

Swarmalatorbots

Robots that sync and swarm

Christian Bettstetter

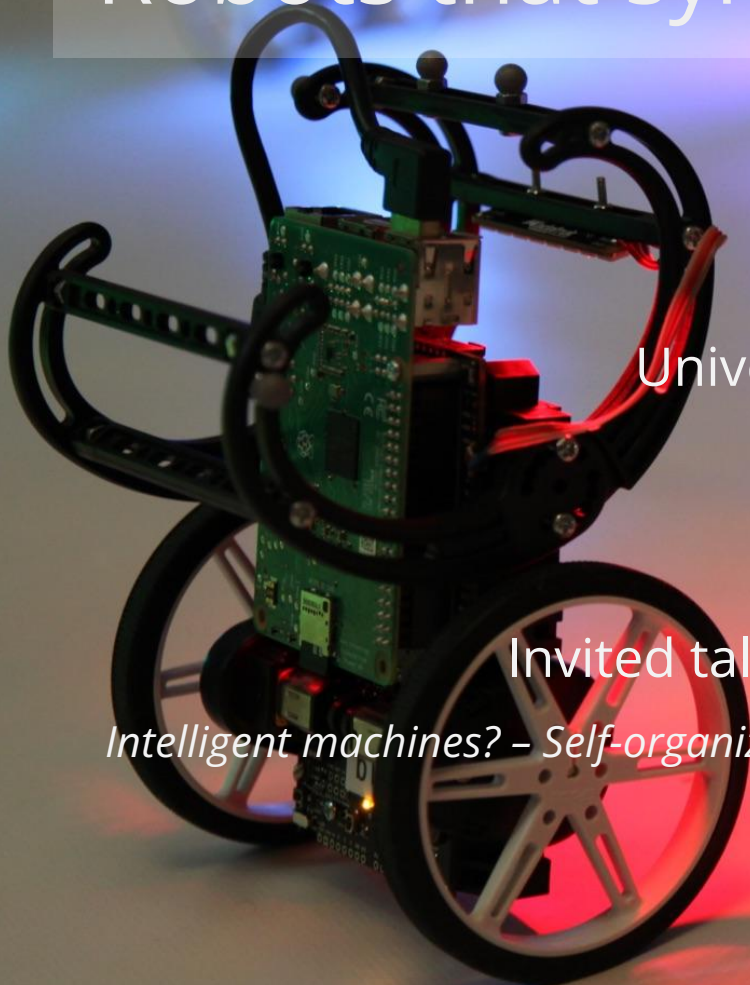
University of Klagenfurt and Lakeside Labs

with Agata Barciś and Udo Schilcher

Invited talk at MPI Physics of Complex Systems

Intelligent machines? – Self-organized nonlinear dynamics of machines across scales

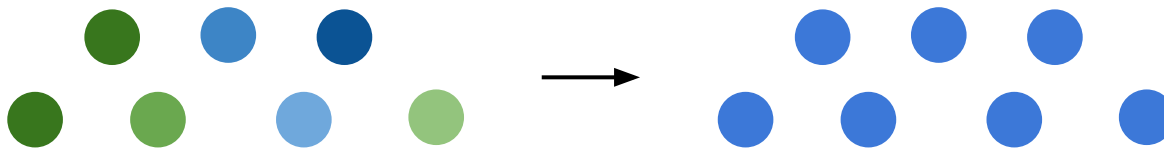
Dresden, June 21, 2022



Synchronization



Coordination of entities
to achieve order in the
time domain.



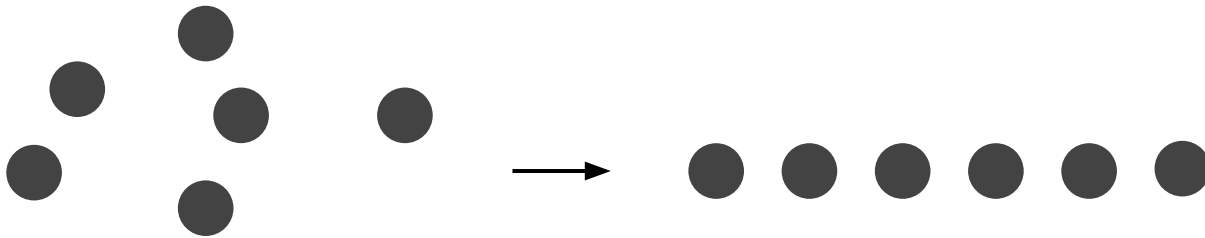
Color represents phase ϕ_i of entity i .

Adjustment of *phases* ϕ_i

Swarming



Coordination of entities
to achieve order in the
space domain.
(includes aspects of time)



Adjustment of *locations* \mathbf{x}_i

Synchronization and swarming



Synchronization

Phase ϕ_i



Swarming

Location \mathbf{x}_i

Swarmalators

- Unified model
- Bidirectional coupling
- Emergence of space-time patterns

O'Keefe, Hong, Strogatz:
Oscillators that sync and swarm.
Nature Communications, 2017

Swarmalatorbots

- 1 Theory of swarmalators
- 2 Robots that sync and swarm
- 3 Drones that sync and swarm
- 4 Take-away messages



Swarmalators

Synchronization

The *phases* ϕ_i of entities influence each other.

E.g.: Phases synchronize to a common value, or “desynchronize” to differing values (splay states).

Swarming

The *locations* \mathbf{x}_i of entities influence each other.

E.g.: Entities physically attract or repel each other based on their distance.



Swarmalators: Bidirectional coupling between sync and swarming

The *phases* ϕ_i influence the *movements* $\dot{\mathbf{x}}_i$, and the *positions* \mathbf{x}_i influence the *phase dynamics* $\dot{\phi}_i$.

E.g.: Entities with similar phases may attract or repel each other stronger, and close-by entities may synchronize faster.

Swarmalators

Entities that sync and swarm

- N entities indexed by i
- Location \mathbf{x}_i , distance \mathbf{x}_{ij}
- Phase ϕ_i , phase diff ϕ_{ij}

- Movement depends on phase:

$$\text{Velocity } \dot{\mathbf{x}}_i = \frac{1}{N} \sum_{j \neq i}^N \left[\underbrace{\mathbf{I}_1(\mathbf{x}_{ij})}_{\text{Attraction}} \underbrace{F(\phi_{ij})}_{1 + J \cos \phi_{ij}} - \underbrace{\mathbf{I}_2(\mathbf{x}_{ij})}_{\text{Repulsion}} \right]$$

- Phase dynamics depends on location:

$$\text{Phase change } \dot{\phi}_i = \left[\underbrace{\frac{K}{N}}_{\text{Attraction}} \sum_{j \neq i}^N \underbrace{H(\phi_{ij})}_{\text{Attraction}} \underbrace{G_\phi(\mathbf{x}_{ij})}_{\frac{1}{\|\mathbf{x}_{ij}\|}} \right]$$

Behavior is governed by two parameters J and K .

O'Keeffe, Hong, Strogatz:
Oscillators that sync and swarm.
Nature Communications, 2017.

Swarmalators

Two control parameters govern the system behavior

Coupling strength $J \in [-1, 1]$

How strong is the influence of phase similarity on spatial attraction?

Positive: entities are attracted by others with *similar* phases



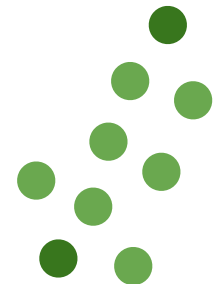
Negative: entities are attracted by others with *opposite* phases



Sync strength $K \in [-1, 1]$

How strongly coupled are the phases of two entities?

Positive: reduces the phase differences

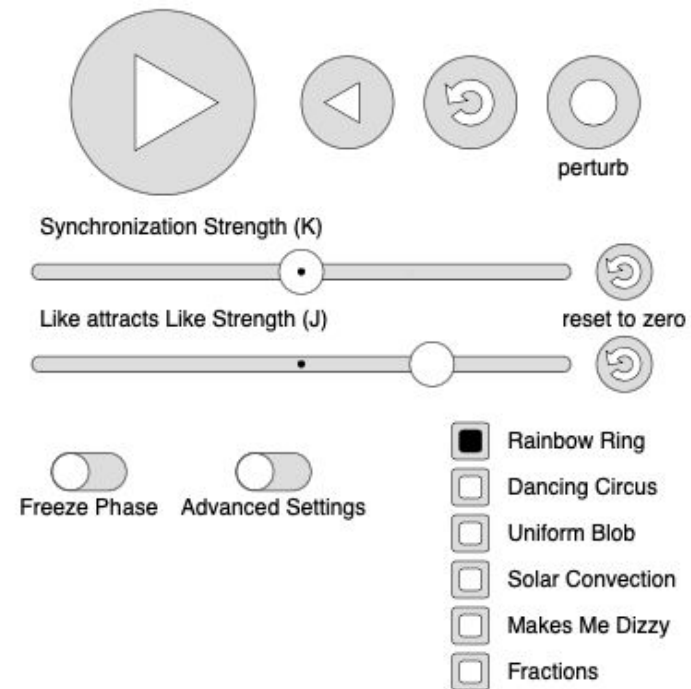
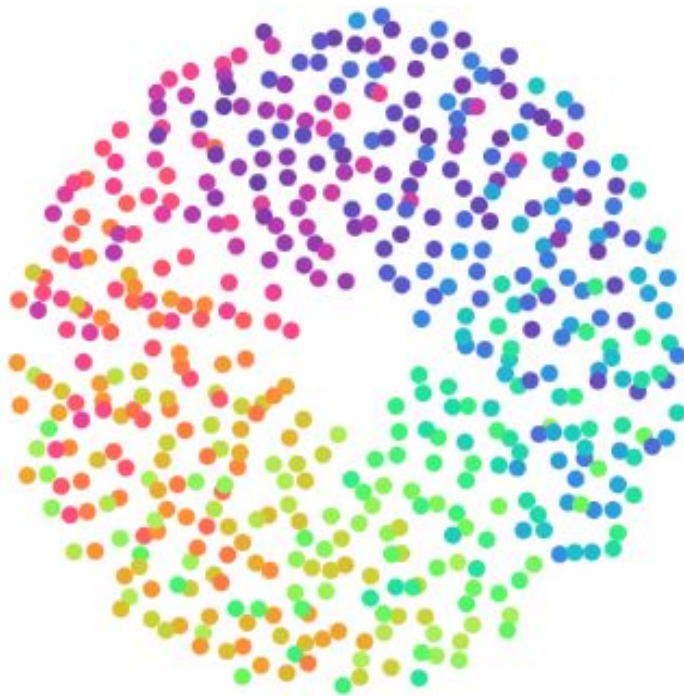


Negative: increases the phase differences



Complexity explorable “Swårmalätørs”

By Dirk Brockmann

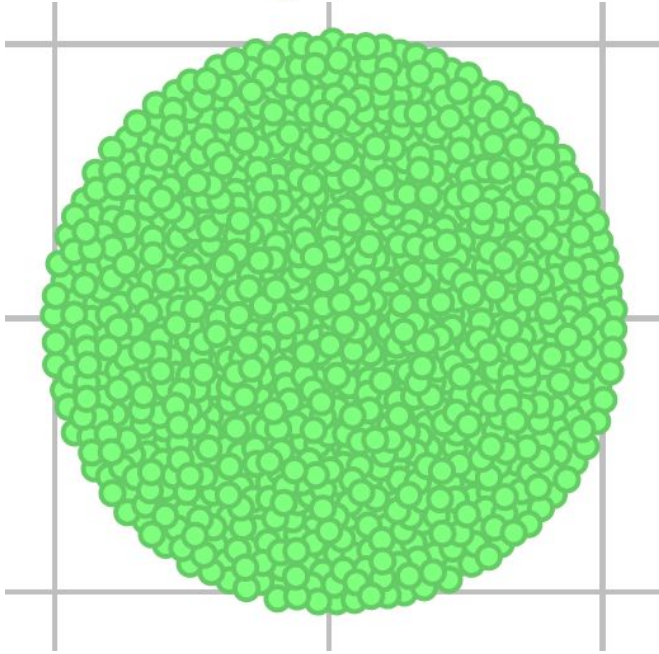


Brockmann: Complexity explorable: Swårmalätørs - Pattern that emerge when collective motion and synchronization entangle, complexity-explorables.org, 2021.

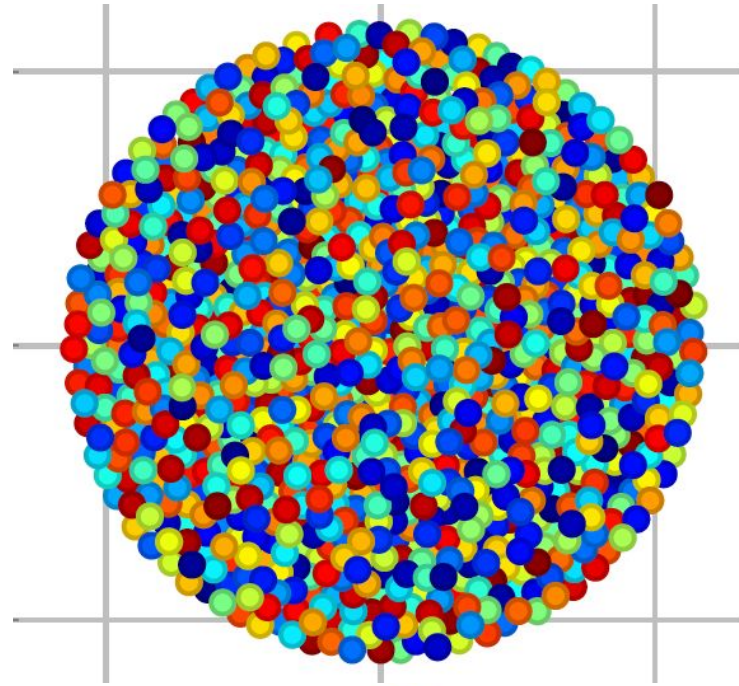


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Swarmalator patterns

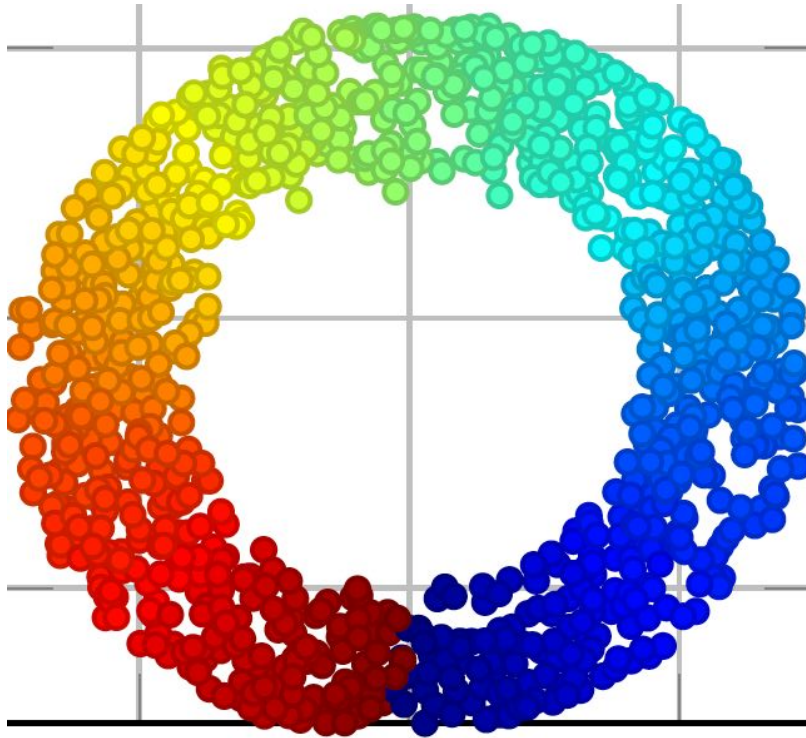


Static sync
 $(J, K) = (0.1, +1)$

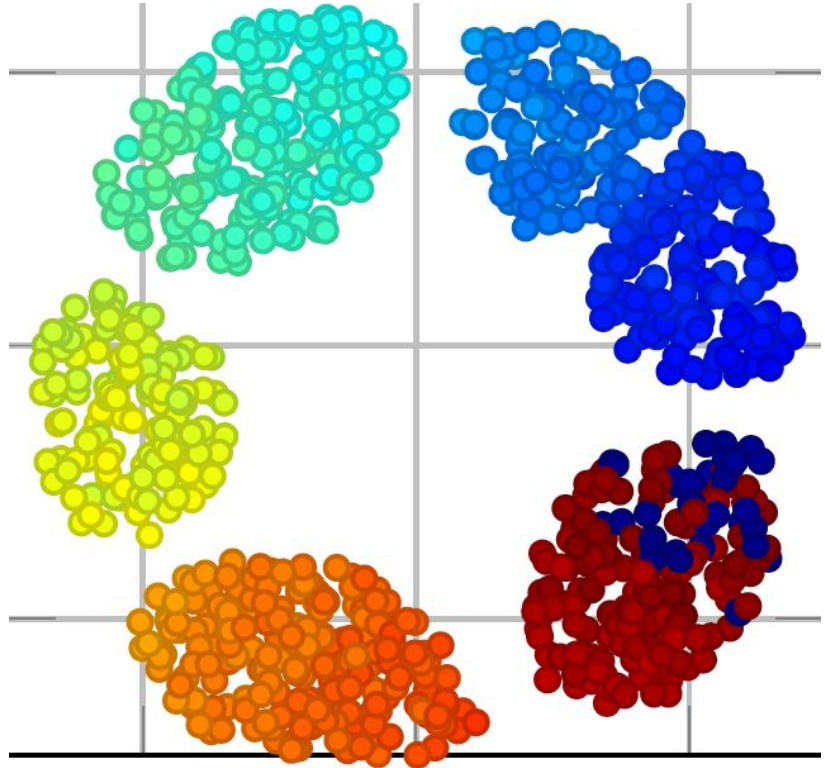


Static async
 $(J, K) = (0.1, -1)$

Swarmalator patterns

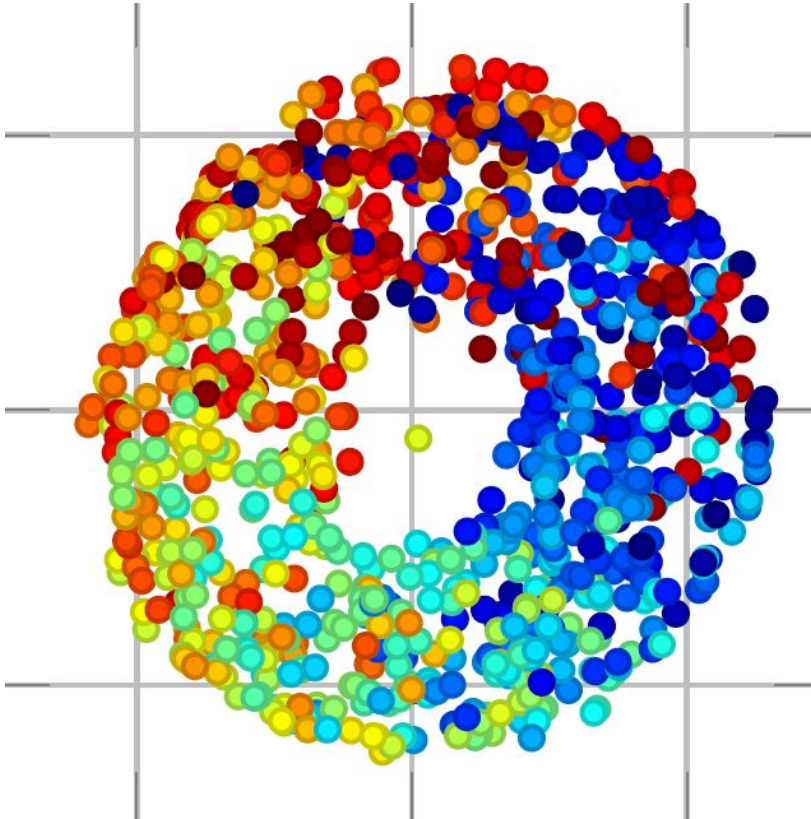


Static phase wave
 $(J, K) = (1, 0)$



Splintered phase wave
 $(J, K) = (1, -0.1)$

Swarmalator patterns

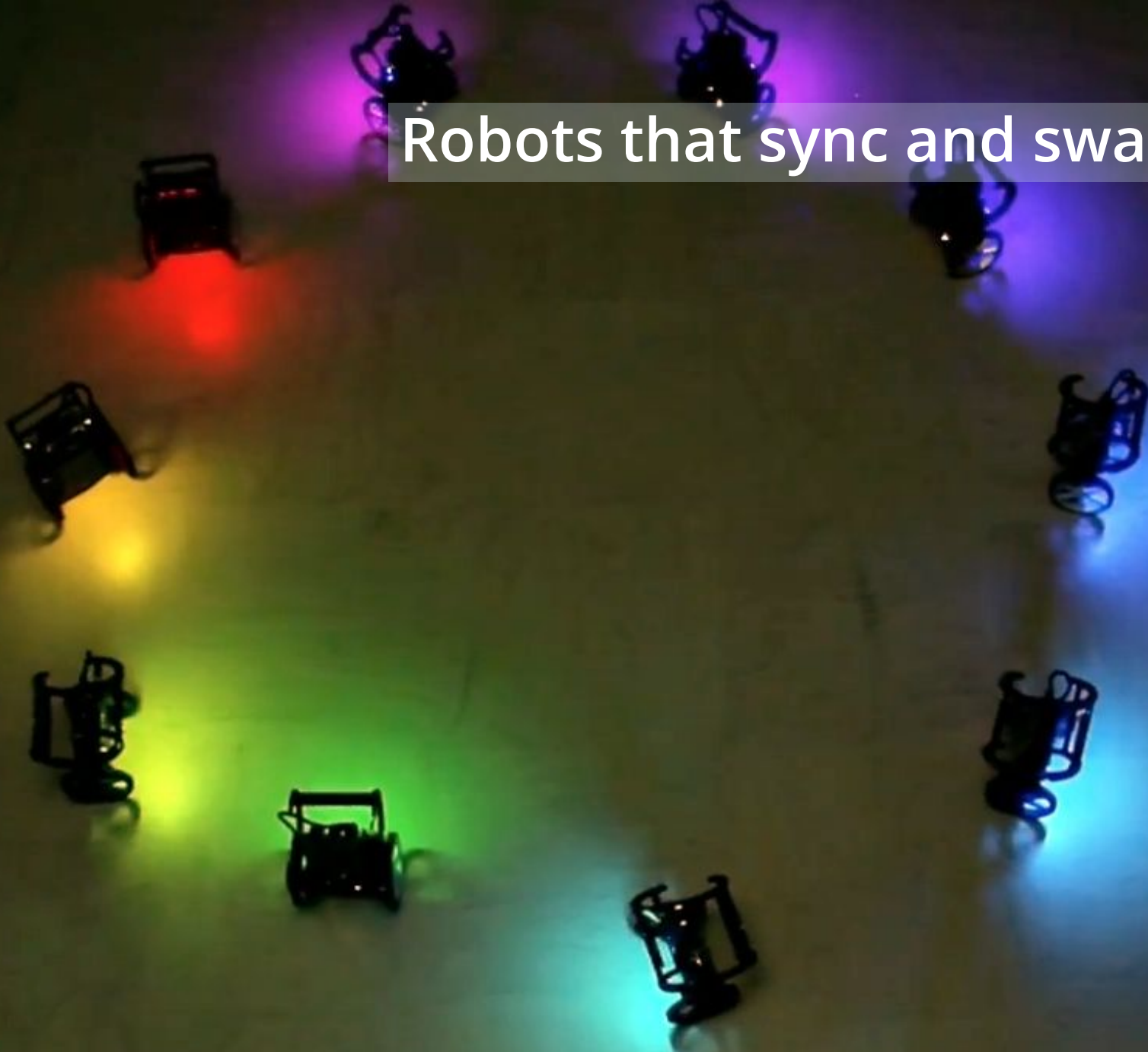


Active phase wave
 $(J, K) = (1, -0.75)$

Source of pictures

Schilcher, Schmidt, Vogell, Bettstetter: Swarmalators with stochastic coupling and memory. *IEEE ACSOS*, 2021

Robots that sync and swarm



From theory to practice

Transfer of the swarmalators concept to robotics

Research issues

- How to *adapt* the swarmalator model for use in robotics?
- Does the adapted model lead to *identical patterns*?
- Which *applications* exist for swarmalatorbots?

Barciś, Barciś, Bettstetter: Robots that sync and swarm: A proof of concept in ROS 2.
IEEE Intern. Symp. on Multi-Robot and Multi-Agent Systems (MRS), 2019.

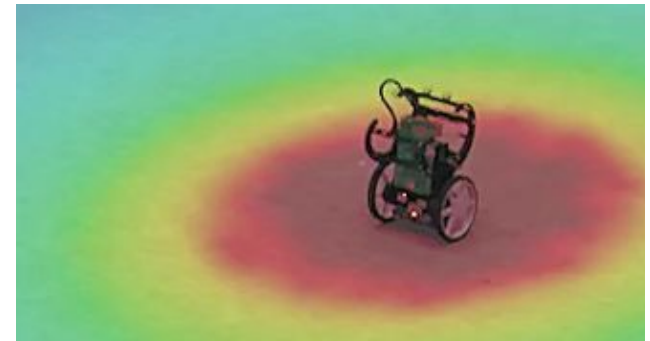
Schilcher, Schmidt, Vogell, Bettstetter: Swarmalators with stochastic coupling and memory.
IEEE Intern. Conf. on Autonomic Computing and Self-Organizing Systems (ACSOS), 2021.

From theory to practice

Transfer of the swarmalators concept to robotics

Mechanics

- Robots have speed limits and other movement constraints.
- Robots require collision avoidance.



Interaction between robots

- Robots are typically *not* continuously coupled but instead interact at discrete points in time.
- Interaction via exchange of messages or sensor measurements.
- The communication range is limited (no all-to-all coupling).
- Messages over radio channels can be lost.
- Messages experience a propagation and processing delay.

Swarmalatorbots

A swarmalator model suited for robots

Each entity ...

- periodically broadcasts its own state (ϕ , predicted x)
- stores the latest states received from others (memory)
- updates its own state (ϕ , x) using time-discrete models of
 - temporal coordination
 - spatial coordination
 - coupling between temporal and spatial coordination

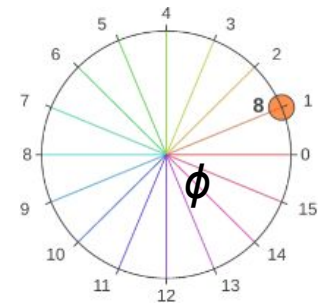
Barciś, Barciś, Bettstetter: Robots that sync and swarm: A proof of concept in ROS 2.
IEEE Intern. Symp. on Multi-Robot and Multi-Agent Systems (MRS), 2019.

Barciś, Bettstetter: Sandsbots: Robots that sync and swarm. *IEEE Access*, 2020.

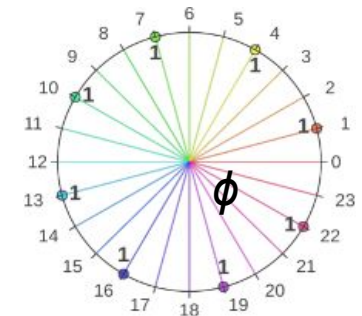
Swarmalatorbots

Temporal coordination

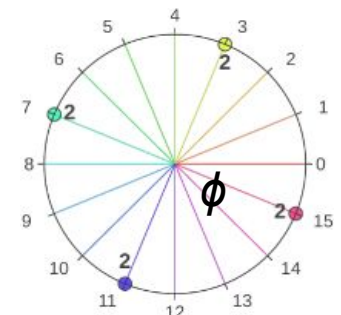
Synchronized:



Splay:



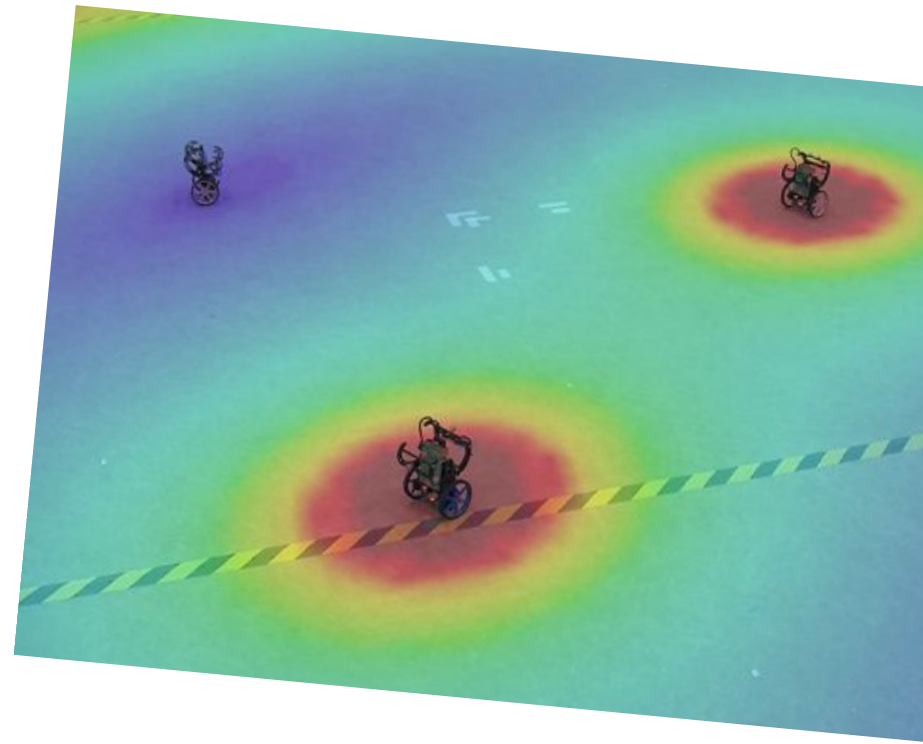
Clustered:



Swarmalatorbots

Spatial coordination

- Use of potential fields
- Collision avoidance
 - Safety area around robot
 - Adaptation of speed



Problems found and solved

- Physical oscillations occur and need to be mitigated
- Rate of state updates needs to be optimized adaptively

Swarmalatorbots

Experimental proof-of-concept with real robots

- Implemented revised model in ROS2
- Solved self-localization using pre-installed cameras (OptiTrack)
- Used Wi-Fi adhoc mode for wireless exchange of states
- Demonstrated proof-of-concept with small robots

All five original swarmalator patterns can be qualitatively reproduced both in simulation and in the real world.

Barciś, Barciś, Bettstetter: Robots that sync and swarm: A proof of concept in ROS 2. *IEEE Intern. Symp. on Multi-Robot and Multi-Agent Systems (MRS)*, 2019.

Barciś, Bettstetter: Sandbots: Robots that sync and swarm. *IEEE Access*, 2020.

Robots that sync and swarm

Robots that Sync and Swarm

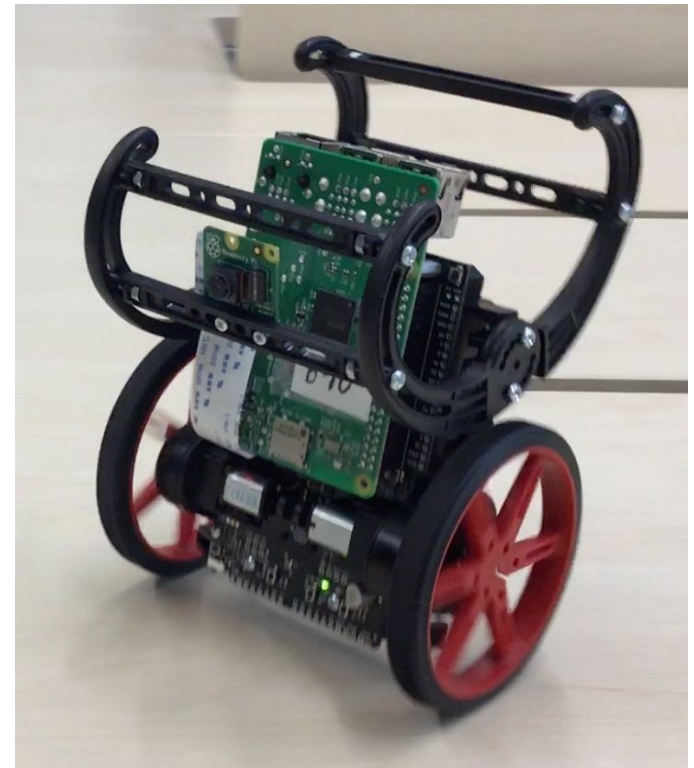
A proof of concept in ROS 2

Balboa robot

- Company: Pololu
- Price: about 120 US\$
- Computing: RaspberryPi
- Integrated inertial measurement unit (IMU) for state estimation

For our needs

- Tuned low-level control
- Modified interface between low-level controller and RaspberryPi
- Used LED to display ϕ -value
- Self-balancing



[balboa-32u4-arduino-library](https://github.com/balboa-32u4-arduino-library)

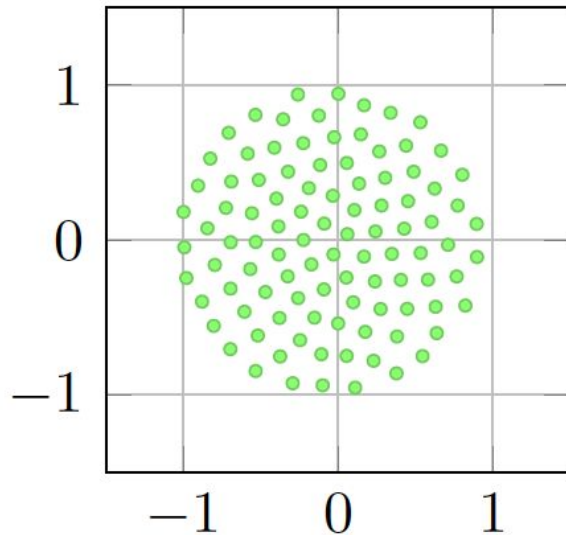
Swarmalators with real-world constraints

Constraint	Impact
Limited speed and acceleration	Slower pattern formation
Low localization accuracy	Same patterns "Jittering" of movements
Unreliable wireless channel	Same patterns Slower pattern formation
Limited communication range	New patterns

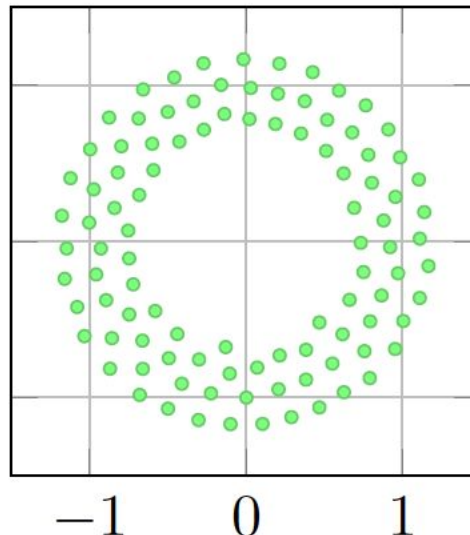
Impact of limited communication range

Static sync pattern

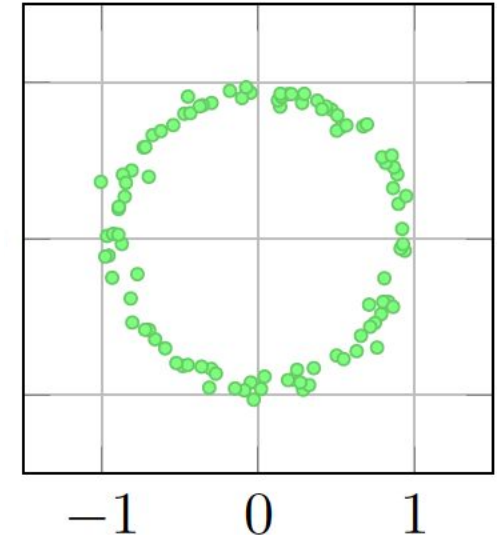
Full range
 $r = 2$



Half range
 $r = 1$



Small range
 $r = 0.01$



Schilcher, Schmidt, Vogell, Bettstetter: Swarmalators with stochastic coupling and memory.
IEEE Intern. Conf. on Autonomic Computing and Self-Organizing Systems (ACSOS), 2021.

Drones that sync and swarm

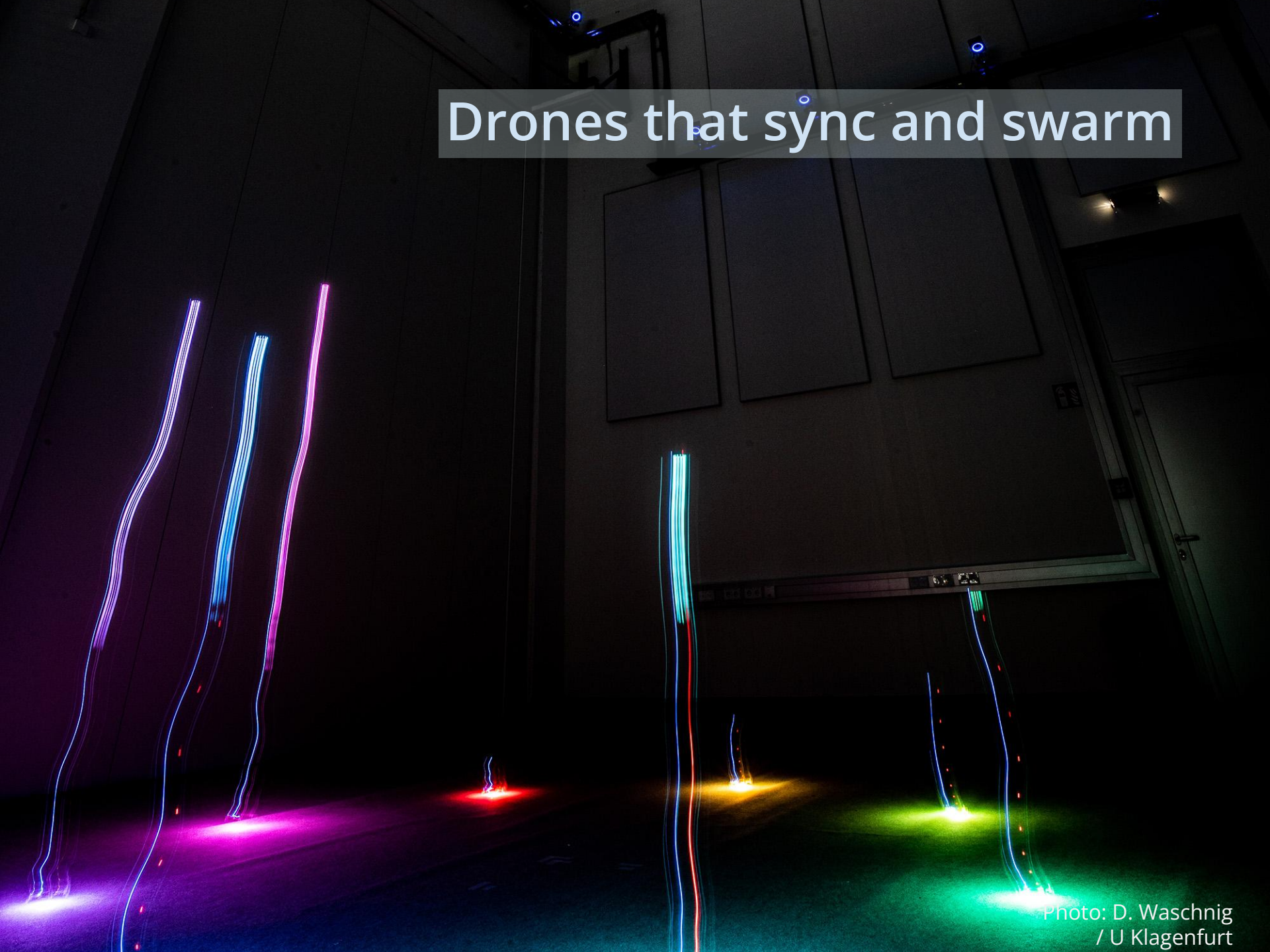



Photo: D. Waschnig
/ U Klagenfurt

Drone hall Klagenfurt

Size of 100 m² × 10 m height
Millimeter-precise localization
with 37 OptiTrack cameras
Powerful, dimmable lights
Protected control center
5G wireless connectivity
Located on campus





Swarmalator drones implemented
with Crazyflies and the Crazyswarm
platform (Klagenfurt, 2019)

Drones that sync and swarm

Drones that Sync and Swarm

Work in progress with CrazyFlies in the drone hall of Klagenfurt





Ars Electronica
Futurelab's *Drone 100*
for Intel (2015)

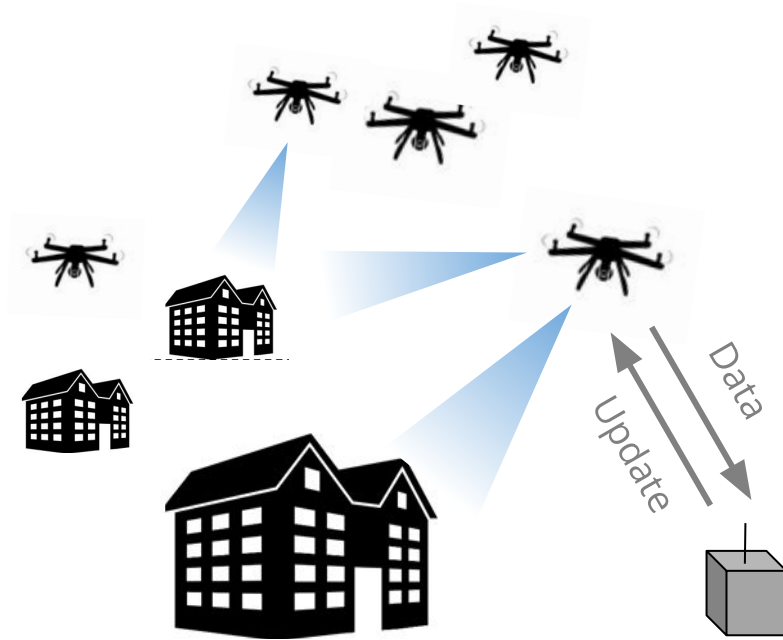
Photo: M. Hieslmair / Ars Electronica
Used with kind permission

A person is seen from behind, sitting on a bench and playing a piano. The piano is illuminated with warm lights. Above the piano, a large number of small, bright blue lights are arranged in a pattern that resembles a large, stylized letter 'A' or a similar abstract shape. The background is dark, and the ground appears to be a flat, light-colored surface. In the distance, there are some faint lights and structures, possibly a city skyline or a festival area.

Studio Drift performs
Franchise Freedom with
Intel drones (2018)

Application

Real-time 3D mapping with aerial swarms



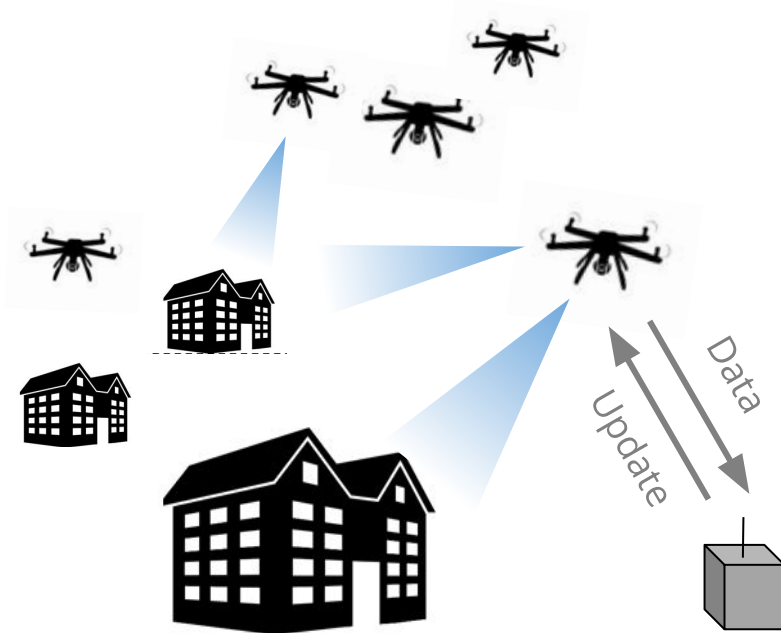
Drones use cameras and sensors to navigate and collect data about the environment.

Multiple drones act in a coordinated way.

Edge computers perform computations, fuse data, and update the drones.

Application

Real-time 3D mapping with aerial swarms



Spatial and temporal coordination required

Swarmalators:

- complement existing path planning algorithms
- form certain patterns required for sensing

Research Directions

Swarmalatorbots

Localization

- Inaccuracies in the localization of robots
- Autonomous localization (e.g., using ultrawideband (UWB))

Wireless state exchange

- Adaptive communication in swarms

Pattern space

- Patterns for the orientation of entities
- Patterns in three spatial dimensions (3D)

Drones forming a 3D pattern



Publications

Multidrone systems: More than the sum of the parts. *IEEE Computer*, 2021

Swarmalators with stochastic coupling and memory. *IEEE Intern. Conf. on Autonomic Comput. Self-Organizing Syst. (ACSOS)*, 2021

Sandsbots: Robots that sync and swarm. *IEEE Access*, 2020

Robots that sync and swarm: A proof of concept in ROS 2. *IEEE Intern. Symp. on Multi-Robot and Multi-Agent Syst. (MRS)*, 2019

Beyond sync: Distributed temporal coordination and its implementation in a multi-robot system. *IEEE Intern. Conf. on Self-Adaptive Self-Organizing Syst. (SASO)*, 2019



Funding



Austrian Science Fund (FWF)

Grant P30012: Self-organizing synchronization with stochastic coupling

Duration: 2018–23



University of Klagenfurt

Karl Popper Kolleg:
Networked autonomous aerial vehicles

Duration: 2017–21



Magenta (formerly: T-Mobile Austria)

Collaboration: Drone communications
over cellular networks

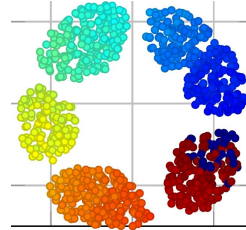
Duration: 2017–21

Take-away message



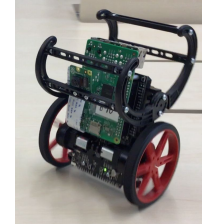
Syñc

Swarm



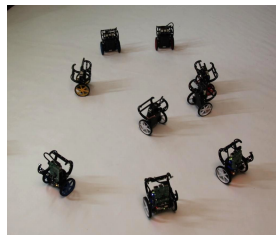
Swarmalator
theory

transferred



Technology

enables



Multi-robot
systems

form



Space-time
patterns

shape determined
by a small set of
parameters.

in a self-organized way
(w/o explicit path programming)

Joint work with ...

Team members

Agata Barciś (2017–21)

Udo Schilcher

Jorge Schmidt

Arke Vogell (2018–22)

Faculty at Dronehub

Hermann Hellwagner

Bernhard Rinner

Stephan Weiss (drone hall)

External collaborator

Kevin O'Keeffe (2019)



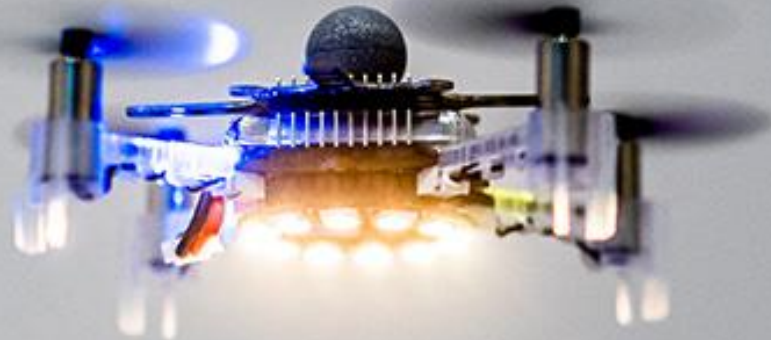
Photos: D. Waschnig



Key facts

- Started 2008
- 9 Professors
- 41 PhDs and Postdocs
- > 150 publications

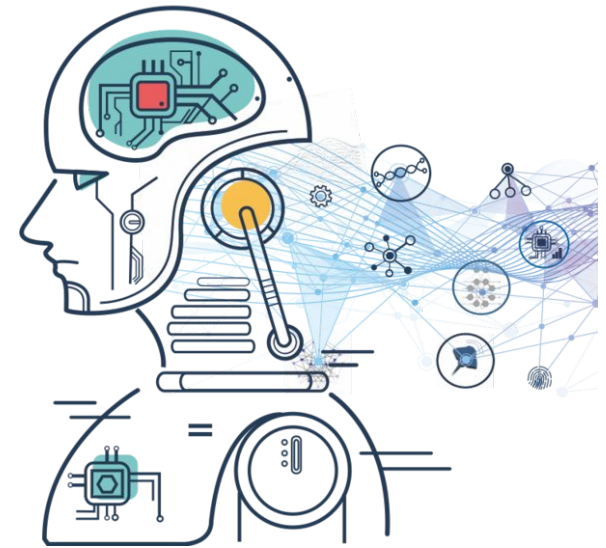
- Autonomous navigation
- Coordination and swarming
- Wireless communications
- Mission and path planning
- Human-drone interaction
- Image processing



Flying “intelligent machines”

Emerging topics

- More autonomy and self-organization
- Learning drones
- Multidrone systems and swarms
- Counter-drone technologies
- Drones with 5G and edge computing
- Hybrid aerial and ground systems
- Methodology for systems design
- Societal and ethical aspects



Intelligent machines? –
Self-organized nonlinear
dynamics of machines
across scales

Figure taken from workshop Website
at MPI Physics of Complex Systems.



Photo:
Daniel Waschnig

C. Bettstetter, U Klagenfurt, Lakeside Labs, bettstetter.name, [@bettstetter](https://twitter.com/bettstetter)