Course: Natural Computing

*9. Swarm Robotics and Nanorobotics

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Main characteristics of a swarm robotics system

- Robots are autonomous
- Robots do not have access to centralized control or to global knowledge
- Robots' sensing is local
- Robots' communication capabilities are local
- Robots are situated in the environment
- Robots can act and cause changes (?) in the environment
- Robots combine cooperation and competition to tackle a given task
- A swarm typically has 10 to 1000 robots (some principles can be demonstrated as few a three robots)
- Scalability is critical (otherwise: multi-robot systems)

Brambilla, Ferrante, Birattari and Dorigo (2013)
Swarm robotics. *Swarm Intelligence* **7**(1) 1-41.

Why robot swarms in NAT?

- Robot swarms are often biologically inspired: Swarms, groups, herds, flocks, schools
- Robot swarm principles used also in particle swarms, ant colonies, etc.
- Swarm robotics shared the hope to realise *swarm intelligence*
- Practical control of massive robot swarms by defining fitness functions plus swarm rules

Natural computing

- Beyond bio-inspired algorithms:
  Use the complex dynamics of a real biophysical system
  - Parallel by nature
  - Non-deterministic
- Do real systems process information?
  - Can we describe problems to be solved by a fitness function?
  - What computational mechanism are useful in practice?
- Potential for engineering, material science, medicine, agriculture, logistics, communication, ...

We turn to biology not just as a metaphor, but as an actual implementation technology . . .

Harold Abelson et al., MIT, 2000

Why robot swarms?

- Task-related parallelism: Search, agriculture, terraforming, medication
- Hierarchical organisation rather than central control
- Ideally, self-organisation of *situated* robots
- Flexibility, adaptivity, robustness
- Super-linear improvement by cooperation
- Super-organisms, modular robots, reconfigurable robots

Timeline of swarm robotics

1990s: New paradigm for self-organization of behaviour, stigmergy and local interactions, clustering

2000s: Manipulation of objects, collective localisations, task allocation, heterogeneous robot swarms (*Swarmanoid*)

2010s: *Kilobots*, swarms of flying drones, Control without computation, automatic design (*AutoMoDe*, novelty search)

2020s: Autonomous learning, precision agriculture, infrastructure monitoring and maintenance, maritime ecological monitoring, insect- or pet-like devices, delivering goods, mining, surveillance, space exploration and on-site construction

2030s: Millimeter-scale soft robot swarms for agricultural pest control or to collect microplastics

2040s: Medical applications beyond targeted drug delivery

adapted from: Dorigo, Theraulaz, Trianni (2020) Reflections on the future of swarm robotics. *Science Robotics* **5**(49).

Evaluation: Scaling in robot swarms

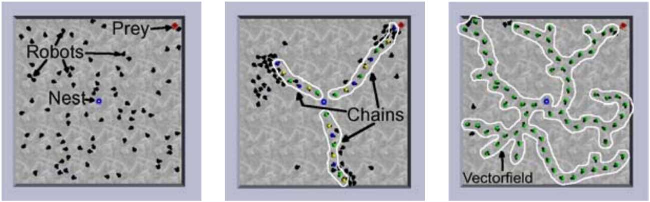
How much better can N robots do compared to one?

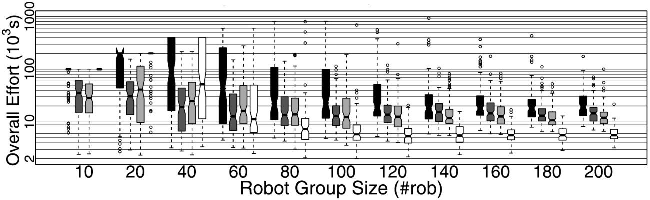
- Linear scaling requires robots not to block each other
- Tasks that require several robots: Transport of large objects, crossing a trench crossing, rounding-up other agents
- Ants are known to achieve super-linear scaling, as well as "the more, the faster" [1]
- Decision-making in honey bees (Szopek et al., 2012), adopted for robots (Bodi et al., 2012)
- Super-linear increase in efficiency in foraging + rounding-up task [2]

[1] Gallotti & Chialvo (2018) How ants move: Individual and collective scaling properties. *J. R. Soc. Interface* **15**, 0223.

[2] Nouyan, S., Campo, A. and Dorigo, M., 2008. Path formation in a robot swarm. Swarm Intelligence, 2(1), 1-23.

Super-linear improvement by cooperation

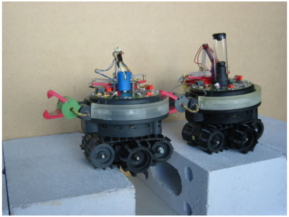




S. Nouyan, A. Campo, M. Dorigo (2008) Path formation in a robot swarm. Swarm Intell. 2:1-23.

Collective behaviours: Spatial, social, collaborative

- Aggregation
- Pattern formation: Chain, ring, sphere, ...
- Self-assembly and morphogenesis
- Collective exploration and sensing
- Coordinated action (motion)



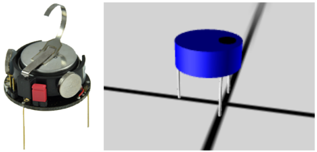
Mondada e.a., 2005

- Decision making: Consensus achievement, task allocation
- Problem solving: Collective transport, object clustering and assembling, division of labour, ...

Brambilla, Ferrante, Birattari, Dorigo (2013)
Swarm robotics. *Swarm Intelligence* **7**(1) 1-41.

Kilobots

- A low-cost scalable robot system ($10) for collective behaviours, e.g. 1024 robots is possible
- Vibration based locomotion
- Can send and receive nondirectional light signals
- Robot design is open-hardware, but is also commercially distributed



A Kilobot and a Kilobot simulated in ARGoS.

Rubenstein, Ahler, Nagpal (2012) Kilobot. IEEE Conf. Robotics & Autom. 3293-3298.

Self-organisation in robot swarms

Can something like *swarm intelligence* be realised technically?

Emergent collective intelligence of groups of simple agents
Bonabeau et al. (1999) Swarm intelligence: From natural to artificial systems

Emergence (what): Dynamic interaction of micro-level elements brings about a new form of organisation at the macro-level

- Examples: Temperature, language, life, mind

Self-organisation (how): Order arising from local interaction of elements based on an unspecific driving force

- Examples: Finding an agreement, periodic chemical reactions (Bray, 1921), language, life

Reaction–diffusion mechanisms

- Turing, A. M. (1952). The chemical basis of morphogenesis. Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, B237(641), 37–72.
- Consider spatially extended system with one or more substances (chemicals, messages, robots)
- Interesting effects occur for two substances, an activator A and an inhibitor B: A produces more A and more B, and B reduces both A and B, but the processes have different characteristics and the substances diffuse away with different speeds.

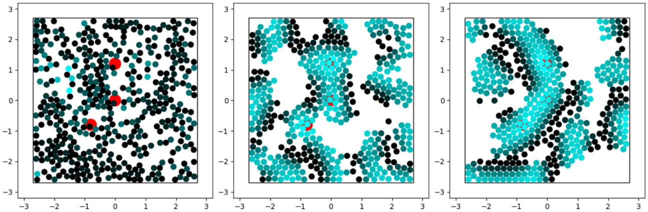


Image: Calum Imrie (2018)

Slavkov, I. et al. (2018) Morphogenesis in robot swarms. *Science Robotics* **3**(25).

Simulation of robot swarms

- ARGoS modular, different robot platforms, parallelisable, different levels of abstraction
- Kilombo for simulation of Kilobots
- Webots, Gazebo, V-rep, Isaac sim, MOSRE, LPZ robots

Deception in robot swarms

- In this study, robots search for a food source and emit signals according to their state.
- The other robots learn to interpret these signals as an invitation.

- If the food was limited, some robots learned the ability to produce deceptive visual signals to divert unrelated robots.
- This resulted in a decrease in colony performance after the initial increase.

Floreano et al.(2007) Evolutionary conditions for the emergence of communication in robots. *Current Biology* **17**(6), 514-519.

Robot Swarms: Applications in agriculture

- Many tasks are trivially parallisable: soil preparation, seeding, planting, crop management, harvesting.
- Most swarm project are related to surveillance.
- Interesting examples include a variety of local tasks to be solved individually, but in coordination. Polleniation or harvesting of small fruit are still under research

Daniel Albiero et al. (2022) Swarm robots in mechanized agricultural operations. *Computers and Electronics in Agriculture* **193**, 106608

Robot Swarms: Natural computing

- Particle models of swarms: Reynolds' rules for local navigation
- Simple rules attraction, repulsion, communication
- Spread of "innovations", i.e. retargetting of a swarm
- Redundancy, stochasticity, sub-optimality,
- Swarm tasks such as: Search and rescue, forageing, exploration, surveillance can be mapped to an optimisation paradigm

- Compositionality remains a problem (e.g. DNA computing (Leonard Adleman, 1994): even trillons of molecules do not cover large search spaces)

https://ed-ac-uk.zoom.us/rec/share/Sktc722dlGugG1Me-QTL2jRjQuoiFb-TtIdei9SjKAlayCULTVeVy4hALWzreE5Z.mzC8lDJYfxoc0c8x

Robot Swarms: Conclusion

- Applications in autonomous driving and smart transport, industry, inspection, emergency response (search and rescue), environmental monitoring, agriculture, space missions, medical applications, ...
- Challenges: Hardware (sensing and actuation), modelling, design, validation & verification, goal-oriented control, transparency

Schranz, M. et al. (2021) Swarm intelligence and cyber-physical systems: Concepts, challenges and future trends. *Swarm and Evolutionary Computation* **60**, 100762.

see also: Heiko Hamann (2018) Swarm robotics: A formal approach. Springer.

Nanorobotics

- 1 nm $= 10^{-9}$ m

- Smaller than size of most electronics components
- Biological machines: Ribosomes (20-30nm), kinesin (8nm step)
- Challenges: Manufacturing, recycling, biohybrids, medical use

Nelson, Dong & Arai (2009) Micro-/Nanorobots
Mavroidis & Ferreira (2013) Nanorobotics: Past, Present, and Future

Nanorobotics

- R. P. Feynman: There's plenty of room at the bottom. *Caltech Eng. Sci*. **23**, 22–36 (1960).
- J. von Neumann: Theory of Self-Reproducing Automata. University of Illinois Press (1966).
- In particularly interesting for medicine: Biology is largely "nano", but robotics (so far) isn't.
- Harold J. Morowitz (1978) On swallowing a surgeon: Discusses potential of mirco- and nano-medicine inspired by science fiction movie *Fantastic Voyage* (1966)
- First occurrence of the term "Nanomedicine" in 2000, relevant papers since 1990.
- Large number of review articles, but not too many different applications
- Applications mostly for targeted drug release
- Transition to in-vivo study only recently

Normal-sized Robots in Medicine

- Surgery
- Prosthetics, diagnosis, and treatment of movement disorders, posture balance, prevention of fall
- Care
- Analytic tools
- Delivery
- Telepresence
- Stabilisation of physiological parameters by feedback control
- Learning, optimisation, personalisation

Control Systems and Robots in Medicine

Increasing autonomy

- Remote control
- Remote command
- Shared autonomy
- Emergency OFF
- Removing robot components

Increasing integration

- Feedback control
- Adaptive control
- Pattern recognition and decision-making
- Embodied intelligence
- Co-existence with artificial life forms

Nanorobots vs. Microrobots

- Microelectromechanical systems (MEMSs) (late 1980s)
  - characterisation, inspection and maintenance, e.g. narrow tubes
  - micro-optics, e.g. positioning of micro-optical chips, micro-lenses and prisms
  - micro-factories, e.g. assembly
  - medical: Camera pills (“Swallowing the surgeon”)
- The potential of nanorobotics (It’s just starting ...)
  - not only smaller, but also aiming to exploit the strange properties of the nanoworld, see Feynman’s paper
  - tubes as thin as blood capillaries
  - repair of tissue, e.g. nerve fibres
  - identification and destruction of cancer cells

Nelson et al. (2016) Micro-/Nanorobots (*Handbook of Robotics*, Ch. 27)

The Nano-World

Opportunities

- Self-organisation
- Self-assembly
- Self-replication
- Self-maintenance
- (Self-)triggered conformational changes

Challenges

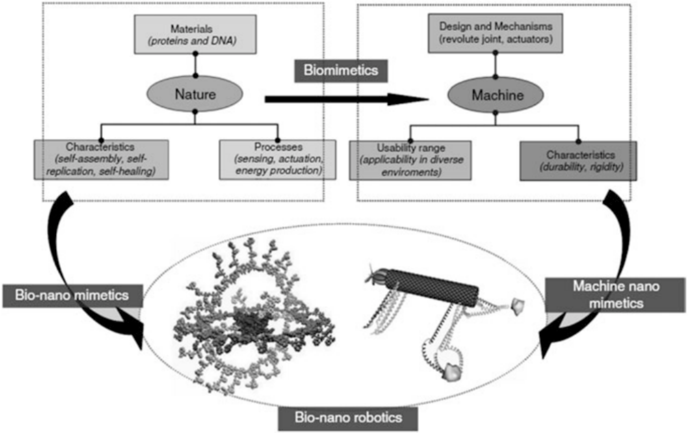
- Interfaces?
- Fully functional?
- Fully artificial?
- Autonomy?
- Compatibility?
- Removal?

Why is Nanorobotics interesting here?

- Nanorobots need to *incorporate* computation, as digital computers are too big
- Like particles in PSO, nanorobots need to *explore* individually as they cannot be controlled individually
- At the nanoscale, *randomness* is not only unavoidable, but can be exploited
- *Interaction* among the robots is important for improving their capabilities as a swarm
- In addition to their function there is the *design* problem: How to evolve suitable robot morphologies and functions?

Bionanorobotics: A field inspired by nature

Ummat A, Dubey AA, Mavroidis C (2006)



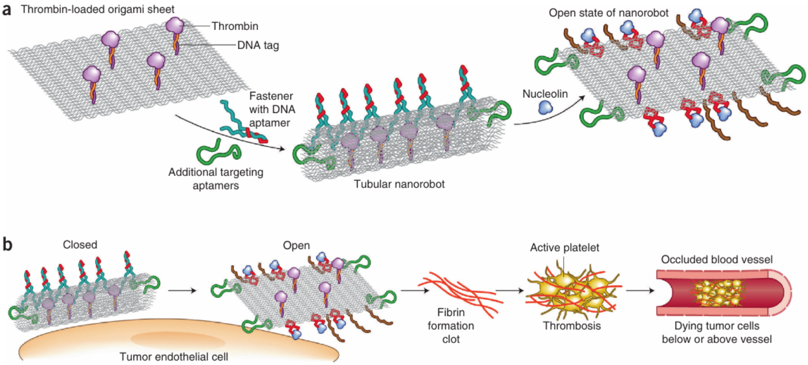


Figure 1 A DNA-origami nanorobot for cancer therapy. (**a**) A flat DNA sheet is loaded with DNA-tagged thrombin enzymes. The addition of DNA fasteners converts the sheet to a tube, shielding thrombin from the environment. The fasteners contain the aptamer sequence that specifically binds nucleolin. The interaction with nucleolin displaces the fastener and causes the tube to open. (**b**) Upon reaching the tumor vasculature, the nanorobot binds nucleolin expressed on endothelial cells in the tumor microenvironment. Unfolding of the nanorobot exposes thrombin to the blood, triggering the formation of blood clots. Vascular occlusion leads to tumor cell starvation and death.

Ennio Tasciotti (2018) Smart cancer therapy with DNA origami. *Nature Biotechnology* **36**(3), 234-235.

Wireless Actuation of Micro/Nanorobots

Soichiro Tottori, Li Zhang, and Bradley J. Nelson

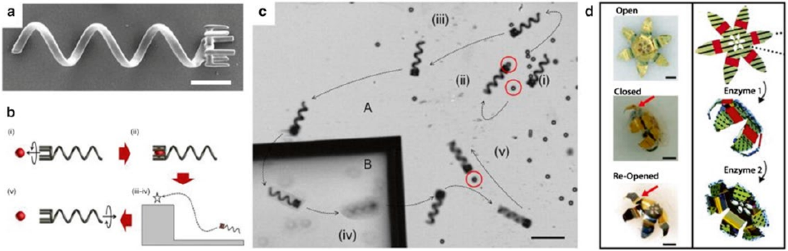
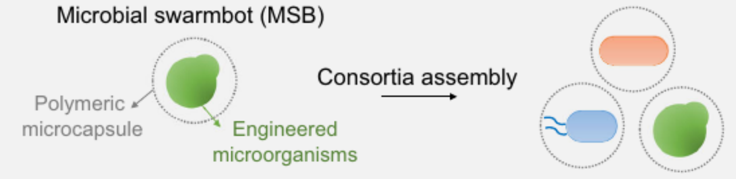


Fig. 9.8 Wirelessly-actuated robotic tools. (**a**) SEM image of a helical micromachine with a hand-like microholder. The scale bar is 10 μm. (**b**) Schematic illustration of cargo transport by the magnetic helical micromachine with a hand-like microholder. (**c**) Time lapse image of transporting 6-μm-diameter micro-bead in 3D. The scale bar is 50 μm ((**a–c**) Adapted with permission from Tottori et al. [41]. Copyright 2012 John Wiley and Sons). (**d**) Biochemically activated microgrippers. The scale bars are 200 μm ((**d**) Adapted with permission from Bassik et al. [78]. Copyright 2010 American Chemical Society)

see also: Nain & Sharma (2015) Propulsion of an artificial nanoswimmer

Microbial swarmbots

Many bacteria or yeasts require a certain density to survive. On the other hand, 30% medically active substances derive from bacteria. If a membrane allows for diffusion of nutrients and active sustancies, drug delivery from the colony is possible over extended times, until finally the bubble isp popped and the bacteria are removed by the immune system. MSBs are around for a few years., today already heterogeneous swarms are controllable.



Lin Wang et al (2022) Engineering consortia by polymeric microbial swarmbots. Nature Communications 13, 3879

Hematology

- Use of magnetotactic bacteria to transport and navigate nanorobots
- Circulating “respirocyte” nanorobots to deliver oxygen and return remove waste products from periphery
- Circulating “clottocyte “nanorobot with hemostatic functions
- Phagocytic “microbivores” with customisable antigen binding sites for targeting of pathogens

Saadeh & Vyas (2014) Nanorobotic applications in medicine.

Dentistry

- Dental anaesthesia and sensitive teeth through nanorobot penetrating dentinal tubules for occlusion or administration of targeted analgesic
- Enhancement of the success rate of root canal procedures by providing visualisation of root
- Improved daily dental hygiene and teeth cosmetics by replacement of enamel layers

Saadeh & Vyas (2014) Nanorobotic applications in medicine.

Neurosurgery

- Single axon manipulation and transection with use nanoknife
- Circulating nanorobot for the monitoring of intracranial aneurysm development and progression
- Neuroelectric Nanosensors for Action Potential Monitoring

Saadeh & Vyas (2014) Nanorobotic applications in medicine.

Oncology

- Direct drug delivery to cancerous tissue to limit systemic toxicity and increase effectiveness
- Mechanical destruction of cancer cells
- Mapping of margins of tumour to improve resection during surgery

Saadeh & Vyas (2014) Nanorobotic applications in medicine.

~~10~~ 9 Facts about nanorobots

1. Can interact with viruses and bacteria in a 1-to-1 manner in the blood stream
2. Can detect toxins
3. Can detect small-scale degradation and repair materials
4. Can produce electronic circuits by forming a network; the properties of the circuit can be changes by learning or MH search
5. Nanosensors and nanoactuators
6. Capabilities like gripping and navigation are currently studied
7. Potential problems are biocompatibility (within and without the target organism) and uncontrolled reproduction
8. Can be powered by piezoelectric nanogenerators or triboelectric nanogenerators (based on the coupled effect of contact electrification and electrostatic induction): self-powered systems (Yang et al. 2018: The grand challenges of science robotics)
9. Size would be from 100nm to a few micrometers

adapted from: www.10interestingfacts.com/10-interesting-facts-about-nanobots.html

Challenges for robotics

- Robotics has aimed at copying life forms at medium scales, but "there's plenty of room at the bottom".
- Complexity of subject matter and lack of theory for
  - Robotic design, function, recovery, maintenance
  - Analogue, morphological computation, smart matter
  - Multi-objective, multi-agent learning
  - Decomposition, removal, recycling of robots
  - Shared autonomy New paradigms for learning, control, evolution
  - Artificial physics, artificial chemistry, artificial life