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

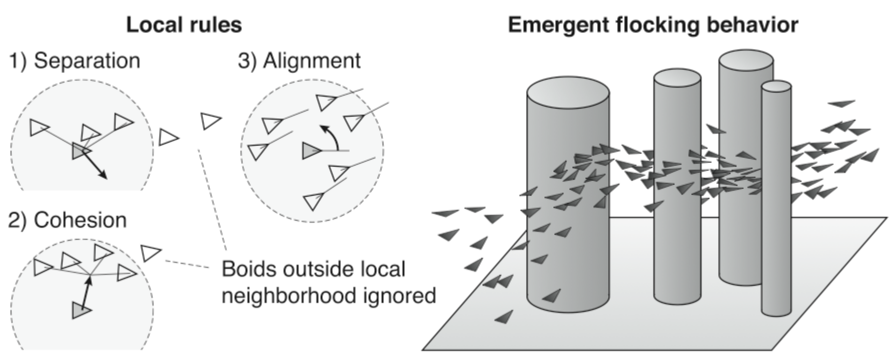
  Centralized = agents transmit individual position to ground computer and receive next location

- Collective Motion in nature

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

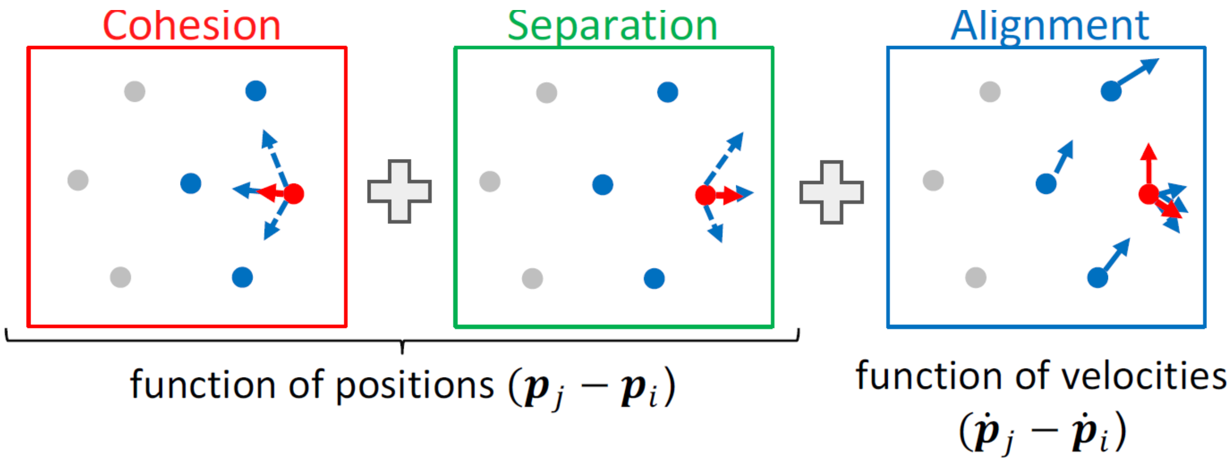
Reynolds flocking algorithm (Reynolds, 1987)

- radius of communication or neighborhood R



- **Separation**: avoid collision
- **Cohesion**: attempt to keep close
- **Alignment**: attempt to match velocity

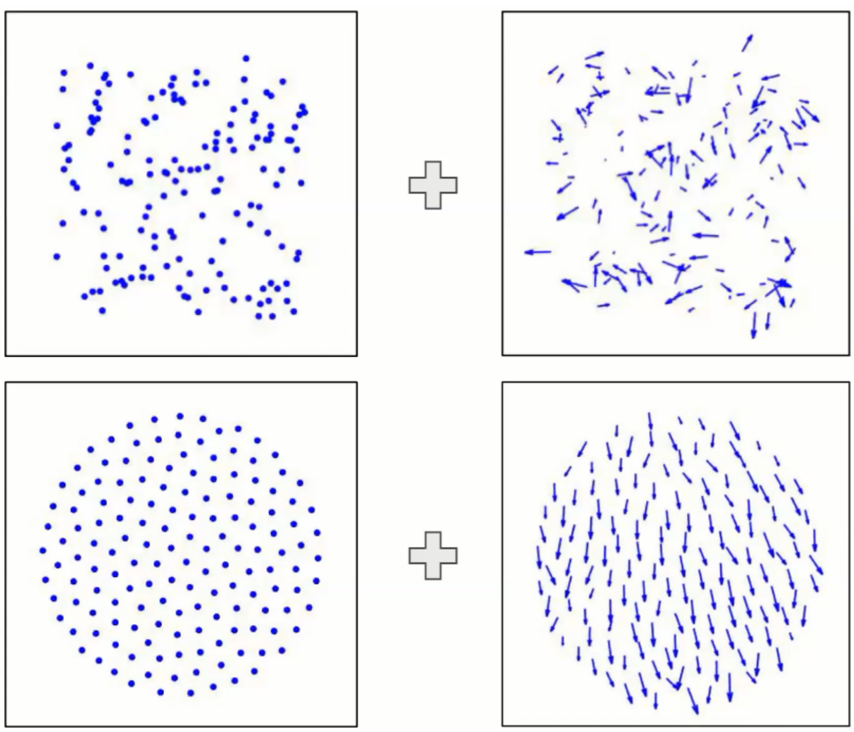
Reynolds flocking: model



- 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

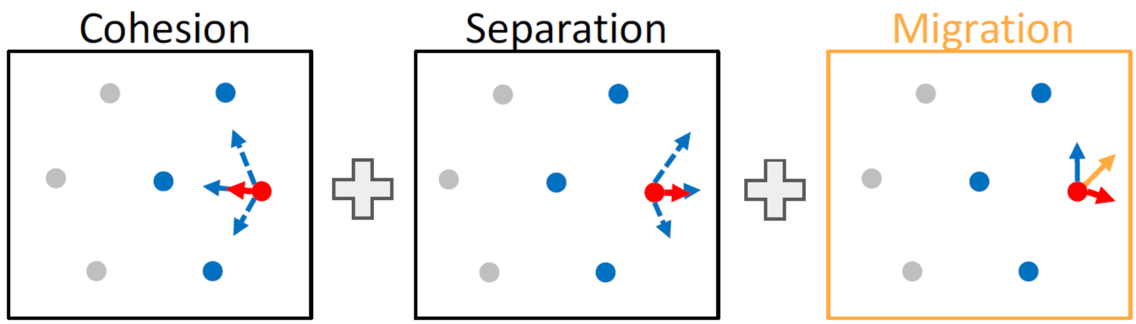


  - Positions **converge** to a lattice formation (晶格式)
  - Velocities **converge** to the average of initial velocities

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

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



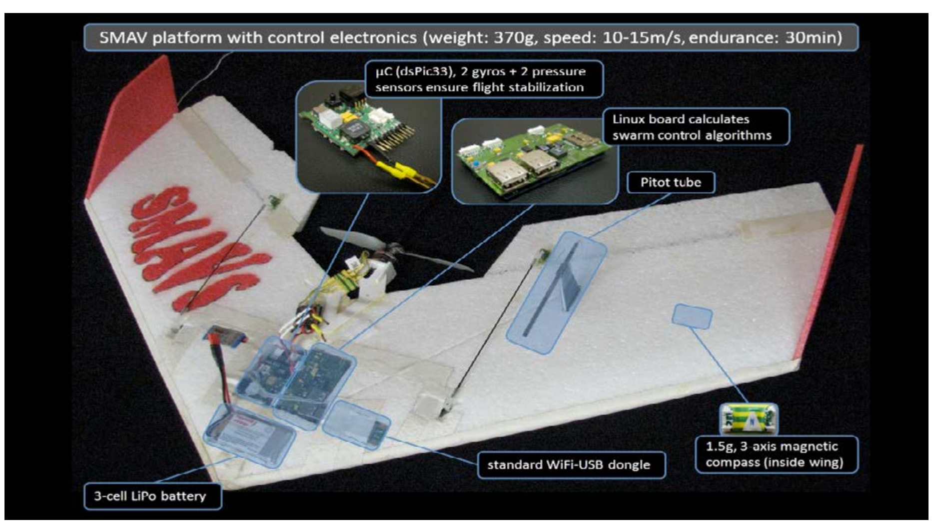
- Equation

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

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

- parameters
    - migration velocity $\mathbf{v}_{mig}$
    - Denominator = 1 since **neighbors are not relevant for migration**

Case: Aerial swarms for disaster mitigation



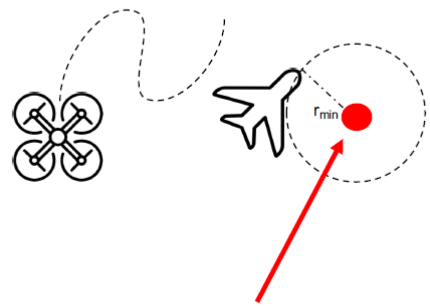
SMAV platform with control electronics

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

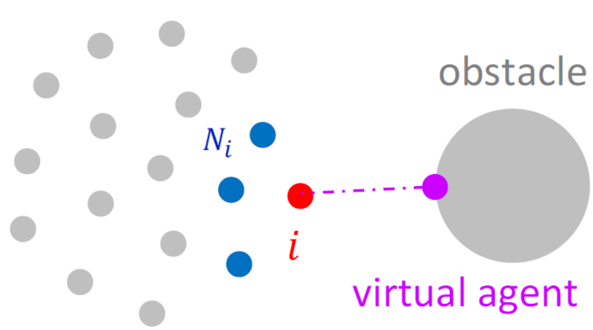
  video: https://youtu.be/FYsd2VckGA0

Reynolds flocking with obstacles (Virtual agents)

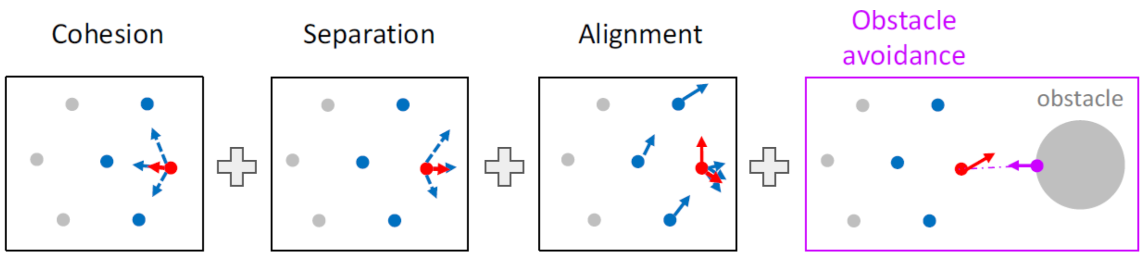
- Obstacles are modelled as **virtual agents**
  - Its **position** is the obstacle's **closest point** to the agent
  - Its **velocity** is **perpendicular to the tangent** to the obstacle

  $(\mathbf{p}_k, \dot{\mathbf{p}}_k)$ 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)

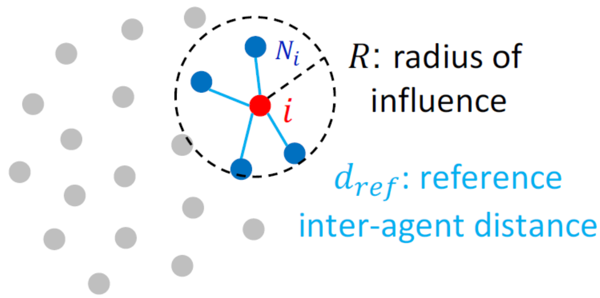
> *Vasarhelyi et al., Optimized flocking of autonomous drones in confined environments, Science Robotics, 2019*
>
> *DOI: http://doi.org/10.1126/scirobotics.aat3536*
>
> *Video: https://youtu.be/E4XpyG4eMKE*
>
> *Project web: http://hal.elte.hu/drones/scirob2018.html*

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

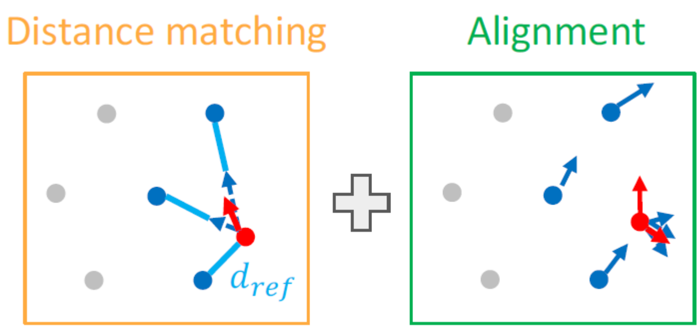
  $$\begin{cases} \dot{\boldsymbol{p}}_i = \boldsymbol{u}_i \\ \boldsymbol{u}_i = \boldsymbol{v}_{sep,i} + \boldsymbol{v}_{spp,i} + \boldsymbol{v}_{\text{fric},i} \end{cases}$$
- The full equation contains 12 parameters and **requires heuristic methods for optimization**

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



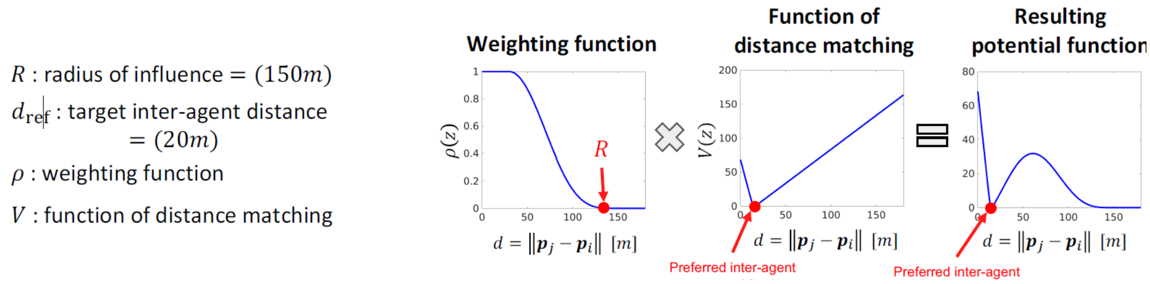
- Equation

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

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

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

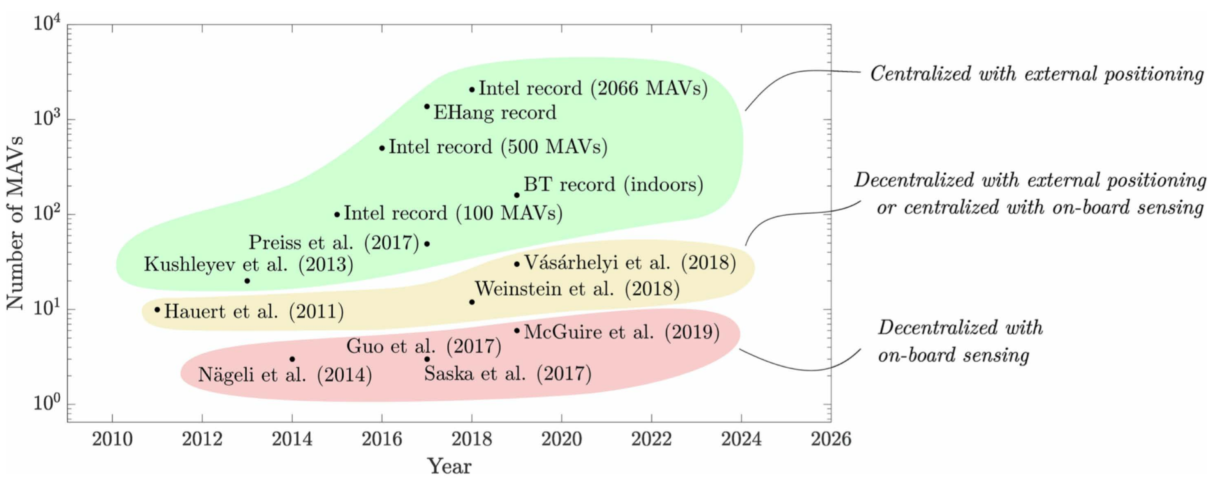
    - radius of influence R
    - desired inter-agent distance d_{ref}
    - weighting function ρ
    - distance matching function V
    - gradient, derivative in three dimensions $\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)$
- **distance matching 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

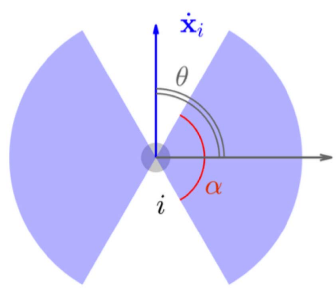
   Saska et al. (2017)

Visual information in flocking

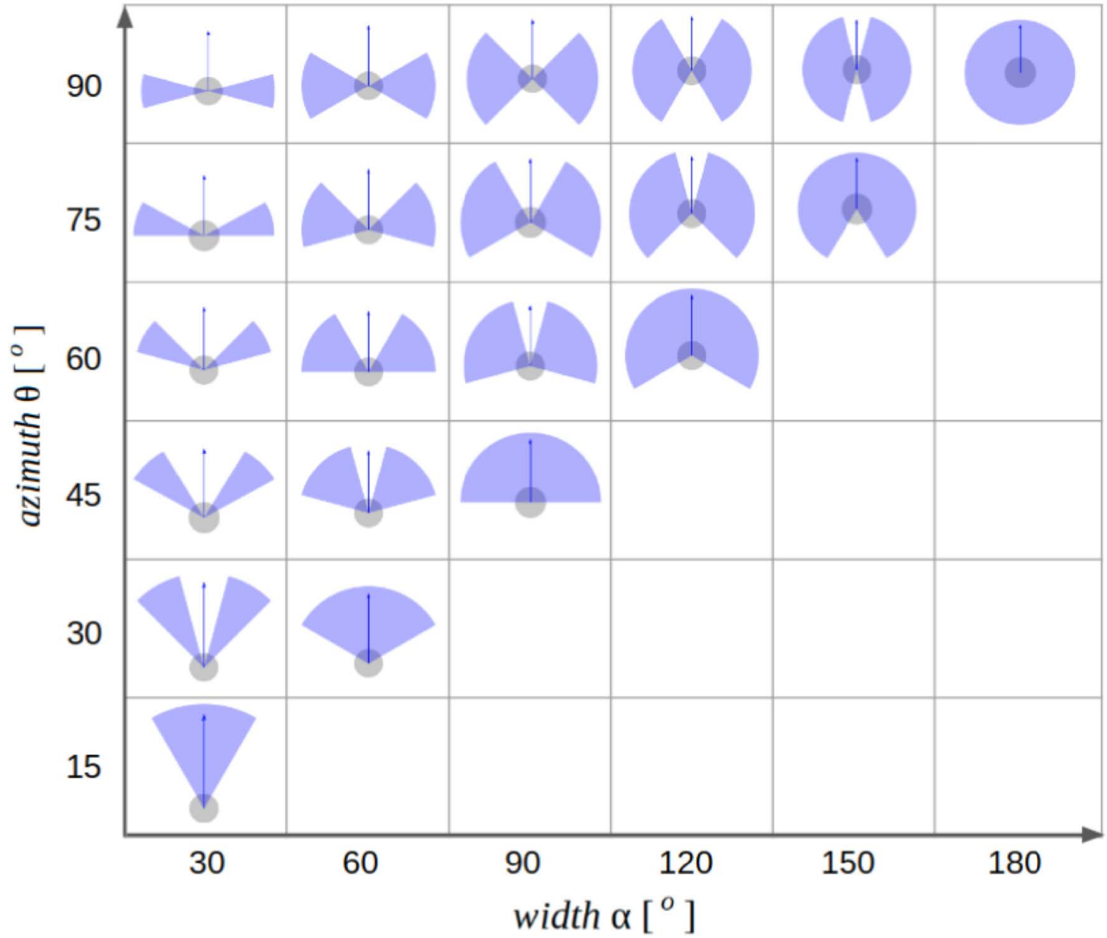
Soria2019IRC-influence of limited visual sensing using Reynolds

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

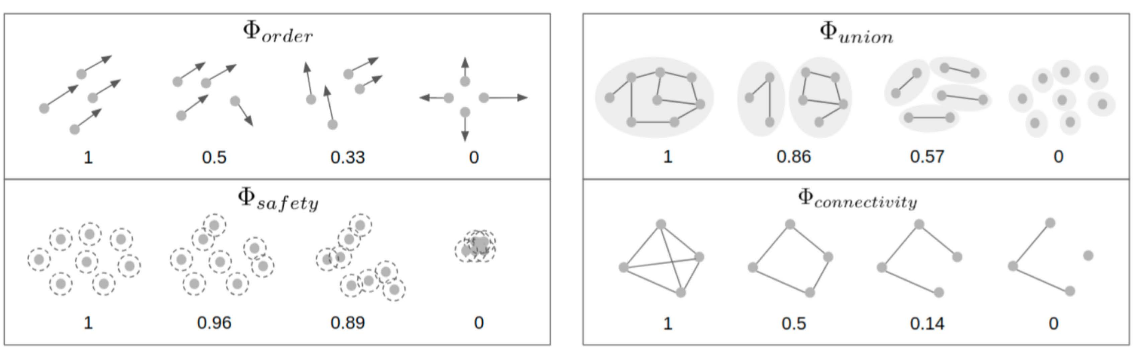
- generate flocks with different fields of view



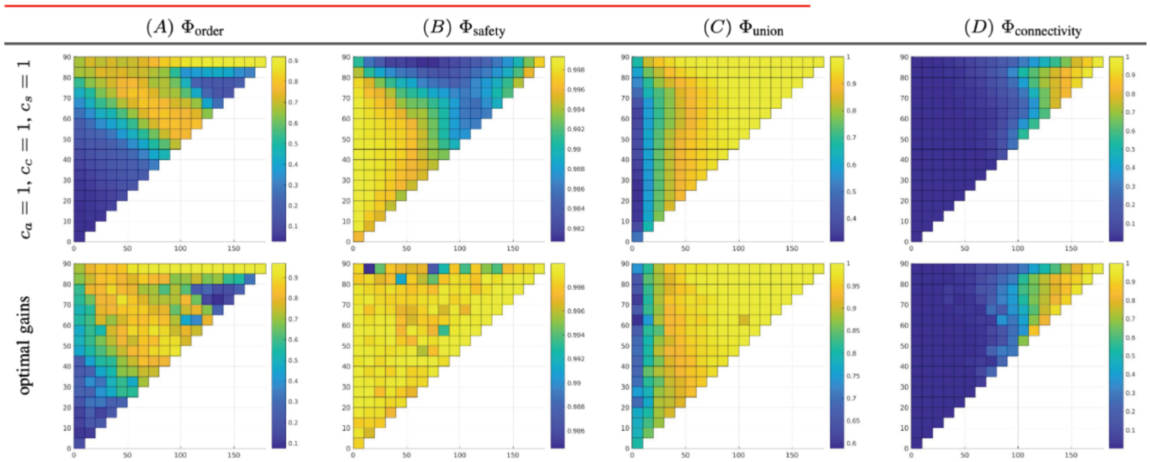
  - azimuth/方位角 $\theta[°]$
  - width $\alpha[°]$



- 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

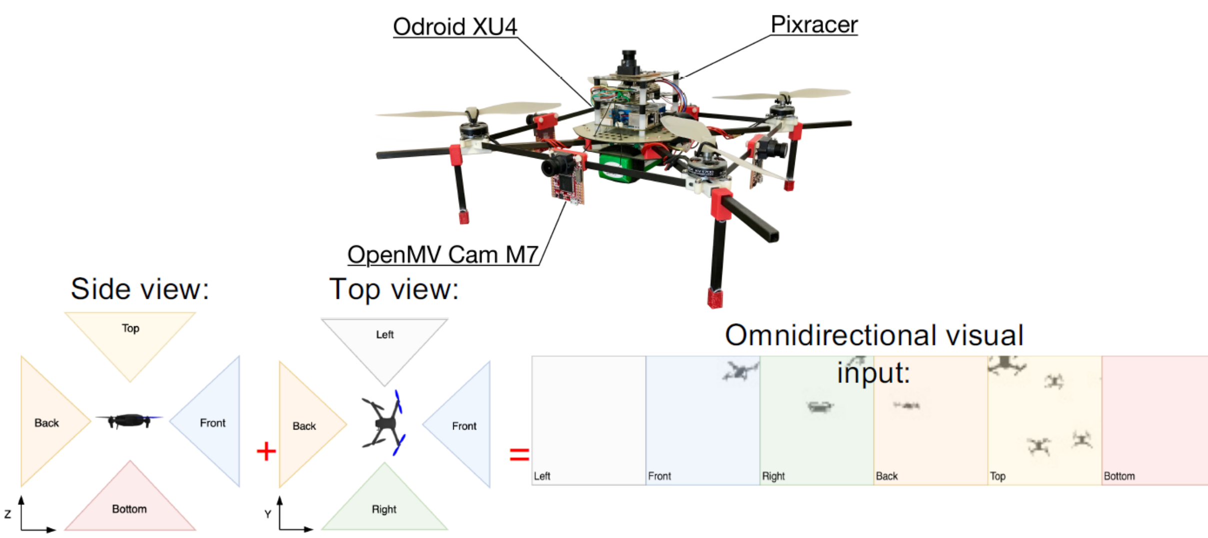


- focus on order and safety (alignment and collision prevention capability)
- largest azimuth and FoV has best performance
- increase in either azimuth or FoV only will degrade the performance
- safety can be achieved even with lower FoV

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

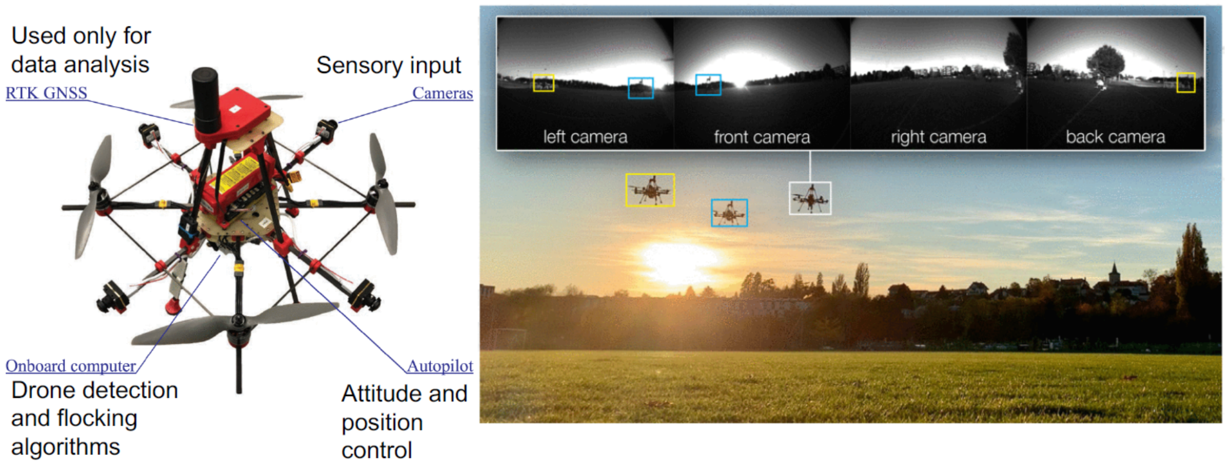


- Stages
  - Dataset generation: Flocking algorithm as ground truth
  - Training phase: Learn **mapping between vision and control output**
  - Vision-based control: **Neural controller for collision-free and cohesive flight**
- Note

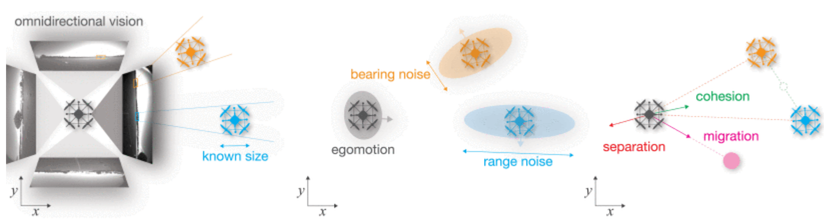
- work well in simulation indoor environment
- it can be robust when individuals has different migration points
- cannot generalize well in background clutter and different lighting condition

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

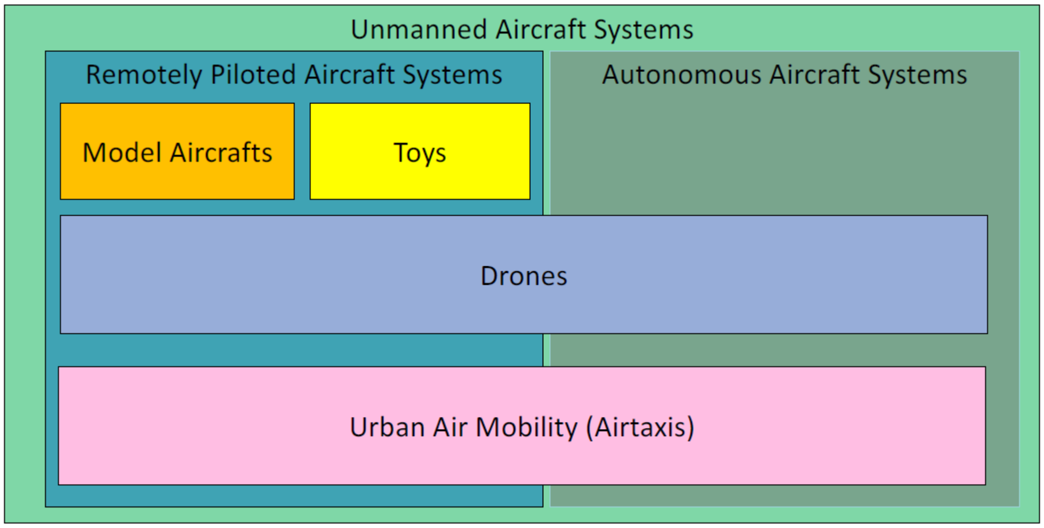
  images from 4 cameras -> x,y coordinates of perceived drones in images -> Range and bearing of all perceived drones -> velocity vector

🚧 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

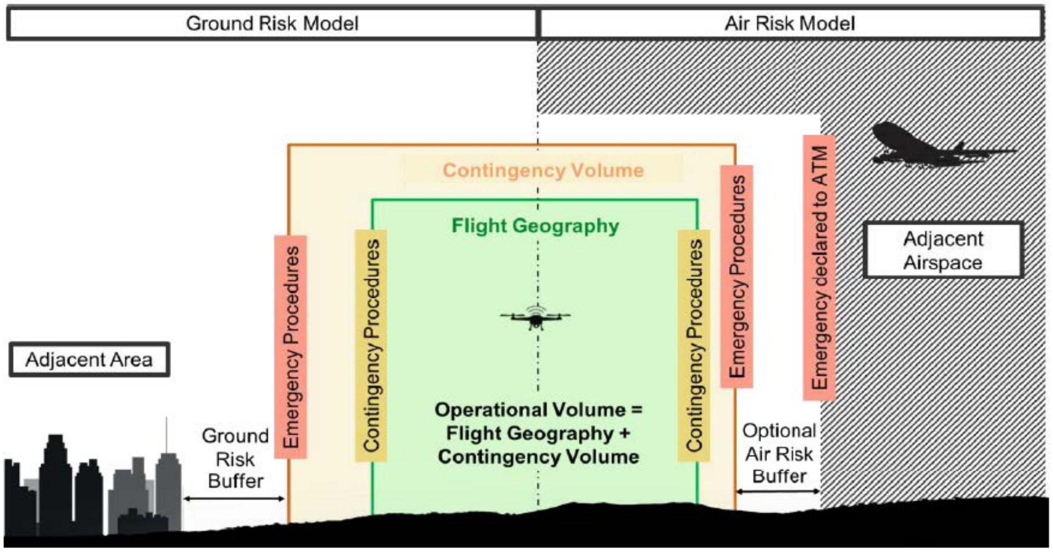


- Rules in Aviation: Federal Office of Civil Aviation Switzerland
- Everything which is not forbidden is allowed -> Switzerland

  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				
Cons				
Comment				

metric when considering materials

- Young's modulus [wiki]

  弹性模量，正向应力与正向应变的比值

- 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。

Energy sources

Actuators for propulsion and maneuvering

Propellers

Sensors

Autopilots

Communication protocols