Swarm intelligence

Solving complex problems using nature's simple principles

Jennifer Simonjan

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Lakeside Labs
SELF-ORGANIZING NETWORKED SYSTEMS

Swarm intelligence

Dumb parts, properly connected into a swarm, yield smart results.

(Kevin Kelly)

Ant trail, © pixabay

Swarm intelligence

But how to connect the parts properly?

- **Social insects, bacteria and living organism do it**

Bee swarm, © pixabay

Swarm intelligence

Is a mindset rather than a technology

Bottom-up approach to design and optimize distributed systems

Using resilient, self-organized techniques

Slime mold, © pixabay

Swarm intelligence in nature

Coordinated and purposeful navigation in animal societies

Individuals only rely on local information about neighbors and environment

Thousands of individuals can create a collective behavior without a leader

Ant trail, © pexels

Emergent collective behavior in nature

Movement decisions are based on locally available information

- distance, perceived speed and movement direction of neighbors

Fish schooling, © pexels

Bird flocking, © pixabay

Swarm intelligence properties

Act in a coordinated way without the presence of an (external) controller

Scalable
operate under a wide range of group sizes

Robust
ability to compensate for failures

Flexible
adapt to changes in the environment

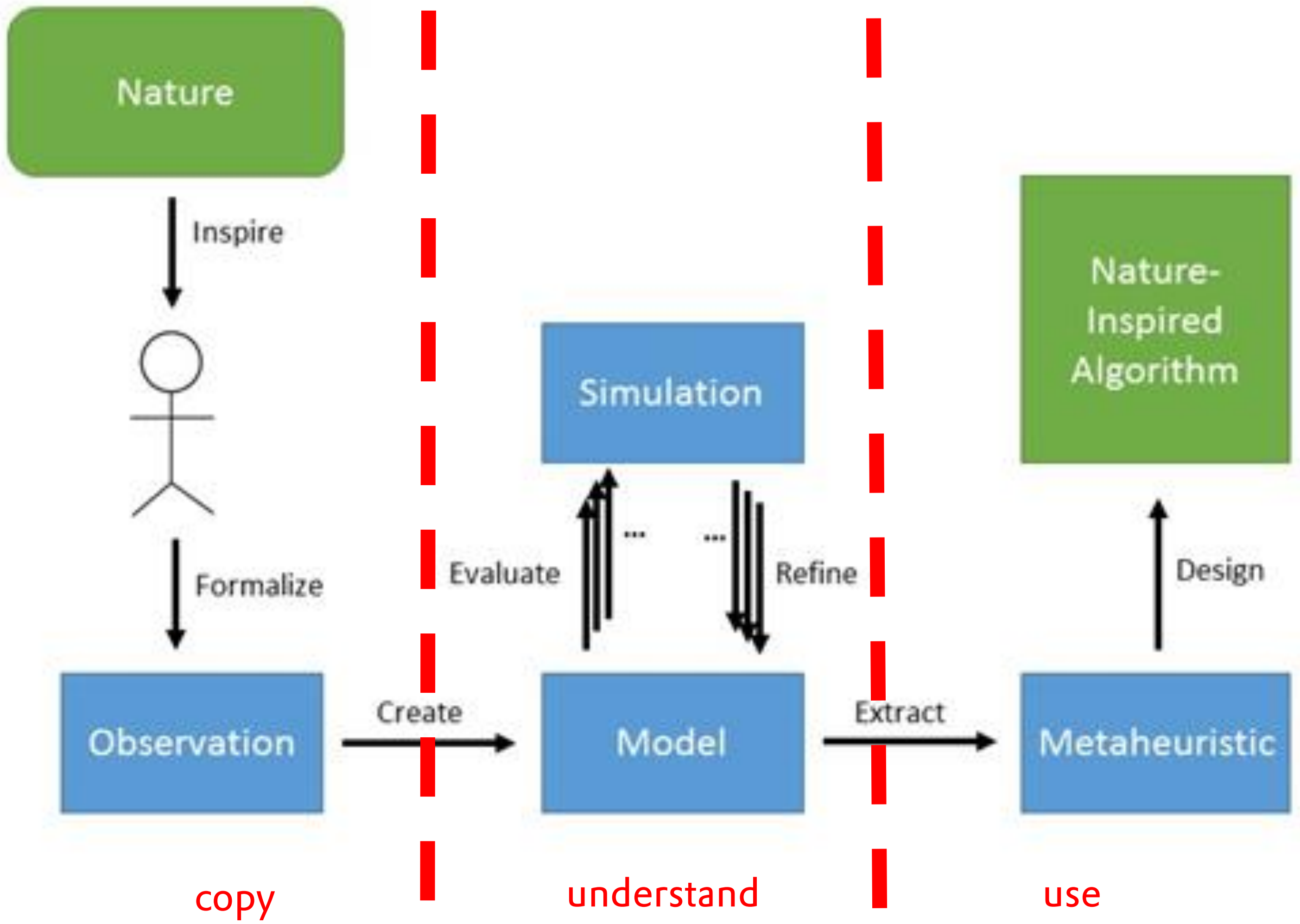
Self-organized
solution paths are emergent rather than predefined

Source: www.nextnature.net

Swarm intelligence design

How can we define individual behavior and local rules to achieve the desired collective behavior?

- difficult to predict collective behavior from individual rules
- the behavior of a single swarm member does not tell us much about the group behavior
- small changes in rules lead to different group behavior



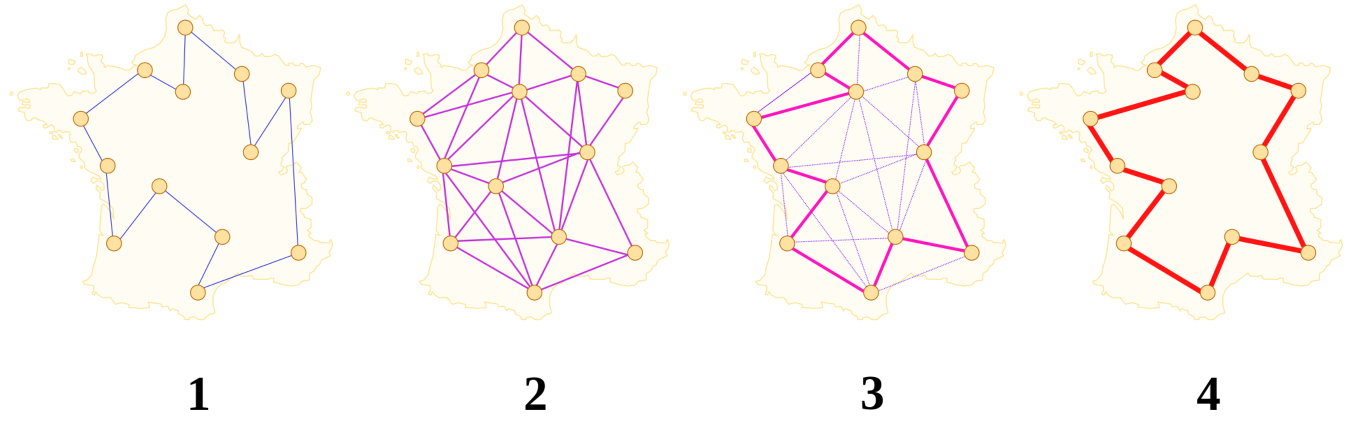
Simple rules can also fail sometimes

Source: Feed Your Curiousity- youtube.com/watch?v=CJ2HMoznzEo

Ants trapped in a death spiral

From natural swarm behaviors to artificial systems

Ant colony optimization
(Dorigo, 1992)

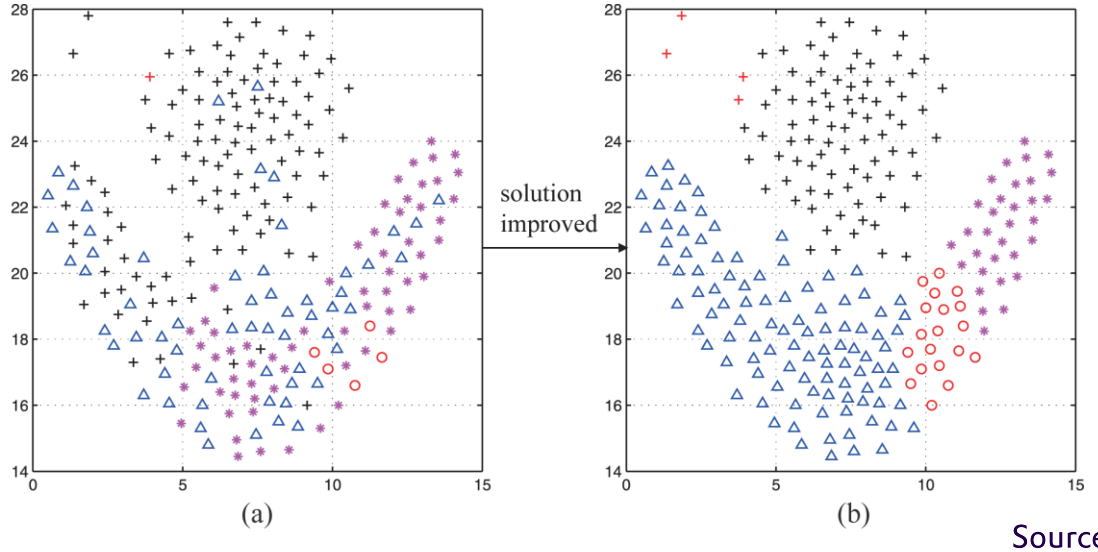


Source: Monmarché 2010

Applications

Dynamic factory scheduling, supply chain optimization, truck routing, routing in communication networks, …

Particle swarm optimization
(Kennedy & Eberhart, 1995)



Source: https://doi.org/10.1371/journal.pone.0188815.g006

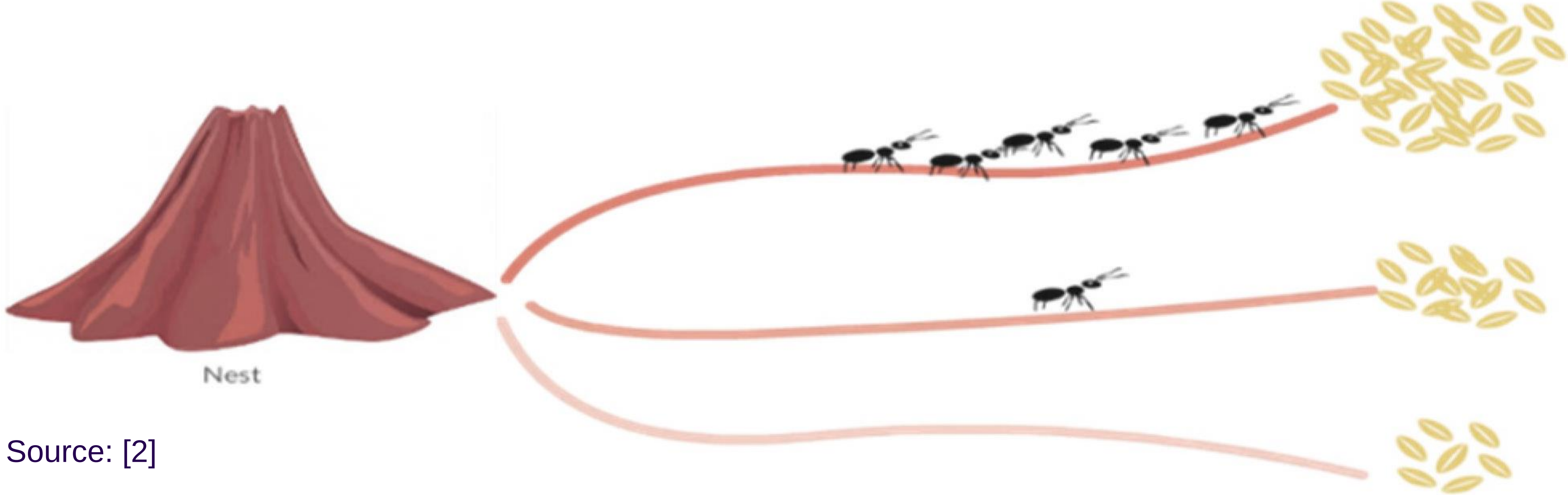
Applications

Energy-storage optimization, antenna design, data clustering, controlling robot swarms, …

Ant colony optimization (ACO) [1]

Nature-inspired metaheuristic modeled on the actions of an ant colony

- based on the foraging behavior of ants for seeking a path between their colony and a food source



Source: [2]

[1] Dorigo, "Optimization, learning and natural algorithms", Doctoral dissertation, 1992.
[2] Al-Otaiby et al., AntTrust: An Ant-Inspired Trust Management System for Peer-to-Peer Networks, Sensors, 2022.

Particle swarm optimization (PSO) [1]

Population based stochastic optimization inspired by bird flocking and fish schooling

Source: blog.stratio.com/swarm-intelligence-metaheuristics-part-2-particle-swarm-optimization

[1] Eberhart, Russell, and James Kennedy. "Particle swarm optimization.“, IEEE IJCNN, 1995.

Swarm intelligence in CPS and robotics

synchronization

collective exploration of unknown territory
(terrestrial, aerial, aquatic)

drone swarms for target search or delivery

sorting or clustering robots
(e.g., warehouses, industrial plants)

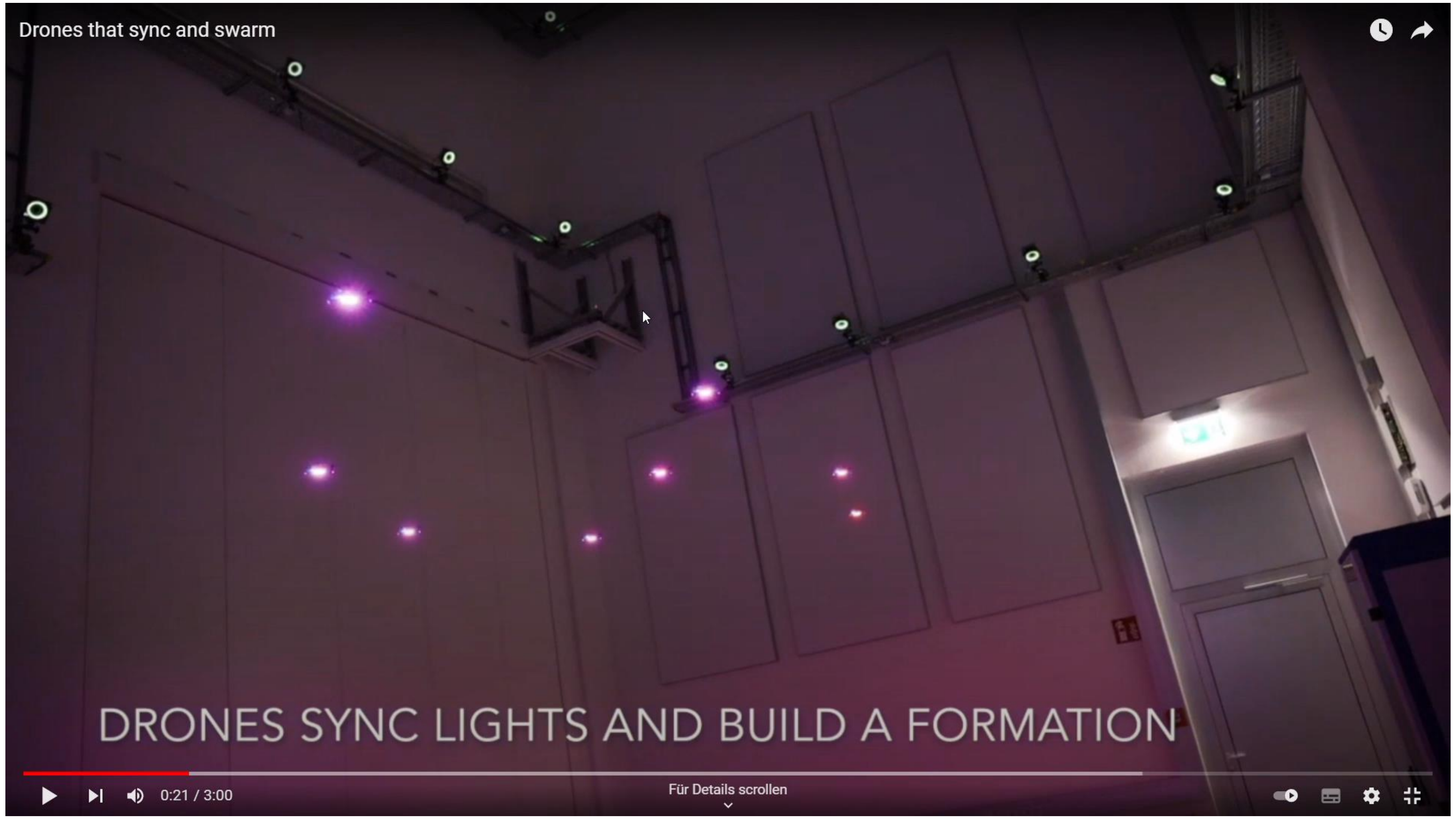
pattern formation
(e.g., entertainment, environmental monitoring)

collective transport of heavy items

UAV swarm synchronization and pattern formation

Swarmalators demonstration

- form five different types of space-time patterns which are not known in advance but emerge over time in a self-organizing manner
- Karl Popper doctoral school on Networked and Autonomous Aerial Vehicles at University of Klagenfurt
- Original model: O'Keeffe, Hong, Strogatz, Oscillators that sync and swarm, Nature Communications, 2017



Source: Karl Popper doctoral school on Networked Autonomous Aerial Vehicles, Drone hall, University of Klagenfurt

Robotic swarms for autonomous target search

Autonomous drones and rovers for target oriented applications

- H2020 CPSwarm at Lakeside Labs, Klagenfurt, Austria
- Further information: www.cpswarm.eu

Source: H2020 CPSwarm, Lakeside Labs

UAV swarms for search and resuce applications

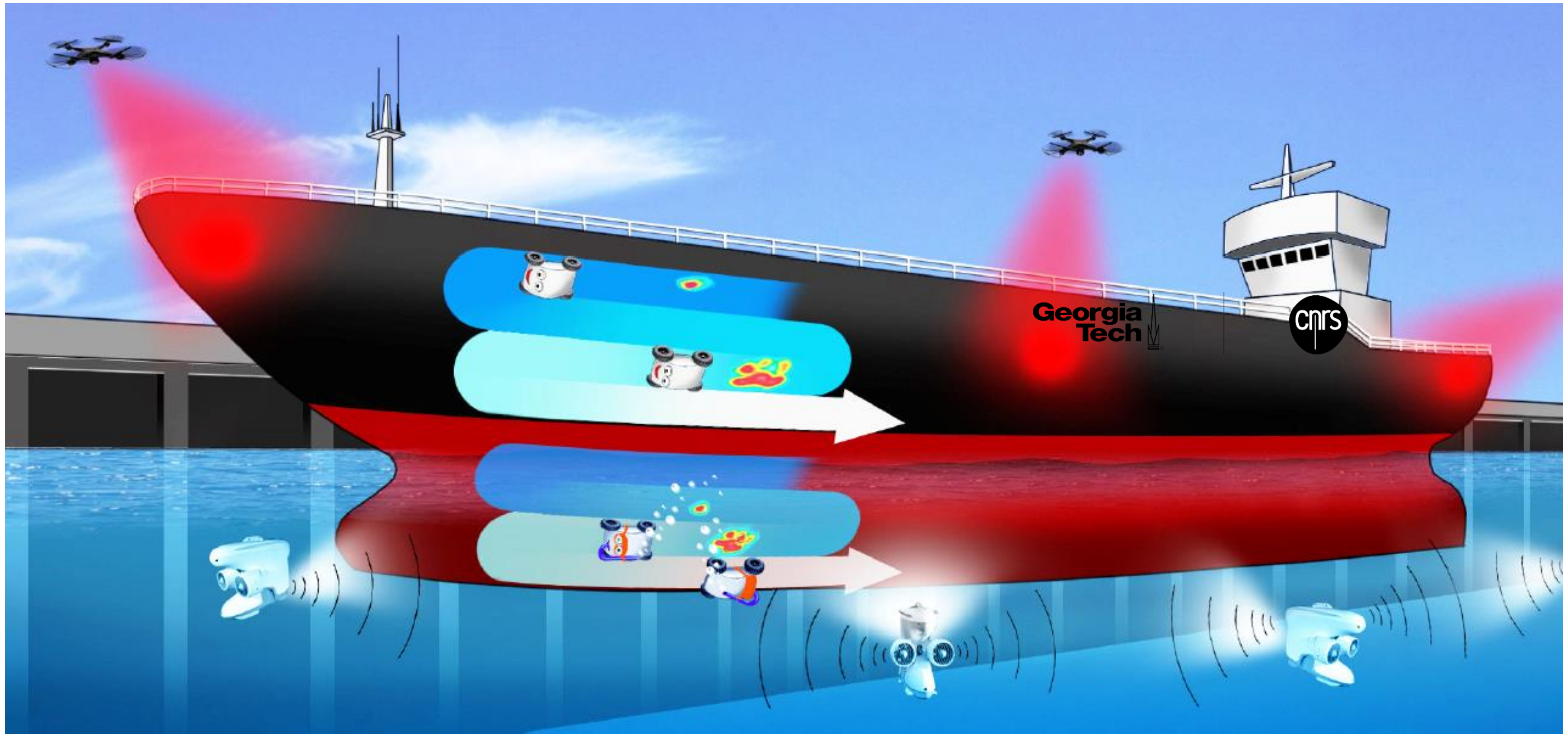
Disaster response support with drones

- support rescue teams with UAV swarms
- search targets
- stream images to the rescue teams
- deliver goods and care packets

Source: University Klagenfurt & Lakeside Labs

Current swarm projects at Lakeside Labs

Bugwright2



Inspection and 3D reconstruction of large ships with teams of aerial robots, underwater robots, and magnetic crawlers

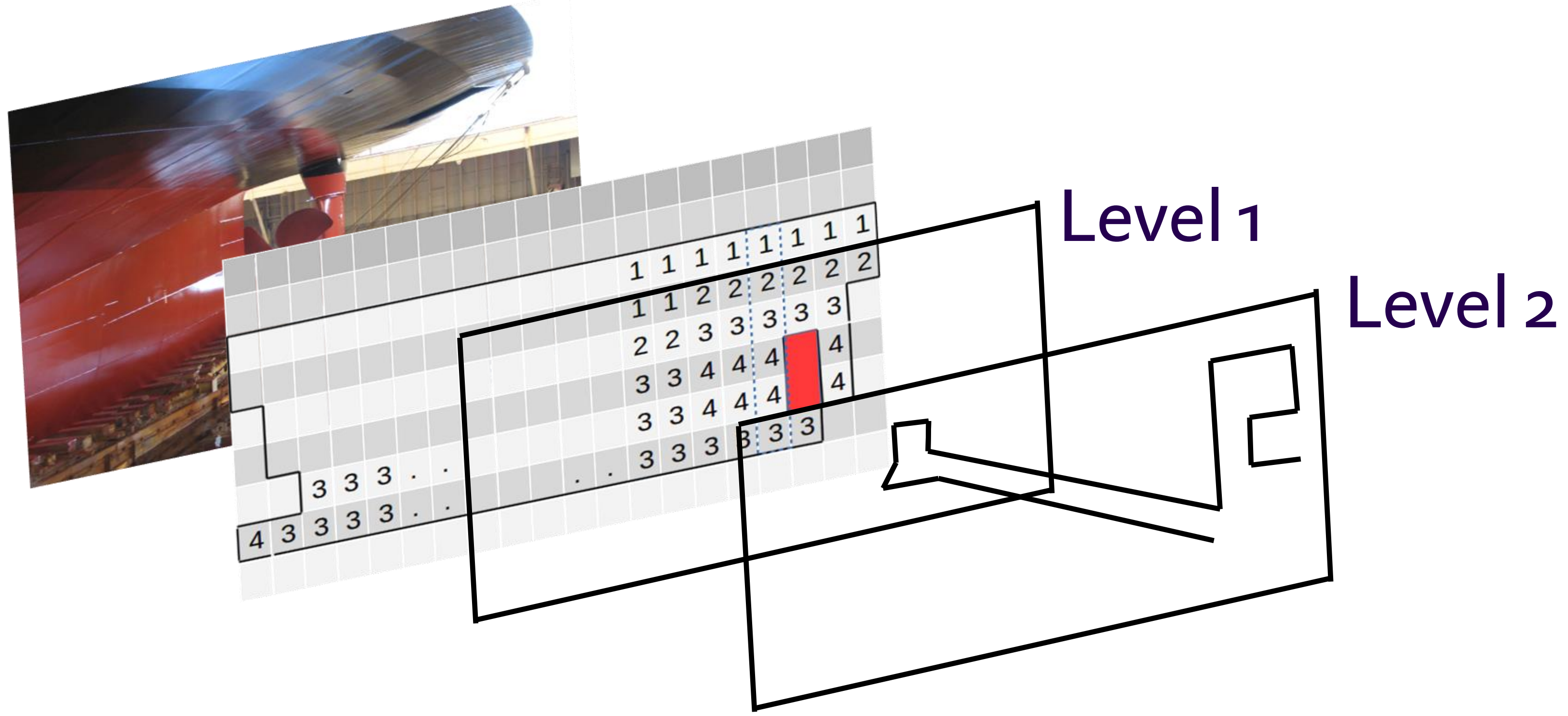
Bugwrigth2 - Project Goals

Autonomous outer hull service

1. **Precise navigation on large low-textured structures**
2. **Heterogeneous multi-robot inspection and cleaning**
   3 MAVs, 3 AUVs, 4 crawlers
4. **Cross-domain autonomous operation and inspection**
   above water and underwater
5. **Advanced inspection technologies**
   highly precise detection and localization of defects
6. **Remote inspection through virtual-reality**

Bugwright2: Lakeside Labs Mission

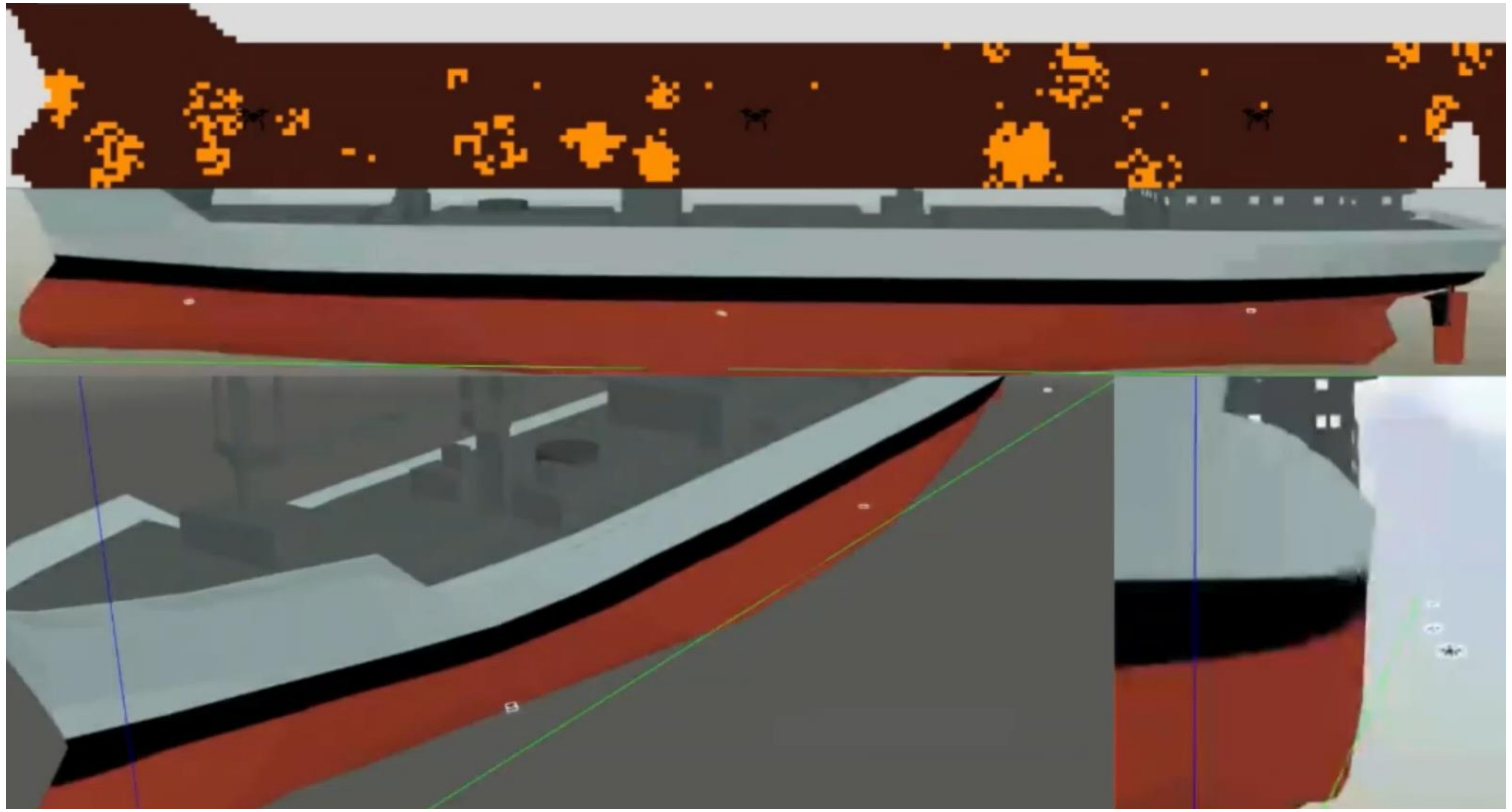
- Swarm of drones to search defects with low resolution at large distance
- On defect detection, go closer to inspect with high resolution
  - ship hull is mapped on a depth grid
  - drones fly at two distances to execute the mission (2.5D space)



Bugwright2: Partitioned TSP Algorithm

Dividing the problem into a set of Traveling Salesman Problems

- considering prior information
- partitioning into connected sub-areas of similar size via DARP [1]
- re-computing paths online when new information is disclosed
- How to perform the task without any prior knowledge?



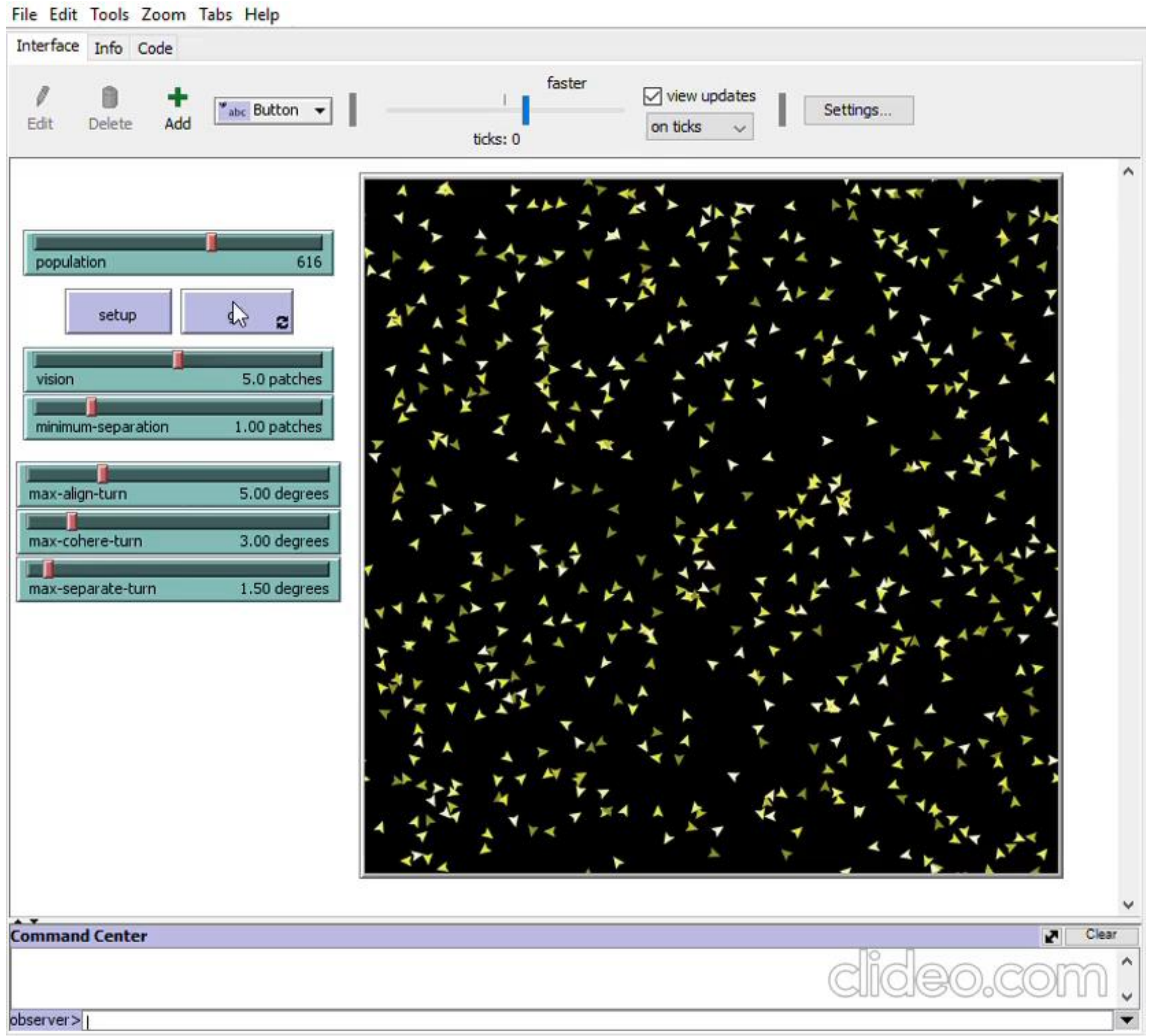
Source: Ship hull inspection simulation in Gazebo, Lakeside Labs

[1] A. Kapoutsis et al., "DARP: Divide Areas Algorithm for Optimal Multi-Robot Coverage Path Planning," J Intell Robot Syst, 2017.

Excursus: Principle of flocking

Three simple rules to achieve flocking in swarms [1]

1. **Repulsion**
2. **Alignment**
3. **Cohesion**

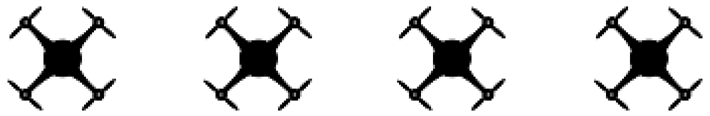


Source: Flocking simulation in Netlogo, Lakeside Labs

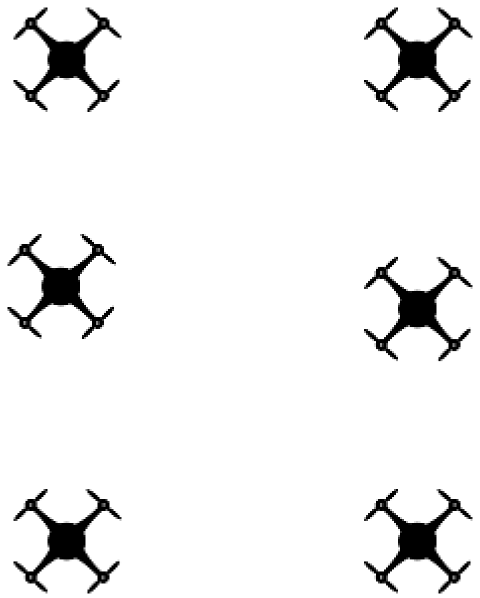
[1] Reynolds, Craig W. "Flocks, herds and schools: A distributed behavioral model.“, ACM SIGGRAPH, 1987.

Excursus: Flocking in formation

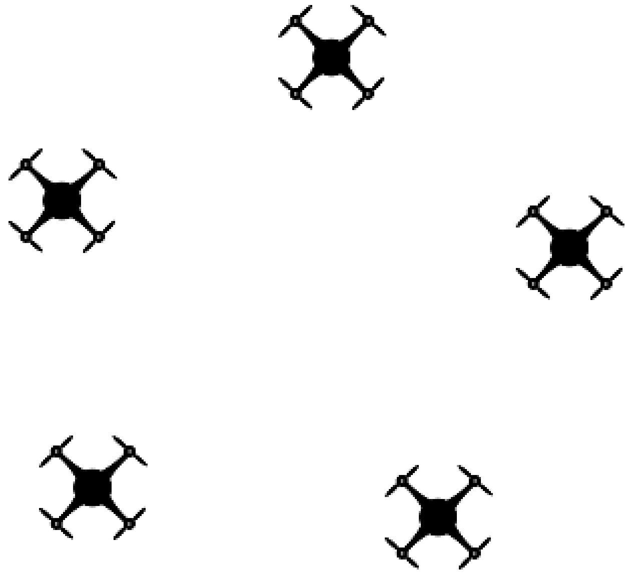
Apply additional rules on how agents position themselves in regard of their neighbors to achieve certain formations



Line



Grid

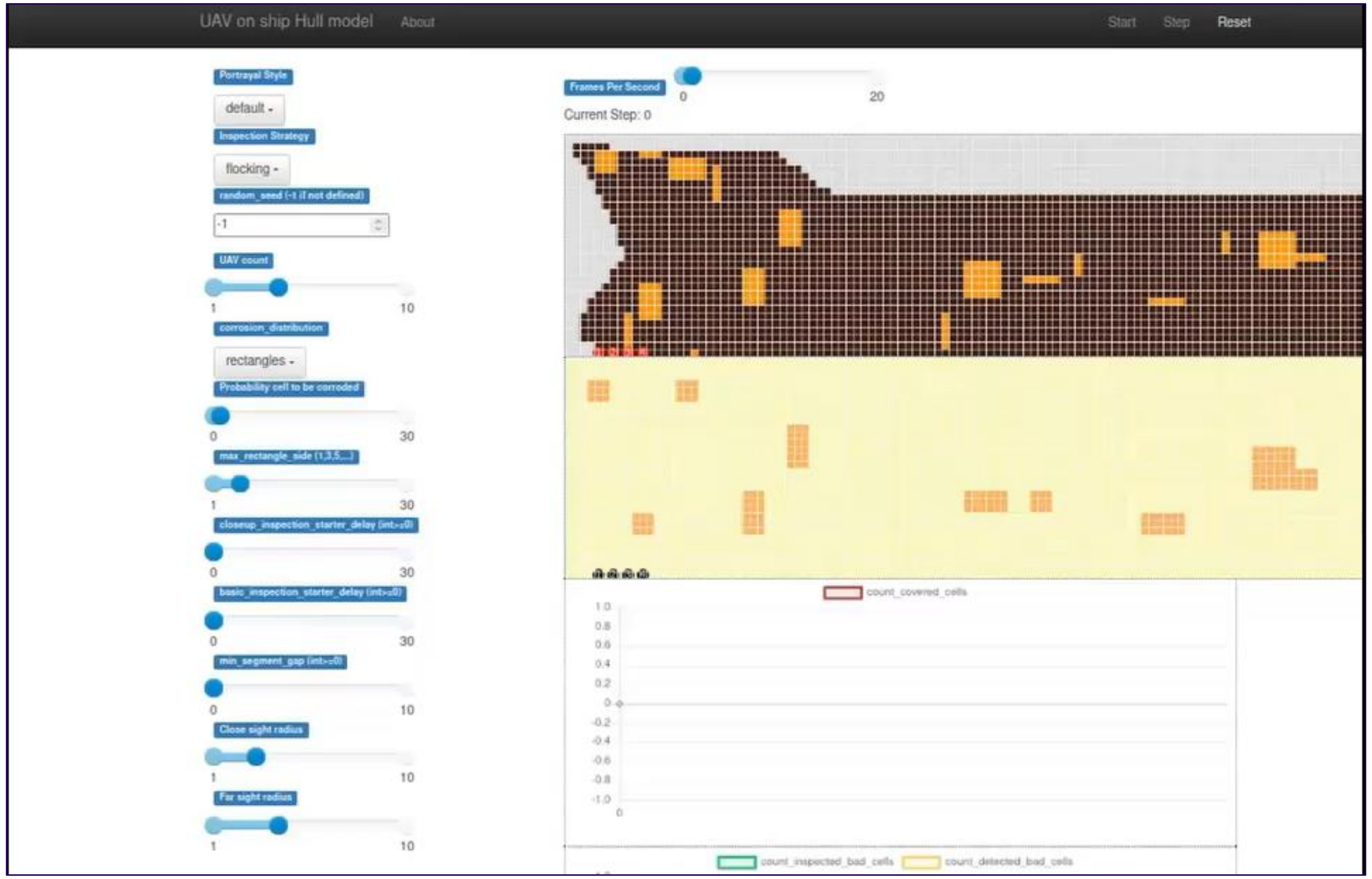


Ring

Bugwright2: Flocking for Autonomous Hull Inspection

Stay together in a flock to inspect the ship hull

- sweep the unknown area in a line formation [1]
- no a-priori knowledge or planning required
- task division to perform close-up inspection



Source: Ship hull inspection simulation in MESA, Lakeside Labs

[1] Vásárhelyi et al. "Outdoor flocking and formation flight with autonomous aerial robots." IEEE IROS, 2014.

SWILT (*Swarm intelligence in industry 4.0*)

Scheduling in production is a typical problem coming with the increased complexity in industry 4.0 components

Main issues

- given constraints
- global objective in production plants

→ high mixture of product diversity together with historical growth of the industrial plant leads to an NP-hard problem of the WiP flow

SWILT

Existing optimization approaches exploit linear optimization methods which

- can only be used on a subset of the plant (with similar requirements)
- do not consider the entire system behavior
- have very long calculation times
- do not exploit the optimization potential

SO FAR: no optimal solution can be generated in polynomial time!

SWILT Challenges

1.500 products, **150** process classes, **10.000** lots

- What should be modeled as agent and what is the right level of abstraction?
- How to deal with inhomogeneities among entities?
- How to implement swarm communication paradigms in the setting of a production plant?
- How to implement a solution on top of a working environment?
- How to validate the approach?

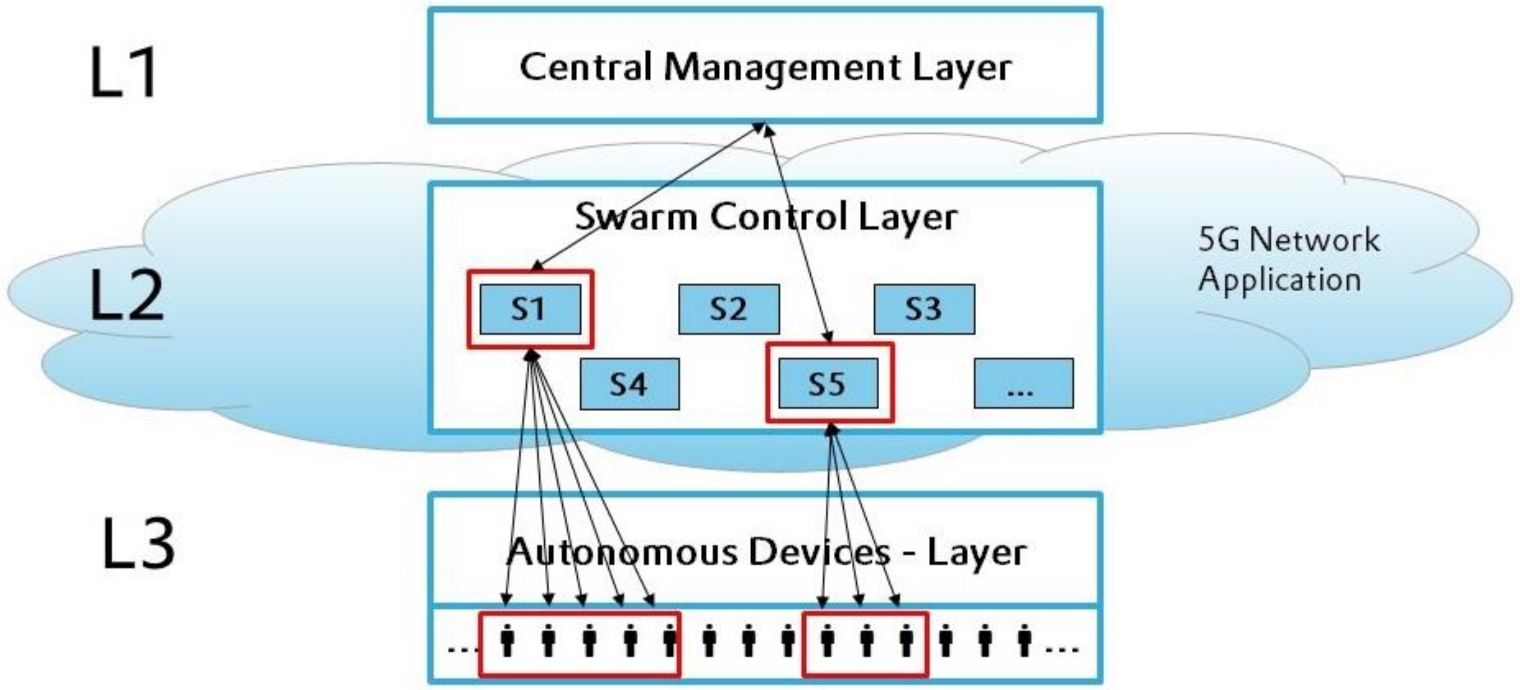
Source: Infineon Technologies AG

SWILT (*Swarm intelligence in industry 4.0*)

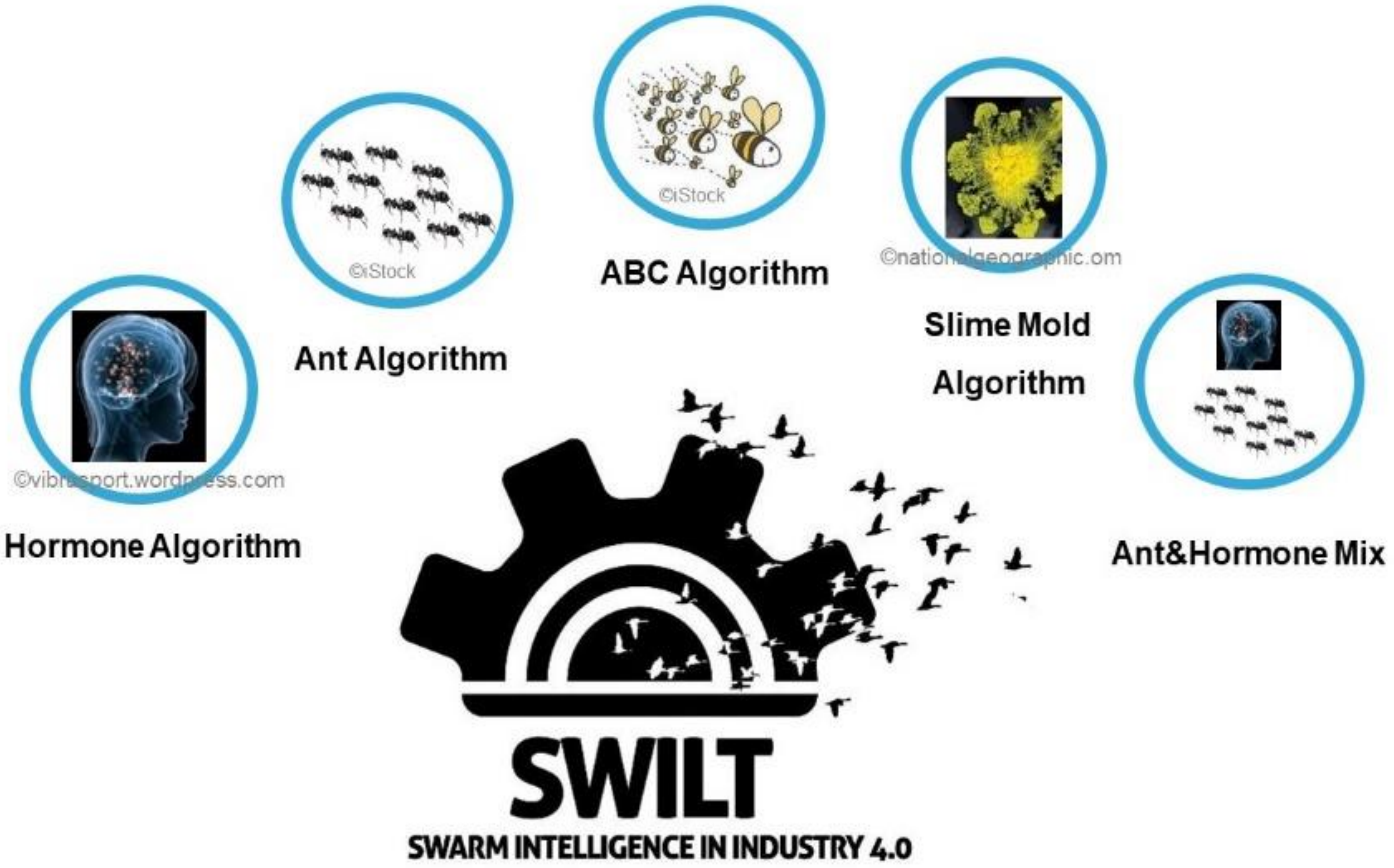
Model each WiP step as autonomous swarm agent
(e.g., machines, products, queues)

Establish an entirely new concept to consider inter-swarm activities

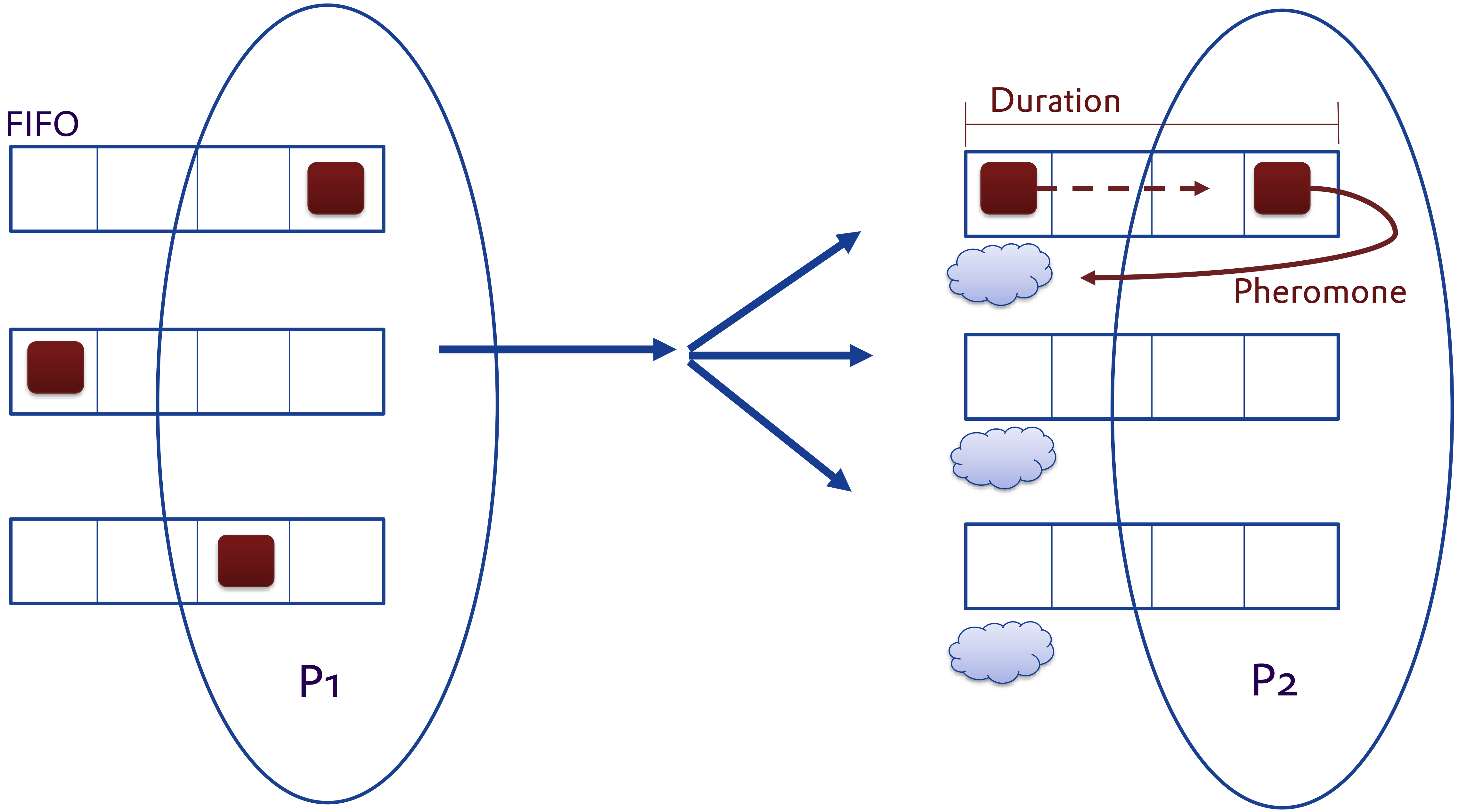
- behavior and communication between
  - different swarms
  - swarms and humans
  - swarms and central management units



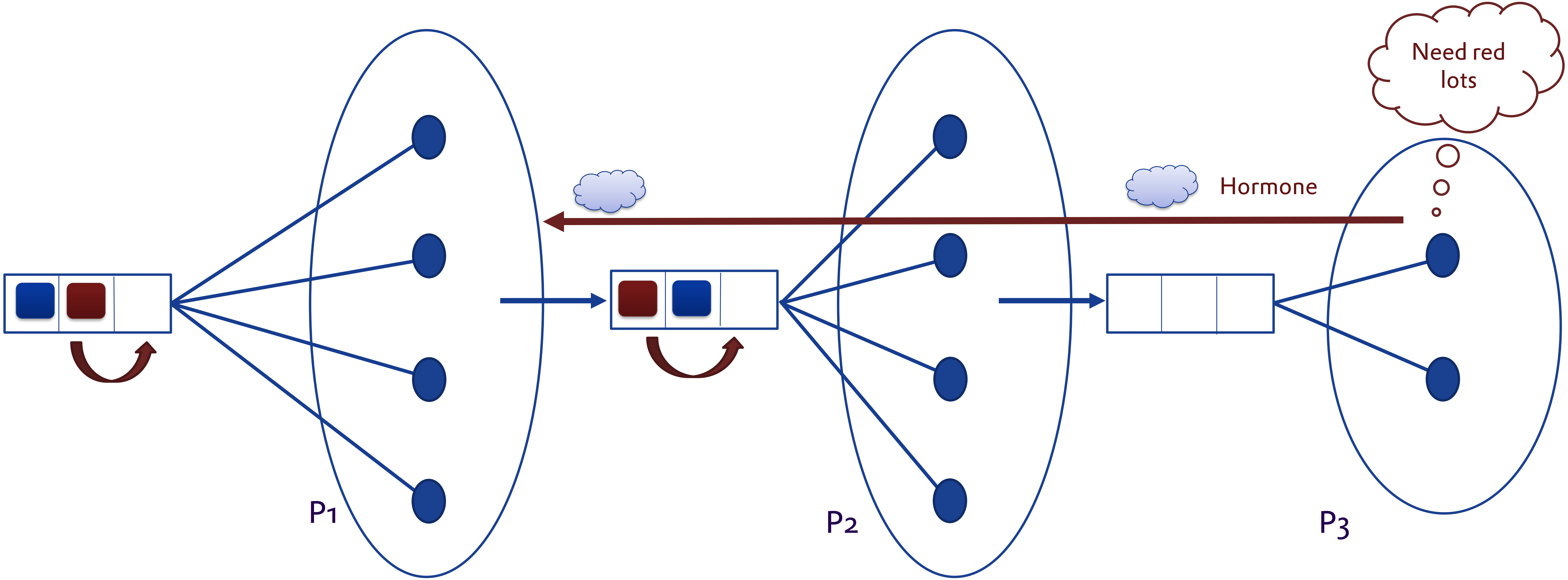
SWILT Swarm Algorithms



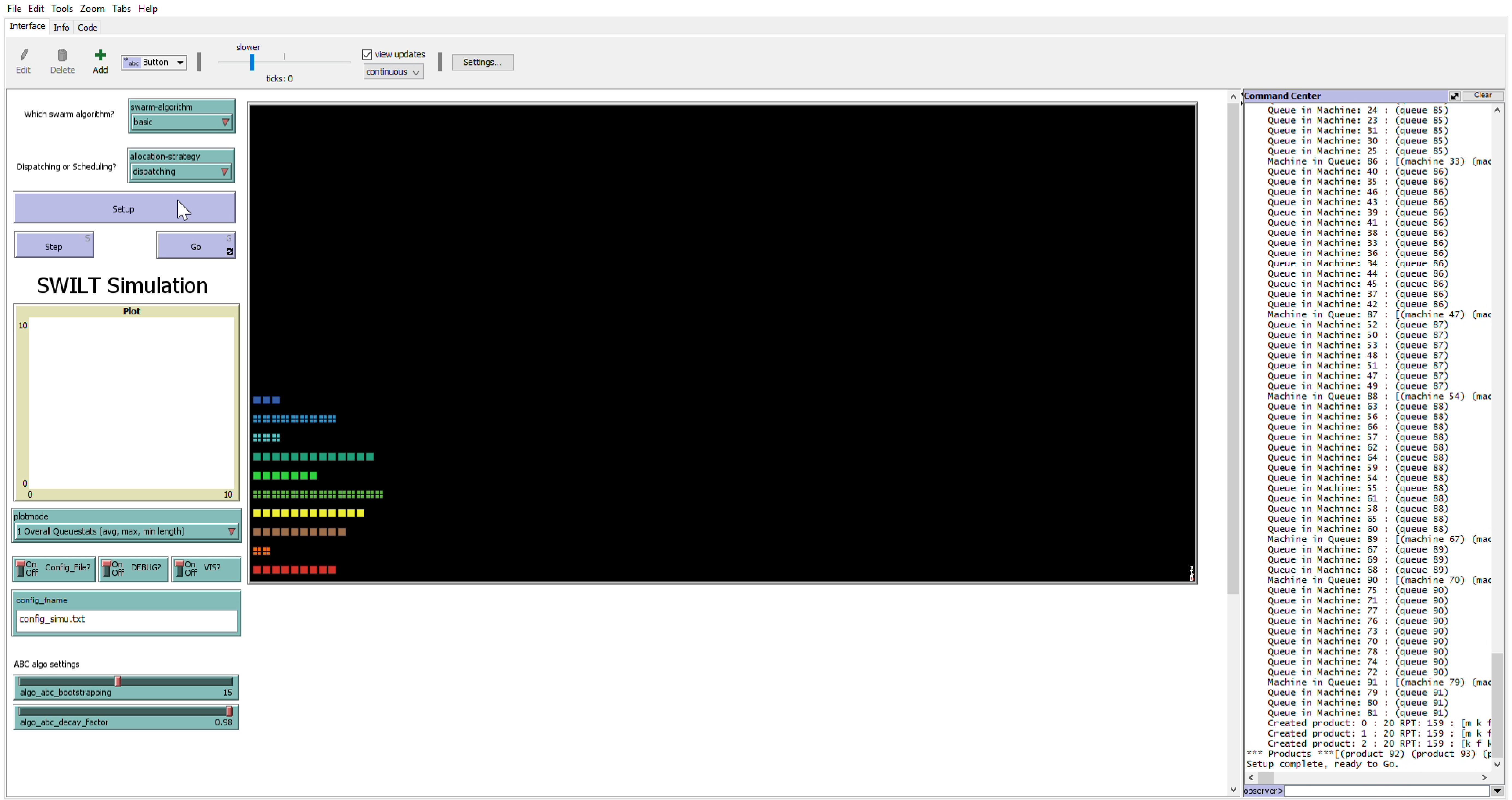
SWILT: Ant algorihtm for scheduling



SWILT: Hormone algorihtm for dispatching



SWILT: Netlogo simulation environment



MCUAS – Military Counter Unmanned Aerial Systems

Developing defense strategies against attacking UAV swarms

- appearing in a swarm, autonomous drones detect, pursue and attack targets autonomously
- dynamics should not be underestimated

Source: Andy Dean Photography

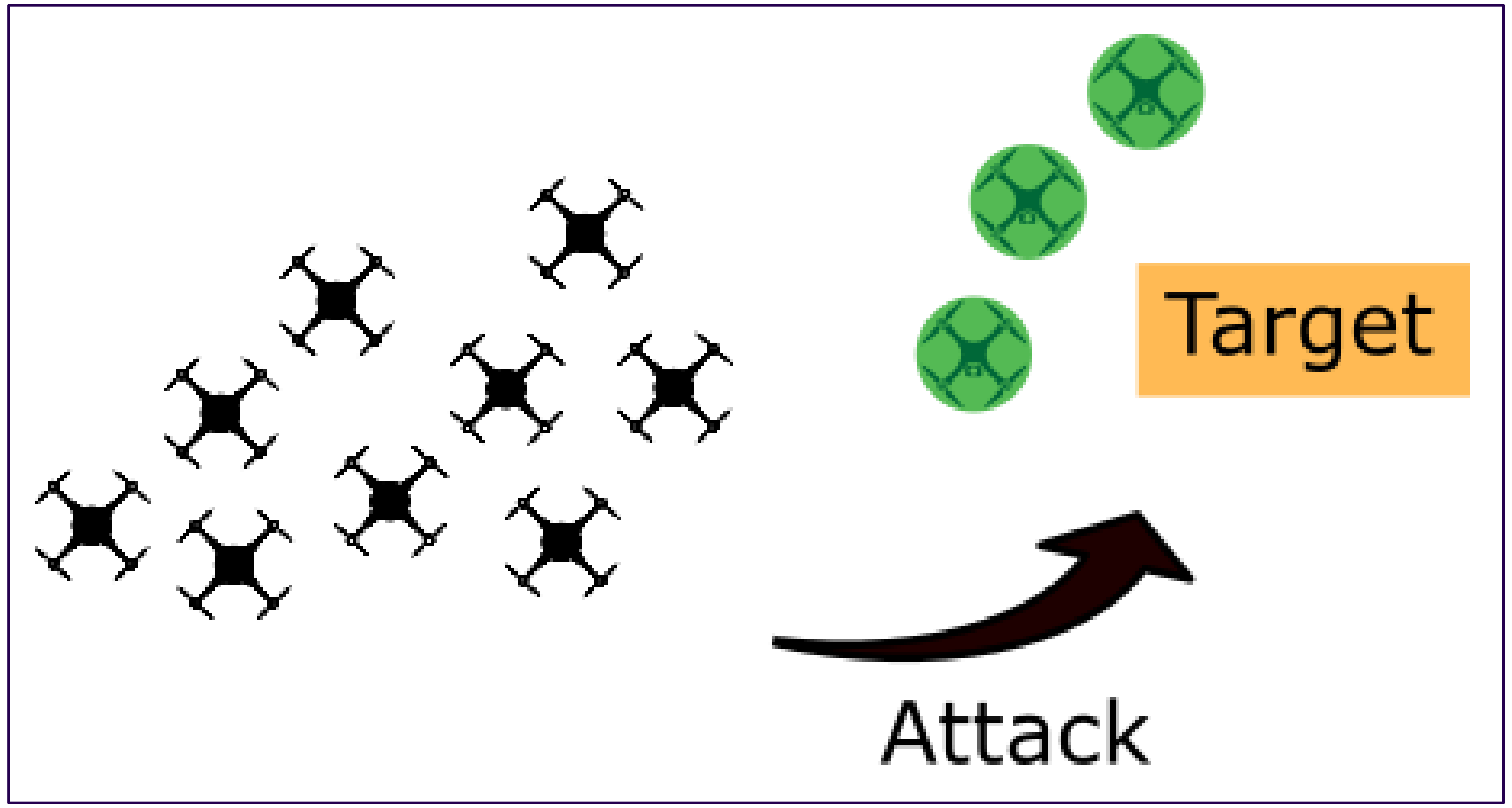
KIRAS Sicherheitsforschung AIT Austrian Institute of Technology Lakeside Labs Self-Organizing Networked Systems Joanneum Research LEADER Photonics INRAS

MCUAS - defense strategies

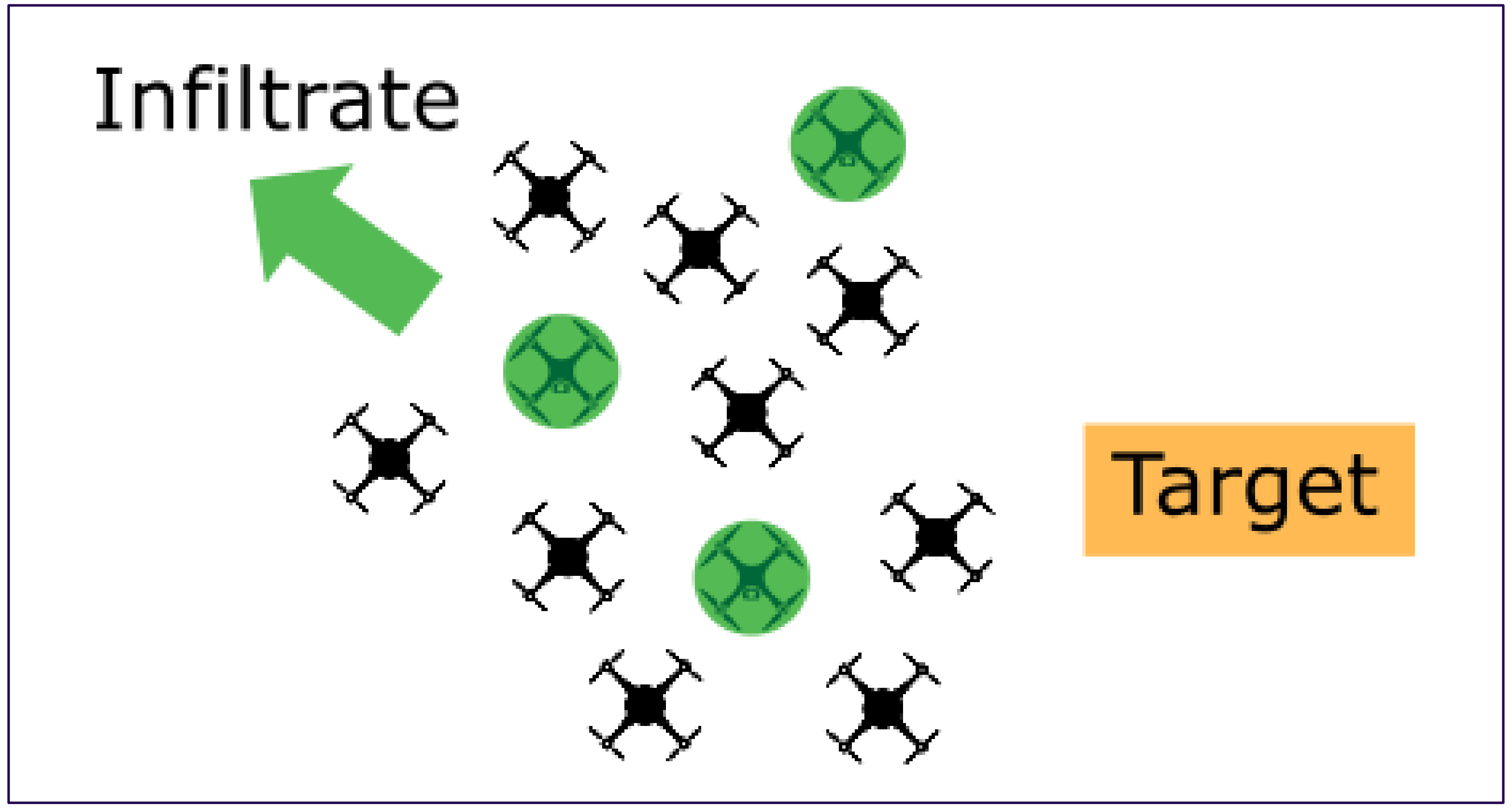
What can we do to defend against attacking drone swarms?

- GNSS jamming or spoofing
- exploiting physical force against the attackers
  - catch nets, lasers, trained birds, ballistic cannons, …
- trying to hide or protect the target area
- use a defender swarm (swarm against swarm)
- use defender UAVs to mislead the attackers from the target (induce drones)

MCUAS – Inducing drones to mislead attacking swarms



A few drones (e.g., three) are used to mislead an attacking swarm from the target.



The drones infiltrate the attacking swarm with the intention to either buy time or to mislead them.

KPIs: number of UAVs, how long its possible to keep the attackers away, how fast is the defending swarm…

MCUAS - Swarm algorithms for attack

As a starting point, we assume the attacking swarm to search and attack a specific target via target-oriented swarm algorithms

1. **Grey Wolf Optimizer** (GWO) [1]
2. **Slime Mould Algorithm** (SMA) [2]

Grey wolf hunting behavior [3]

Physarum Polycephalum [4]

[1] S. Mirjalili et al., "Grey wolf optimizer,"Advances in engineering software, 2014.
[2] S. Li et al., "Slime mould algorithm: A new method for stochastic optimization,"FutureGeneration Computer Systems, 2020.
[3] C. Muro et al., " Wolf-pack (canis lupus) hunting strategies emerge from simple rules in computational simulations", Behavioural processes, 2011.
[4] N.Edwards,"Physarum polycephalum essayant de sortir de sa boıte," 2020.

MCUAS – Defense

First attempt: use a similar strategy for the defense as is used for the attack

1. Inject false information
2. Move with the attacking swarm, distracting it gradually away from the target

MCUAS – Visualization of GWO defense

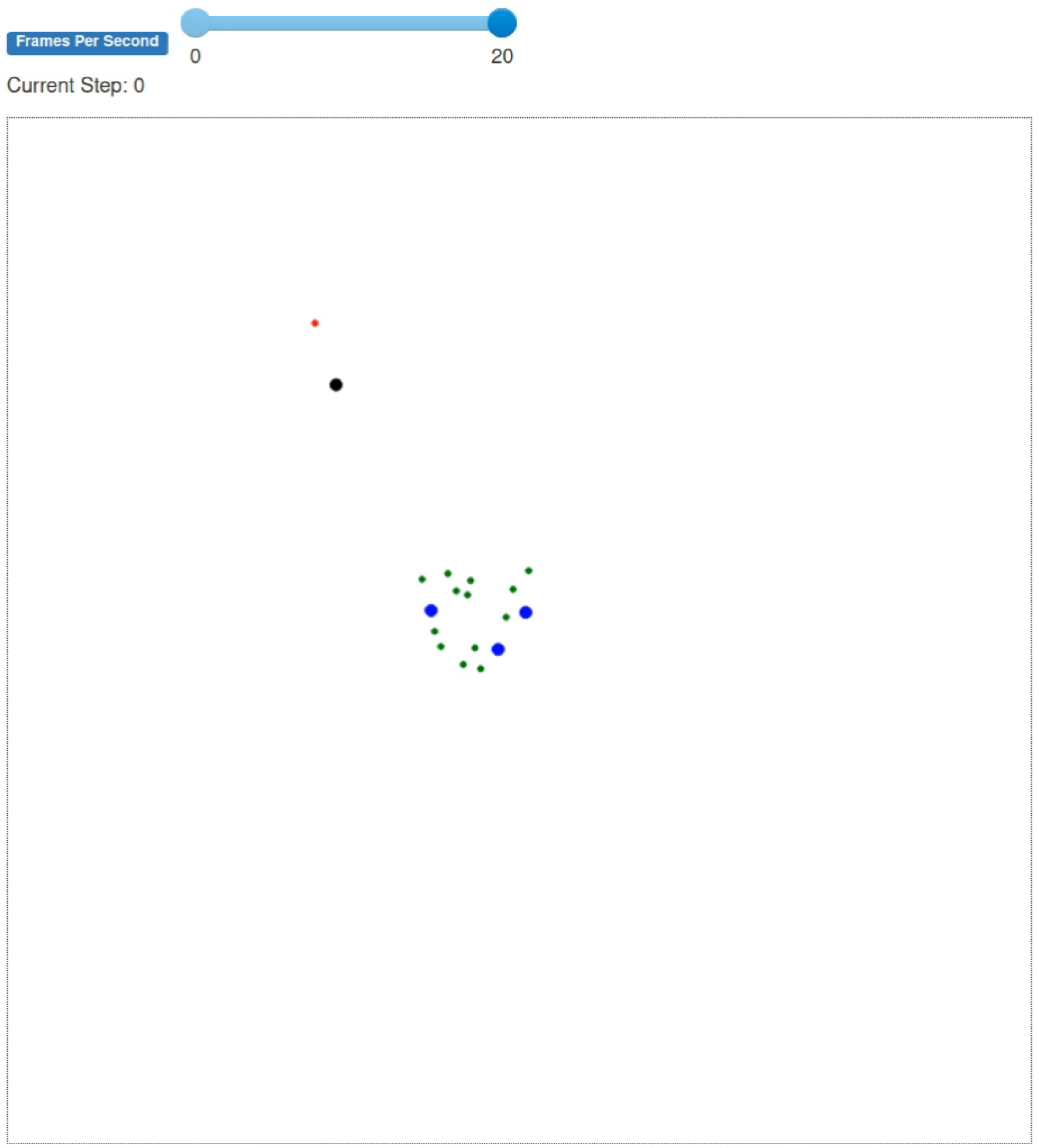
Target

Omega wolves

Leader wolves

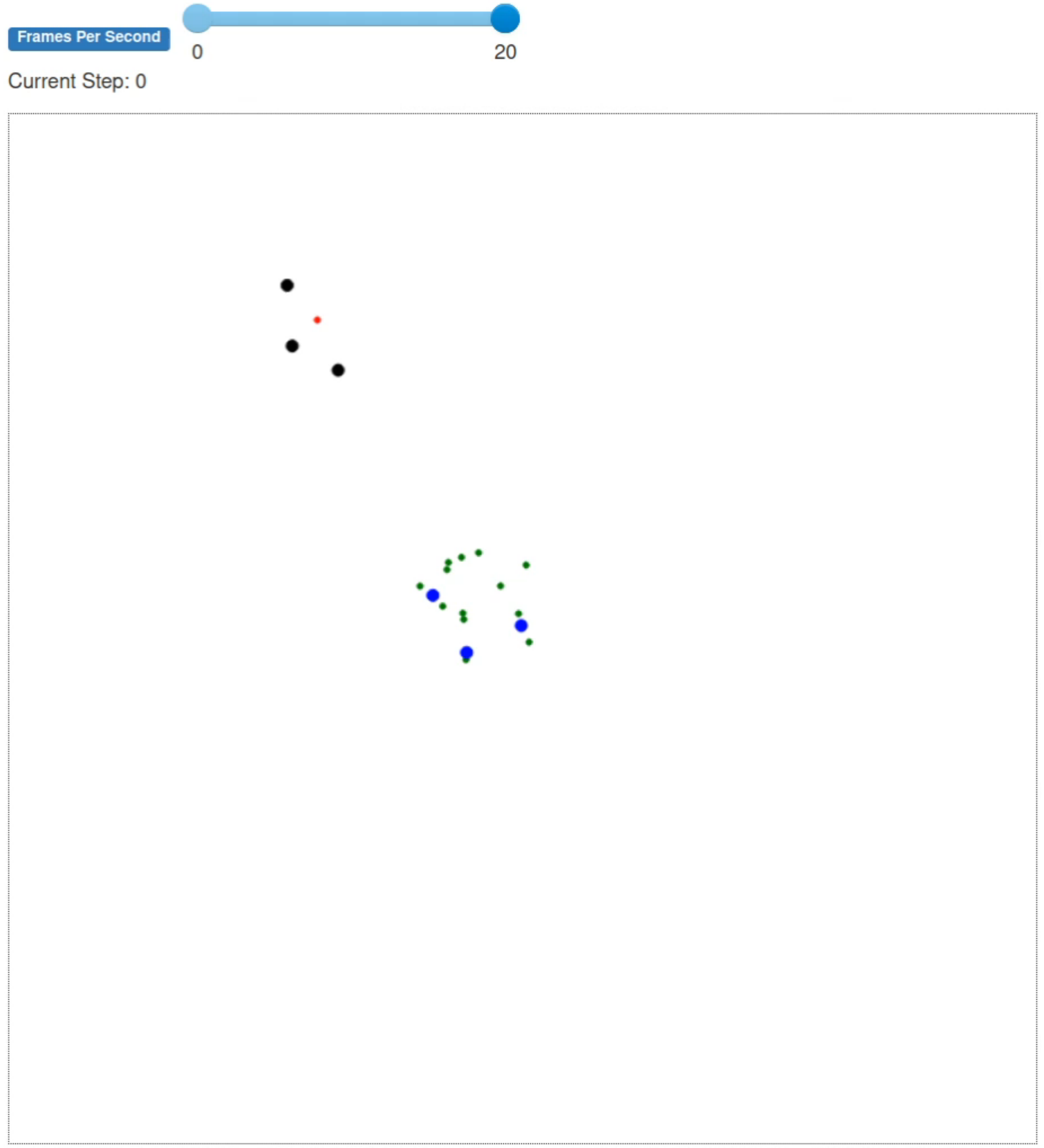
Defender drones

No defenders



One defender

MCUAS – Visualization of GWO and SMA defense



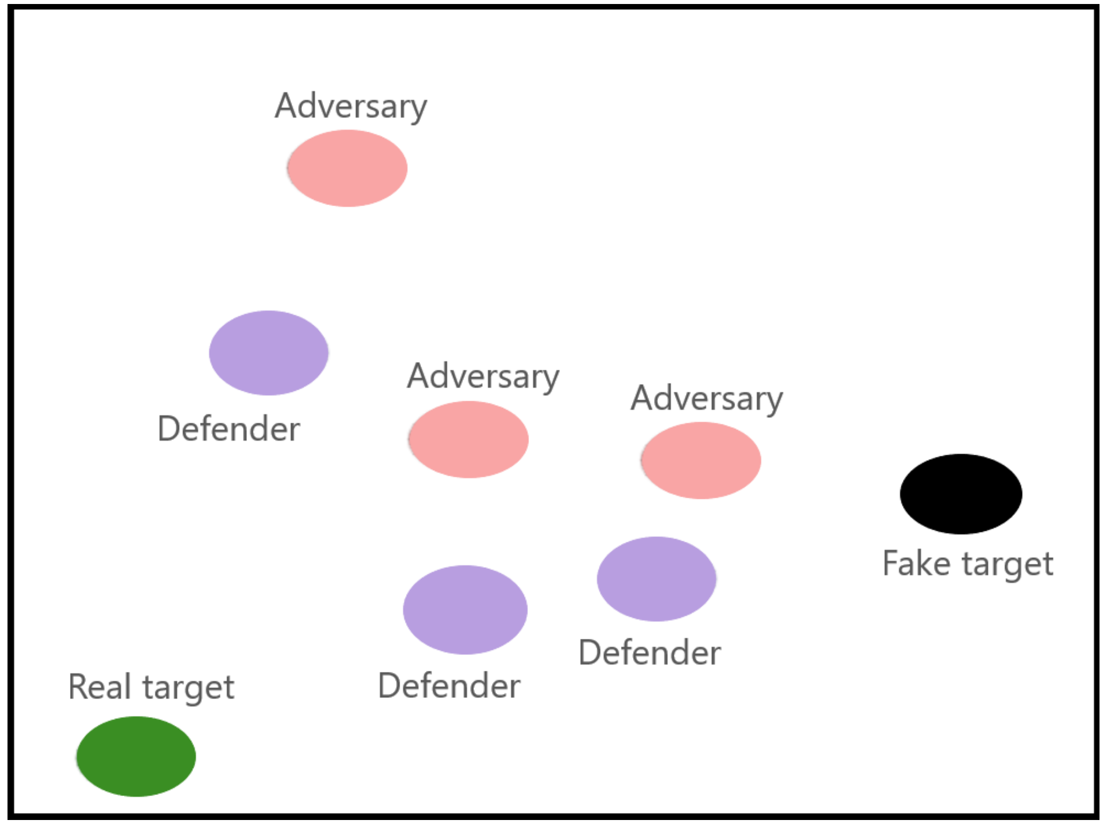
Three defenders (GWO)

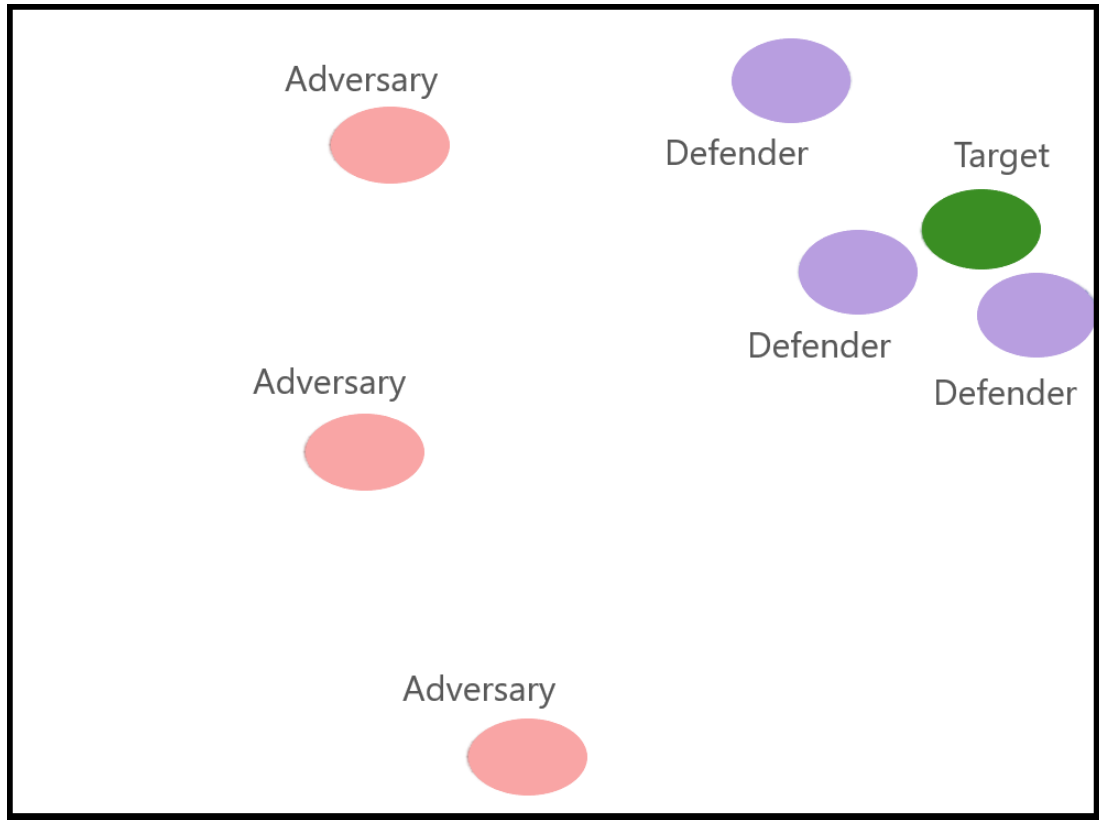
Five defenders (SMA)

MCUAS – Defense

- **Generalized defenders working against a group of different attack algorithms**

1. Machine learning
    - RL-based attackers & defenders
    - communication vs. physical defense





Swarm Intelligence – Emerging topics

Lack of a formal definition of robustness

- "simple" robustness observations such as scalability
- descriptive characteristic without formally defined measures

Lack of end-to-end swarm methodology

- simulation tools deal with two levels of abstraction:
  1. whole swarm from a high level of abstraction (MESA and Netlogo)
  2. physical simulation of the swarm (GAZEBO and AirSim)
- no tools integrating both aspects

More exploration and demonstrations of swarm intelligence for industry applications

Jennifer Simonjan

Lakeside Labs, Austria

Jennifer.Simonjan@ieee.org