Lecture 8: Behavior-based systems

B3M33MRS — Aerial Multi-Robot Systems

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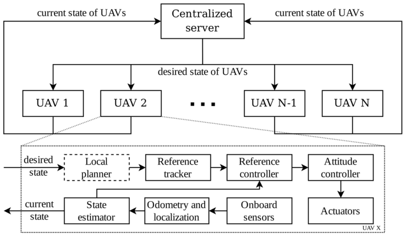
Issues and challenges related to UAV formations – can swarms help?

- Navigation in dynamic environment changed by the UAVs themselves
  - ✓ Behavior-based method well suited for highly dynamic and changing environment
- Reliable communication required all the time
  - ✓ Do not require explicit communication at all
- Scalability of formation control approaches
  - ✓ One of the main requirements and motivations of swarming systems
- Failure detection and recovery
  - ✓ High redundancy always considered
- Cooperative navigation and localization of closely flying UAVs
  - ✓ Relying on onboard bio-inspired localization methods
- Reliable formation shape changing – transition between required states
  - ✓ No required shapes
- Synchronization
  - ✓ Not required

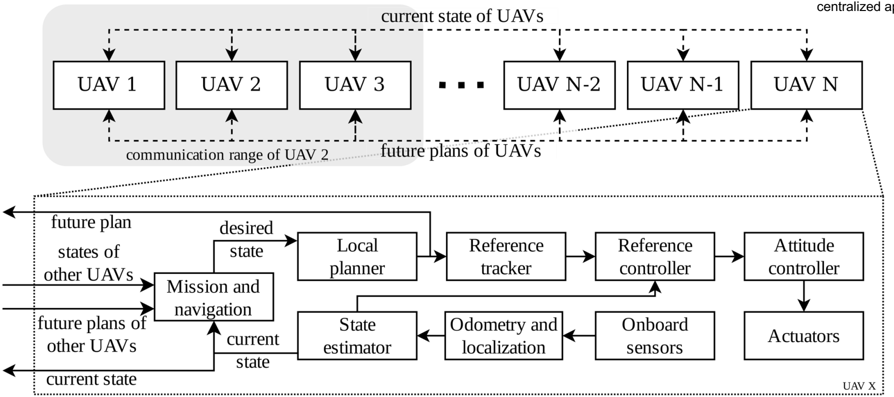
Centralized vs. Decentralized control architecture

Centralized vs. Decentralized control architecture



centralized approach for comparison

- Decentralised control architecture



Swarming intelligence / behavior-based systems

- How to design the behavior-based systems to tackle the issues of formations
- Inspiration in biological systems

For example*: Social insects [...] stand as fascinating examples of how collectively intelligent systems can be generated from a large number of individuals. Despite noise in the environment, errors in processing information and in performing tasks, and the lack of global communication system, social insects can coordinate their actions to accomplish tasks that are beyond the capabilities of a single individual: termites build large and complex mounds, army ants organize impressive foraging raids, ants can collectively carry large prey.*

Dorigo and Sahin, 2004

- See the great motivation talk of Radhika Nagpal from Princeton University, USA

https://youtu.be/8_UBE9rUv2w

Swarming intelligence / behavior-based systems

Key terms in behavior-based systems

- Agent (or intelligent agent) - particle
  - ✓ An entity perceiving the environment and taking autonomous actions to achieve individual or common goals
- Swarm (or flock)
  - ✓ An abstract term for a group of agents
  - ✓ A system amplifying its group intelligence by forming groups from simple agents
- Emergence
  - ✓ Not intended/preprogrammed properties/behaviors at the individual/local level emerging at the group/global level
  - ✓ The group behavior emerges from cooperation between the agents

Key terms in behavior-based systems (swarms)

- Stigmergy
  - ✓ Indirect coordination between agents by leaving traces in the environment
  - ✓ It serves as stimuli for other agents
  - ✓ Apparently spontaneous activity without need for planning, control, or direct communication
  - ✓ Found in multiple biological systems, such as ant colonies
- Self-organization
  - ✓ “A process in which pattern at the global level of a system emerges solely from numerous interactions among the lower-level components of the system” [Camazine et al., 2001, p. 8]
  - ✓ A system self-organization driven by its own components
  - ✓ Interaction relying only on local information, without any reference to the system as a whole

Self-organization

- Camazine et al., (2001) for swarm intelligence require:
  - ✓ Decentralization
  - ✓ Flexibility and robustness
  - ✓ Embodiment
  - ✓ Locality of sensing
  - ✓ Dynamic interactions between agents

- Self-organization is a basic principle for designing a system capable of these properties

Swarming intelligence / behavior-based systems

Self-organization example from the Czech republic

- Bark beetle larvae Dendroctonus micans (CZ: kůrovec)
  - ✓ larvaes individually searching for a feeding site (moving randomly)
  - ✓ emitting a chemical signal in a good feeding location – a pheromone
  - ✓ the pheromone diffused in air providing a stigmergic communication
  - ✓ other larvaes moving in the gradient direction of pheromone concentration

- The global behavior (order) emerging from simple individual rules and local interactions

- Some birds can also detect the pheromone …
  (unfortunately we have probably more spruce trees than the birds)

Self-organization – robotic tasks and examples of applications

✓ Navigation	➢ Search and rescue, exploration
✓ Flocking	➢ ???
✓ Item collection	➢ Cooperative transportation, automatic construction
✓ Foraging	➢ Smart agriculture – harvesting, fruit collection
✓ Scouting	➢ Patrolling, security
✓ Shepherding	➢ Smart agriculture – solving problem with returning of predators to nature
✓ Predator avoiding	➢ Human-UAV safe interaction

Applications of behavior-based flocking methods

- Always if the chaotic movement in nonspecified group shapes into nonspecified positions can be accepted

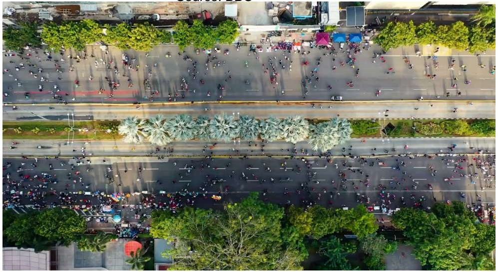
Motivation

Source: National Geographic

Source: BBC

Source: Caters Clips

Source: BBC



Murmuration

- A swooping mass of thousands of birds whirling in the sky
  - ✓ From September during early evening just before dusk
  - ✓ Up to 100.000 birds
- Unknown purpose. Theories:
  - ✓ Grouping for safety from predators (e.g., falcons cannot target one bird in the middle of the flock)
  - ✓ Keeping warm at night
  - ✓ Exchanging information (e.g., feeding areas)
  - ✓ Social gathering before roost for the night
- Perception: visual, acoustic signals, airflow (?)

Source: National Geographic

sturnus vulgaris (CZ: špaček obecný)

Fish schools

- Different behavior-based examples
  - ✓ Aggregation: unorganized gathering of fish of various species
  - ✓ Single-species aggregation: Shoal
  - ✓ Schooling: polarized shoal → pointing in similar directions and swimming together
- Gathering reasons are mostly social
  - ✓ Safety: confusing predators making it difficult to single out individuals (similar to birds)
  - ✓ Feeding: easier to find food
  - ✓ Breeding
- Perception: visual, hydrodynamic signals, pheromones (?)

Source: BBC

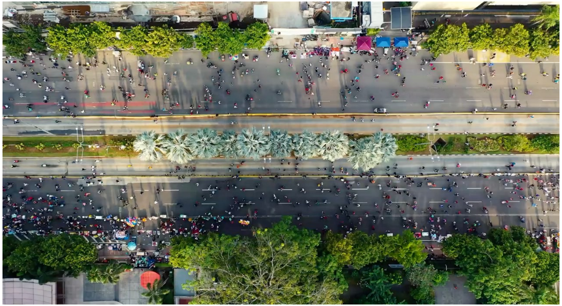
Herding

- Herding: act of bringing individuals together into a group (herd), maintaining it, and move it from place to place
  - ✓ Grouping for safety from predators
  - ✓ Keeping warm at night
  - ✓ Social gathering
- Instinctive herding behavior observed in wolves, dogs, sperm whales
- Group of the individuals which is being herded is swarming

Source: Caters Clips

Crowding

- Coordinated movement of people in large groups
  - ✓ Not organized movement of crowds
  - ✓ People going from a sport match or concert at the same time
  - ✓ Design of stadiums is verified using simulations of crowds



- Perception: acoustic (verbal and none verbal), visual, tactile

Applications of behavior-based flocking methods

Lecture 8 Swarms
Martin Saska
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Swarming definitions
Motivation
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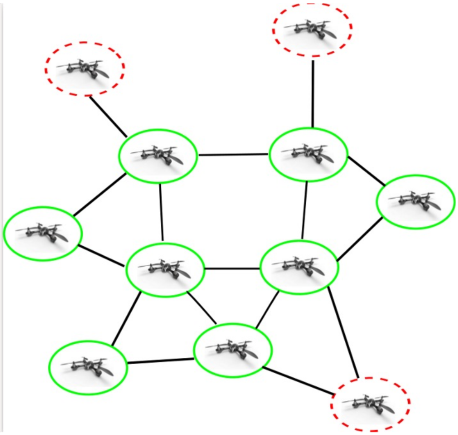
Boids model
Vicsek's model
Beeclust model
Agile swarming
Conclusion

- As a backup mechanism if failing communication and/or global localization
- Even if the basic single UAV state estimation fails, behavior-based methods can help
- Estimation of non-observable states through observation of other team members
  - ✓ Loss of localization performance (sensory outage, GNSS jamming)
  - ✓ Increased sensory noise
  - ✓ Singularities in data processing (e. g., visual or lidar localization in feature-less environments)
- Defense and security applications
  - ✓ GNSS and communication spoofing and jamming
  - ✓ Blinding visual sensors (but also Lidars)



Source: https://www.arscontrol.org/research/decentralized-estimation-methods/

Self-organization towards flocking/swarming intelligence: definitions

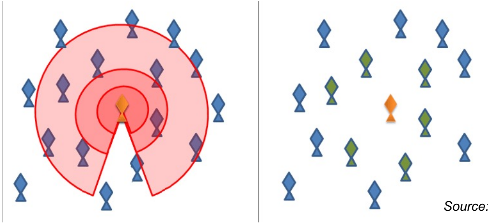
- Collective motion of large number of self-propelled entities
  - ✓ Motivated by aggregation, migration, …
- Emergent behavior arising from simple rules that are followed by individuals without involvement of any central coordination element
- But we must be more specific for robotic swarming/flocking

Behavior based flocking - swarming intelligence requirements

- Dorigo and Sahin (2004) specified properties of a robotic system to be considered as a swarm:
  - ✓ Coordination and control of large number of robots
  - ✓ High redundancy required within each group (highly heterogeneous systems cannot achieve it)
  - ✓ Solving tasks unsolvable by a single agent due to individual limitations
  - ✓ Local and limited sensing and communication capabilities in nature (global knowledge and complex communication are likely not scalable)
- Swarming requirements (on a robotic system)
  - ✓ Scalability
  - ✓ Homogeneous robots – redundancy
  - ✓ Usability in tasks not solvable by a single robot
  - ✓ Local sensing
  - ✓ Without global communication

Mathematical models: local neighborhood

- Definition of a local neighborhood is important for achieving interaction/sensing locally → scalability
- Metric model of local neighborhood
  - ✓ Only robots in certain zones considered (three-level zone in the image)
  - ✓ Usually defined by perceptual capabilities of the agent and/or by density of robots in the flock
- Topological model of local neighborhood
  - ✓ Only a given number of agents is considered (in most of the cases the nearest or best visible)
  - ✓ Motivation by nature: for example sturnus vulgaris (špaček in czech) considers only six or seven neighbors while flocking [Ballerini et al., 2008]



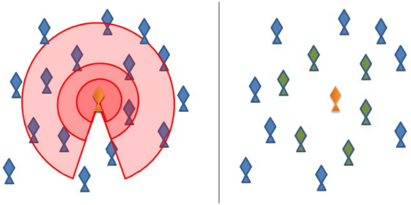
Source: Reynolds's archive

Mathematical models

- Idea of virtual physics: each agent is a virtual particle that exerts a virtual force on its neighbors
- No memory: pure reactive
- Assumptions:
  - ✓ Robots able to distinguish between other robots and obstacles
  - ✓ Robots can estimate relative positions and angles of other robots
- Features:
  - ✓ Mathematical rules: no need of complex coding
  - ✓ Possibility to combine a variety of diverse forces
  - ✓ Only some properties can be proven mathematically

Mathematical models

- The basic concepts of animal swarms [Reynolds, 1986] represent agents' actions by three rules
  - ✓ **Alignment** - align the movement towards the direction of your neighbors
  - ✓ **Cohesion** - stay nearby your neighbors
  - ✓ **Separation** - avoid collisions with your neighbors
- Different rules can be applied in different zones
  - ✓ Separation zone (the inner in the image)
  - ✓ Alignment zone (middle)
  - ✓ Attraction zone (outer)



- Or the rules can be applied on different number of neighboring particles

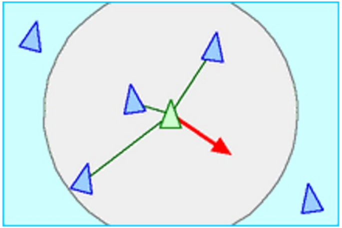
Mathematical models

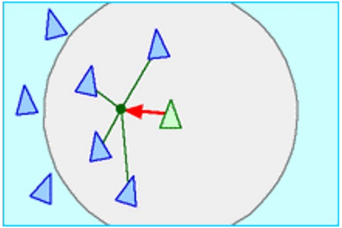
- Boids [Reynolds, 1986]
    - ✓ Originally proposed for computer graphics to animate flocks
    - ✓ Dimension-less particles
    - ✓ Holonomic motion
    - ✓ Each particle reacts to local neighborhood → complexity O(N)
    - ✓ The three rules (alignment, cohesion, separation) only, in the original method
- Self-propelled particles [Vicsek et al., 1995]
    - ✓ Inspired by flock of birds and particle physics
    - ✓ Adding robotic constraints (dimension of robots, motion constraints)

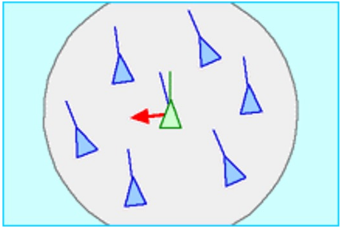
Mathematical models: Boids

- Agents modeled as particles with state composed of position and velocity

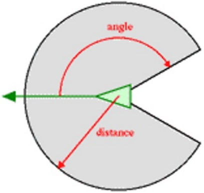
- Separation
- Cohesion
- Velocity alignment (steering)







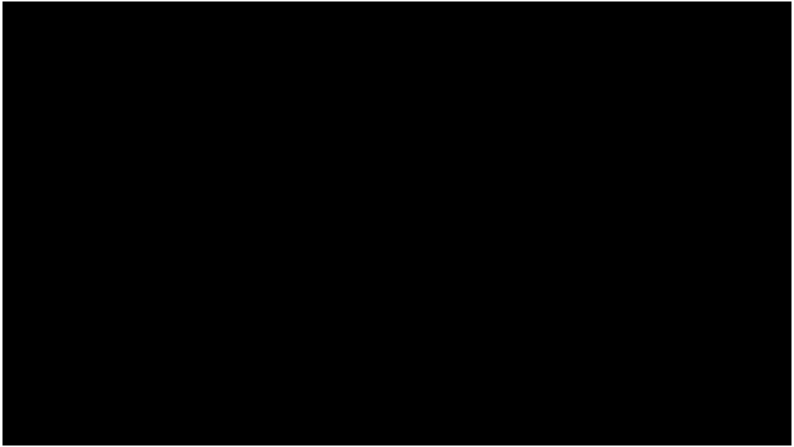
- Agent's neighborhood



C. Reynolds, "Flocks, Herds, and Schools: A Distributed Behavioral Model," *Computer Graphics, 1987.*

Mathematical models: Boids

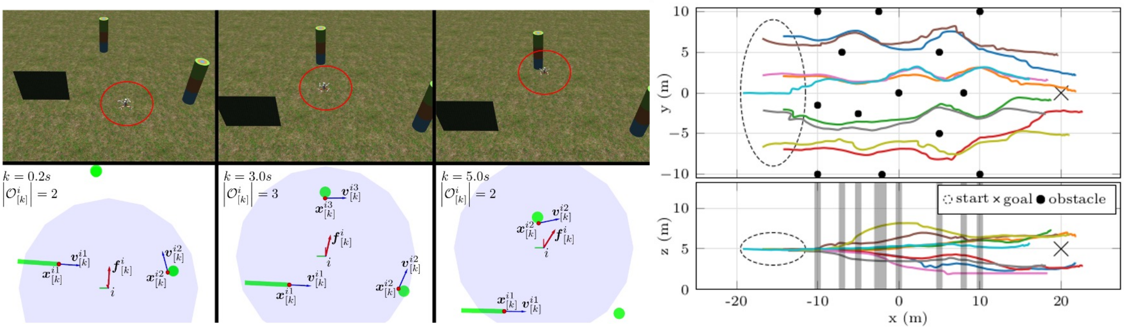
- Used in computer graphics, games, movies, robotics
- Try it out: eater.net/boids



Source: Neat AI (YouTube)

Mathematical models: Boids extensions

- Obstacle avoidance ability – a concept of virtual agents
  - ✓ Each obstacle is represented by a virtual agent with the state composed of position and velocity
- Navigation towards a common goal – using a long-range attraction
- The same three Boids rules, only with different parameters (the simplicity and full decentralisation kept)



P. Petracek, … M. Saska, “Bio-Inspired Compact Swarms of Unmanned Aerial Vehicles without Communication and External Localization,” *Bioinspiration & Biomimetics 16(2):026009, December 2020.*

Mathematical models: Boids extensions

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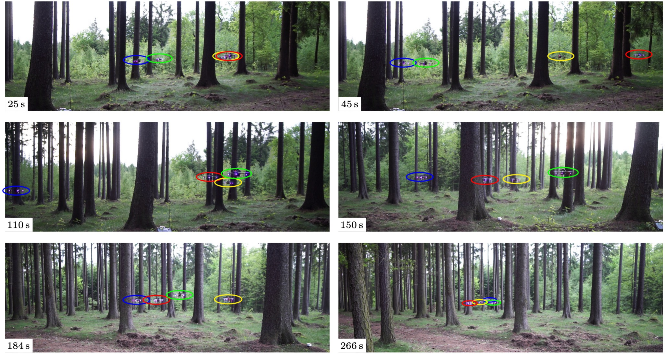
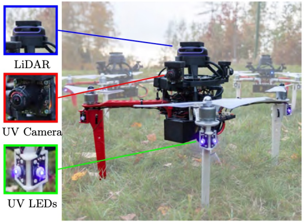
Mathematical models: Boids extensions

- Local sensing (without GNSS) – mutual localization
- Implicit communication (without global broadcasting of states)
- Real-world deployment





Afzal Ahmad, Daniel Bonilla Licea, Giuseppe Silano, Tomas Baca and Martin Saska, "PACNav: A Collective Navigation Approach for UAV Swarms Deprived of Communication and External Localization," *Bioinspiration & Biomimetics 17:1-19, November 2022.*

Mathematical models: Boids extensions

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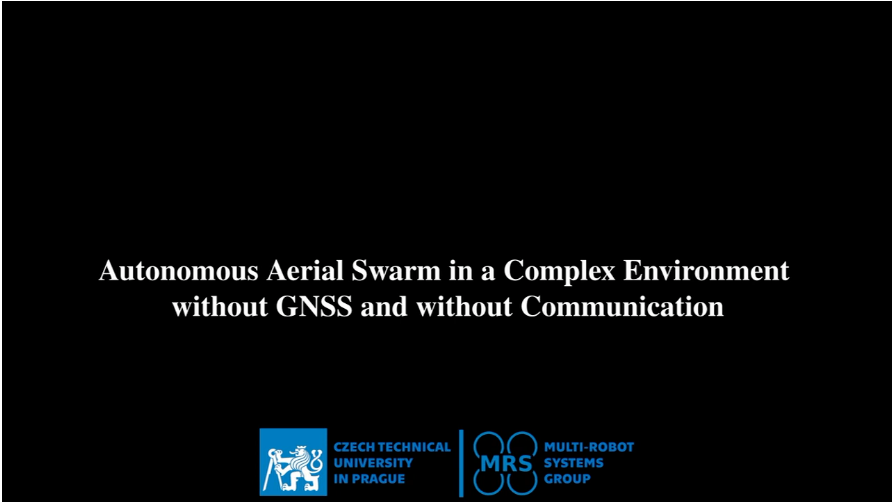

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Mathematical models: Vicsek's model

- Self-propelled particles (SPP) model
- Based on particle physics - used to model active matter
- An extension of the Boids model

  - ✓ Align the movement towards the direction of your neighbors + some noise
  - ✓ Stay nearby your neighbors
  - ✓ Avoid collisions with your neighbors

- Agents modeled as particles with constant speed aligning their velocity with their neighbors in presence of perceptual noise

T. Vicsek, et al. "Novel type of phase transition in a system of self-driven particles." *Physical review letters 75* (1995): 1226-1234.

Mathematical models: Vicsek's model

- In every time step *t*, the position of particle *i* evolves as

$$\theta_i(t+\Delta t) = \frac{1}{\mathcal{N}_i(r)} \sum_{j=1}^{|\mathcal{N}_i(r)|} \theta_j(t) + \mu_i(t)$$

$$\mathbf{p}_i(t+\Delta t) = \mathbf{p}_i(t) + \mathbf{v}\Delta t \begin{pmatrix} \cos(\theta_i(t)) \\ \sin(\theta_i(t)) \end{pmatrix}$$

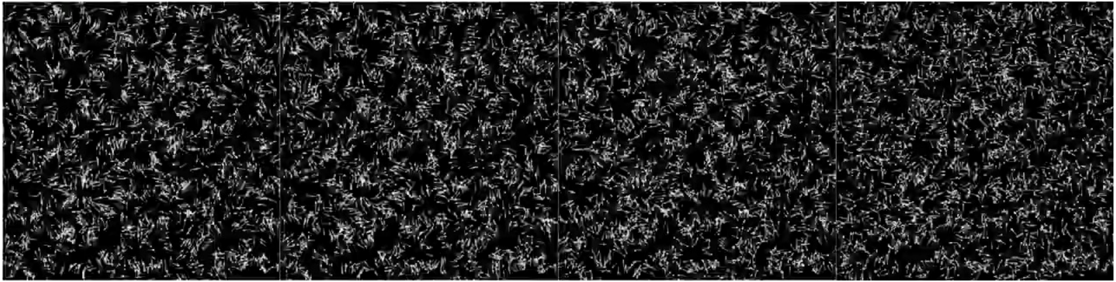
Source: Vicsek's archive

$\mathcal{N}_i(r)$
- a set of neighbors inside a radius r of the i-th robot
- equivalent to the number of neighboring robots of a focal robot n_n

$\mu_i(t)$
- the noise in the velocity vector orientation

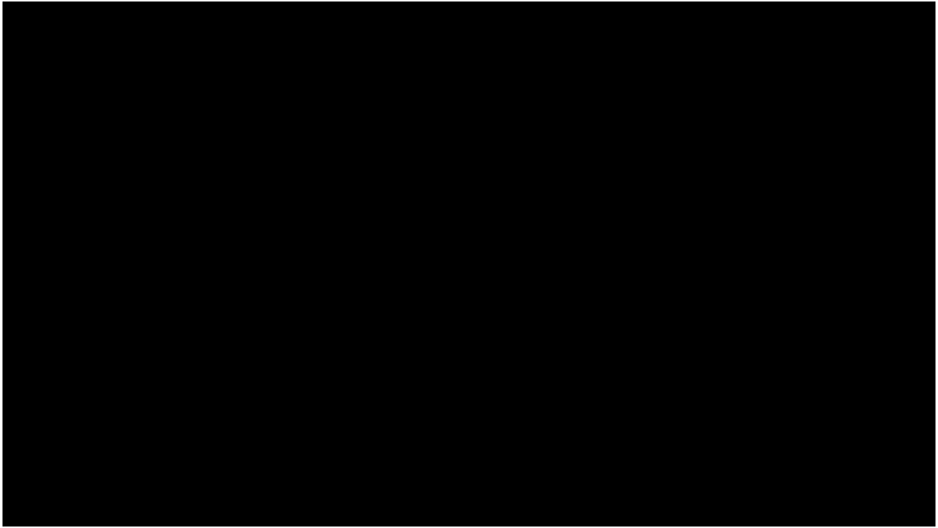
Mathematical models: Vicsek's model

- 2000 agents
- Noise levels of 0.01, 0.1, 0.25 and 0.4 rad from left to right.



Source: Damian Sowinski (YouTube)

Mathematical models: Vicsek’s model

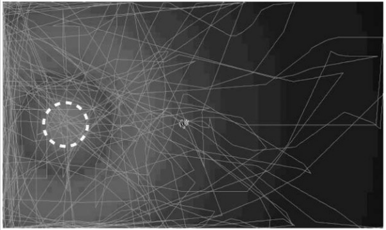


G. Vásárhelyi, ..., T. Vicsek. "Optimized flocking of autonomous drones in confined environments." *Science Robot 18; 3(20), 2018.*

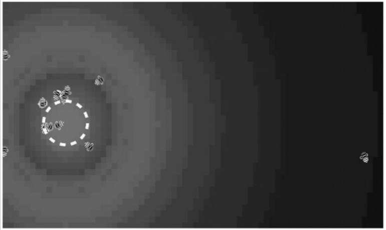
Mathematical models: Beeclust

- Swarm algorithm inspired by honeybees
- Aggregation of bees in a temperature gradient field
- Bees cannot sense local temperature differences in a flat gradient field
- Bees fly randomly and form clusters around warmer spots
- Distributed search behavior can be designed based on the observed behavior

T. Schmickl, and H. Hamann. "BEECLUST: A swarm algorithm derived from honeybees." *Bio-inspired computing and communication networks* (2011): 95-137.



(a) A single bee in the simulation (trajectory).

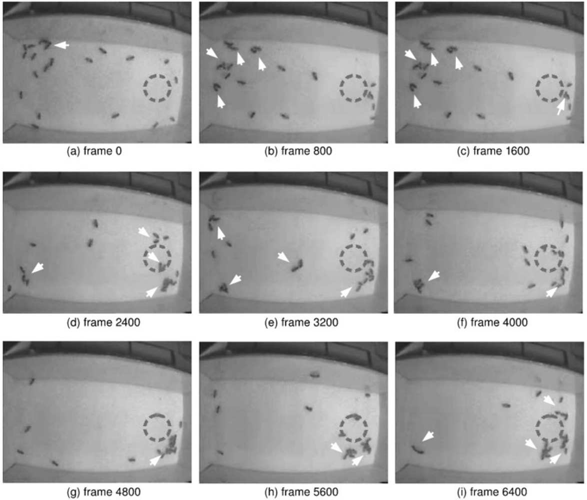


(b) 12 bees in the simulation (final positions).

Mathematical models: Beeclust

- Collective behavior using Beeclust
  - ✓ Bees move randomly straight
  - ✓ Turning if approaching an obstacle
  - ✓ Forming a cluster if meeting another bee
  - ✓ Bees stay in clusters at warmer locations longer
  - ✓ At the end, only the cluster(s) at the warmest location remaining

T. Schmickl, and H. Hamann. "BEECLUST: A swarm algorithm derived from honeybees." *Bio-inspired computing and communication networks* (2011): 95-137.



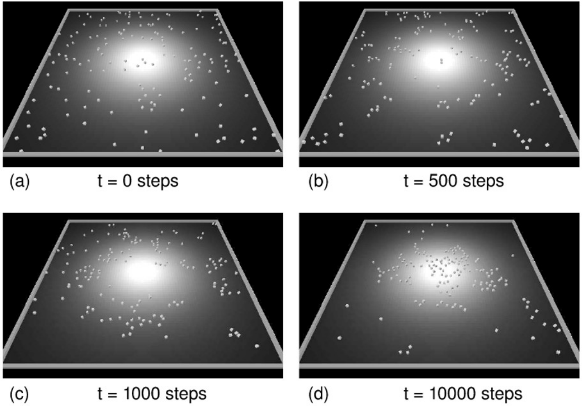
(a) frame 0 (b) frame 800 (c) frame 1600

(d) frame 2400 (e) frame 3200 (f) frame 4000

(g) frame 4800 (h) frame 5600 (i) frame 6400

Circles – warm spots, arrows – bee clusters

- An experiment of decentralized aggregation of a robot at the brightest spot
- Robots are waiting longer in clusters with higher luminance
- The biggest cluster is formed around the maxima of luminance



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Mathematical models: Beeclust

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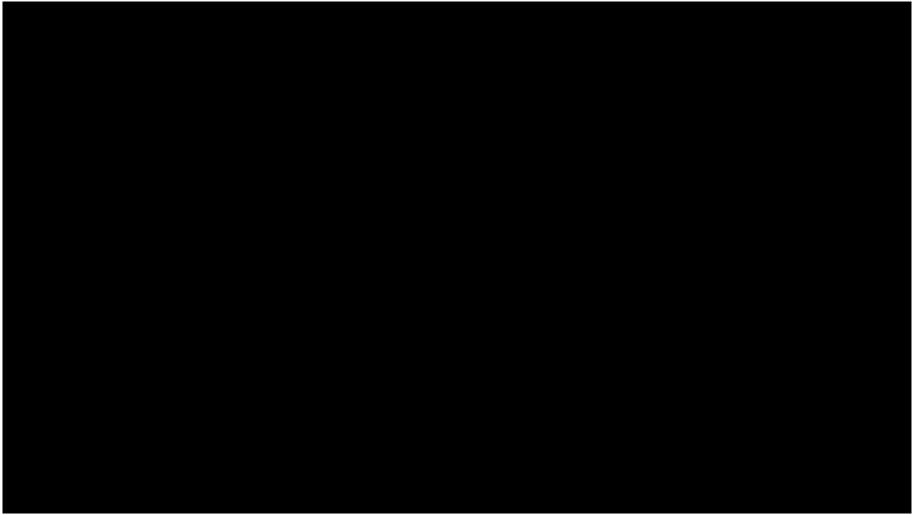
Agile aerial swarming

- Fast swarming in constrained environment
- Based on an advanced planner gathering:
  - Collision avoidance
  - Obstacle avoidance
  - Swarm coordination
  - Feasibility and efficiency of the flight

Zhou, X., ... & Gao, F. (2022). Swarm of micro flying robots in the wild. *Science Robotics*, *7*(66).

Agile aerial swarming



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Agile aerial swarming

Lecture 8 Swarms
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Conclusion

?

- Homogeneous robots – redundancy ?
- Usability in tasks not solvable by a single robot ?
- Local sensing ?
- Without global communication ?
- Scalability ?

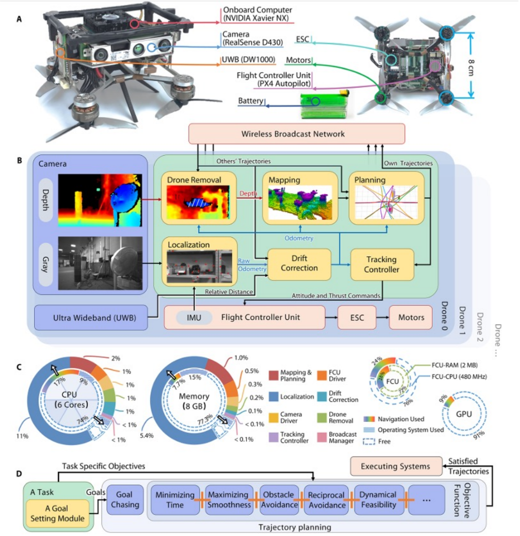


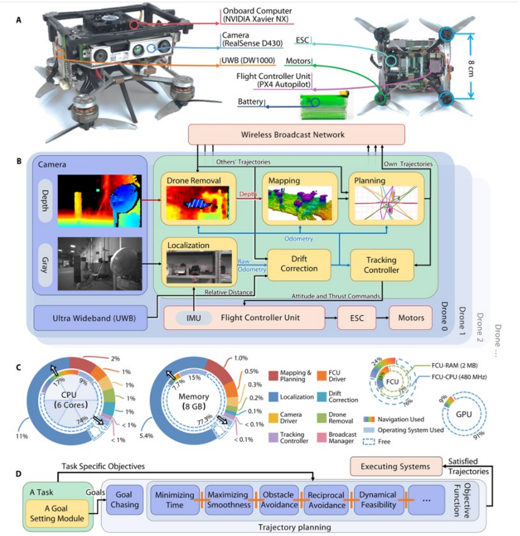
Fig. 2. Hardware and system architecture specifics. (A) Hardware components of our flight platform. See the "Palm-sized drone hardware" section for more details. (B) The system architecture. Visual-Inertial State Estimator (5) and probabilistic occupancy grid (7) are adopted for localization and mapping, respectively. (C) Computation and memory usage. Planning and mapping run in the same thread to reduce latency. (D) The planning framework.

Zhou, X., ... & Gao, F. (2022). Swarm of micro flying robots in the wild. *Science Robotics, 7*(66).

Agile aerial swarming

- Homogeneous robots – redundancy
  - ✓ All robots are identical
- ~~Usability in tasks not solvable by a single robot~~

  Single UAV would fly faster (the "real" robotic task is not solved)
- Local sensing
  - ✓ VIO for localization
  - ✓ UWB for VIO drift correction - to avoid mutual collisions



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Agile aerial swarming

- ~~Without global communication~~

  UAV communicate their desired trajectories to exploit the solution space in deep

  Avoiding circumnavigation of UAVs known from boids-like algorithms

- ~~Scalability~~

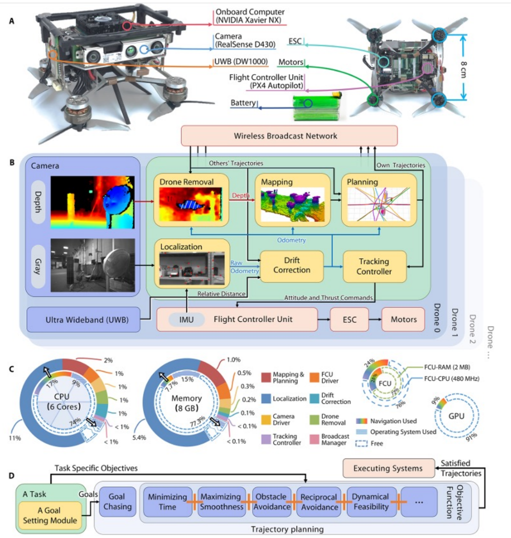
  Reliable and full communication infrastructure in wild is a bottleneck

  UWB localization requires knowledge of ID

- ~~Is it fully decentralized?~~

  ✓ Decentralized motion planning, state estimation, and control

  UWB localization requires global knowledge from all UAVs



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Conclusion – key features of behavior-based self-organizing systems

- Decentralization
  - ✓ Autonomous agents with the same individual behavior
  - ✓ No leader driving organization of the system
- Locality
  - ✓ Every agent relies only on local information and interacts locally with the other agents in its proximity
- Flexibility and robustness
  - ✓ Natural resiliency to environmental changes and external disturbances
  - ✓ Behavior based systems "live at the edge of chaos"
  - ✓ Capable of handling non-linearities and complex far-from-equilibrium dynamics → fast adaptation to changes, unexpected situations, and robust to failures
- Emergence
  - ✓ all agents contribute to the emergence of the self-organization by the distributed behavior
  - ✓ global order is the result of numerous local interactions between agents

References

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