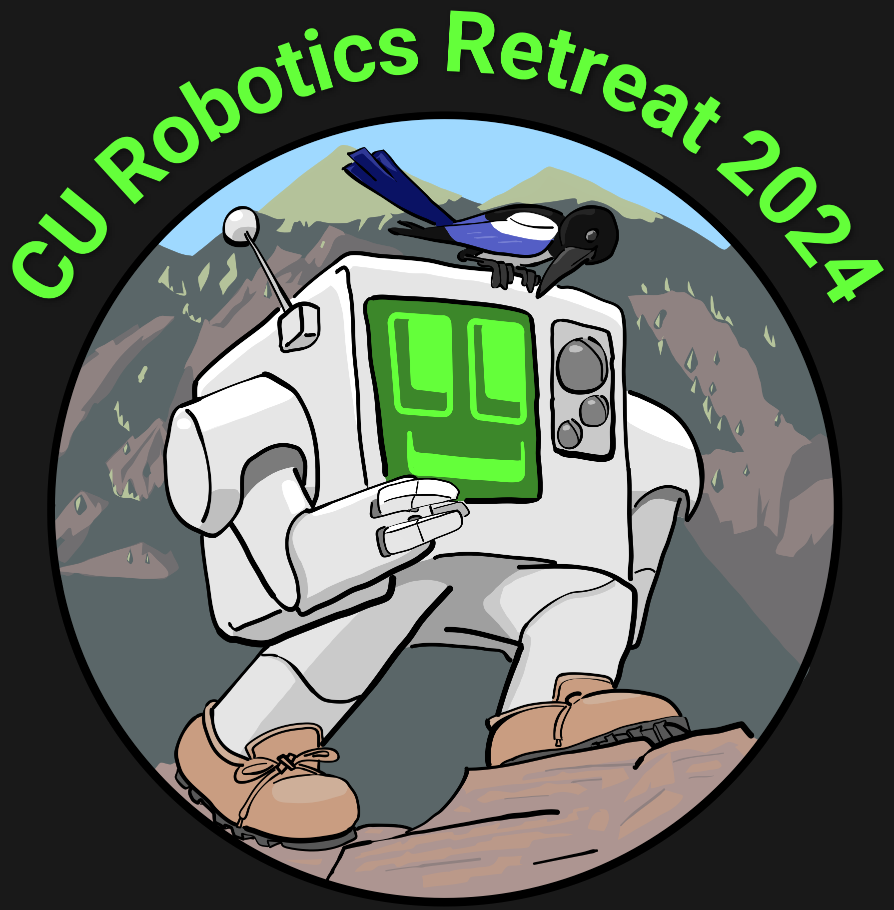
Mechatronics

How to Design and Build a Robot



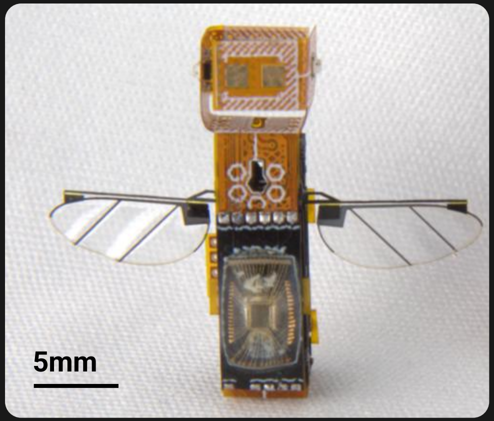
Alex Hedrick and Parker McDonnell

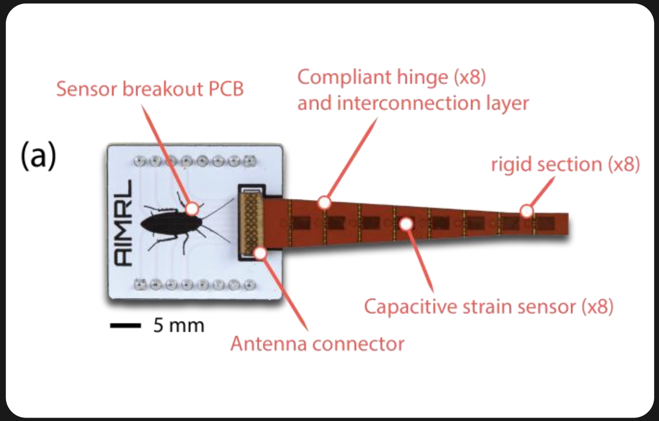
November 24, 2024

Introduction

Who are we?

- Alex Hedrick
  - 3rd year PhD student at CU Boulder (2022-present)
  - Member of Animal Inspired Movement and Robotics Lab
  - Mechanical engineering background
- Parker McDonnell
  - 4th year PhD student at CU Boulder (2021-present).
  - Member of Animal Inspired Movement and Robotics Lab.
  - Electrical engineering background.





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Agenda

1. What is mechatronics?
2. How to design a robot
   - Actuators
   - Drivers
   - Sensors
   - Processors
   - Power sources and regulation
   - Control Systems
3. A fun system design game!

What is Mechatronics?

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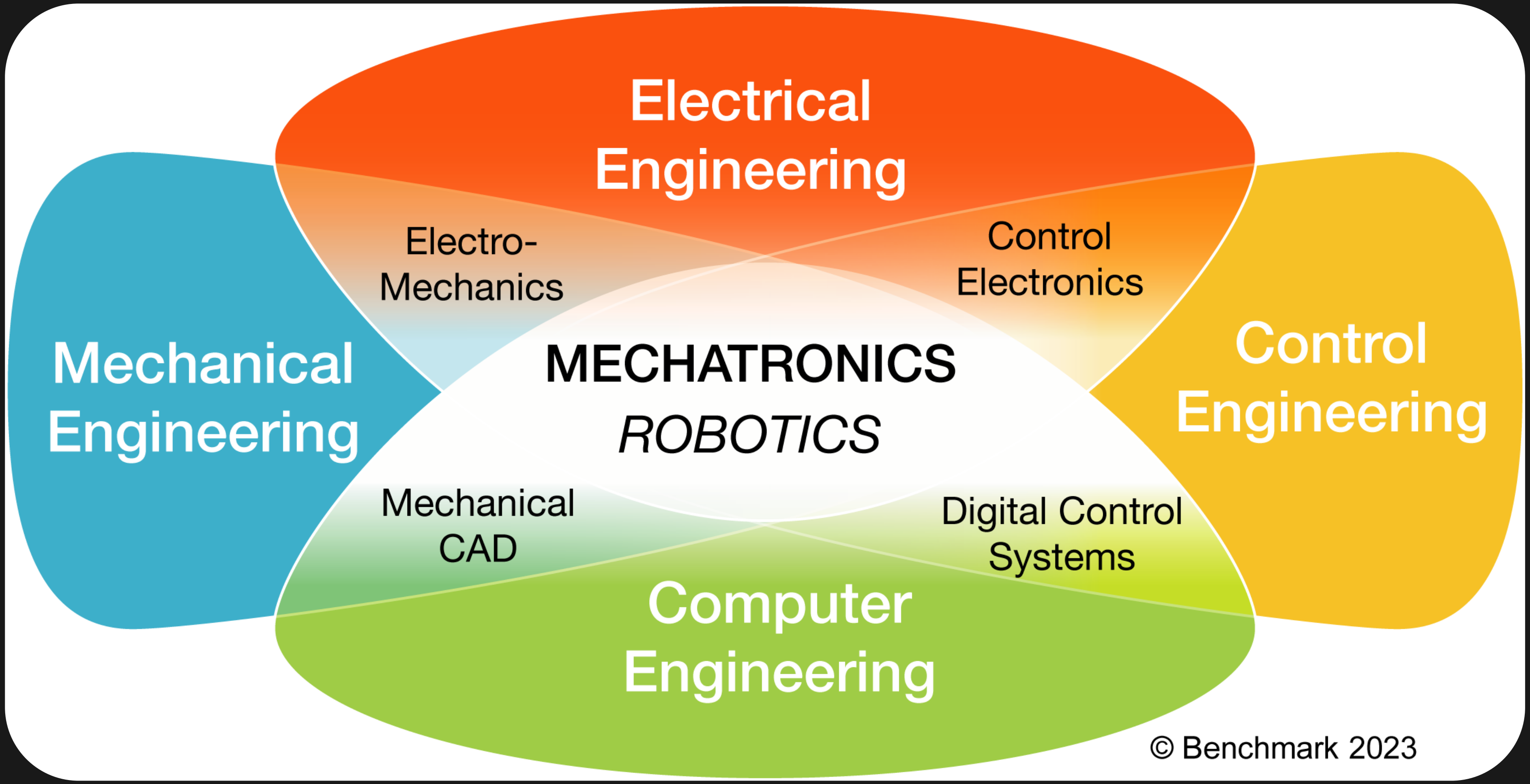
What is mechatronics?



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Mechatronics subsystems

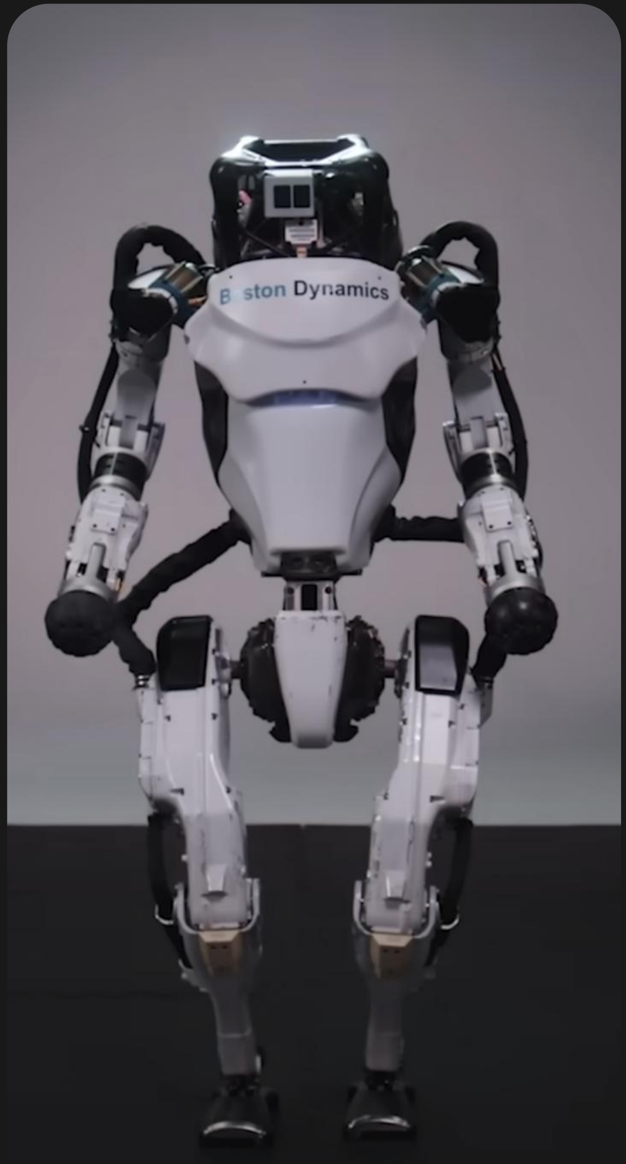
- Mechanical
- Electrical
- Controls
- Software

How to Build a Robot

Set Goals and Requirements

What, where, why?

- Applications and Abilities
- Operating Conditions
- What is Success? What is Failure?
- Project Timeline
- Cost
- Technical Specs
  - Size, power, materials
- Safety



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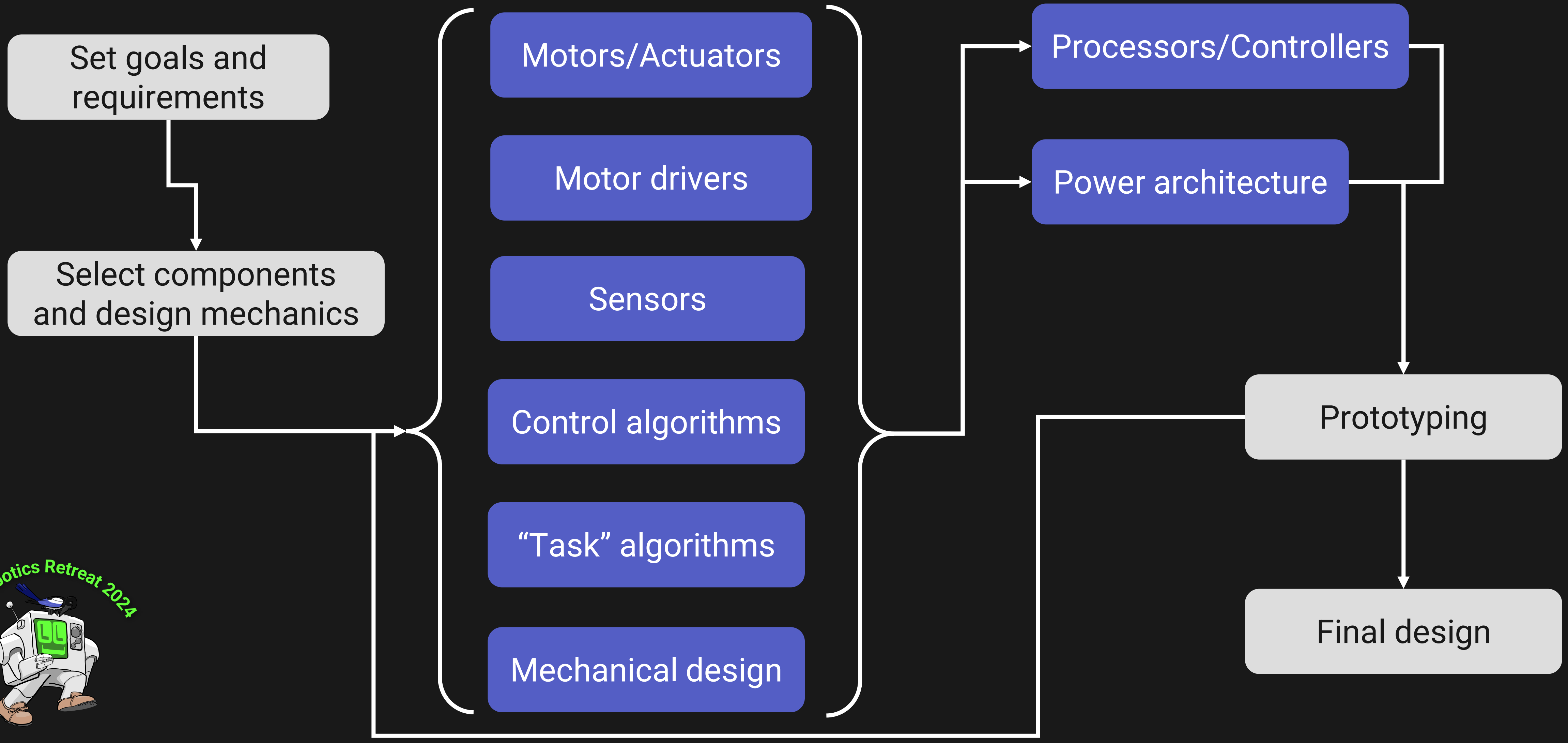
Robot workflow and subsystems

High-level how to build a robot



Actuators/Motors

Brushed DC Motor

Ol' Reliable!

- Size & Weight: wide variety (1g - 1kg+)
- Voltage: commonly 6, 12, or 24 V
- Efficiency: 75 - 80%
- Speed: ~ 2,000 - 30,000 rpm
- Pros: Cheap, wide size/power variety, simple control, high speed, high torque if geared down, PWM
- Cons: Requires motor driver, brushes can wear out, can overheat, high speed

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Brushless DC Motor

Fancy!

- Size & Weight: wide variety (1g - 1kg+)
- Voltage: commonly 6, 12, or 24 V
- Efficiency: 85 - 90%
- Speed: ~ 2,000 - 15,000 rpm
- Pros: Quieter, high efficiency, less maintenance than brushed DC, PWM
- Cons: Requires BLDC motor driver, more expensive and complex

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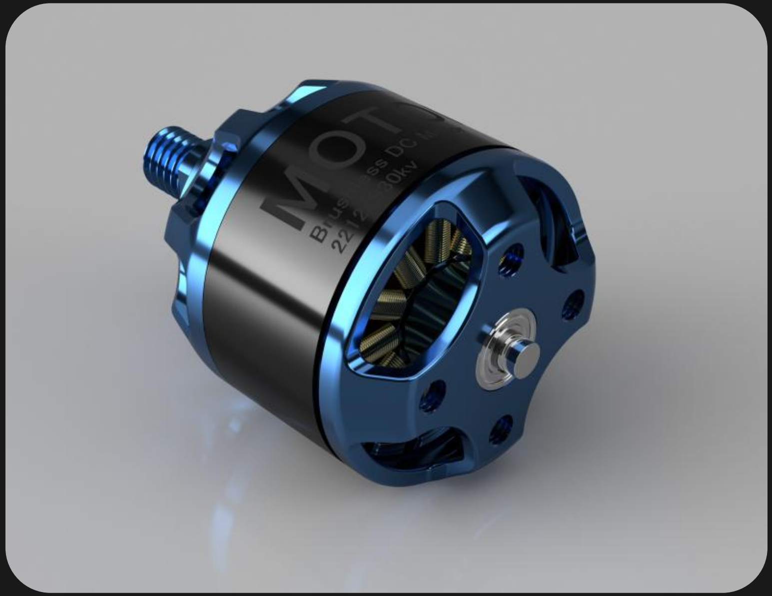
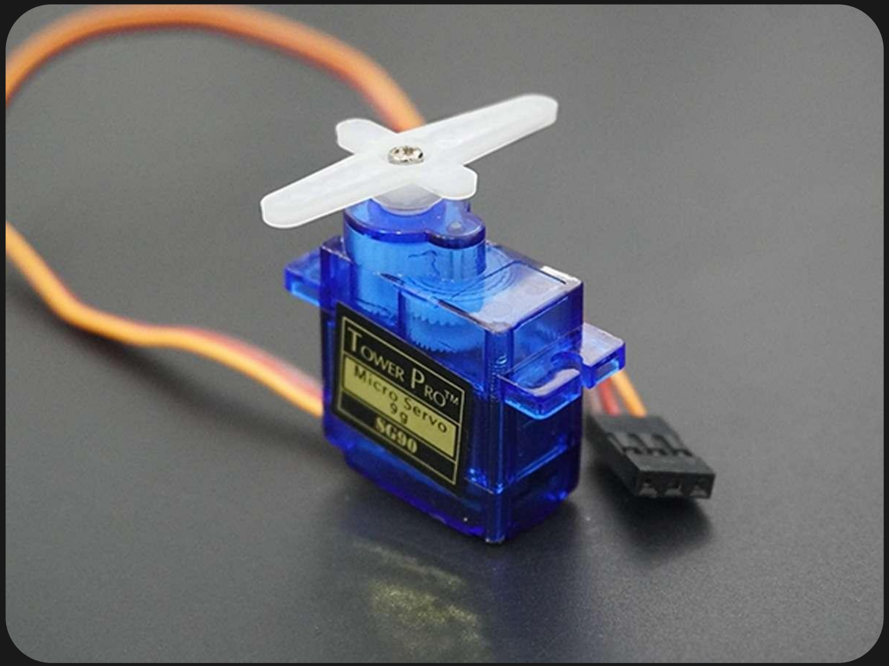


Servo Motor

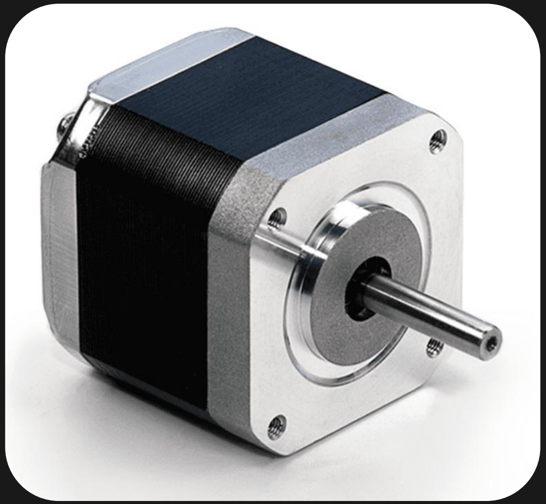
All-in-one! Two types: Positional vs. Continuous

- Size & Weight: wide variety (1g - 1kg+)
- Voltage: commonly 4.8 V, also 6 and 12 V
- Efficiency: up to 90%
- Speed: ~ DC - 5,000 rpm
- Pros: High torque at high speed, cheap, positional encoder built in, easy to control
- Cons: Some NOT continuous rotation, jitter

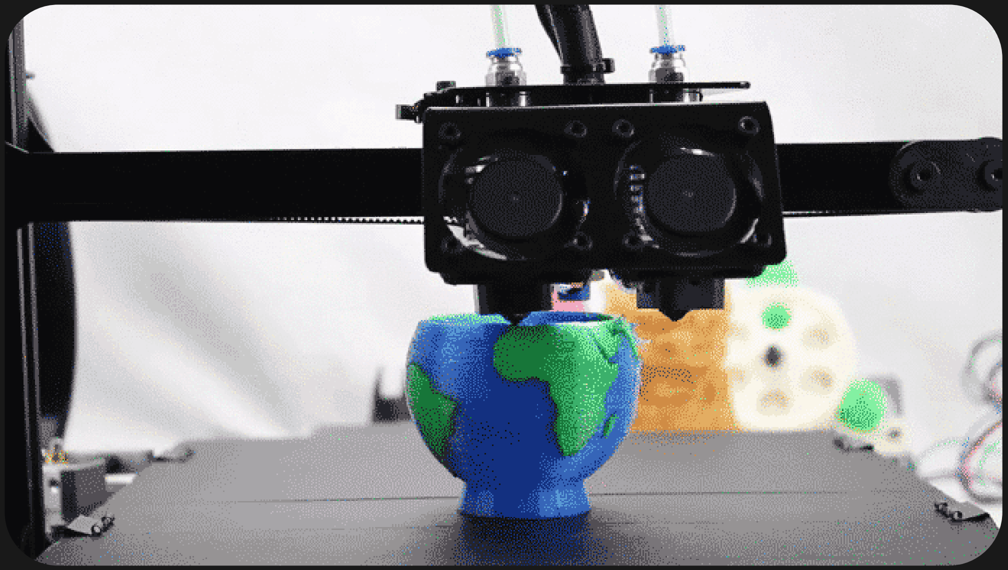


Stepper Motor

Chunky!



- Size & Weight: wide variety (100g - 1kg+)
- Voltage: commonly 6, 12, or 24 V
- Efficiency: up to 80%
- Speed: up to 1,000 rpm
- Pros: High precision positioning, precise speed control, high torque at low speed, easy to control
- Cons: Low torque at high speed, low efficiency, can skip steps, lower speed than DC motors



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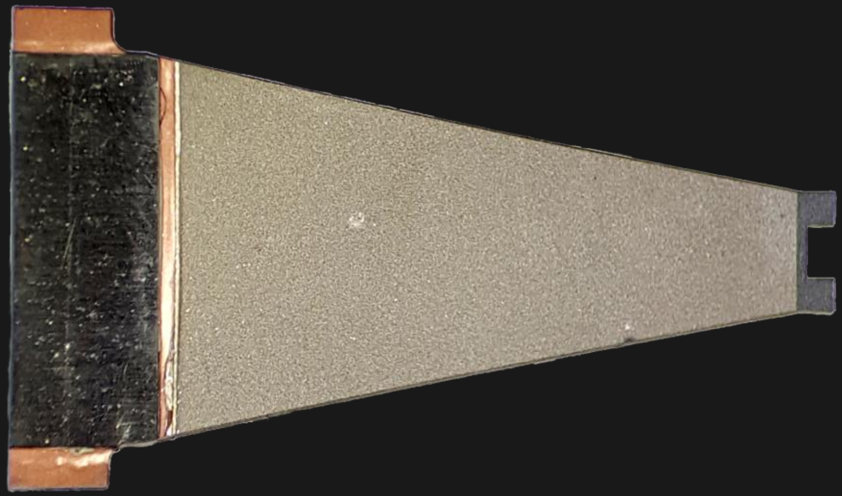
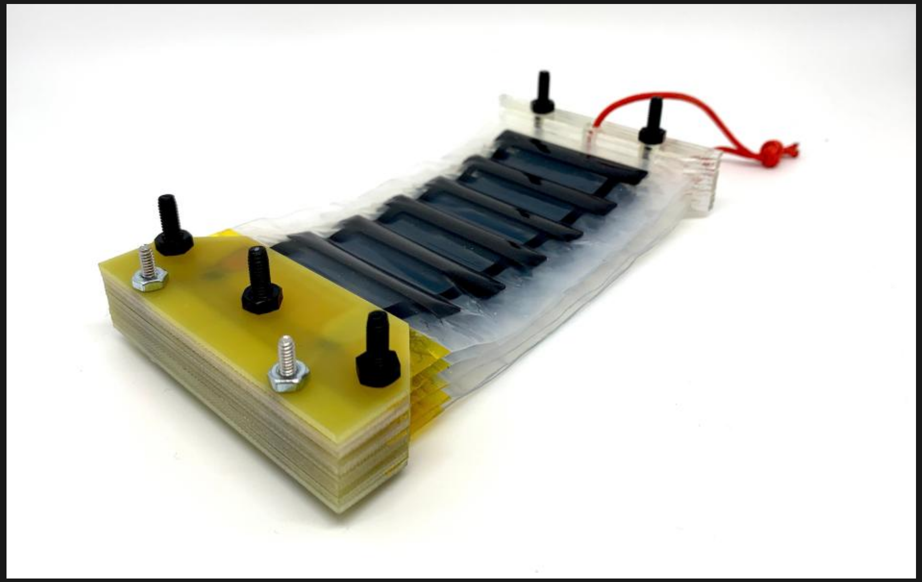
Misc. Motors/Actuators

Rare!

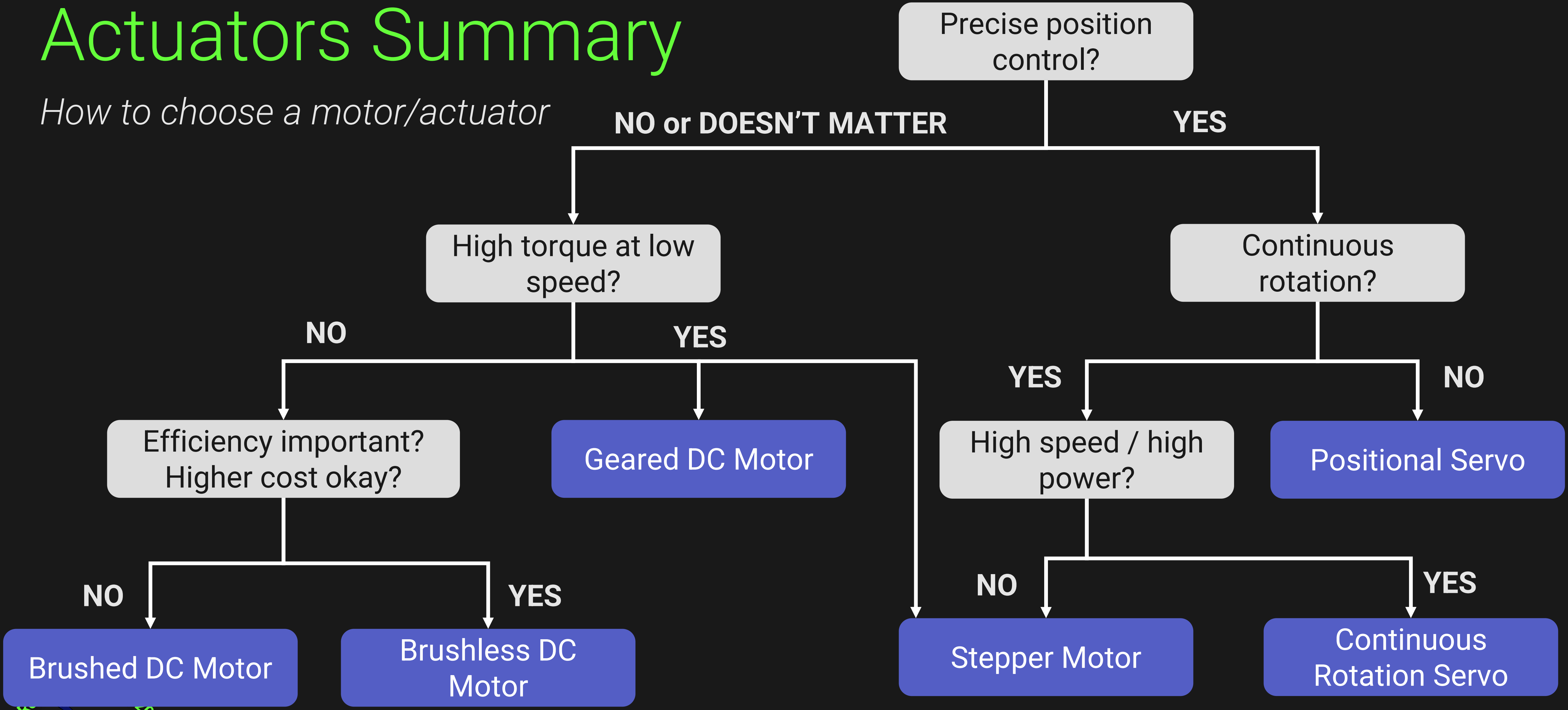
- AC motors: Typically, higher power and torque, high lifespan
- Piezoelectric actuators: High power density, high voltage, small displacement, high bandwidth
- Hydraulic actuators: High force, high power, robust
- HASEL actuators: Very high voltage, flexible, many configurations
- Many more…





Actuators Summary

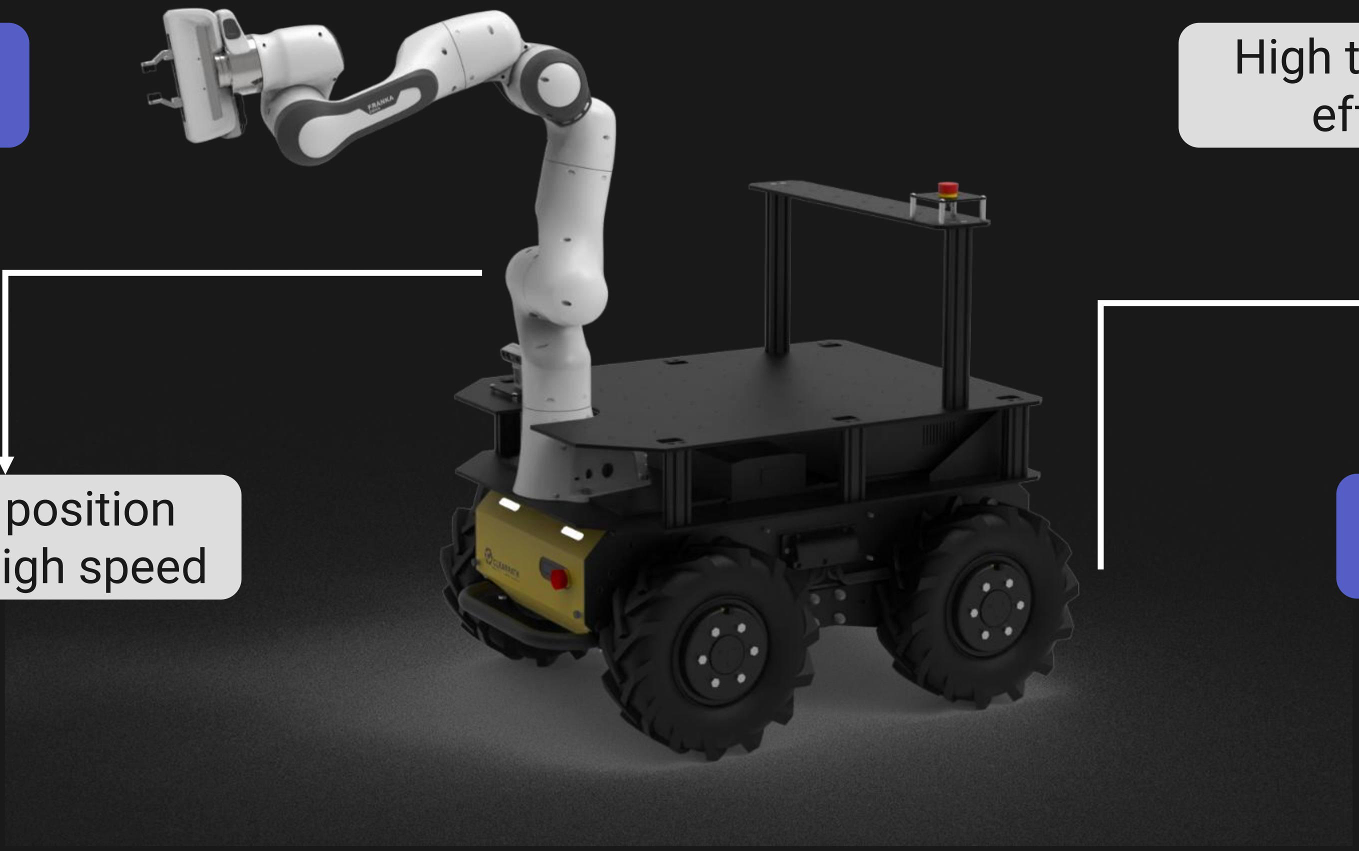
How to choose a motor/actuator



Actuators Example: Fully Loaded Husky

Continuous Rotation Servos

Precise position control, high speed



High torque, high efficiency

Brushless DC Motors

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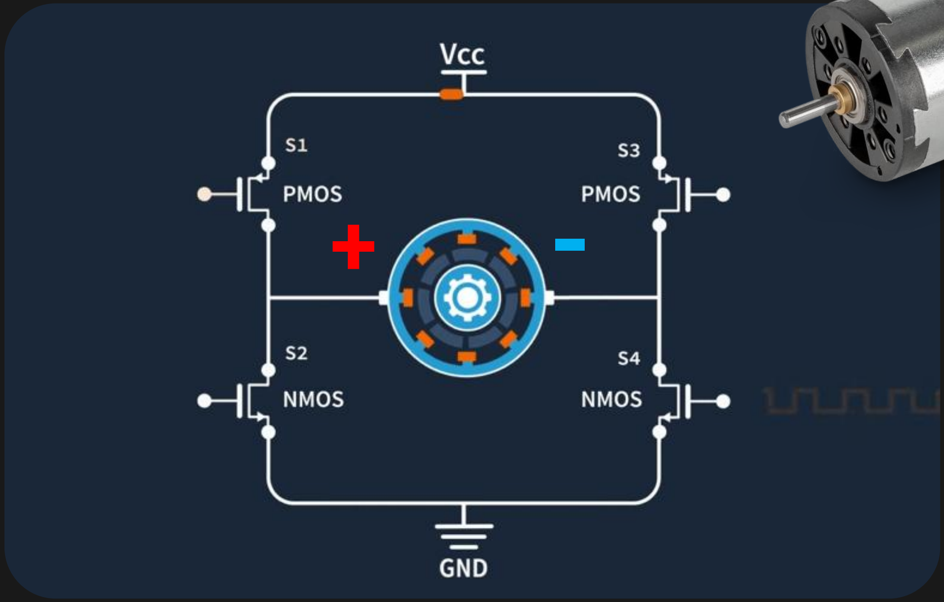
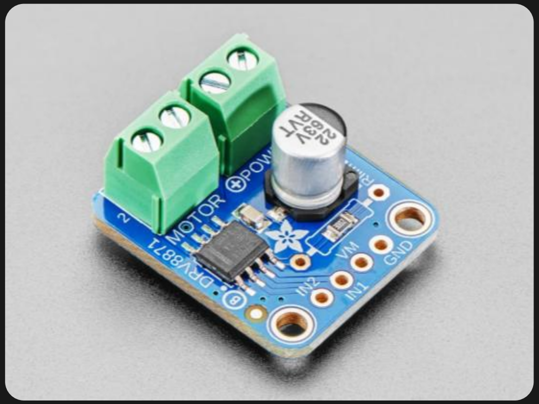
Driving Actuators

Brushed DC Motor Driver

Easy peasy to build and use!

- Voltage: 3-24V typical.
- Interface: GPIO, PWM
- Availability: discrete transistors, ICs, module PCBs
- Vendors: Texas Instruments, Adafruit, Pololu etc.
- Favorites: Ti DRV series (e.g. DRV8833)





3.6A, 25x20x15mm

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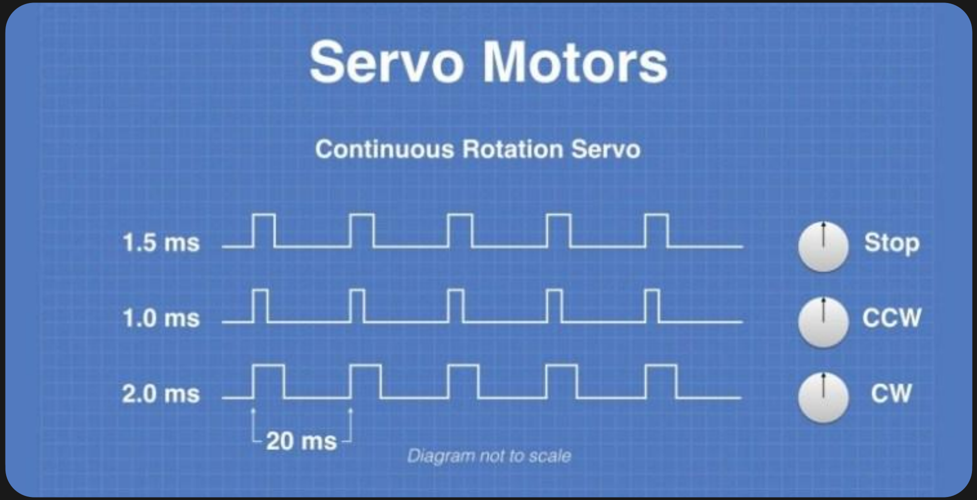
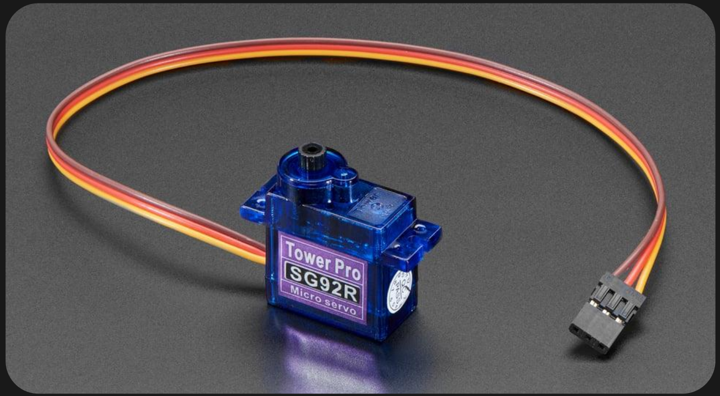
Servo Motor Driver

Easy peasy! Just need power and PWM

- Voltage: Logic = 3.3V, Power = 5.8-12V
- Interface: 50 Hz PWM
- Availability: MCU, ICs
- Vendors: Texas Instruments, Analog devices, NXP
- Favorites: NXP PCA9685, Adafruit 16-Channel Servo Driver, Almost any microcontroller



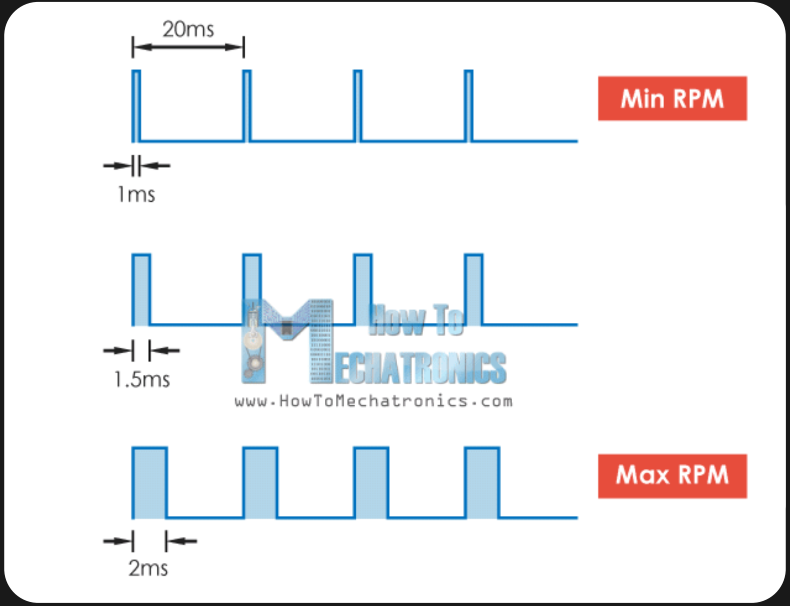


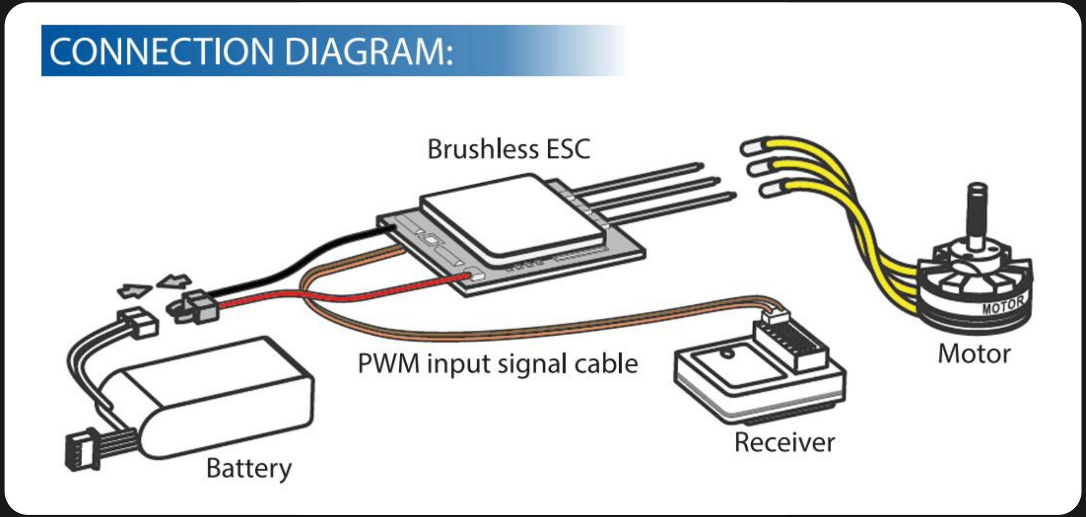
Red = Power, Brown = Ground, Orange = PWM

Brushless DC Driver

Complex! Commercial speed controller makes it easy

- Power & Voltage: Logic = 3.3V, Power = ~11-36V
- Interface: 50 Hz PWM
- Availability: Discrete components, ICs, modules (ESC).
- Vendors: Texas Instruments, ST, Turnigy, Amazon
- Favorites: Any Turnigy Brushless ECS.



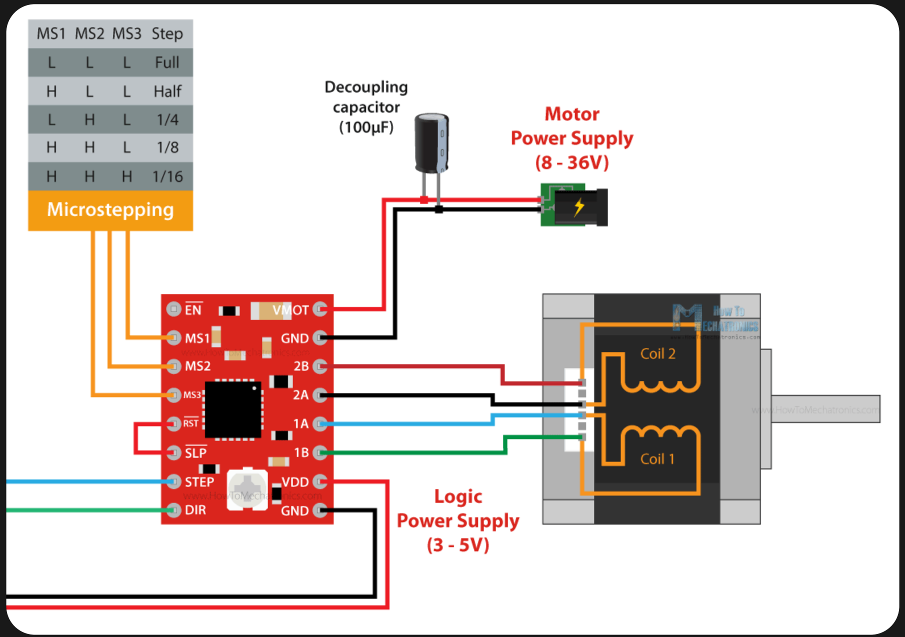


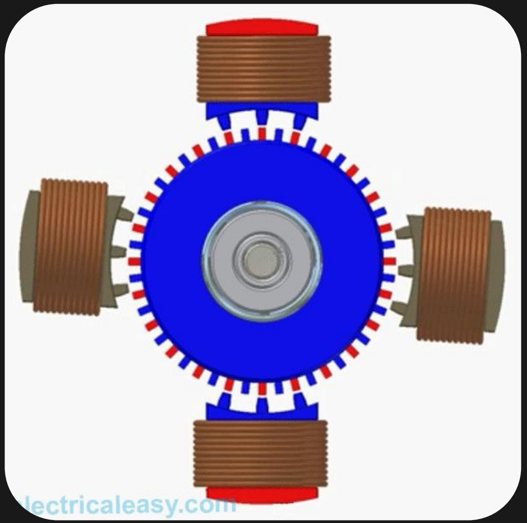
Stepper Motor Drivers

Complex! Recommend using an integrated stepper IC!!!

- Power & Voltage: Logic = 3.3-5V, Power = 8-36V
- Interface: STEP/DIR/Enable
- Availability: ICs, modules
- Vendors: Analog Devices, Allegro, Ti, ST, Pololu, Adafruit, Sparkfun
- Favorites: Sparkfun Big Easy Driver

STEP
DIR
+3.3V





Driver Summary

What motor are you using?

↓

Google and use the corresponding driver…

Sensors

How to choose a sensor

1. Application
   - What do you need to be able to sense?
2. Size, weight, power and cost:
   - How constrained are you?
3. Required accuracy
   - How accurate do your measurements have to be?
4. Environment:
   - Expected temperature, indoor, outdoor, ambient lighting, environment material composition?

Scenario: User controlled, outdoors, flying platform, unstable. Need high accuracy sensing.

Scenario: Need visual navigation and ability to detect objects. Autonomous, inherently stable. Lower accuracy orientation.

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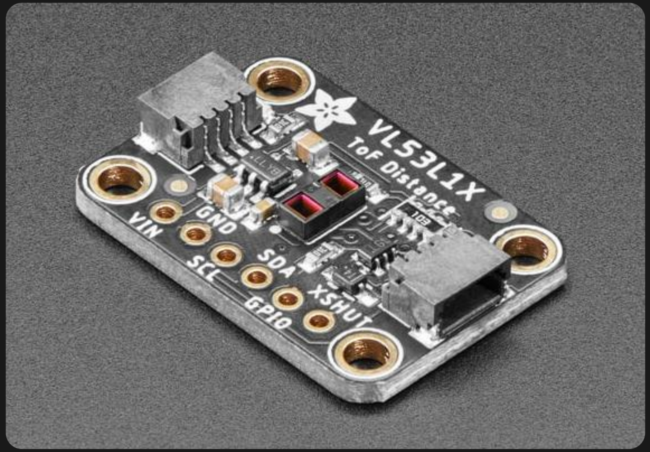
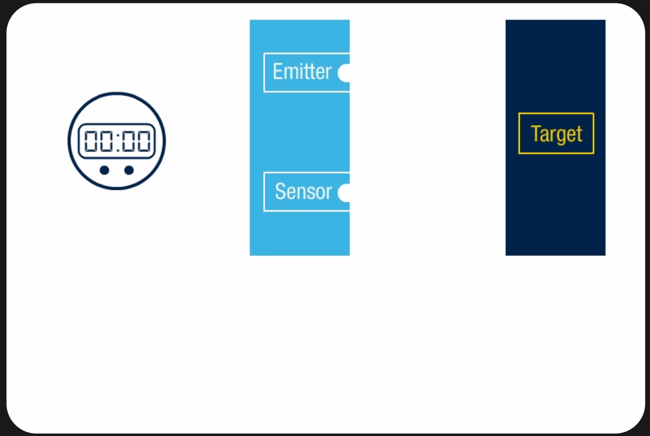
Time of Flight Distance Sensor

The poor mans LiDAR

- Power & Voltage: Analog = 2.8V, Digital = 1.8-3.3V, 30-300 mW
- Interface: I2C or SPI
- Pros: Small, light, wide operating distance.
- Cons: lighting conditions, surface reflectivity impacts performance.
- Availability: bare ICs (ST), breakout boards, development boards
- Vendors: ST, Adafruit, DF Robotics
- Favorites: VL53L1X



[Adafruit VL53L1X]



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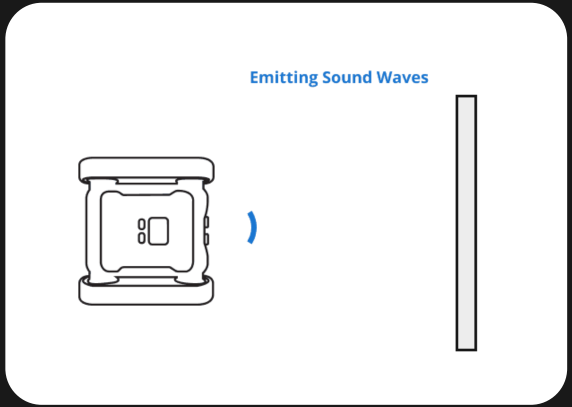
Ultrasonic Distance Sensor

More pixels/faster framerate means more power and readout complexity

- Power & Voltage: ~10 mW, 3.3-5V
- Interface: I2C, UART, PWW, Pulse
- Specs: mm accuracy, 10mm to meters range, 30-100 Hz sampling.
- Availability: bare ICs, modules,
- Vendors: TDK, Adafruit, Maxbotix
- Favorites: HC-SR04, US-100



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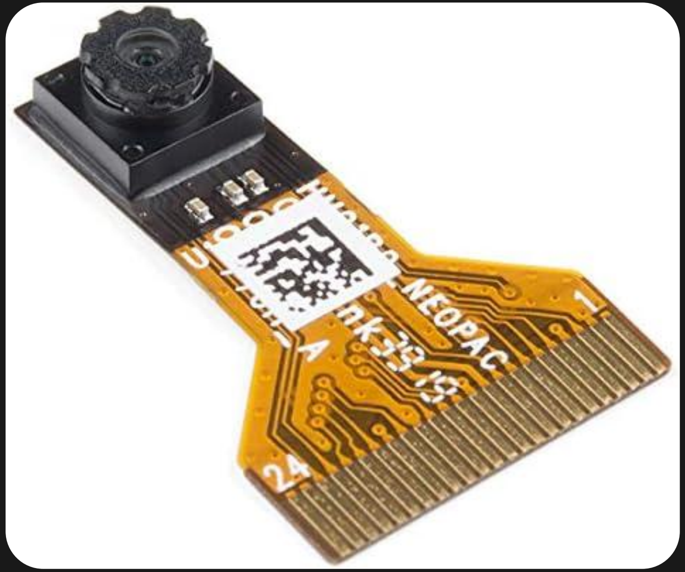
Visible Camera

More pixels/faster framerate means more power and readout complexity

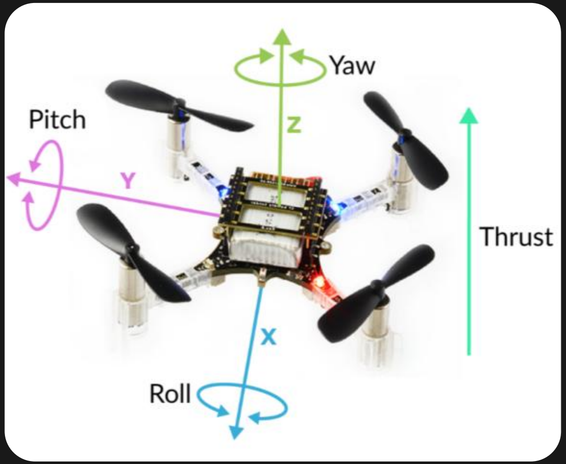
- Power & Voltage: typically, mW to Watts, +1.8V & +2.8V
- Interface: Parallel (8bit), SPI or MIPI CSI
- Pros: Highly flexible, color, shape and motion information.
- Cons: higher power, processing and memory requirements.
- Availability: bare ICs, modules, breakout boards and development boards.
- Vendors: Himax, OmniVision, Raspberry Pi, Adafruit, ArduCam
- Favorites: Himax HM01B0-ANA, Raspberry Pi Camera Module 2

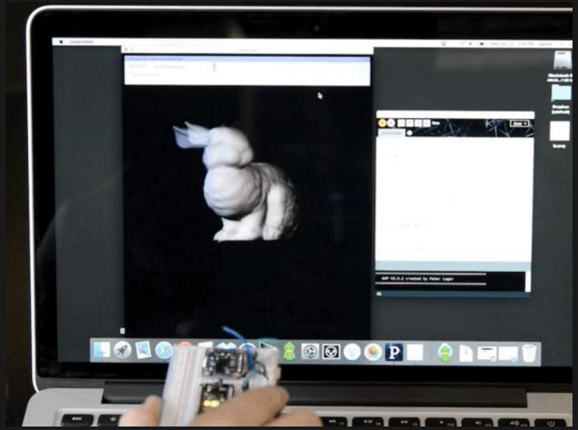


Inertial Measurement Unit

Provide orientation of robot body frame, x/y/z and roll, pitch, yaw

- Power & Voltage: 1-100 mW, Typically 1.8 – 3.3V
- Interface: I2C and SPI common.
- WIP: regulator noise, temperature stability, EMI, vibration,
- Availability: bare ICs, modules, breakout boards and development boards.
- Vendors: TDK, Bosch, Analog devices, ST Micro
- Favorites: BNO085, ICM-20948





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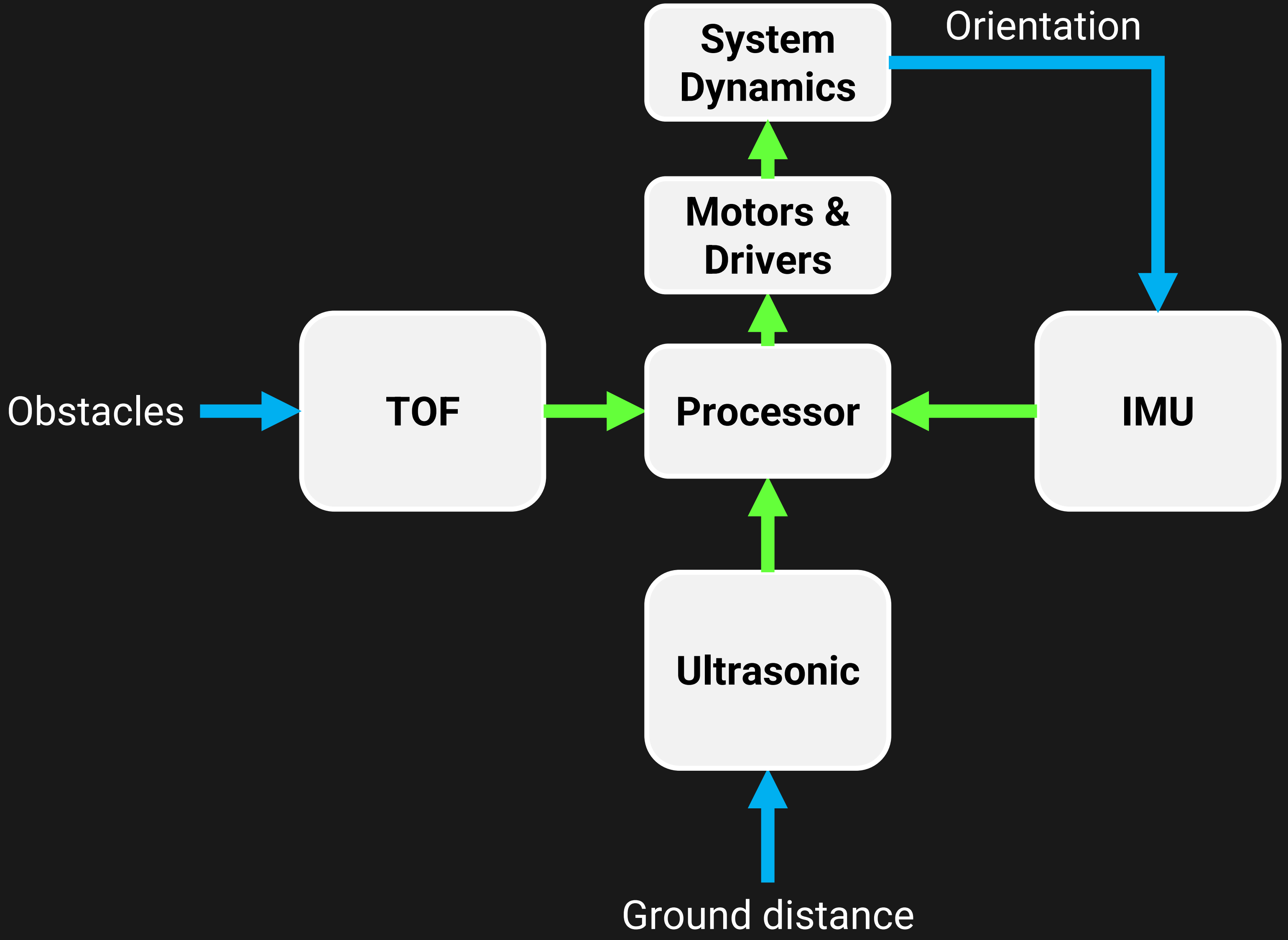
Sensing Example: Quadcopter



Robotic Processing

Processing Options

Larger and more power hungry, but very capable

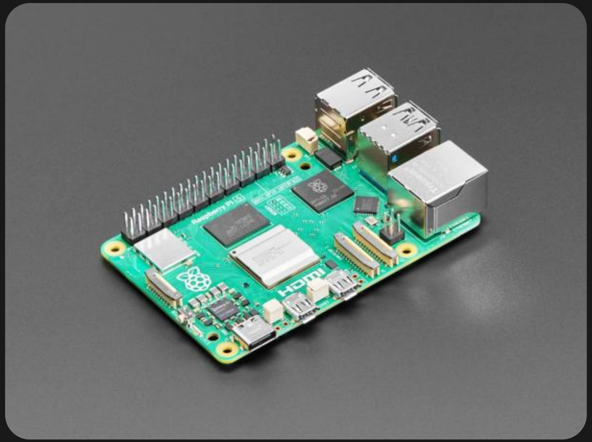
Single Board Computers

Nvidia Jetson(s)

Raspberry Pi

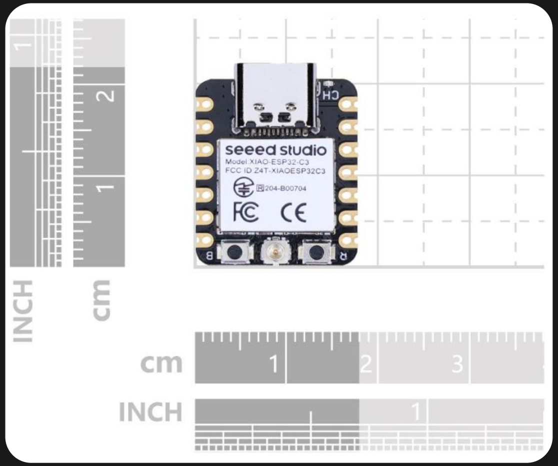
Pros:
High speed & computation
Lots of memory (RAM, Flash)
High level programming
Advanced High-speed interfaces

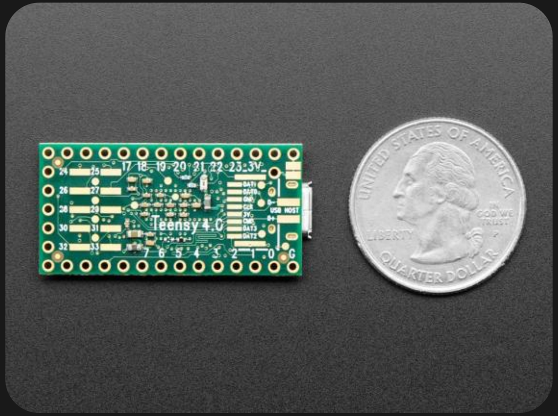
Cons:
High power requirements
Higher latency
Significantly larger and heavier



Processing Options

Lower power, smaller footprint and low latency, but limited memory/bandwidth/processing





Microcontrollers (32-bit)

NXP IMX RT1060	Espressif ESP32-S3	Nordic nRF52840

Pros:
Lower power
Very small
Very low latency (Real-Time)
Rich hardware peripherals

Cons:
Lower speed and processing capacity
Significantly less internal RAM and Flash
Low level programming
Complex hardware peripherals

How to pick a processing unit

1. Sensor Complexity:
   1. How much data does your sensors generate? (RAM, interfaces, speed)
   2. What are your sensors (required interfaces & bandwidth)
2. Algorithmic Complexity
   1. How much data is required for your algorithm? (RAM, Flash)
   2. How fast does your algorithm run? (speed)
3. System dynamics
   1. How stable is your system inherently? (speed)
   2. How fast are your system dynamics? (latency and speed)
4. Size, weight and power limits
   1. What size, weight and power can you handle?

Inherently unstable, very fast, simple sensors (IMU, TOF), low level communication

Inherently stable, low velocity, complex sensors (camera, depth sensors etc.), reduced SWAP constraints

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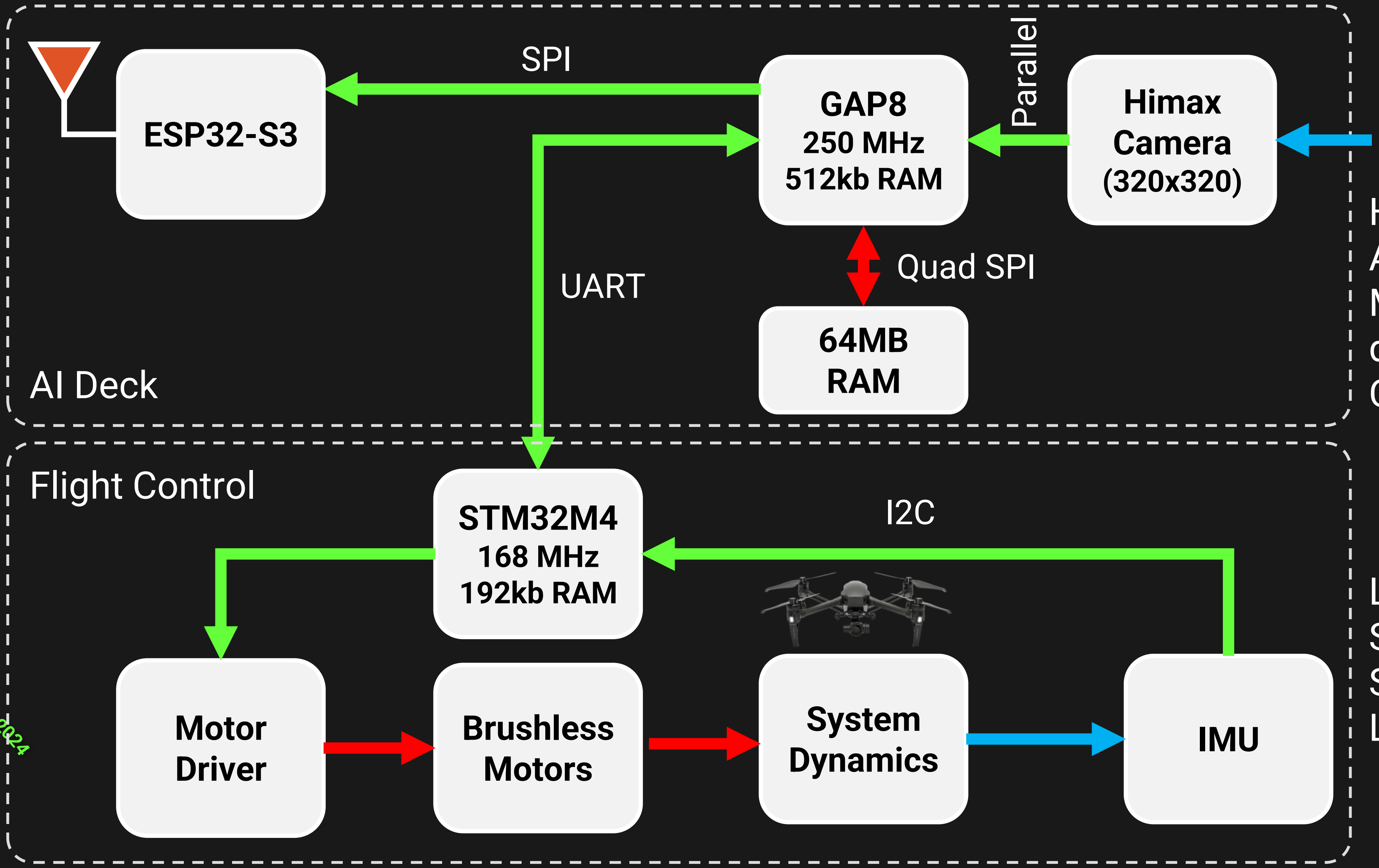
Processing Example: CrazyFlie Quadcopter + AI Deck



Higher latency
Adv. interfaces
More sensor data
Complex algor.

Low Latency
Simple sensors
Simple control
Low lvl comms

Power

Sources and regulation

How to Choose a Battery

1) Define capacity based on runtime, 2) then discharge rate based on max current

1. What are your requirements?

1. Maximum current (Amps)
2. Average current (Amps)
3. Input voltage range (Volts)
4. Size and weight limits (mm, grams)
5. Runtime (minutes)

Key Performance Metrics

	NiMH	**Li-Ion high energy**	**Li-Poly High current**	**Li-Poly high safety type**
Chemistry	NiMH	$LiCoO_2$, $LiNiMnCoO_2$	$LiMn_2O_4$	$LiFePO_4$
Nominal cell voltage	1.2V	3.6 - 3.7V	3.7 - 3.8V	3.2 - 3.3V
Operating cell voltage range	**1.0 - 1.4V**	**3.0 - 4.2V**	**3.0 - 4.2V**	**2.5 - 3.65V**
Max voltage for charging	1.4 - 1.6V	4.2 - 4.3V	4.1 - 4.2V	3.65V
Max charging current	0.1C or 1C (only with ΔV/ ΔT)	~1C	up to 3C	up to 4C
Max discharging current	**1C - 30C**	**1C - 2C**	**5C - 30C**	**1C - 40C**
Charging method	CC with timer or ΔV/ ΔT (faster)	2 stages: CC and then CV	2 stages: CC and then CV	2 stages: CC and then CV
Specific energy	**40 - 120Wh/kg**	**150 - 250Wh/kg**	**100 - 150Wh/kg**	**90 - 120Wh/kg**
Specific power	**100 - 1000 W/kg**	**100 - 400W/kg**	**400 - 5000 W/kg**	**200 - 7000 W/kg**
Internal series resistance for a single cell	5-50 mΩ (for 18650 size)	15-100 mΩ (for 18650 size)	10-50 mΩ (for 18650 size)	6-60 mΩ (for 18650 size)



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Example: battery selection for quadcopter

LiPo battery with high capacity and series connection required

Quadcopter Requirements:

1. Weight: < 700 grams
2. Size: not critical
3. Vin: 15-14V
4. Max current: 60.3 A
5. Ave current: 22.2 A
6. Runtime: >10 min

Battery Requirements:

Capacity: 5000 mAh (.16 hrs. * 22.2 A = 3550 mAh)

Discharge Rating: >12C (60.3A / 5 Ah = 12C)

# of Cells: 4 series (14V / 3.7V / cell = 3.78 cells)

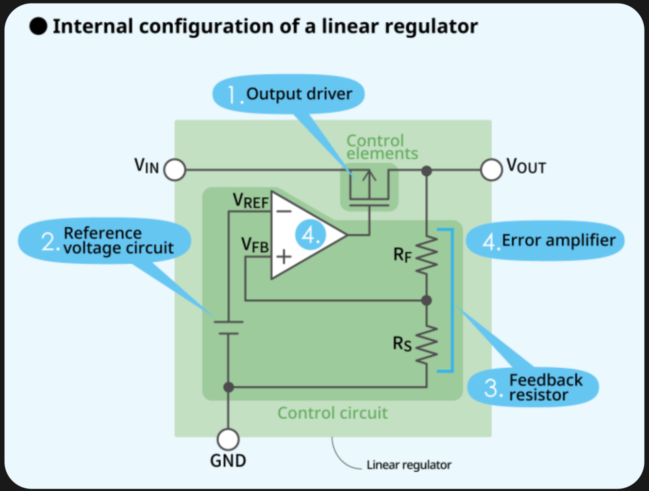
Battery Selection

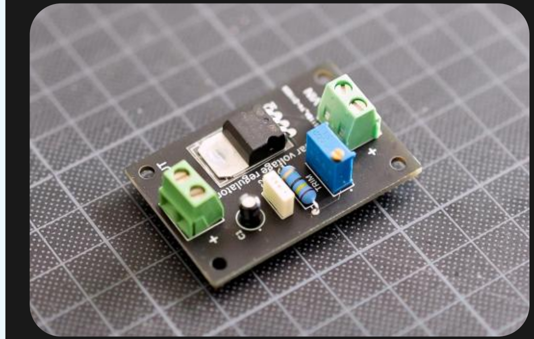
Turnigy Graphene 5000mAh 4S 45C Lipo, 45C continuous, 90C peak

Types of Voltage Regulators

Regulator Types:

1. **Linear Regulator:** steps voltage down. Extremely simple. Low efficiency, low noise.
2. **Buck converter:** steps voltage down. High efficiency and current possible. Switching noise.
3. **Boost converter:** steps voltage up, high efficiency and current possible. Switching noise.
4. **Buck-boost converter:** steps voltage up or down. High efficiency and current possible. Switching noise.





Linear regulator

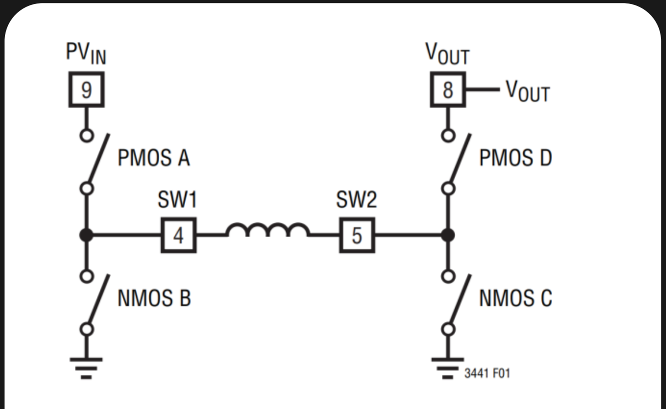


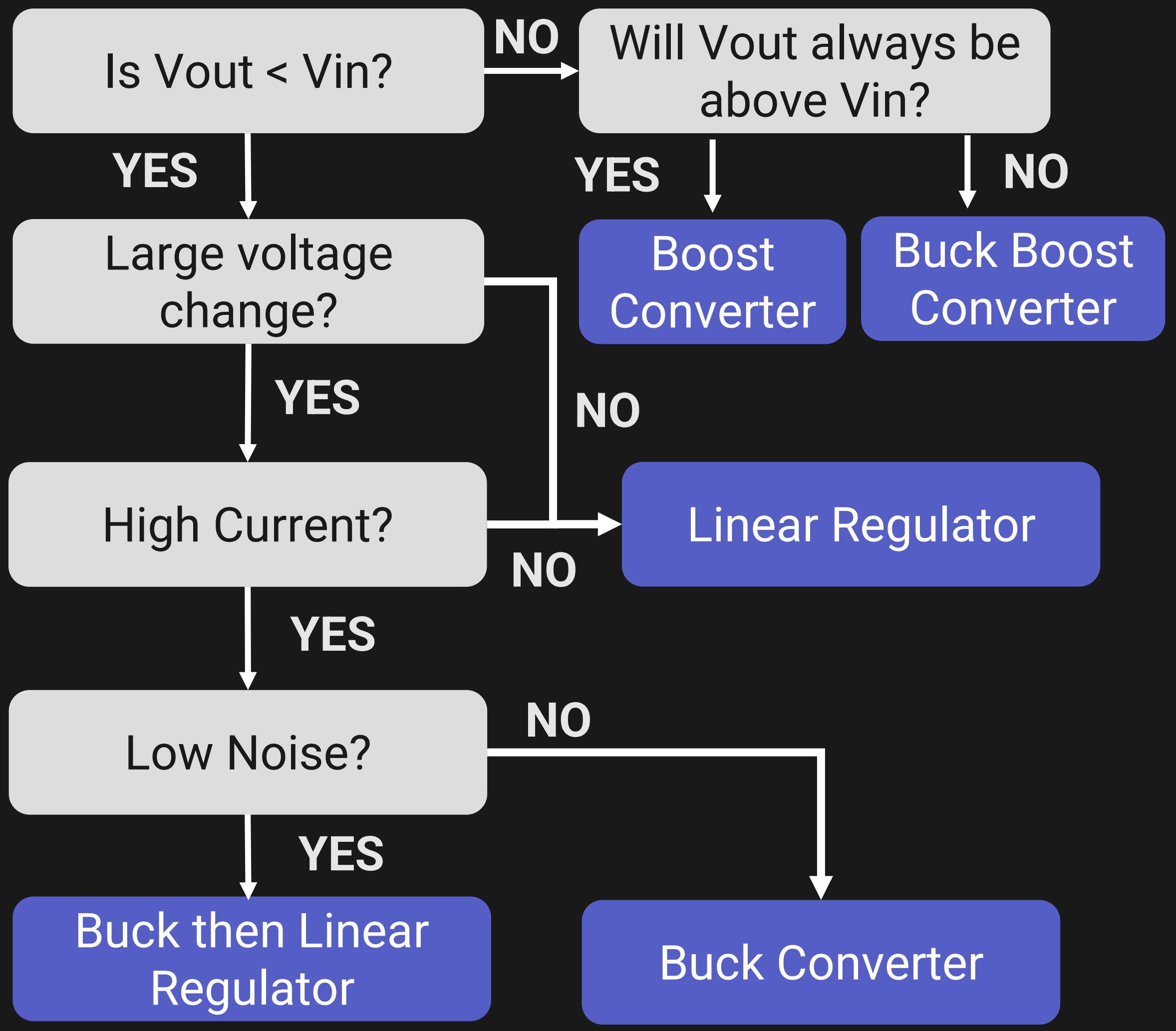
Figure 1. Simplified Diagram of Output Switches

Switching regulator

How to pick a voltage regulator

Define Regulator Requirements:

1. **Output Voltage (V):** what voltage do your device run off?
2. **Input Voltage (V):** what voltage is your input?
3. **Load current (A):** how much your devices draw.
4. **Efficiency (%Pout/Pin):** how efficient do you need, heat sinking?
5. **Noise requirements:** powering analog or digital systems?



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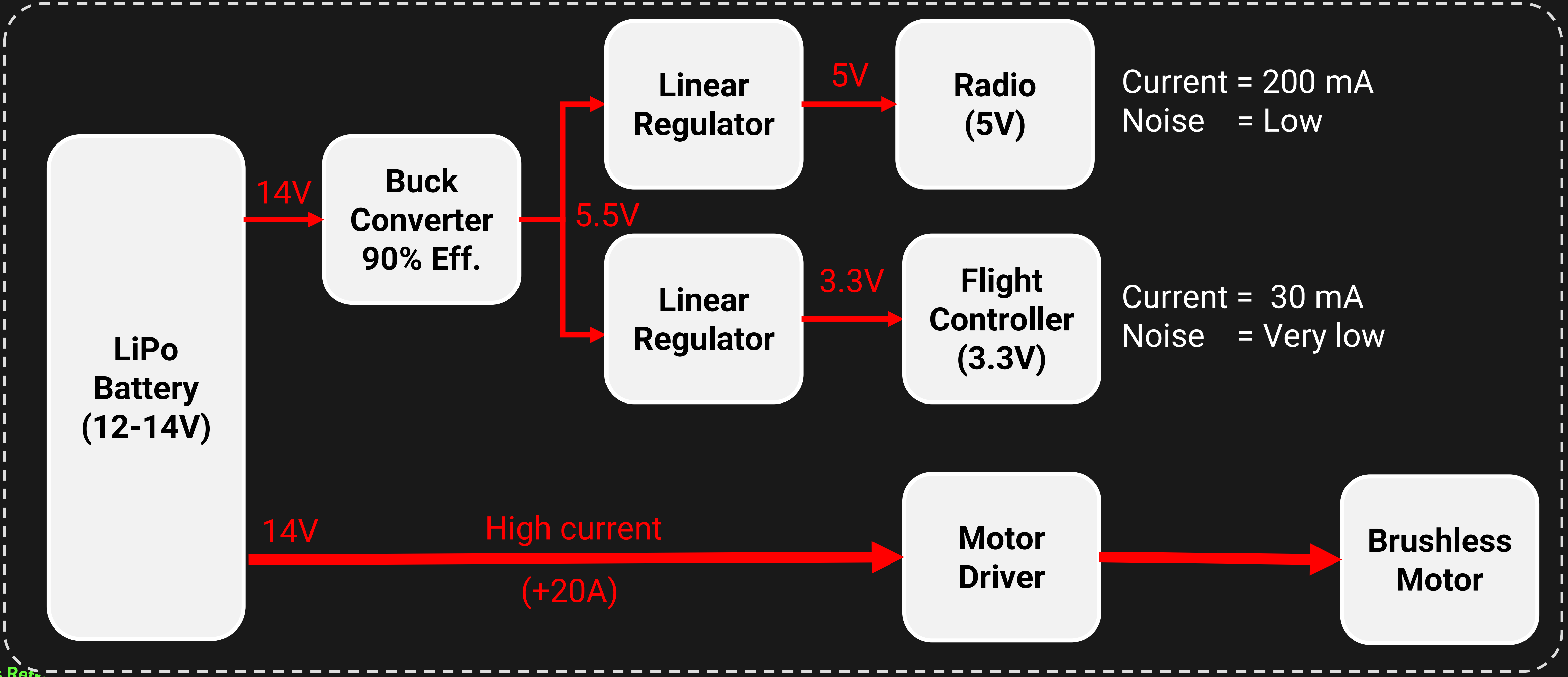
Quadcopter Voltage regulator architecture



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Voltage Regulation Summary

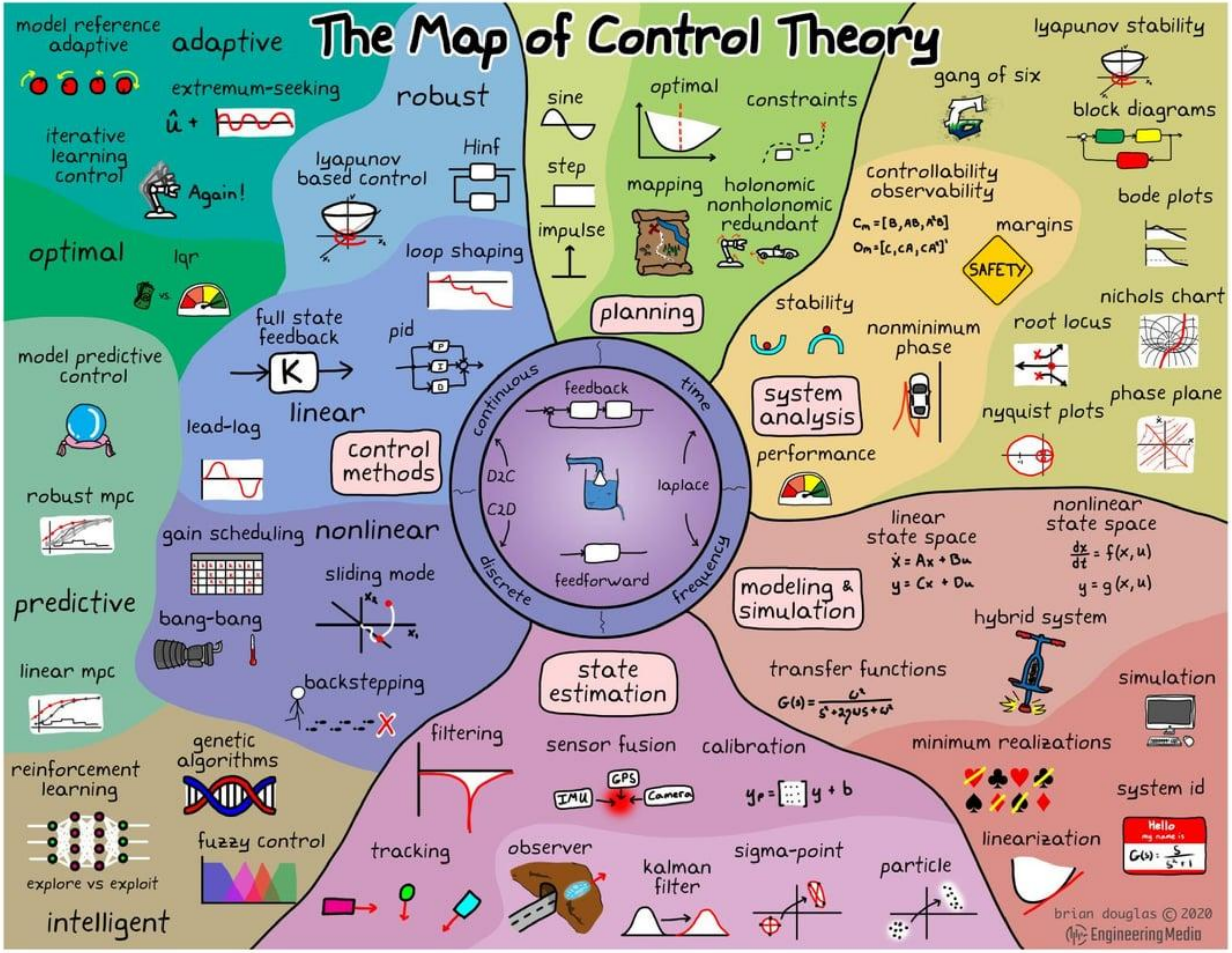
Overall trade between design complexity and performance.

Metric	Linear Regulator	Buck Converter	Boost Converter	Buck Boost
Function	Step down	Step down	Step up	Step up & down
Efficiency	Low	High- Very high	High –very high	High – very high
Max Current	Low*	High	High	High
Components	Very few	Few – lots	Few – lots	Few – lots
Complexity	Very low	Moderate	Moderate	Moderate – High
Noise	Very low	Moderate	Moderate	Moderate

Unless thermally relieved*

- Availability: bare ICs, micro modules, PCB boards and development boards.
- Vendors: Analog device, Texas Instruments, Adafruit, Pololu

Controls



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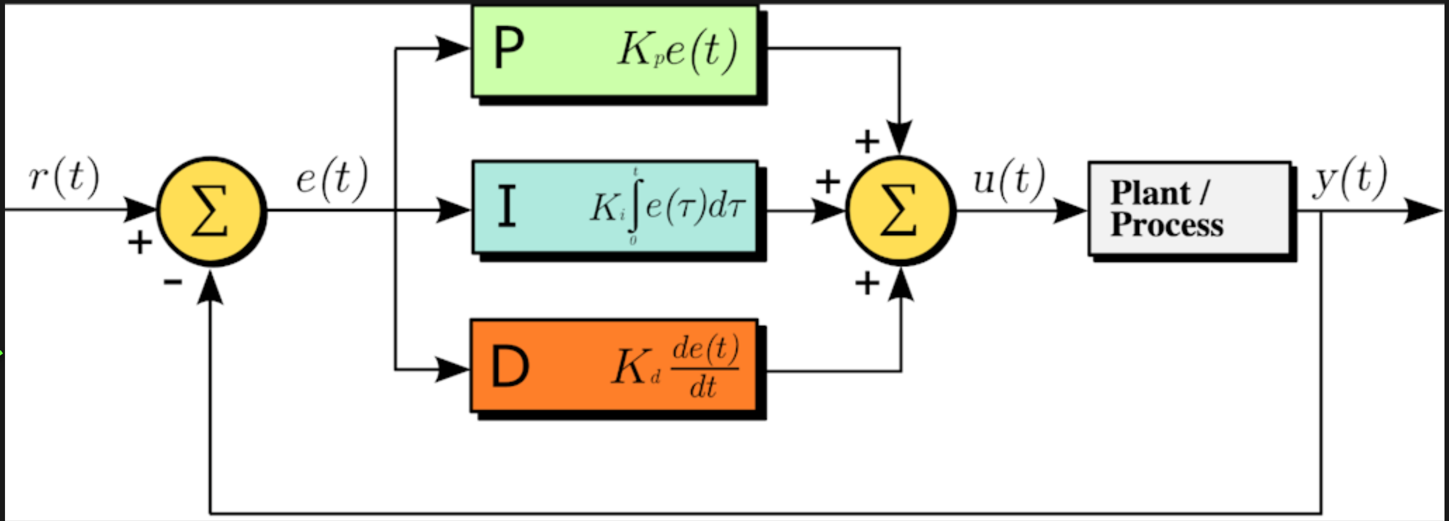
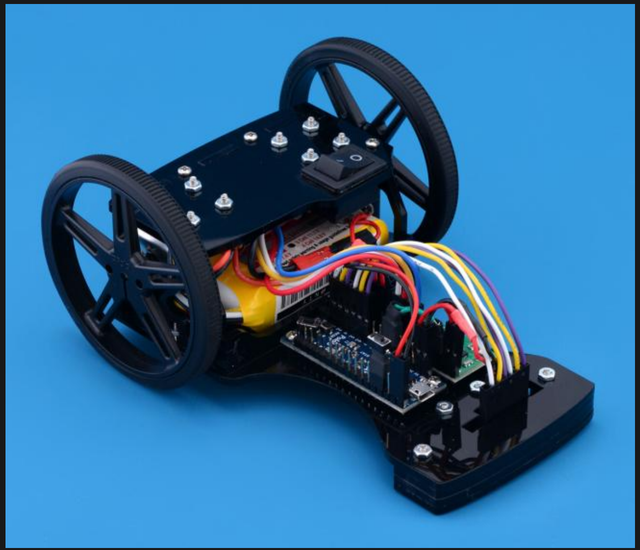
PID Controller

Plug and play!

Simplicity	★★★★★
Stability	★★★★★
Robustness	★★★★
Speed	★★★★
Applications	★★★★★





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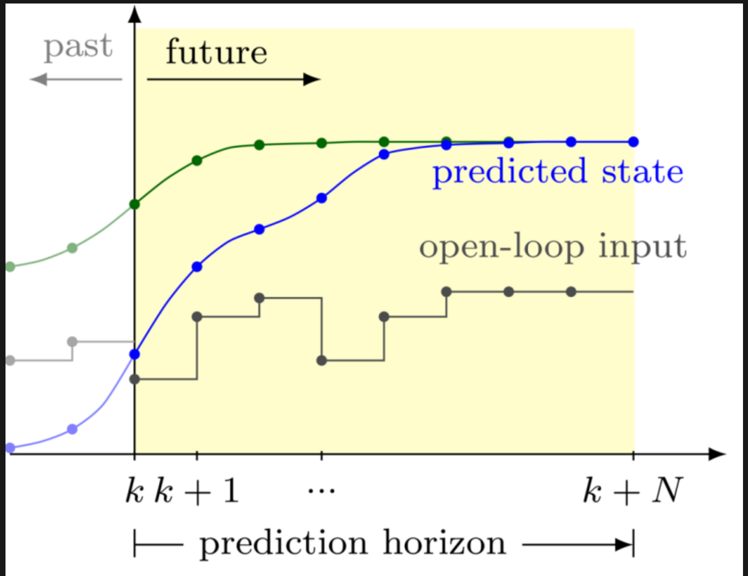
Model Predictive Control (MPC)

Predict the future!

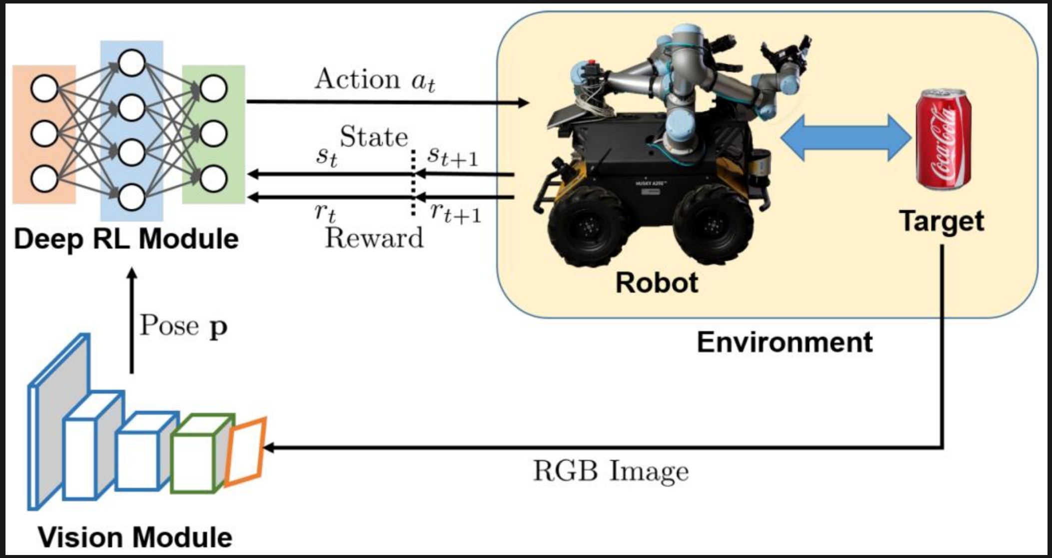
Simplicity	⭐⭐
Stability	⭐⭐⭐⭐
Robustness	⭐⭐⭐⭐
Speed	⭐⭐⭐
Applications	⭐⭐⭐⭐



Reinforcement Learning

AI!

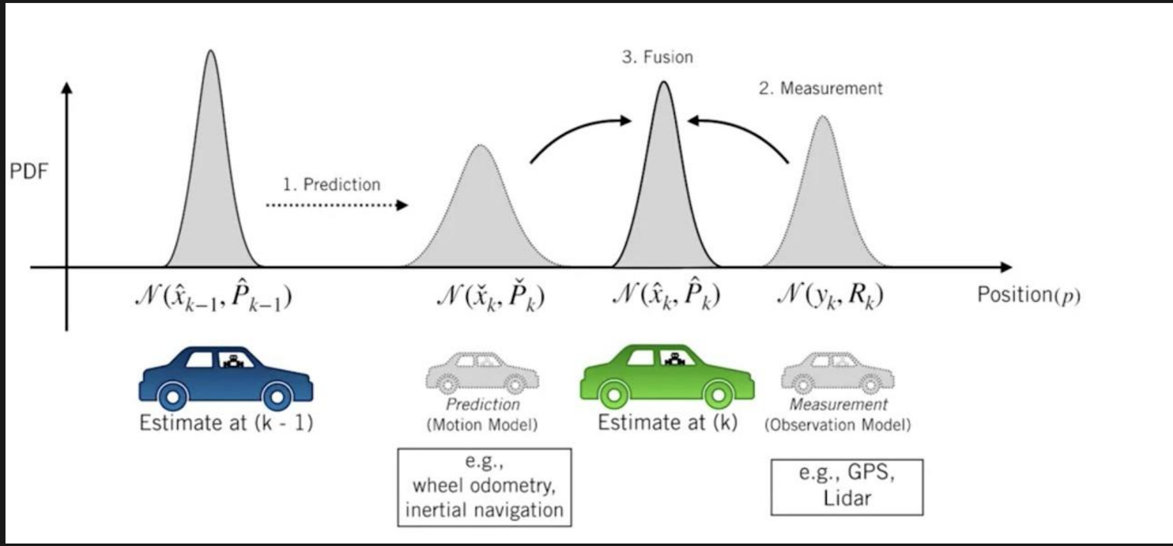
Simplicity	⭐⭐
Stability	⭐⭐⭐
Robustness	⭐⭐⭐
Speed	⭐⭐
Applications	⭐⭐⭐⭐



Kalman Filters (State Estimation)

Where am I?

Simplicity	⭐⭐⭐
Stability	⭐⭐⭐⭐
Robustness	⭐⭐⭐⭐⭐
Speed	⭐⭐⭐
Applications	⭐⭐⭐⭐⭐



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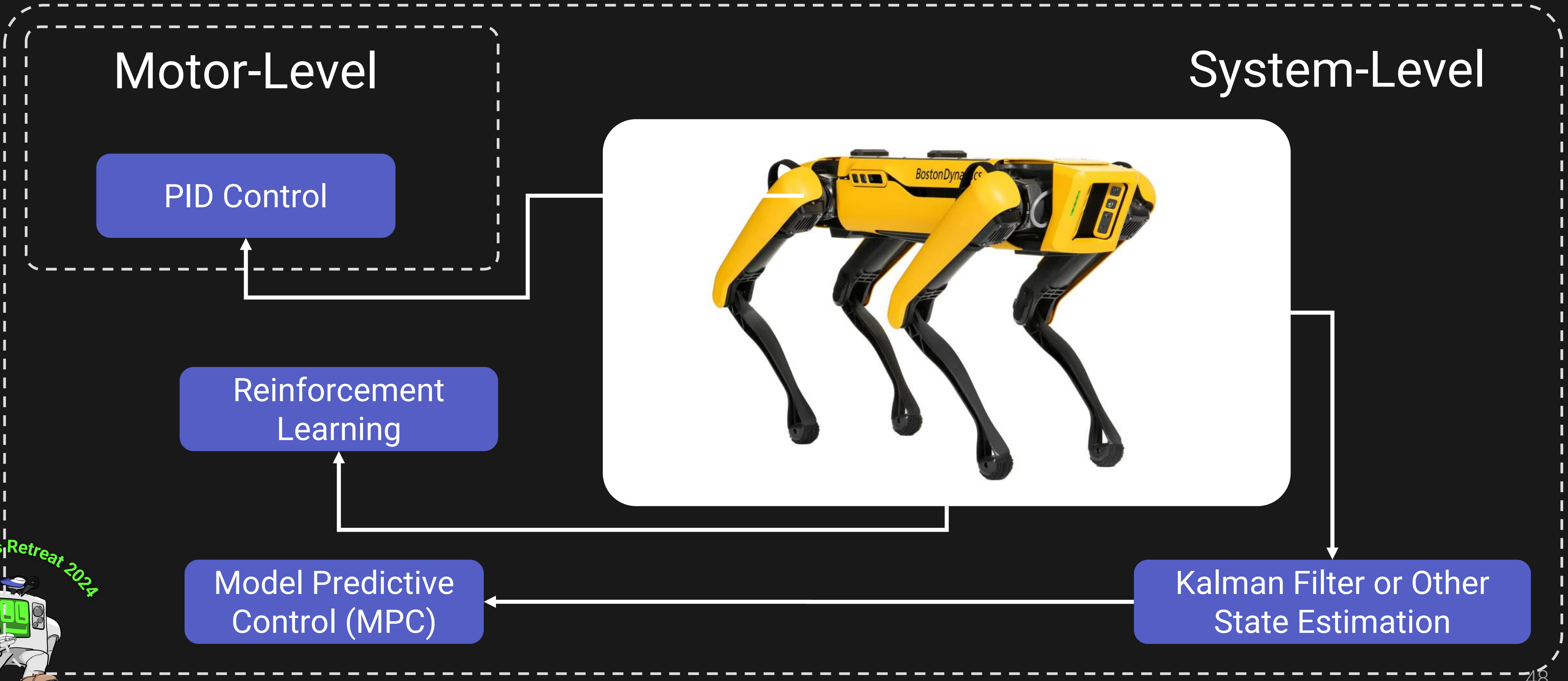
Controls Example: Spot



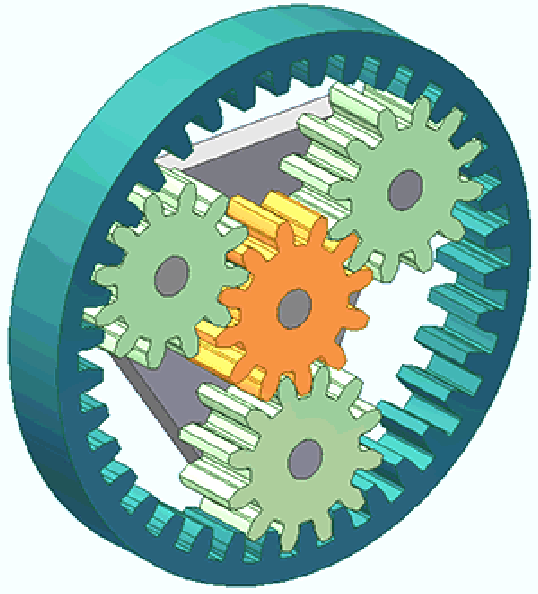
Mechanics

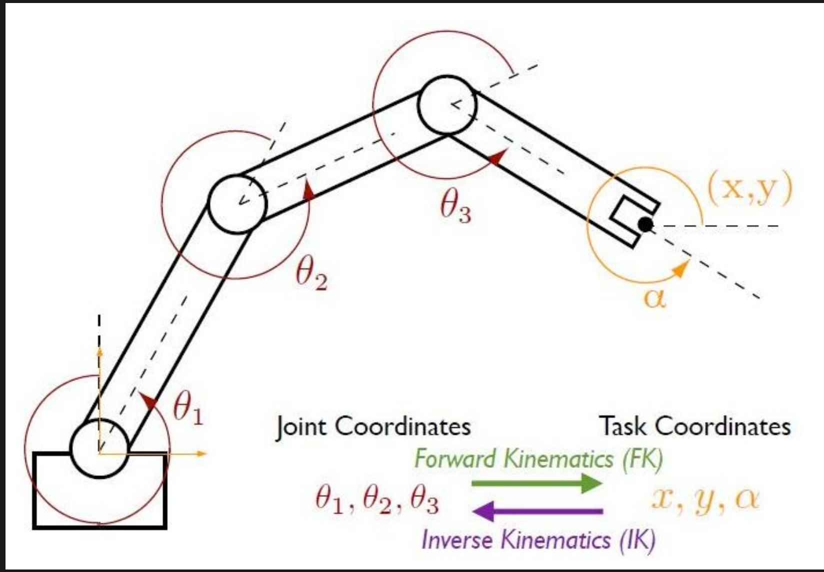
First Principles Modeling

Create a model

$$\sum F = ma$$

Newton's Second Law

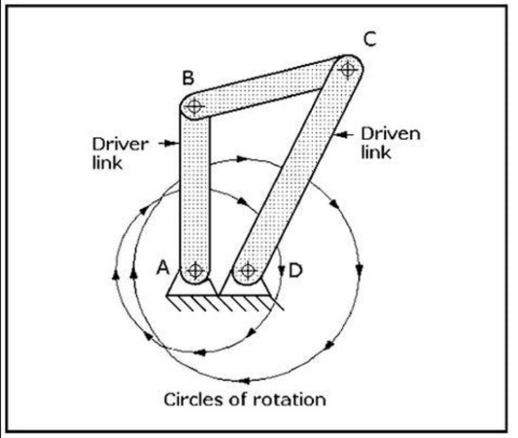




Kinematics

$$\frac{C(s)}{R(s)} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

System Dynamics



Linkage Design

Physical Modeling

	Simplicity	Solid Modelling	Version Control	Add-Ons	Parametric
SOLIDWORKS	⭐⭐⭐	⭐⭐⭐⭐⭐	⭐⭐⭐	⭐⭐⭐⭐⭐	⭐⭐⭐
onshape	⭐⭐⭐⭐	⭐⭐⭐⭐	⭐⭐⭐⭐⭐	⭐⭐⭐⭐	⭐⭐⭐⭐⭐
F 360 (Fusion 360)	⭐⭐⭐⭐	⭐⭐⭐⭐	⭐⭐⭐⭐⭐	⭐⭐⭐⭐	⭐⭐⭐
A (AutoCAD)	⭐⭐⭐	⭐	⭐⭐	⭐⭐⭐	⭐
SIEMENS NX	⭐⭐⭐	⭐⭐⭐⭐⭐	⭐⭐⭐⭐	⭐⭐⭐⭐⭐	⭐⭐⭐⭐

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Physical Model Analysis

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Purchasing Components

Where to buy stuff

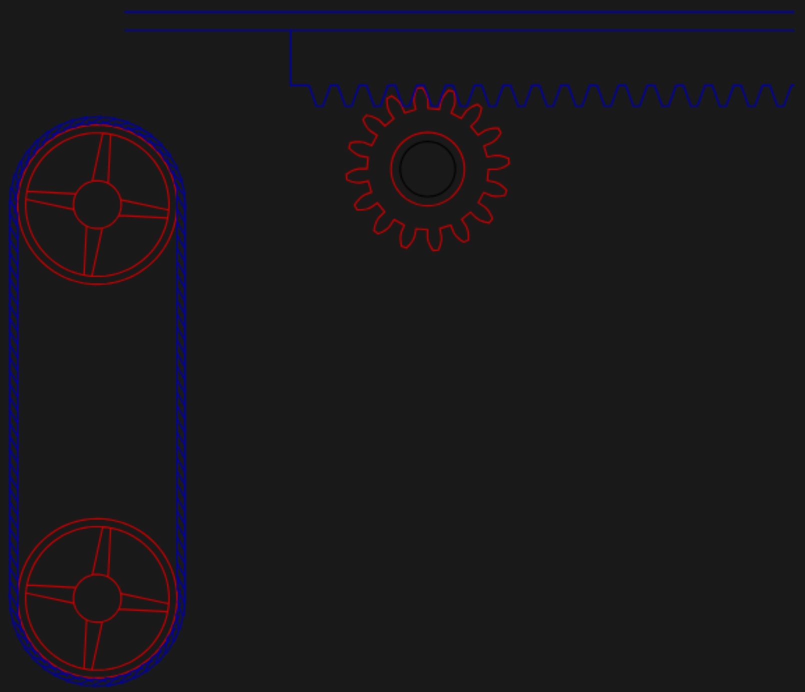
	Electronics	Fasteners	Misc. Stuff	CAD Available	Cost
McMaster-Carr	⭐⭐	⭐⭐⭐⭐⭐	⭐⭐⭐⭐⭐	⭐⭐⭐⭐⭐	⭐⭐
Digikey	⭐⭐⭐⭐⭐	⭐⭐⭐	⭐⭐⭐⭐	⭐⭐⭐⭐	⭐⭐⭐
Mouser	⭐⭐⭐⭐⭐	⭐⭐⭐	⭐⭐⭐⭐	⭐⭐⭐⭐	⭐⭐⭐
Adafruit	⭐⭐⭐⭐	⭐	⭐⭐⭐	⭐⭐⭐⭐⭐	⭐⭐
Amazon	⭐⭐⭐	⭐⭐⭐⭐	⭐⭐⭐⭐⭐	⭐⭐	⭐⭐⭐⭐
ITLL	⭐⭐⭐⭐	⭐⭐⭐	⭐⭐⭐	⭐	⭐⭐⭐⭐⭐

Design Inspiration

Resources for inspiration

- Links for design inspiration
  - 507 Mechanical Movements
  - Instructables - Example Projects
  - Arduino Forum
  - https://www.youtube.com/@thang010146

AUTODESK Instructables



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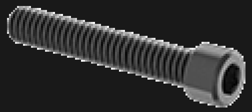
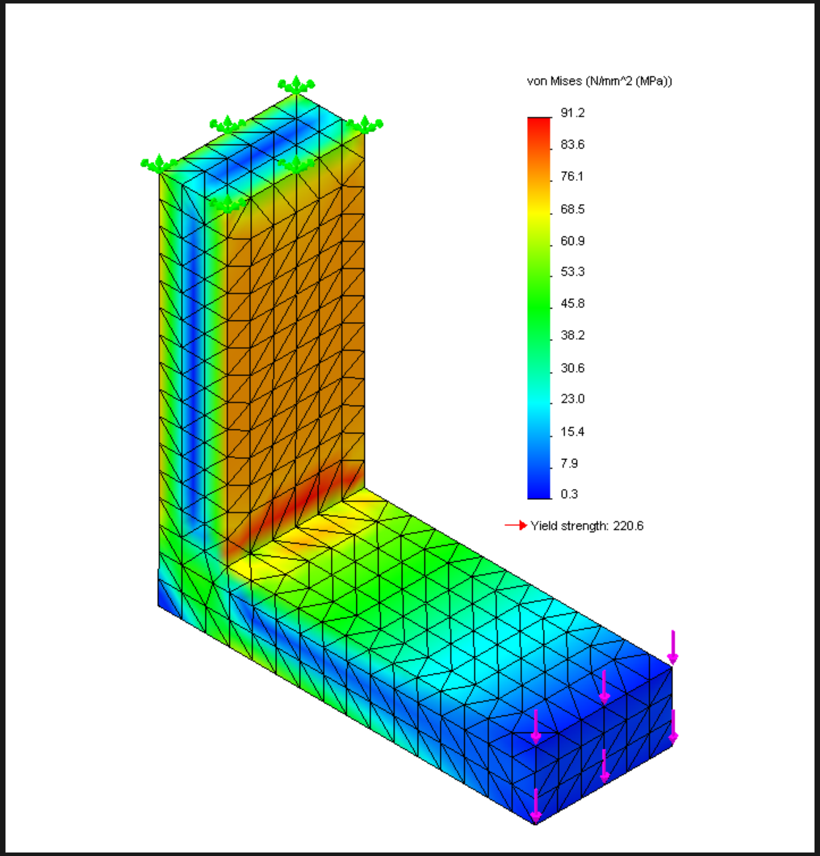
Design Rules of Thumb

- Simplicity
- Use standard components
- Minimize unique components
- Avoid over-constraining
- Design for manufacturing and assembly
- Avoid stress concentrations
- Include redundancy
- Fastener accessibility





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Spot Robot Design Game

https://bostondynamics.com/blog/starting-on-the-right-foot-with-reinforcement-learning/#:~:text=But%20how%20does%20Spot's%20walking,to%20take%20in%20the%20moment.

Spot Robot Design: It is your first day at Boston Dynamics, and you all have spent the morning trying to optimize Spot's backflipping steeze. However, there was an accident! Spot shattered into its individual components while attempting a double backflip (but somehow every component still works fine)! Unfortunately, right after this happened, someone in your group tripped and spilled a box with extra components right on top of Spot's components. You need to put Spot back together before your coworkers see what happened! Use the information below about 3 important high- and mid-level controllers and what you know about mechatronics to fix poor Spot. Remember, Spot can work independently or with a remote controller.

1. Locomotion Controller: May include Model Predictive Control (MPC), Central Pattern Generators (CPG), or other algorithms. Used to optimize Spot's walking motions by predicting how the robot will behave in response to motor inputs. Ensures Spot can robustly operate using different gaits and transition between them. Outputs instructions for the leg motors.
2. Path Planner: May include Simultaneous Localization and Mapping (SLAM) and/or other algorithms. Includes top-level instructions on where Spot should go. The Path Planner is not concerned about specifically how the robot will get to a location; instead, it just creates a path to the desired location.
3. Reinforcement Learning (RL) / Neural Network: Trained in simulation on millions of different terrains to help Spot get over and around obstacles. The neural net takes in the desired trajectory and the robot's state, and it returns a trajectory and gait.

Note: This block diagram has been simplified for this game, and the actual Spot robot uses more components and may use slightly different components/algorithms than are in this game.

Spot Design Game

Human User

- Battery + Architecture
- Voltage Regulator
- **5V Remote Controller Wifi**

Leg Motor (x12)

- Motor Driver
- Motor

Inside Main CPU

- Algorithm
- Algorithm
- Algorithm

LiPo Battery

58.8V (35V minimum) 605Wh

Voltage Regulator

Voltage Regulator

Voltage Regulator

Power Adapter

Spot Microcontroller(s) (64 MHz, 256kB RAM, 1MB flash)

+3.3V
Ethernet
USB

GPIO w/ PWM
I2C
UART

Spot Main CPU (64-bit CPU, Nvidia Volta GPU, 16 GB RAM, 512 GB SSD, 200 TOPS, Wifi, Ethernet, 15-40W power)

Wifi
USB
+19 V

GPIO w/ PWM (16x)
Cameras (6x)
I2C (8x)
UART (4x)

Sensor

Sensor

Sensor

Sensor

Spot Robot

Spot Game Blocks

Power Supplies

- Vin Vout **Buck Converter**
- Vin Vout **Linear Regulator**
- Vin Vout **Boost Converter**
- **USB 19V Power Adapter**
- Vin Vout **Buck-Boost Converter**
- **3.3V LiPo Battery**
- **3.3V LiPo Battery**

Motor Drivers

- 12-14V **DC Motor H-Bridge** PWM
- 12-14V **Stepper Driver** STEP
- 12-14V **Brushless ESC** PWM

Motors

- +6V **Servo Motor** PWM
- **Stepper Motor**
- **Brushless DC Motors**
- **DC Motors**

Algorithms

- **Path Planner**
- **Neural Network**
- **Locomotion Controller**

Sensors

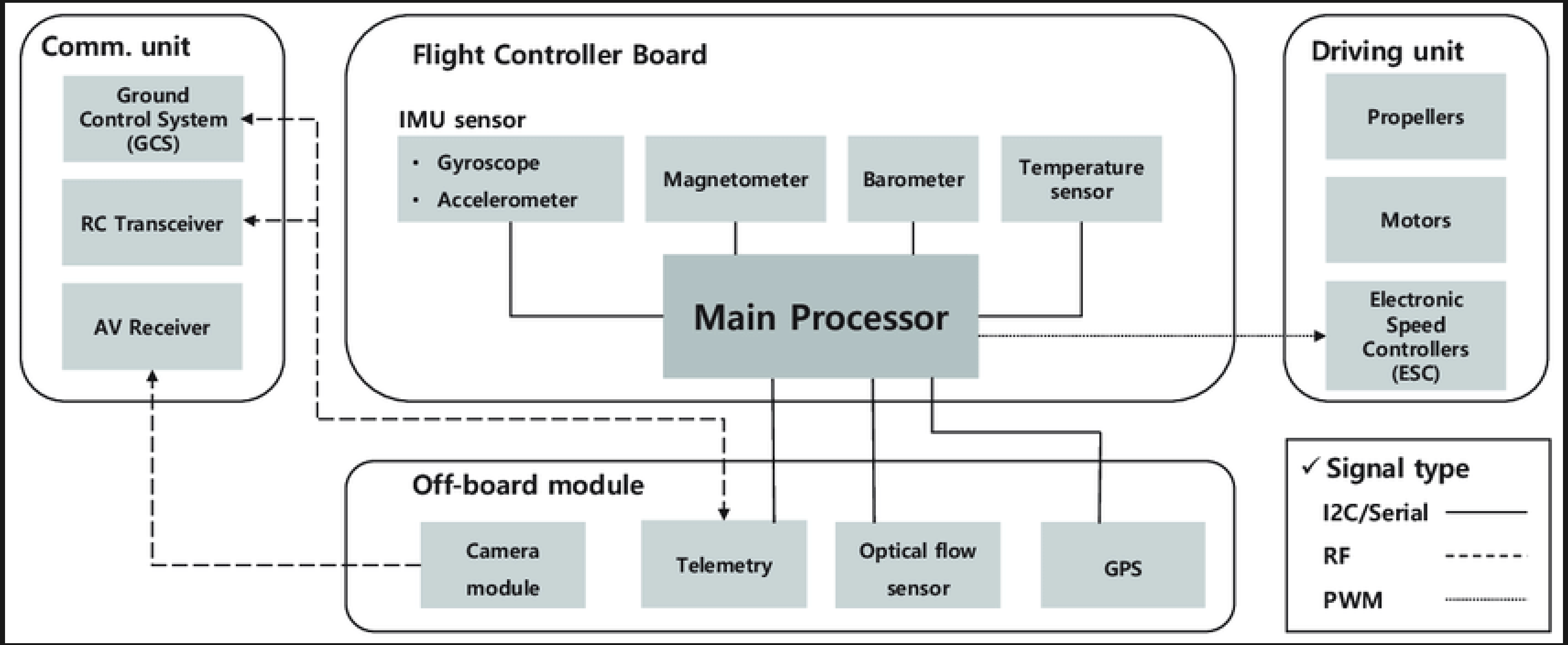
- +3.3V **Force Sensors (4x)** I2C
- +12V **Cameras (5x)**
- +12V **LiDAR** UART
- +3.3V **IMUs** I2C
- +3.3V **Ultrasonic Distance Sensor** I2C
- +3.3V **Soil Moisture Sensor** I2C

Quadcopter Design Game

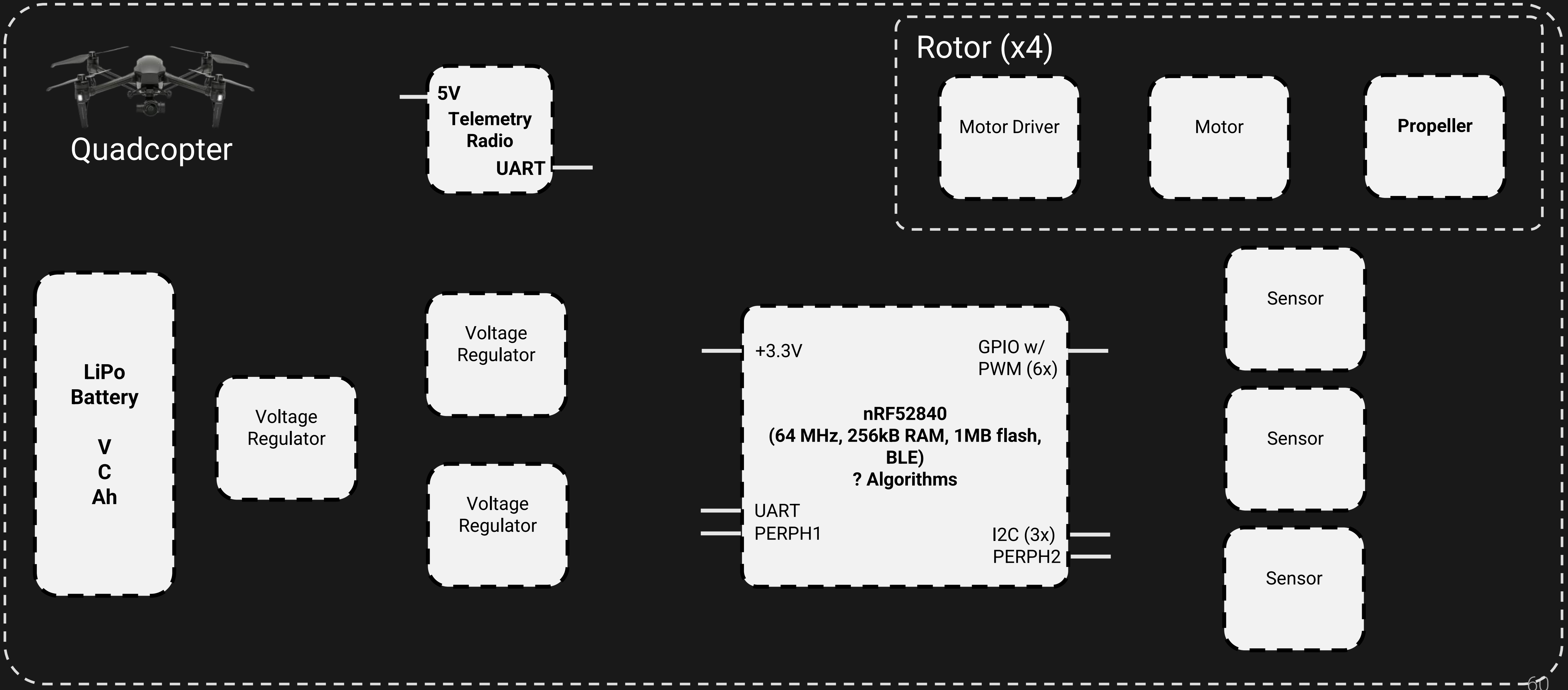
Quadcopter Design: You just hiked to the top of Bear Peak in Boulder but realized you forgot your snack! Luckily, you left your favorite snack in your quadcopter which is turned on in your backyard. Using an app on your phone, you can send the quadcopter your coordinates, and it will autonomously navigate to you. Assume it will take ~15 minutes for the drone to arrive on Bear Peak. Your goal is to put together a block diagram of a drone that can accomplish this task. Write in values where necessary. Good luck!

1. Assume each BLDC motor uses 10A at max torque and 5A average over a typical flight.
2. You only have room for 3 sensors – choose wisely!
3. Feel free to add to the block diagram if you feel like something is missing.

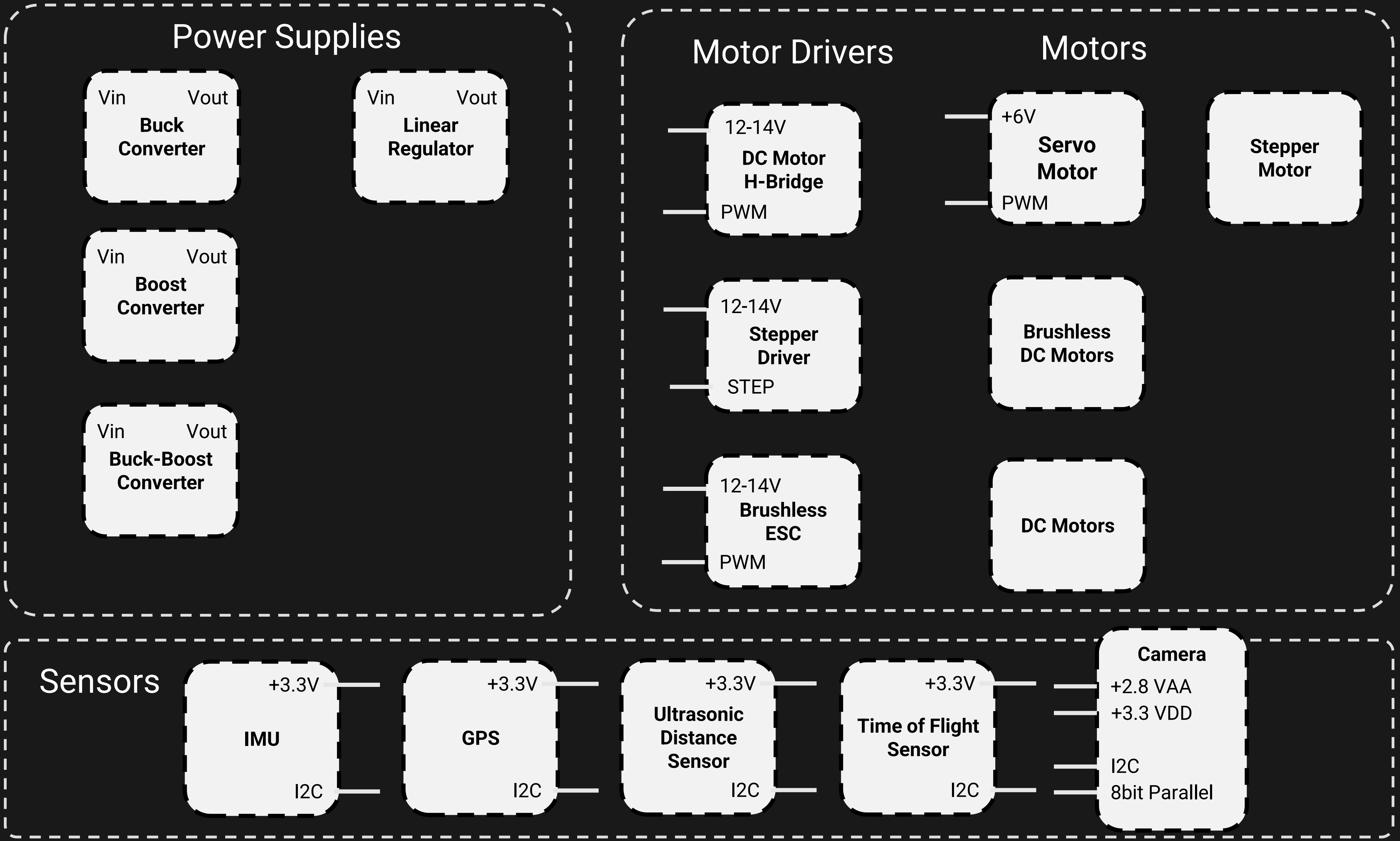
Random block diagram I found online



Quadcopter Design Game



Quadcopter Game Blocks

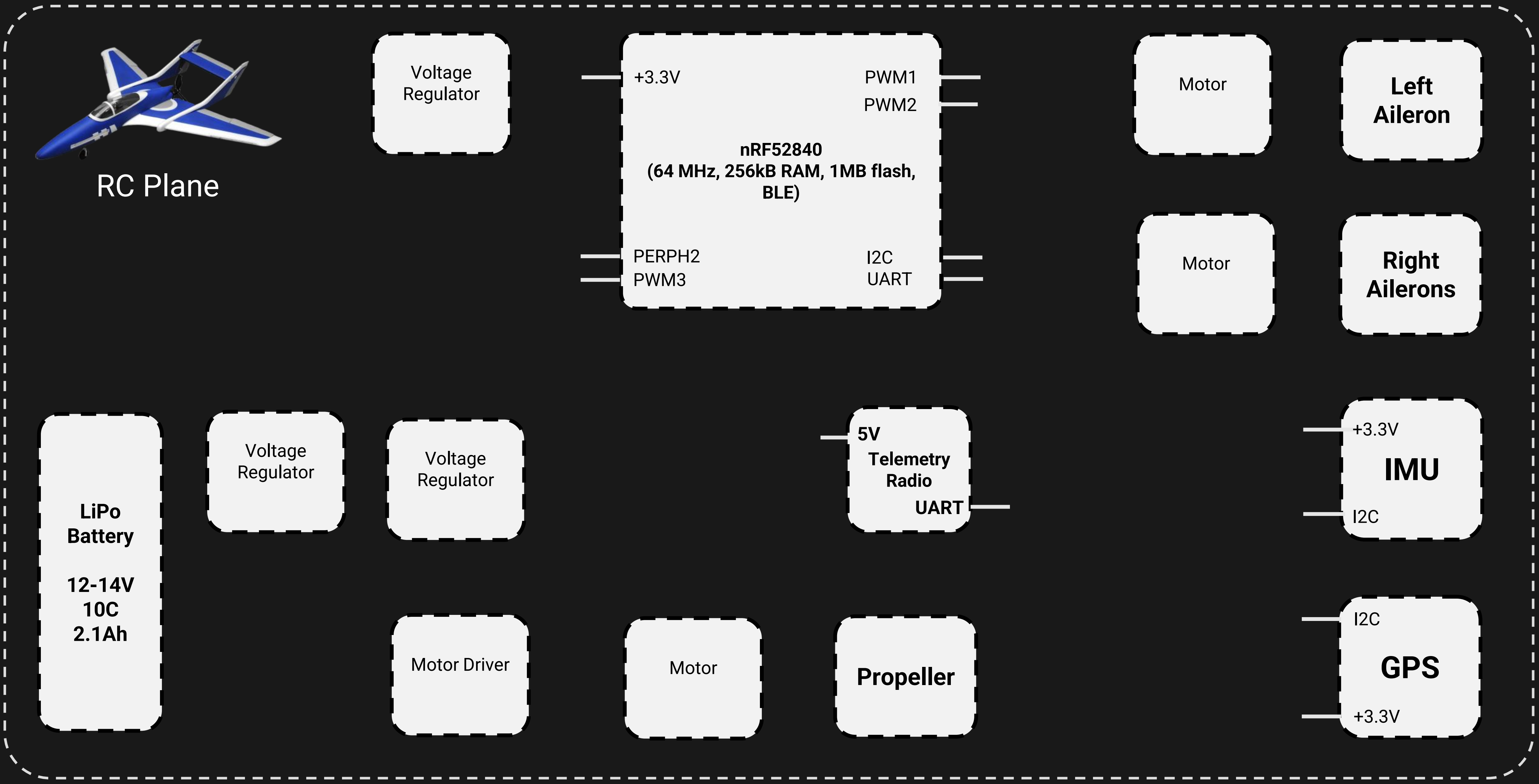


Fixed Wing Aircraft Design Game

Fixed Wing Aircraft Design: You were recently hired to design a fixed wing aircraft system after the previous engineer decided to quit mid way through. Currently the battery, microcontroller and sensors have been selected, but you are in charge of designing the power regulation, motor drivers and motor subsystems. The goals of this design is to

1) maximize energy efficiency
2) minimize noise to sensors and radio subsystems
3) provide good speed and accuracy for turning control
4) Allow for high-speed flight

Fixed Wing System Design Game



Fixed Wing Game Blocks