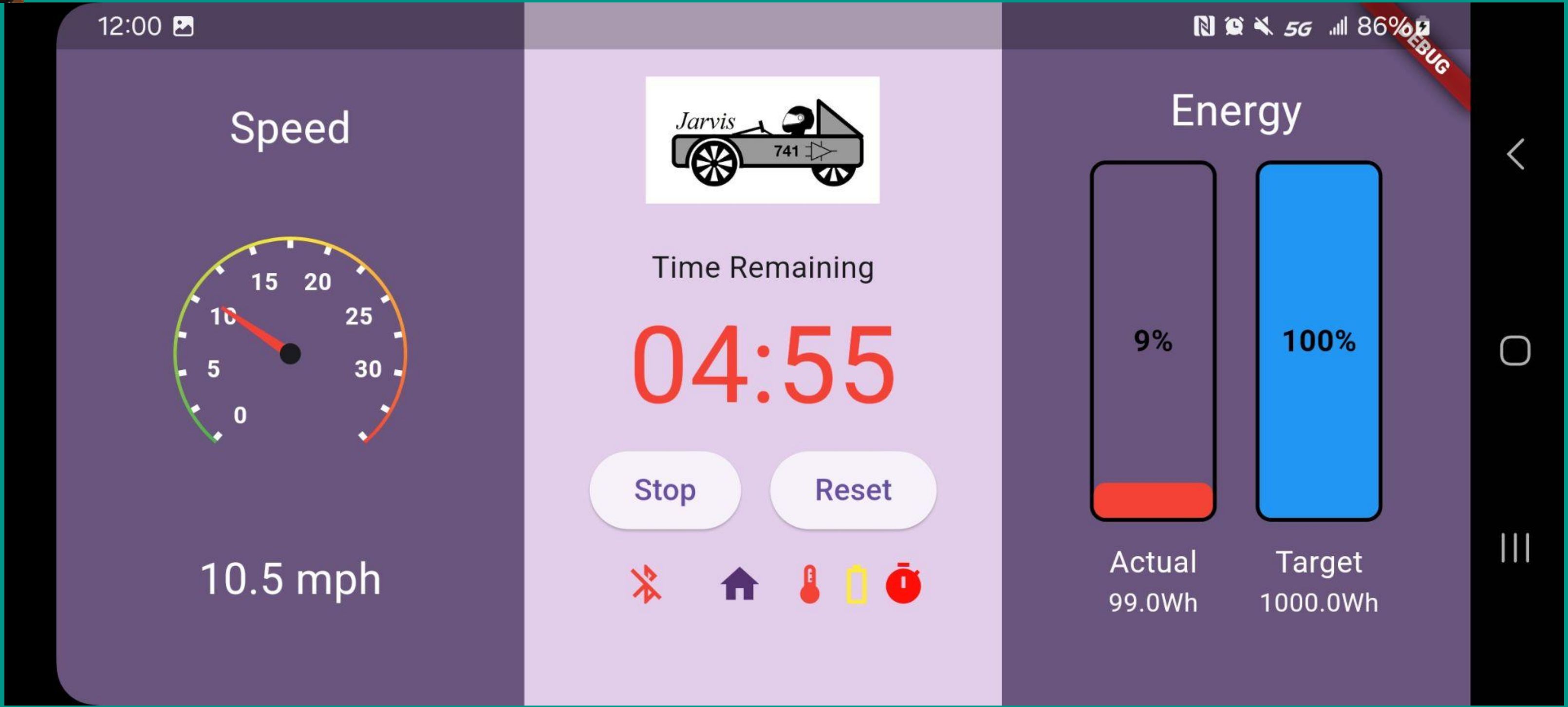
Waiting for Connection



Main Display: Normal Operating Mode



Murphy’s Screen: All Possible Warnings Triggered



Icons

Bluetooth Connected

Not Connected or Connection Lost

Return to homepage

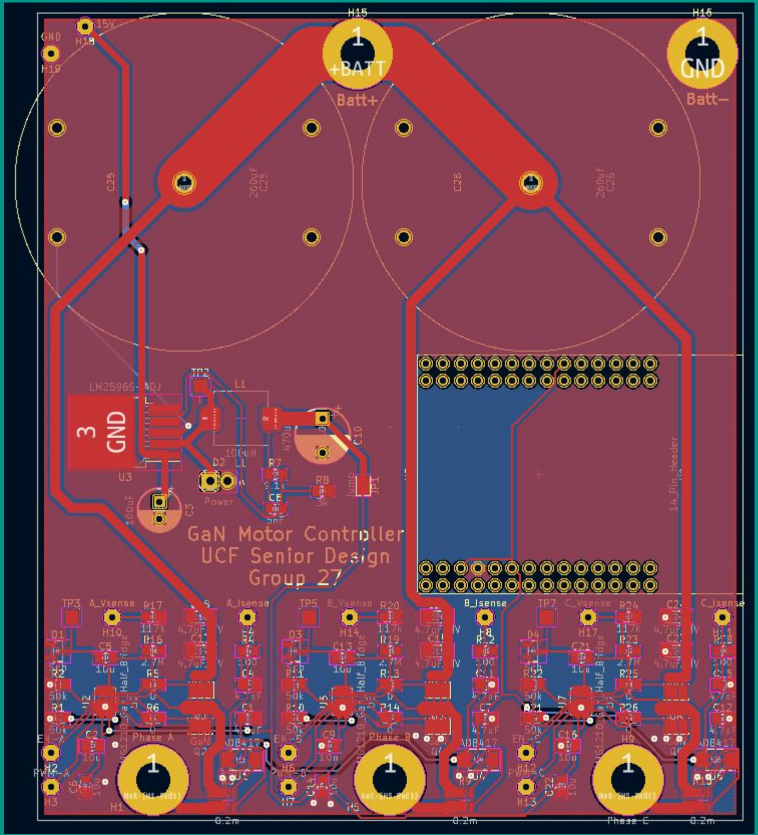
Internal Temperature too high

<10% (100Wh) battery OR Energy use exceeds target energy by >10%

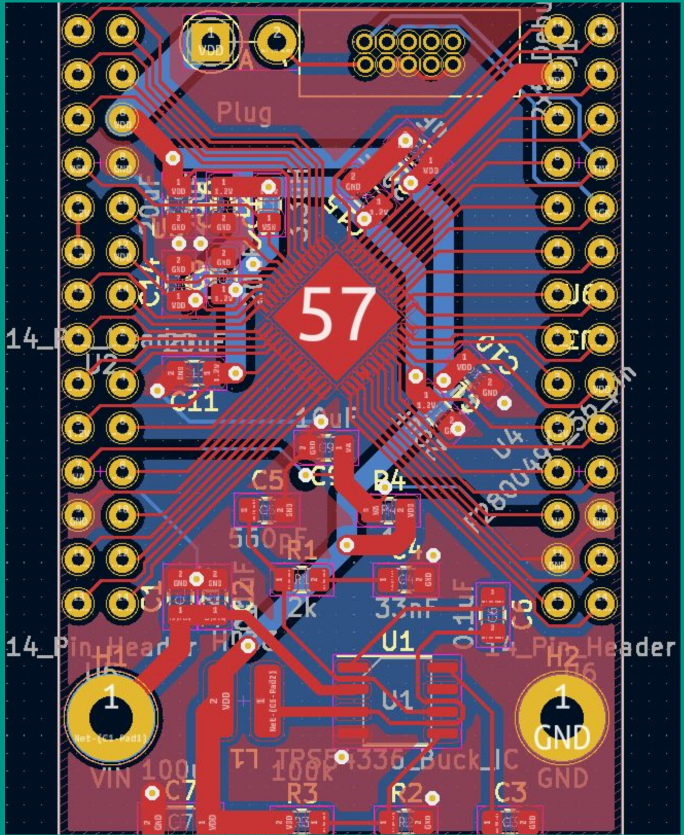
<5 minutes remaining in race

Additional alerts may be added as time permits

PCB Design

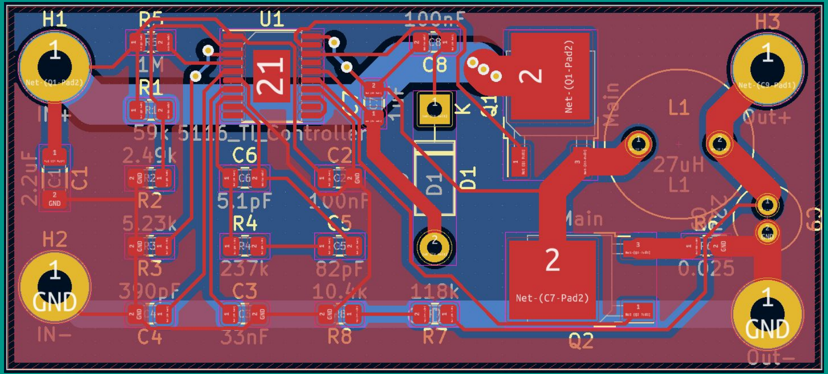


Motor Controller
Power PCB

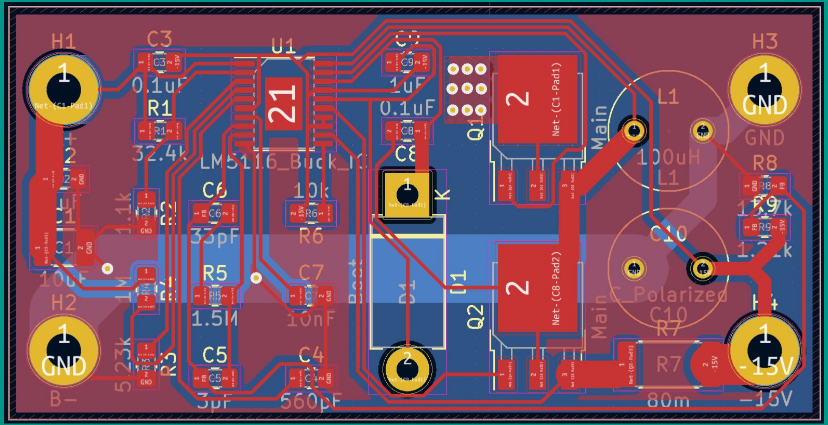


Motor Controller
Logic PCB

PCB Design

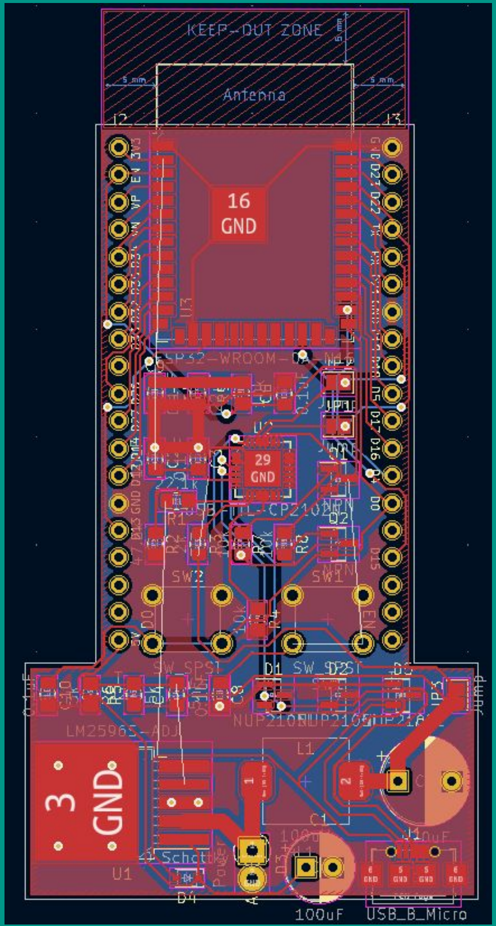


+15V Regulator

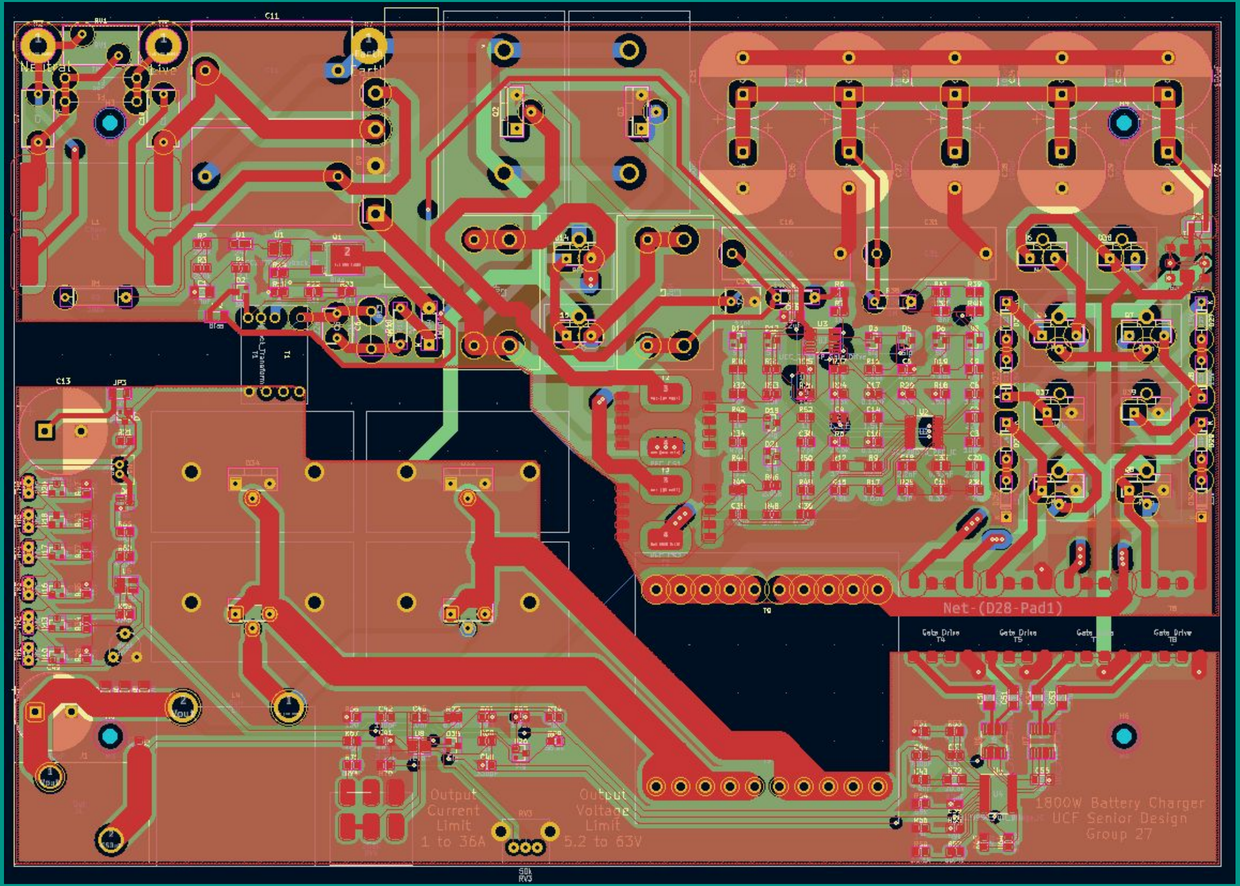


-15V Regulator

Custom ESP32 Control Board



PCB Design



1800W AC-DC Battery Charger

1.8mm creepage on HV side

0.7mm creepage on 63V output side

Budget Estimate

Item	Quantity	Price Estimate
Samsung 20S battery cell	140	$700
Busbars and cell holders	200	$30
Active cell balancer	1	$21
Hacker A60-18L motor	1	$272
Parts for motor controller	1	$300
Circuit breaker	1	$11
Wires and connectors	8	$50
Main microcontroller	1	$20
Sensors	3	$50
Parts for battery charger	1	$250
Total		$1,704

Work Distribution

Abdullah Choudhry (EE)
PCB assembly, debugging, and prototyping

Fouad Braimoh (CpE)
Motor Control programming

Julian Yerger (EE)
Power converter and PCB design

Grace Tuomala (CpE)
Display & Display MCU programming

Current Progress

Hardware

- Current sensor tested and working
- Function generator signals merged for double pulse MOSFET test
- Mk I motor controller tested, not working
- Speed sensor v1 testing and not working
- Microcontroller ADCs tested and working marginally, will replace with ADS1115 external ADC

Software

- Working Display app
  - Bluetooth connectivity
  - Homepage, connecting screen, and main display screens
  - Race timer
  - Speed gauge widget
  - Alert icons for temperature, energy, and time