MICRO-502_Aerial_Robotics_Notes

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> *Lecture notes by Yujie He*
>
> *Last updated on 2021/05/02*

🚧 Intro (week1)

🚧 Multicopters (week1)

🚧 Attitude representations (week2)

🚧 Control (week2&3)

🚧 State Estimation (week3&4)

🚧 Navigation Methods (week5)

🚧 Perception (week5)

🚧 Fixed-wing drones (week6)

Aerial Swarms (week7)

Intro

- Drone light shows

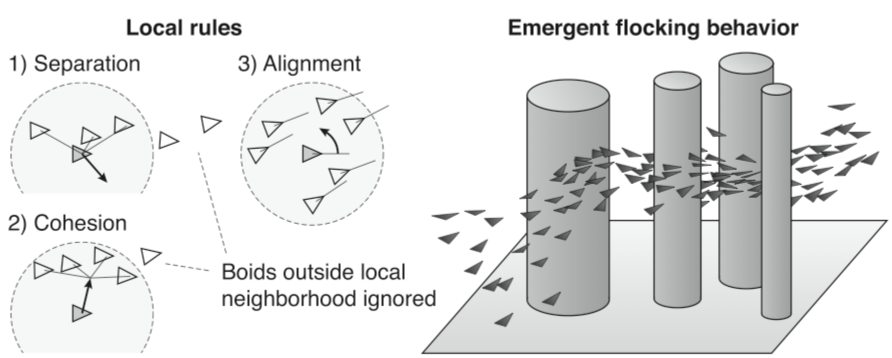
  Centralized = agents transmit individual position to ground computer and receive next location

- Collective Motion in nature

  Decentralized = agents rely on **local information and computation**

Reynolds flocking algorithm (Reynolds, 1987)

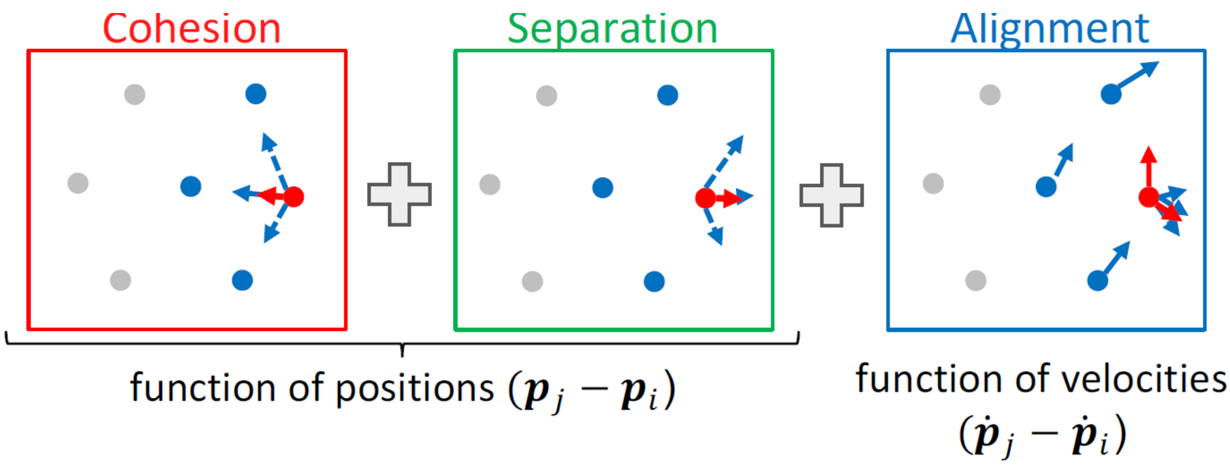
- radius of communication or neighborhood R



- **Separation**: avoid collision

- **Cohesion**: attempt to keep close
- **Alignment**: attempt to match velocity

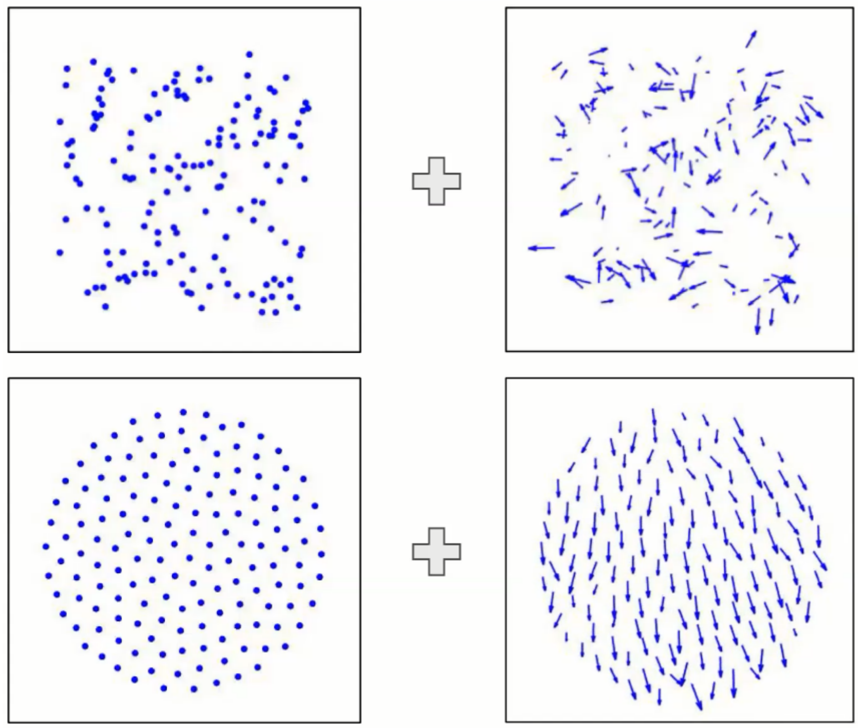
Reynolds flocking: model



- Equations

  week9_swarm_reynolds_equ

  - Set of agents in neighborhood N
  - identity of i-th agent
  - position $\mathbf{p}_i$
  - velocity $\dot{\mathbf{p}}_i$
  - acceleration $\ddot{\mathbf{p}}_i$ = control command
  - acceleration term due to the cohesion/separation/alignment $\mathbf{a}_{coh,i}$, $\mathbf{a}_{sep,i}$, and $\mathbf{a}_{align,i}$
  - constant gains corresponding to the cohesion/separation/alignment C_c, C_s, and C_a
- Equilibrium

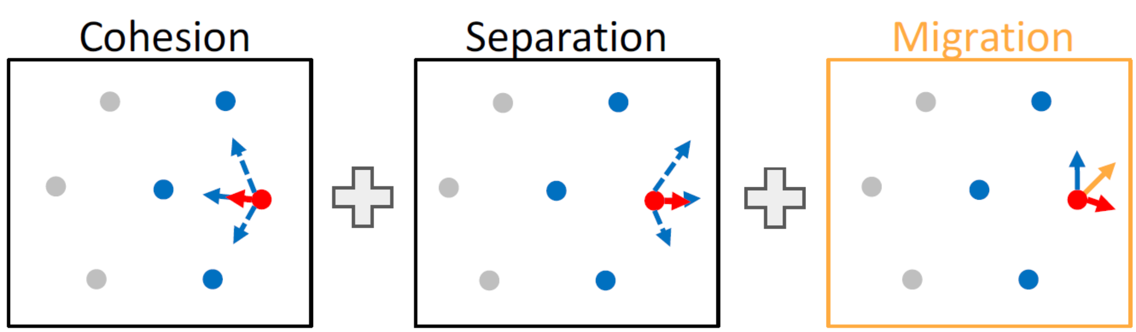


- Positions **converge** to a lattice formation (晶格式)
- Velocities **converge** to the average of initial velocities

$\lim_{t\to\infty} \dot{\boldsymbol{p}}_i = \frac{\sum_{i\in\{1,2,...N\}} \dot{\boldsymbol{p}}_i(0)}{N}$

Reynolds flocking with migration

- new **migration rule** steers the swarm towards a desired direction
  - **replaces** the **alignment rule**
  - **cohesion and separation rules are kept** to regulate the agents distances



- Equation

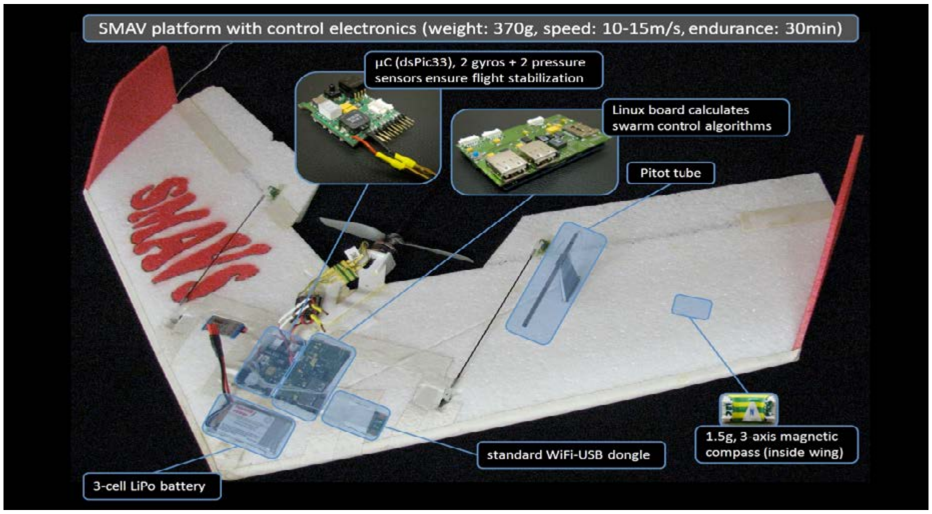
$\ddot{\mathbf{p}}_i = \mathbf{u}_i, \mathbf{u}_i = c_c \frac{\sum_{j\in N_i}(\mathbf{p}_j - \mathbf{p}_i)}{|N_i|} - c_s \frac{\sum_{j\in N_i} \frac{\mathbf{p}_j - p_i}{\|p_j - p_i\|^2}}{|N_i|} + c_m \frac{\mathbf{v}_{mig} - \dot{\mathbf{p}}_i}{1}$

$\forall i \in \{1, 2, \ldots, N\}$

  - parameters
    - migration velocity $\mathbf{v}_{mig}$

- Denominator = 1 since **neighbors are not relevant for migration**

Case: Aerial swarms for disaster mitigation



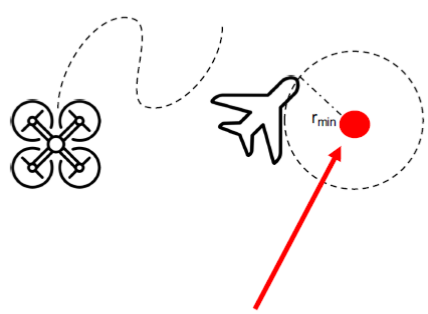
SMAV platform with control electronics

Communication radius and turning angle

- large communication radius -> can make sharp turn together because of knowing the position of other robots
- smaller communication radius -> may separate and gather into a flocking often

Virtual agents for flocking with fixed-wing drones

- Winged drone flies around Virtual Agent which moves according to Reynolds rules



- Varga et al., Distributed Formation Control of Fixed Wing Micro Aerial Vehicles for Uniform Area Coverage, IROS 2015

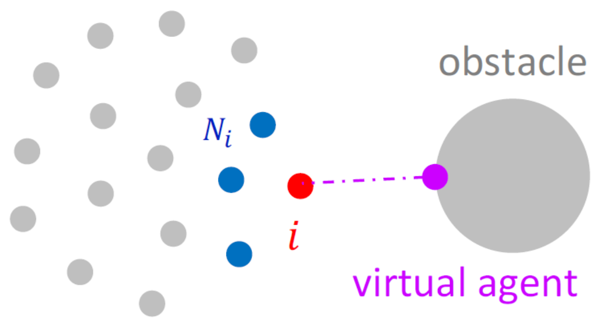
  video: https://youtu.be/FYsd2VckGA0

Reynolds flocking with obstacles (Virtual agents)

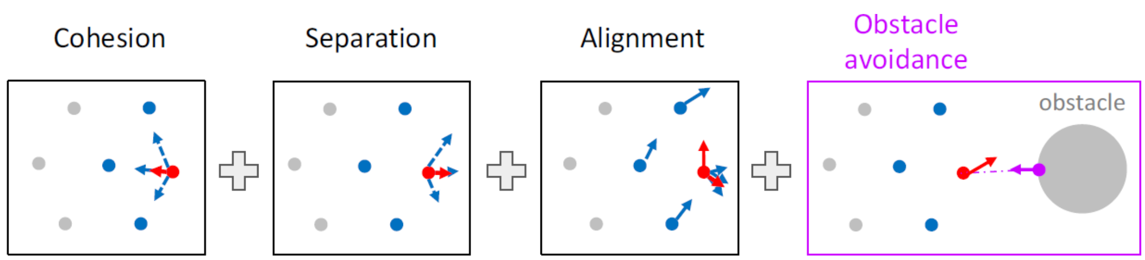
- Obstacles are modelled as **virtual agents**
  - Its **position** is the obstacle's **closest point** to the agent
  - Its **velocity** is **perpendicular to the tangent** to the obstacle

  $(\mathbf{p}_k, \dot{\mathbf{p}}_k)$ position and velocity of the virtual agent

- Virtual agents exert **separation** and **alignment** effects, but not **cohesion** (not collide with the agent)



- Visualization



- Equation (two extra separation and alignment term regarding obstacles)

$$\ddot{\mathbf{p}}_i = \mathbf{u}_i$$

$$\mathbf{u}_i = c_c \frac{\sum_{j\in N_i}(\mathbf{p}_j - \mathbf{p}_i)}{|N_i|} - c_s \frac{\sum_{j\in N_i} \frac{\mathbf{p}_j - p_i}{\|p_j - p_i\|^2}}{|N_i|} + c_a \frac{\mathbf{v}_{mig} - \dot{\mathbf{p}}_i}{1} - \left[c_s \frac{\mathbf{p}_k - \mathbf{p}_i}{\|\mathbf{p}_k - \mathbf{p}_i\|^2} + c_a(\dot{\mathbf{p}}_k - \dot{\mathbf{p}}_i) \right]$$

$$\forall i \in \{1, 2, \ldots, N\}$$

Other models

Vicsek model: particles in confined environments (密闭环境)

> *Vasarhelyi et al., Optimized flocking of autonomous drones in confined environments, Science Robotics, 2019*

> *DOI: http://doi.org/10.1126/scirobotics.aat3536*
>
> *Video: https://youtu.be/E4XpyG4eMKE*
>
> *Project web: http://hal.elte.hu/drones/scirob2018.html*

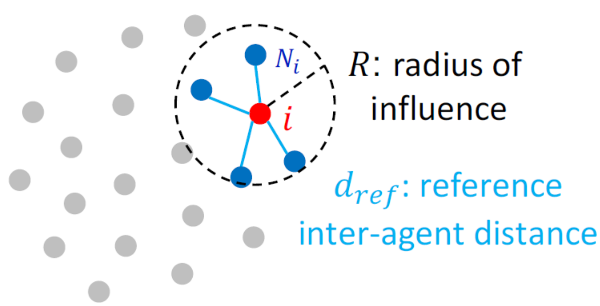
- Rules
  - **Separation**
  - **Self propulsion**: Makes the agent match a preferred speed
  - **Friction**: **Viscosity** (internal friction) for alignment and oscillation **damping**
- Equation

  $$\begin{cases} \dot{\boldsymbol{p}}_i = \boldsymbol{u}_i \\ \boldsymbol{u}_i = \boldsymbol{v}_{sep,i} + \boldsymbol{v}_{spp,i} + \boldsymbol{v}_{\text{fric}\ ,i} \end{cases}$$

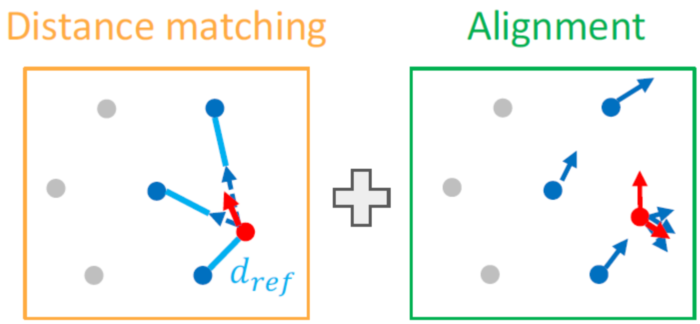
- The full equation contains 12 parameters and **requires heuristic methods for optimization**

Olfati-Saber model

> *R. Olfati-Saber, Flocking for multi-agent dynamic systems: algorithms and theory, IEEE Transactions on Automatic Control, 2006*



- Rules
  - Distance matching
    - Makes the agents **match a desired inter-agent distance**
    - **Replaces cohesion and separation** rules of Reynolds model
    - Mathematically defined as a potential function
  - Alignment: attempt to match the velocity and direction



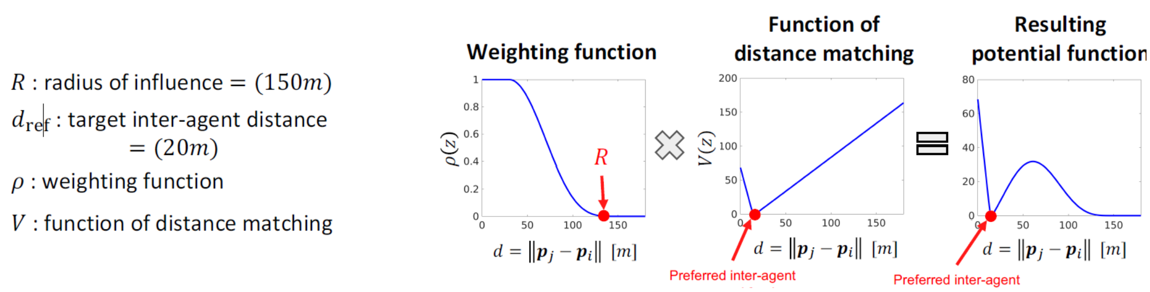
- Equation

  $\ddot{\mathbf{p}}_i = \mathbf{u}_i$

  $\mathbf{u}_i = c_d \frac{\sum_{j \in N_i} \nabla(\rho(\mathbf{p}_j - \mathbf{p}_i) V(\|\mathbf{p}_j - \mathbf{p}_i\|))}{|N_i|} - c_a \frac{\sum_{j \in N_i} (\dot{\mathbf{p}}_j - \dot{\mathbf{p}}_i)}{|N_i|}$

  $\forall i \in \{1, 2, \ldots, N\}$

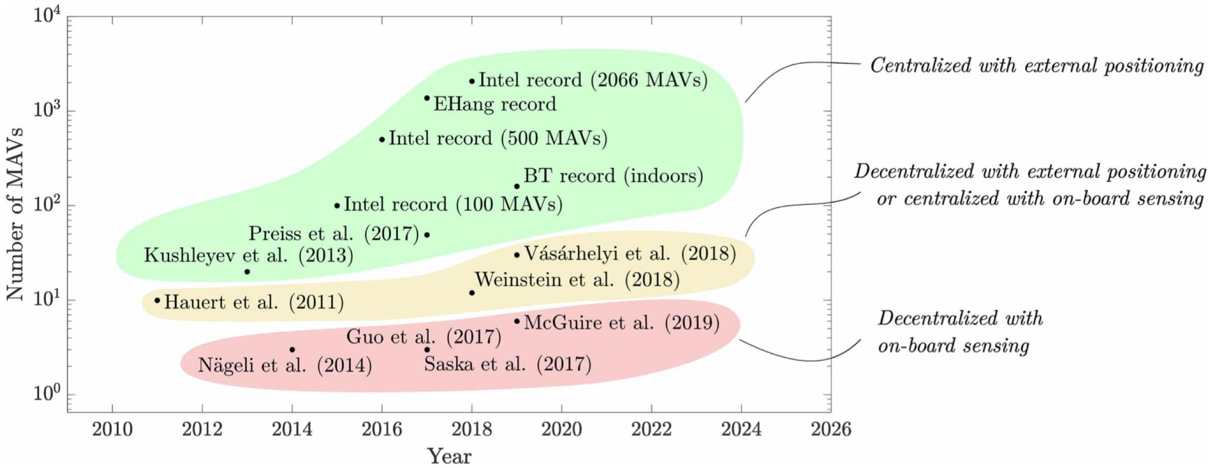
  - radius of influence R
  - desired inter-agent distance d_{ref}
  - weighting function ρ
  - distance matching function V
  - gradient, derivative in three dimensions $\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)$
- **distance matching example**
  - Components
    - **weighting** function 越近影响越大
    - **distance matching** function 越靠近d_{ref}越小，线性
    - Result: **potential function**



  - Note
    - Principle of minimum potential: **minimum** defines the stable equilibrium of the system
    - d_{ref} is a stable equilibrium
    - The force acting on an agent is zero in the minimum of the potential. For $d = d_{ref}$, it holds $\nabla(\rho V) = \mathbf{0}$

Drone Swarms

> *Coppola et al., A Survey on Swarming With Micro Air Vehicles: Fundamental Challenges and Constraints, Front. Robot. AI, '20*



The combination of centralized planning/control with external positioning has **allowed to fly significantly larger swarms**. The **numbers are lower** for the **works featuring decentralized control with external positioning**, or centralized control with local sensing

Three categories

1. Centralized with external positioning

    > *latest: September 20 2020*
    >
    > *3,051 drones*
    >
    > *News: https://www.guinnessworldrecords.com/news/2020/10/3051-drones-create-spectacular-record-breaking-light-show-in-china (Company: https://www.dmduav.com/)*
    >
    > *YouTube: https://youtu.be/44KvHwRHb3A*
    >
    > *Bilibili: https://www.bilibili.com/video/BV1jt4y1q762*

2. Decentralized with external positioning or centralized with on-board sensing

    Vasarhelyi et al. (2019)

3. Decentralized with on-board sensing

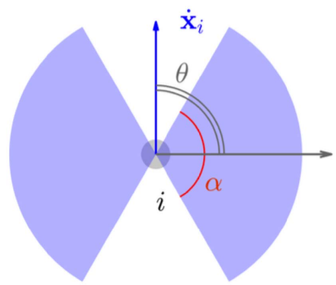
    Saska et al. (2017)

Visual information in flocking

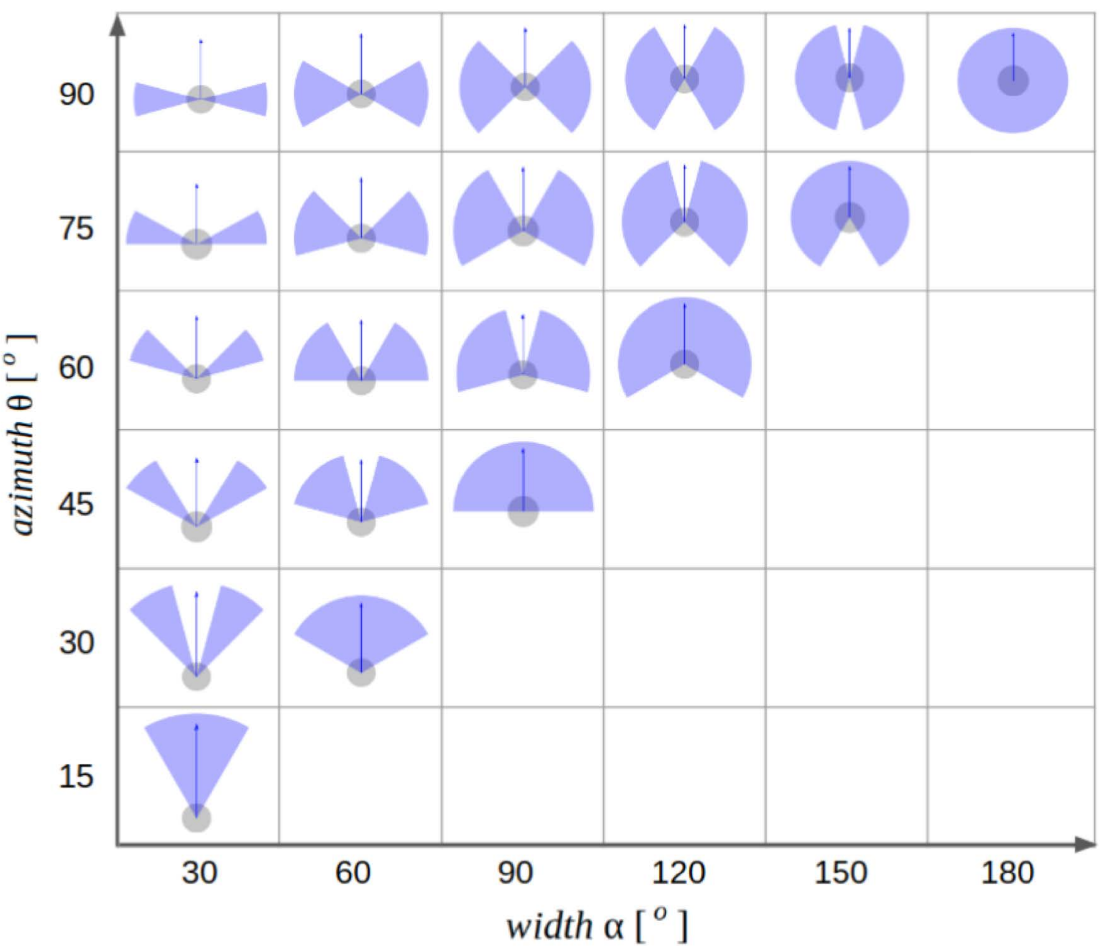
Soria2019IRC-influence of limited visual sensing using Reynolds

> *Soria et al., The influence of limited visual sensing on the Reynolds flocking algorithm, 2019*

- generate flocks with different fields of view

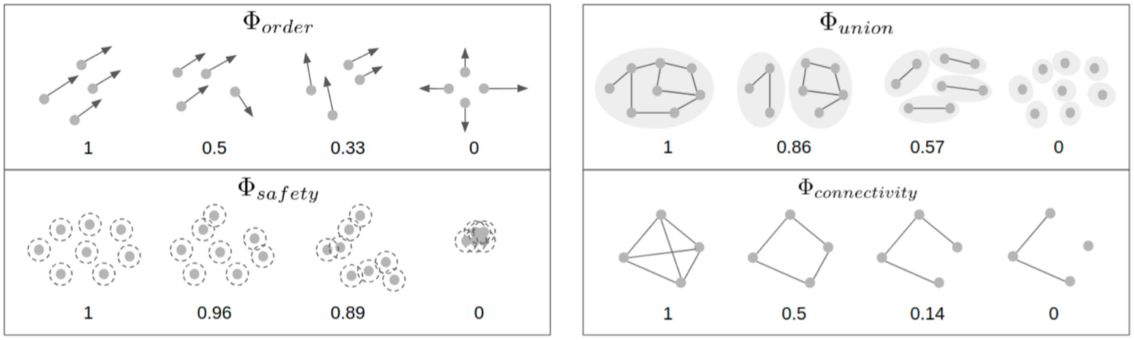


  - azimuth/方位角 $\theta[°]$
  - width $\alpha[°]$

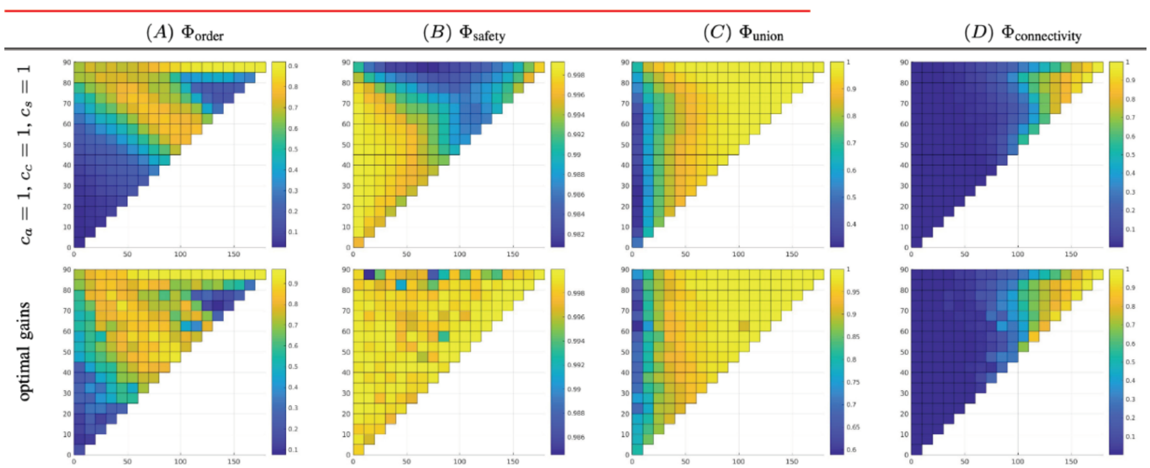


- measure flocking performance (all individuals in the flock have the same visual configuration)
  - **Order**: measure of alignment

- **Safety**: ability to avoid collisions
- **Union**: ability to stay informed on neighbors
- **Connectivity**: ability to broadcast messages among drones



- results

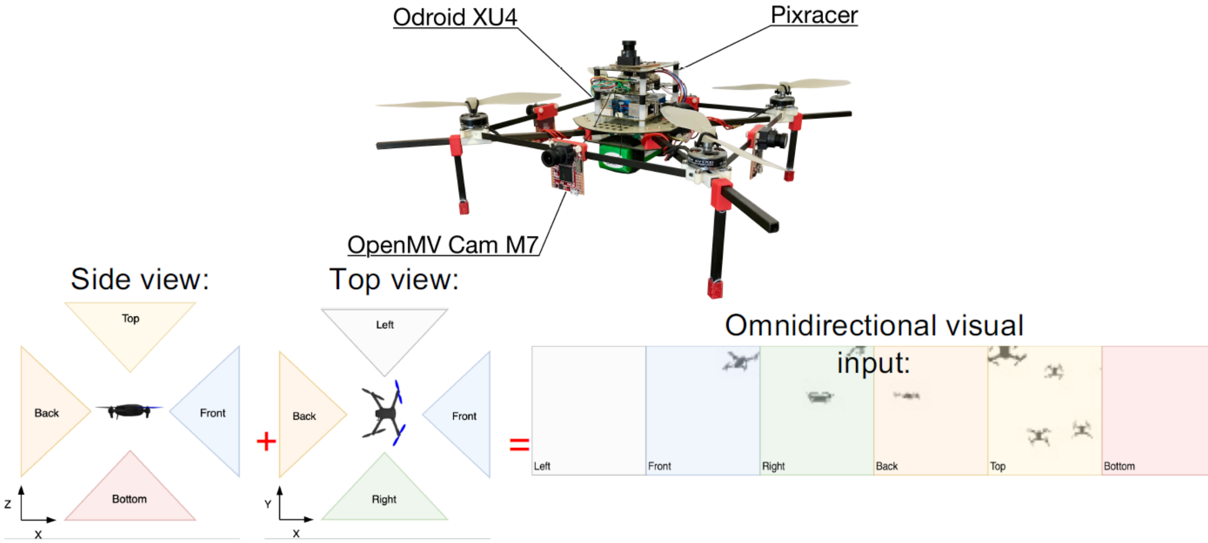


  - focus on order and safety (alignment and collision prevention capability)
  - largest azimuth and FoV has best performance
  - increase in either azimuth or FoV only will degrade the performance
  - safety can be achieved even with lower FoV

Schilling2019RAL-Learning to flock in simulation with vision

> *Schilling et al., Learning Vision-Based Flight in Drone Swarms by Imitation, RAL2019*

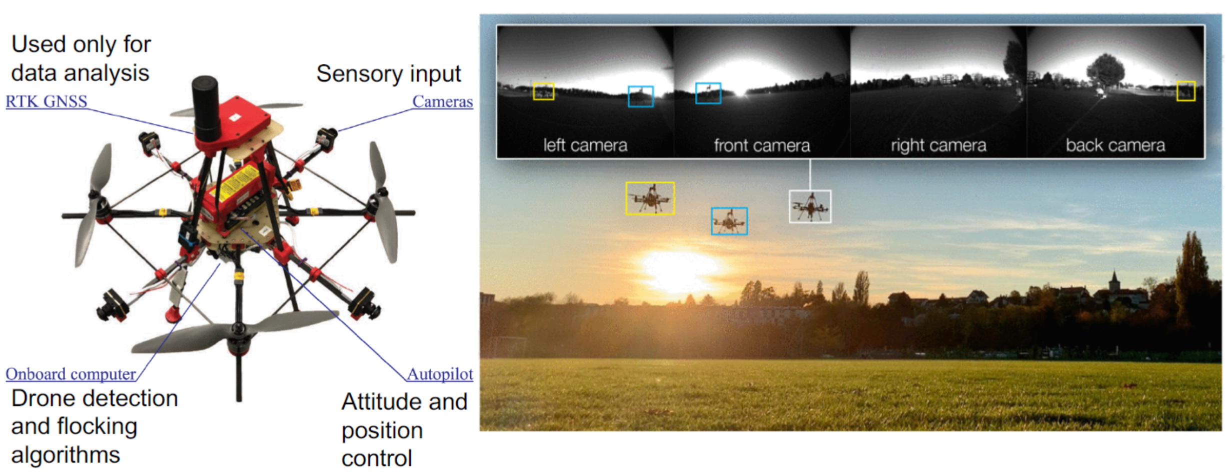
- use 6 cameras in each side
- training on a dataset to generate the velocity vector for the drone



- Stages
  - Dataset generation: Flocking algorithm as ground truth
  - Training phase: Learn **mapping between vision and control output**
  - Vision-based control: **Neural controller for collision-free and cohesive flight**
- Note
  - work well in simulation indoor environment
  - it can be robust when individuals has different migration points
  - cannot generalize well in background clutter and different lighting condition

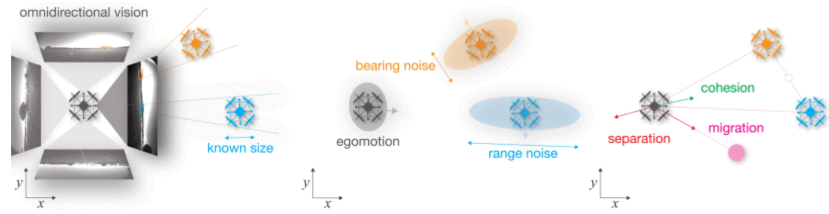
Schilling2021RAL-Learning to flock outdoor with vision

> *Schilling et al., Vision-Based Drone Flocking in Outdoor Environments, RAL2021*



- Setup
  - Drone with only with 4 cameras in four side
  - RTK GNSS is used to compute performance
  - train YOLOv3 tiny to recognize other drones using YOLO

- Control method



(a) Real-time drone detection (b) Multi-agent state tracking (c) Potential-field-based control

1. Real-time drone detection

   - Input: images from 4 cameras

   - Output: x,y coordinates of perceived drones in image frame coordinates

     known size to compute corresponding distance

2. Multi-agent state tracking

   - Input: Locations of drones & noise models
   - Output: **Range and bearing** of all perceived drones with **noise**

3. Potential-field-based control

   - Input: Range and bearing of all perceived drones
   - Output: **velocity vector** resulting from Reynolds algorithm

Check points

- What information does each agent receive in the Reynolds flocking algorithm?

  🚧 position and velocity of self and neighbor agents

- How are obstacles modeled in Reynold's flocking

  visual agent; integrate into equations with alignment and separation term

- How is a migration point incorporated in flocking algorithms

  🚧 add a velocity term?

- What does the Olfati-Saber algorithm ensure?

  distance matching with potent ion function

- What are the three steps of vision-based drone flocking algorithm?

  1. Real-time drone detection
  2. Multi-agent state tracking
  3. Potential-field-based control

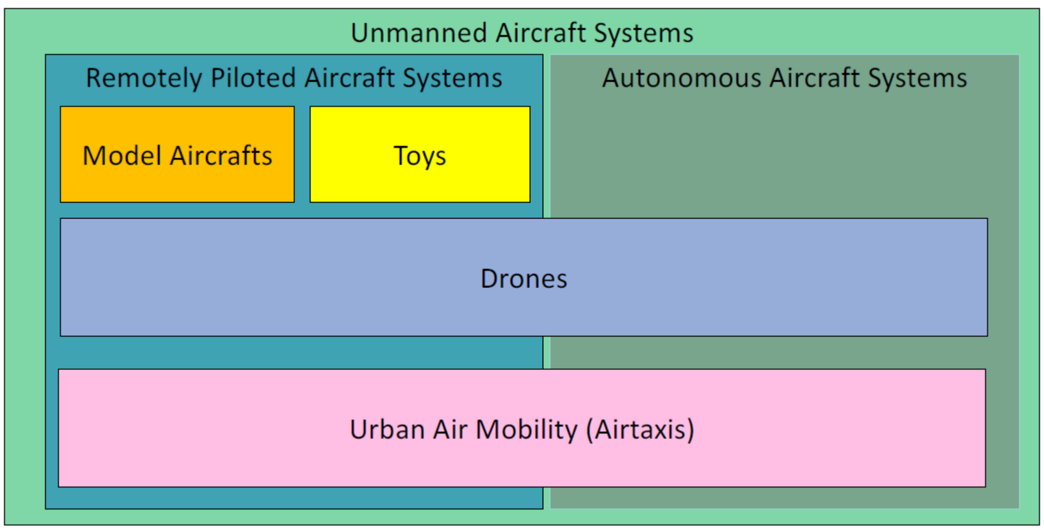
  images from 4 cameras -> x,y coordinates of perceived drones in images -> Range and bearing of all perceived drones -> velocity vector

🚧 Flapping-Wing (week8)

Drone Regulations (week8)

> *Author: Markus Farner*
>
> *https://www.bazl.admin.ch/bazl/en/home/good-to-know/drohnen.html*

- Unmanned Aircraft Systems (UAS) >= Drones; UAS = Remotely piolted aircraft systems / autonomous aircraft systems



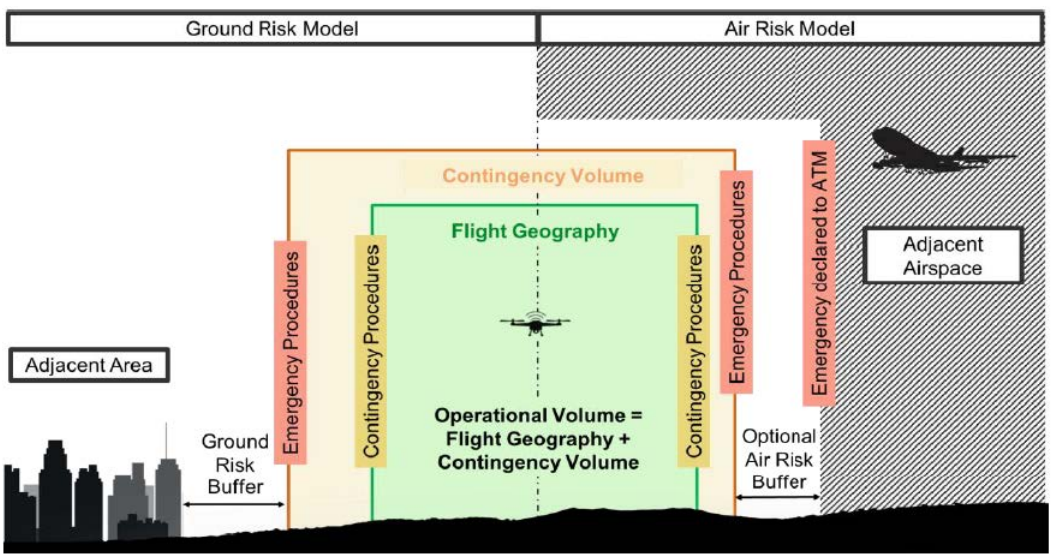
- Rules in Aviation: Federal Office of Civil Aviation Switzerland
- Everything which is not forbidden is allowed -> Switzerland

  Trust, less difficult for innovation
- 3 Pillar Concept / Drone Categories
  1. Open-Within the legal framework (No Authorization required)
  2. Specific-Not sufficiently safe (Authorization required)
  3. Certified-Approved to accepted standards
- Act
  - **Ordinance on Special Category Aircraft**
    - No authorization required for commercial flights
    - No distinction between Unmanned Aircraft and Model Aircraft
  - **DETEC Ordinance on Special Category Aircraft**

        - No authorization below **30kg**
        - Within direct visual contact (VLOS)
        - Not within a distance <=100m around crowds
    - **ANSP (Skyguide) or Airport responsibility**
        - > **5km** Distance to civil & military airports/aerodromes
        - < **150m** AGL (Above Ground Level) within a CTR
- Act in EU
    - Open/Specific/Certified
    - Difference
        - restrictions: MTOM **25kg**
        - maximum flying altitude: **120m**
- Specific Category

> *Application for an operating permit on the basis of the* ***SORA (Specific Operations Risk Assessment)***

Operational Volume = Flight Geography + Contingency Volume



- ❓ Robustness Levels: Integrity + Assurance
- U-Space

> *The U-space is a collection of decentralized services that collectively aim to safely and efficiently integrate drones into the airspace and enable drone operations alongside manned flight.*
>
> *https://www.bazl.admin.ch/bazl/en/home/good-to-know/drohnen/wichtigsten-regeln/uspace.html.html*
>
> *https://www.skyguide.ch/en/events-media-board/u-space-live-demonstration/*

airspace in block to avoid collision and report the location for further path calculation

UAS Hardware (week9)

Introduction

> *main component required*

1. The aerial vehicle
    - Air frame
    - Actuators for propulsion and control
    - Energy source
    - Autopilot
        - Sensors for attitude estimation
        - Electronics for regulation, control and communication
        - Sensor and avoid system
2. Payload
    - Cameras
    - Environmental sensors (wind, temperature, humidity)
    - Robotic arms for manipulation
3. Ground Control Station
    - Communication systems
    - Interface to monitor internal parameters and to send commands to the vehicle

Frame and materials

materials comparison

Material	Composite	ABS/PLA	Wood	Foam
Pros	Stiff, lightweight	Easy to manufacture by 3D printing or injection molding	Lightweight and cheap	Lightweight and soft, resistance to collision

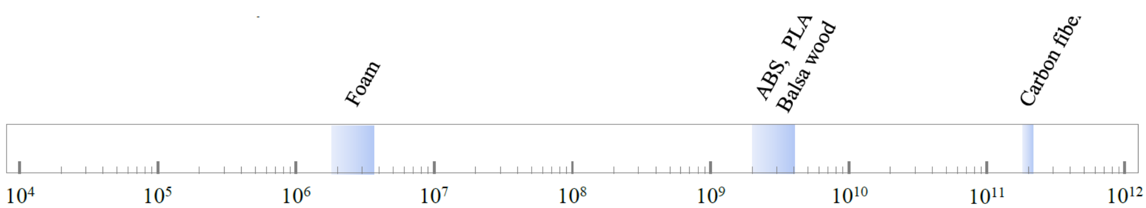
Material	Composite	ABS/PLA	Wood	Foam
Cons	Expensive, complex to manufacture	Heavier, less stiff	complex to work with	limited load
Comment	-	useful for prototyping	-	absorb energy, less prone to damage

metric when considering materials

- Young's modulus [wiki]

  弹性模量，正向应力与正向应变的比值

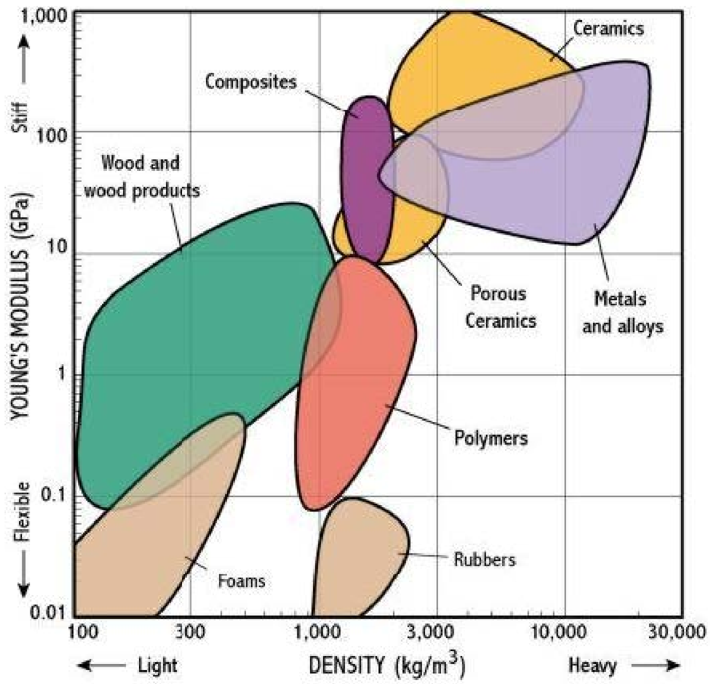
  - measure of **stiffness**
  - defines the relationship between stress and strain
  - Foam < ABS/PLA/Wood < Carbon fiber



- Specific modulus [wiki]

  比模量，单位密度的弹性模量，劲度 - 质量比，在航天工业中有广泛应用。

  - elastic modulus per mass density of a material
  - stiffness to weight ratio
  - **High specific modulus materials** find wide application in UAVs where **minimum structural weight** is required.



Energy sources

> *Goal: power the robots to fly*
>
> *Metric: energy density, power density, charging time and so on*

Category

- Nickel-Cadmium (NiCd) | 镍镉
  - Mature and cheap
  - Low energy and power density -> short flight time
- Nickel-Metal Hydrate (NiMh) | 镍氢电池

  > 由镍镉电池（*NiCd battery*）改良而来的，其以能吸收氢的金属代替镉（*Cd*）。它以相同的价格提供比镍镉电池更高的电容量、较不明显的记忆效应、以及较低的环境污染（不含有毒的镉）
  >
  > *[wiki-zh]*

  - Higher energy density than NiCd
- Lithium-Polymer (Li-Po) | 锂离子聚合物电池
  - rapidly growing market and performance
  - Higher energy and power density compared to NiCd
  - Regular geometry for easy integration, e.g., cuboid or cuboid

- Fuel
    - **Highest energy and power density**
    - **complex and higher weight**-requires tank, distribution system and maintenance
- Fuel cell
    - Electrochemical reaction of hydrogen fuel with oxygen

Energy and power density

- energy density

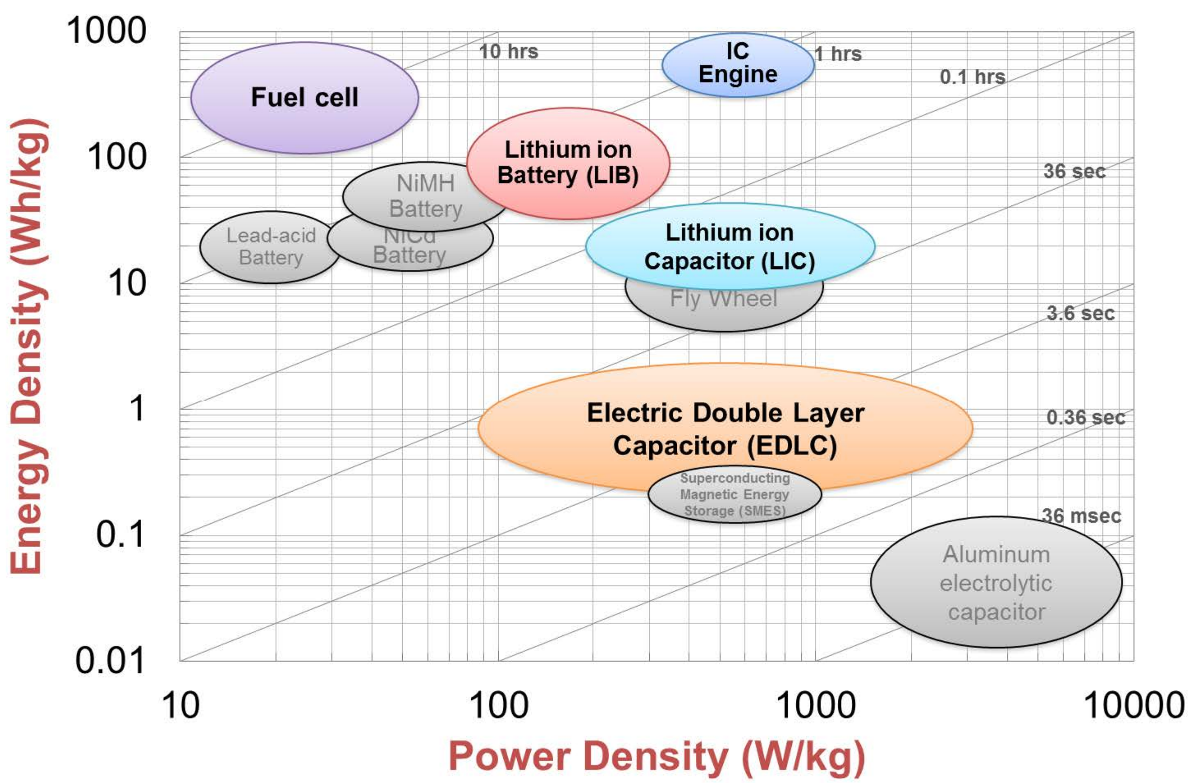
  amount of energy stored per unit volume or mass

- power density

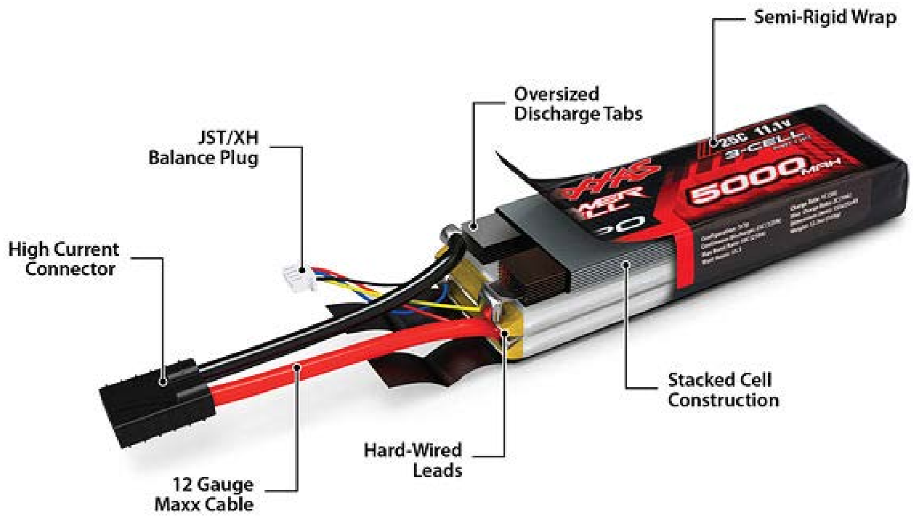
  > *how fast or quickly to discharge into mechanics*

  amount of power (time rate of energy) per unit volume or mass

- Conclusion
    - Fuel has **highest energy and power density**
    - Fuel cell has highest energy but lower power density
    - LiB has higher energy and power density than NiMH and NiCd



Li-Po batteries



- most commonly-used UAV energy source
- Each **battery** composed of one or more **cells** connected in series

  S=series, P=Parallel

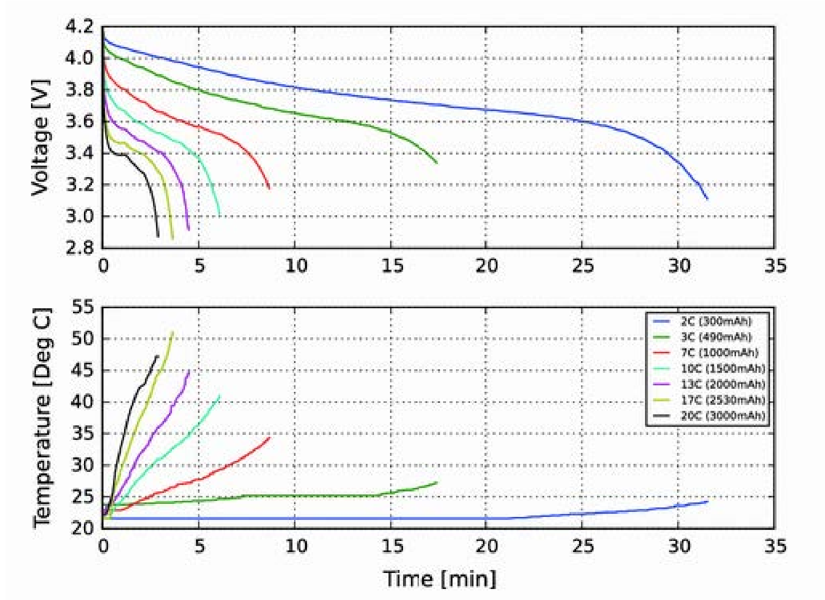
- Each cell has
  - nominal voltage of 3.7 V
  - a maximum voltage of 4.2 V
  - a capacity (mAh)

    e.g., 1000 mAh

  - a specific discharge and charge rate (C)

    e.g., Discharge rate with 25-50C = 25-50 A of max continuous discharge current; Charge rate 2C = 2 A

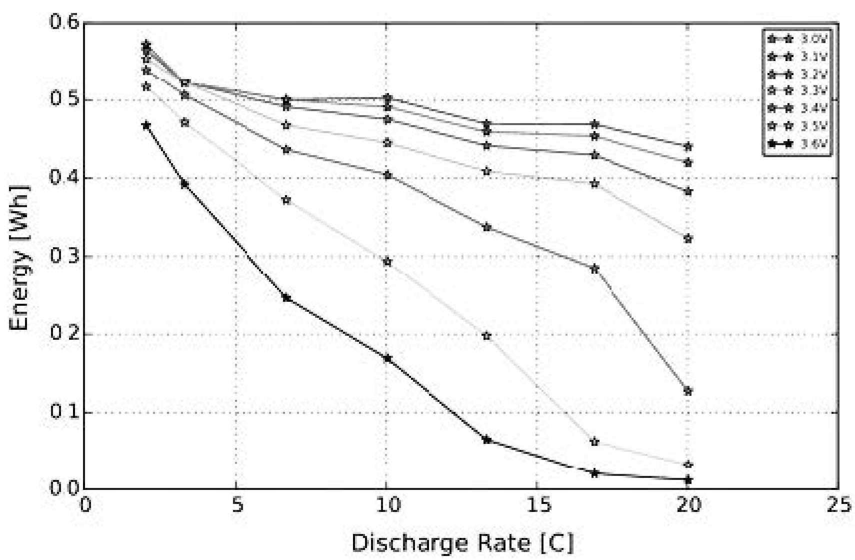
Discharge Curves of Li-Po battery



- not linear of time
- the discharge curve is determined by **the amount of current (expressed in "C")** drawn from the battery.
- higher discharge rates -> faster rising temperature -> poses overheating risks.

> ***Book**: G. C. H. E. Decroon, M. Perçin, B. D. W. Remes, R. Ruijsink, and C. De Wagter, The delfly: Design, aerodynamics, and artificial intelligence of a flapping wing robot. 2015.*

Energy Curve of Li-Po battery



- How much energy the same LiPo battery can provide until its voltage drops below a certain voltage
- 10 times higher battery load (discharge rate) -> 17 times shorter flight time

  nonlinear relationship

Actuators

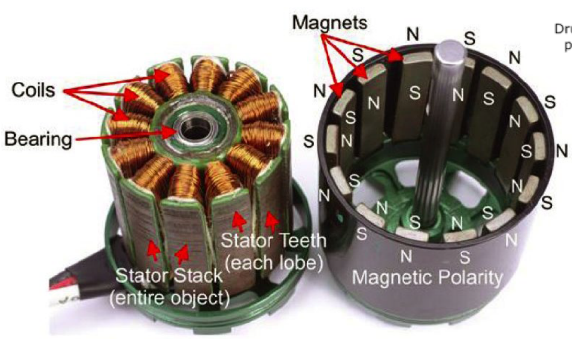
Actuators for propulsion

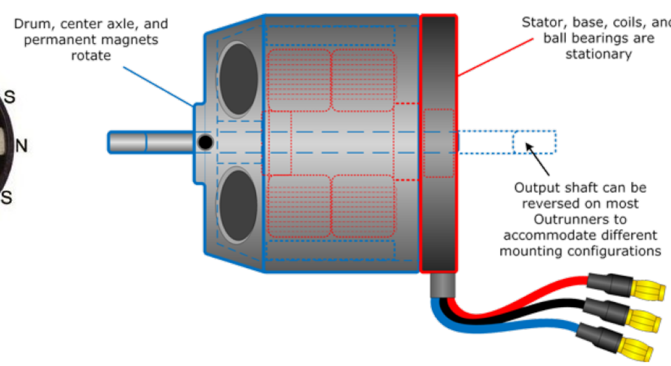
	Electric motors	Combustion engine	Hybrid[2]
Pros	clean and quite; Reliable and easy to maintain; Fast to change operational state (accelerate and decelerate)	High weight to power ratio using fuel	Long endurance; Suited for fast change of speed
Cons	Limited weight to power ratio due to battery	Vibration, dirt, and noise; Requires tuning; Not suited for fast change of speed[1]	Complex and expensive

1. Combustion engine is not suited for fast change of speed (problem in controlling quadcopters)
2. Hybrid systems (fuel generator coupled with electric motor)

   e.g. skyfront drone with 4.5 hour endurance (demonstrated) and 3 kg payload capacity

Electric motor example-Brushless DC electric motors





- Brushless: no electrical physical connection
- Pros
  - High efficiency and high torque/power density
  - High speed range
  - Large range of thrust (from 10^{-2} to 10^{2} N)
- Cons
  - manufacturing complexity -> expensive

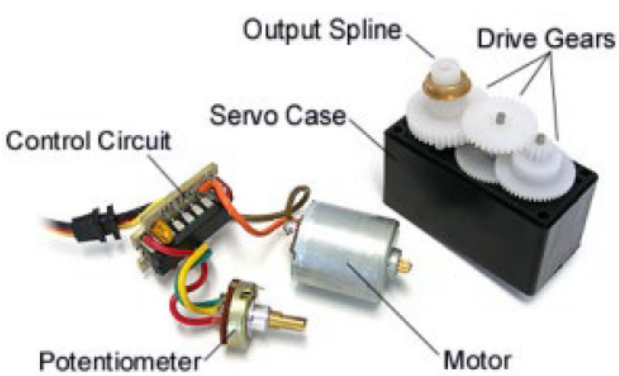
- Control is complex and expensive requiring and **electronic speed controller (ESC, 电控)**
- Main motor data
    - 3 primary data:
        - Size
        - **Nominal** voltage (number of battery cells, e.g., 3S)
        - Speed constant KV (No load rpm/Volt)
            - High KV -> high speed and low torque
            - Low KV -> low speed and high torque

Actuators for control/maneuvering

Servomotors

> *need to deflect the control surfaces*

- rotary or linear actuators



- 3 wires (B-Ground, R-Voltage, Y-Signal) - send power and signal

Propellers

Sensors

Autopilots

Communication protocols