SinESC

FOC Motor Controller for Drones

Erk Sampat

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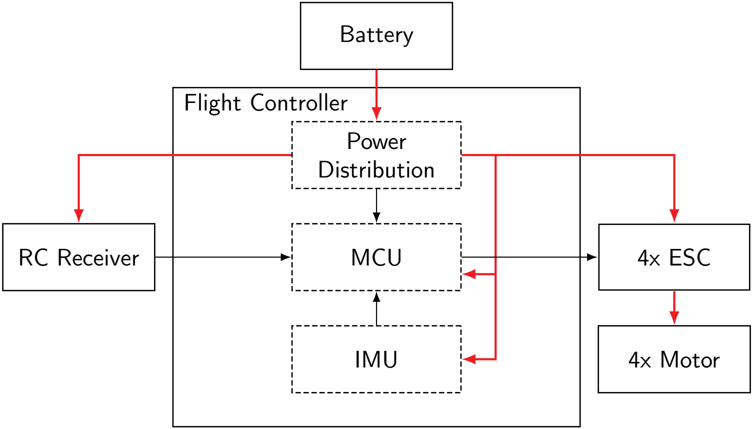
Outline

1. Project Introduction
2. Theory
3. Design Walkthrough

Project Introduction – The Problem

- Typical FPV drone flight time: 5–7 minutes
- Off-the-shelf brushless motor controller efficiency $\approx 70\%$
- Can we achieve closer to 100%?
- Yes! With a better control scheme.
- Motor controller (“ESC”) is accessible for improvement

Project Introduction – System Overview



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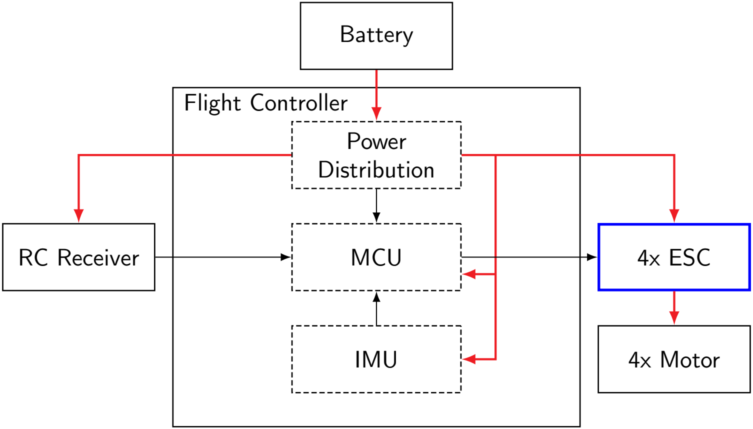

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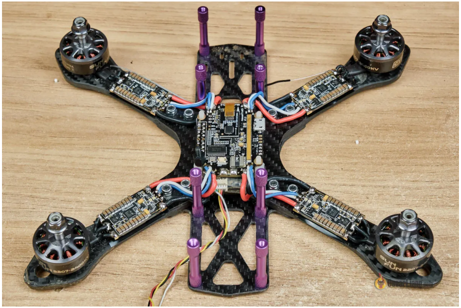
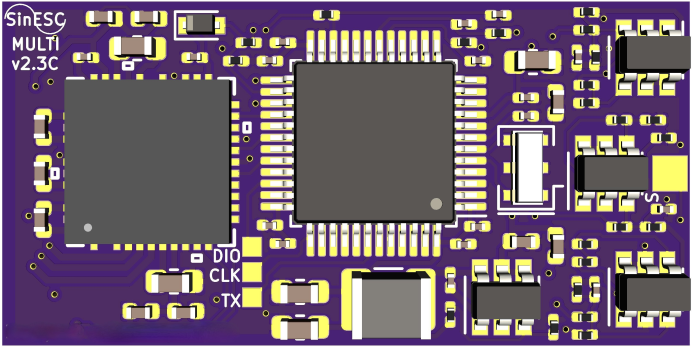


Project Introduction – Scope

- Designed/fabricated/tested custom hardware to run sensorless FOC
- Hardware initially designed in 2020
- Future plan: fully custom firmware



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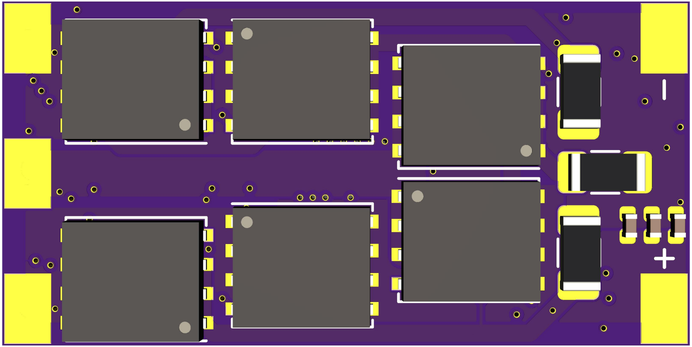
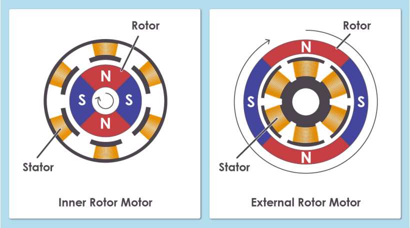


Project Introduction – Primary Specifications

- V_{in}: 12 V–25.2 V (4S–6S Li-po battery)
- I_{in}: 45 A continuous, 55 A burst (5 seconds)
- DSHOT communication protocol support
- Size: comparable to off-the-shelf ESC (15 mm × 30 mm)
- Out-of-box compatibility with broad range of motors
- High reliability: robustness against...
  - Voltage spikes
  - Rapid throttle (speed command) changes
  - Physical shock

Theory – Brushless Motors

- Rotor: permanent magnets
- Stator: coil windings
- Electronically commutated
- PMSM: sinusoidal BEMF
- BLDC: trapezoidal BEMF. . .
  but often looks sinusoidal due
  to LC filtering by windings



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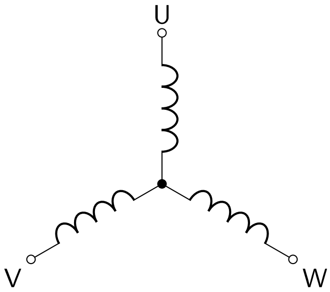


Theory – 6-Step Drive

Operation:

- 6 energized states
- Switch upon zero-crossing
- PWM controls torque

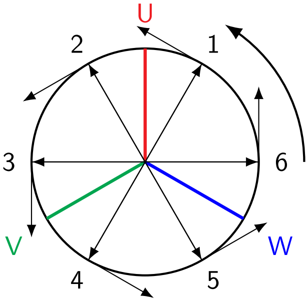
Benefits:

- Simple
- Low switching loss
- Zero-crossings measured on floating phase

Drawbacks:

- Torque ripple
- High-frequency harmonics
- Field not always orthogonal to rotor…inefficient

Step	U	V	W
1	1	0	Z
2	1	Z	0
3	Z	1	0
4	0	1	Z
5	0	Z	1
6	Z	0	1



Theory – Field-Oriented Control

Operation:

- ∞ energized "states"
- Space-vector modulation
- PWM controls torque AND field orientation

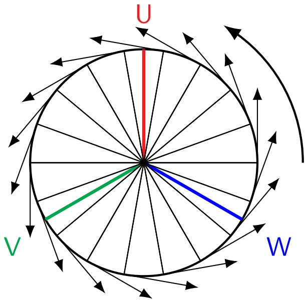
Benefits:

- Low torque ripple
- Reduced harmonics
- Field always orthogonal to rotor. . . highly efficient

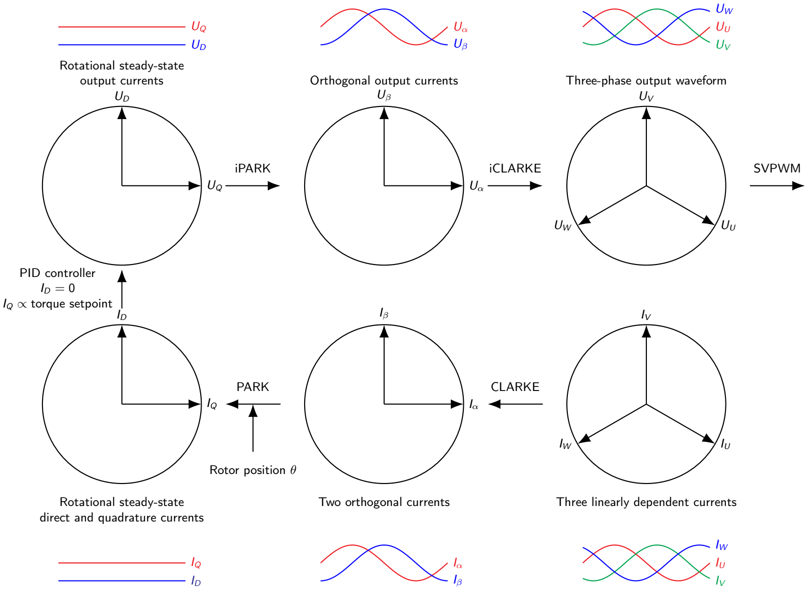
Drawbacks:

- Complex
- Higher switching loss
- Difficult to measure BEMF
- Requires precise position sensing

Step	U	V	W
1	1	0	Z
2	1	Z	0
3	Z	1	0
4	0	1	Z
5	0	Z	1
6	Z	0	1



Theory – Clarke-Park Transforms



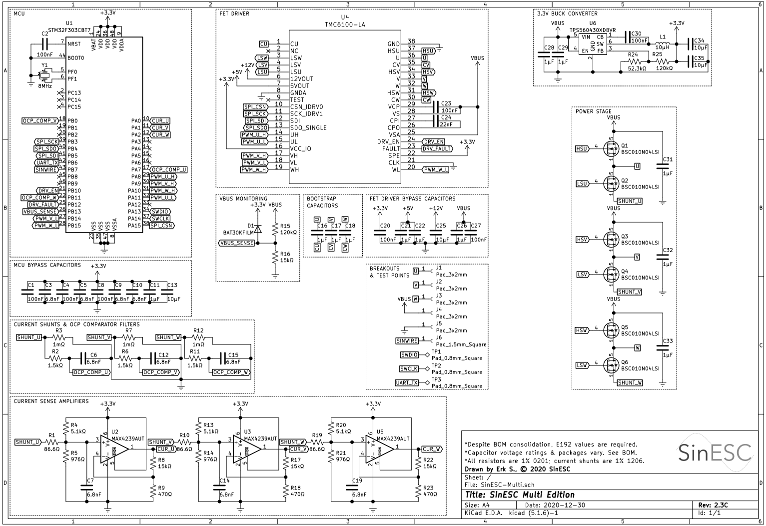
Theory – Sensorless Position Estimation

Key point: knowing BEMF and phase currents = knowing rotor position

1. Measure phase voltage during short non-energized intervals
   - High speed required for large BEMF...
   - but non-energized intervals shorten as speed increases
2. Estimate BEMF using measured currents and motor parameters L and R per phase
3. Calculate electrical angle of rotor, differentiate w.r.t. time to obtain speed
   - Helps to know rotor inertia

More advanced techniques: high-frequency injection, PLL, etc.

Design Walkthrough – Schematic



Design Walkthrough – Key Component Characteristics

Microcontroller

- ST part – FOC library
- Ample analog peripherals
- 32 bit, medium performance

FET driver

- Simplicity
- Robustness against transients
- Sufficient drive current
- High-side N support

Current-sense amplifiers

- Low noise
- Sufficient bandwidth
- Temperature stability

MOSFETs

- $R_{\mathrm{ds,on}}$ low enough
- Q_{g} as low as possible
- Sufficient V_{ds}
- N-channel

Design Walkthrough – Component Choices

Microcontroller: STM32F3xx

- Multiple ADCs
- Comparators for OCP
- ST FOC library
- Cortex-M3

FET driver: TMC6100

- Expensive and complicated
- Charge pump for 100% duty cycle operation
- Controlled through SPI

Current-sense amplifiers: MAX4239

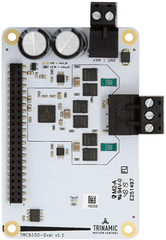
- Somewhat poor choice
- $0.1\,\mu\mathrm{V}$ input offset voltage unnecessary
- Too expensive

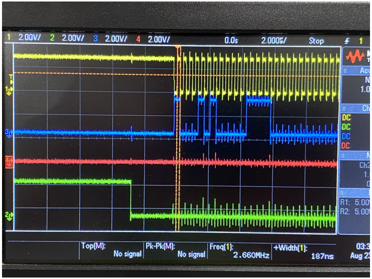
MOSFETS: BSC010N04LSI

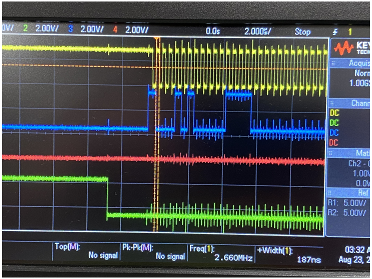
- $V_{\mathrm{ds}} = 40\,\mathrm{V}$
- $R_{\mathrm{ds,on}} = 1.05\,\mathrm{m}\Omega$: too low
- $Q_{\mathrm{g}} = 87\,\mathrm{nC}$: too high
- Ideally, find middle ground by considering product $R_{\mathrm{ds,on}} Q_{\mathrm{g}}$

Design Walkthrough – Challenges

- SPI configuration
- Inappropriate current specification
- 3.3 V rail issue
- Gate driver charge pump filter
- Form factor; difficulty with testing
- ADC resolution for current sensing







Design Walkthrough – Assembly

- Initially: stencil, pick & place, and reflow manually
- Later: assembled at PCBWay