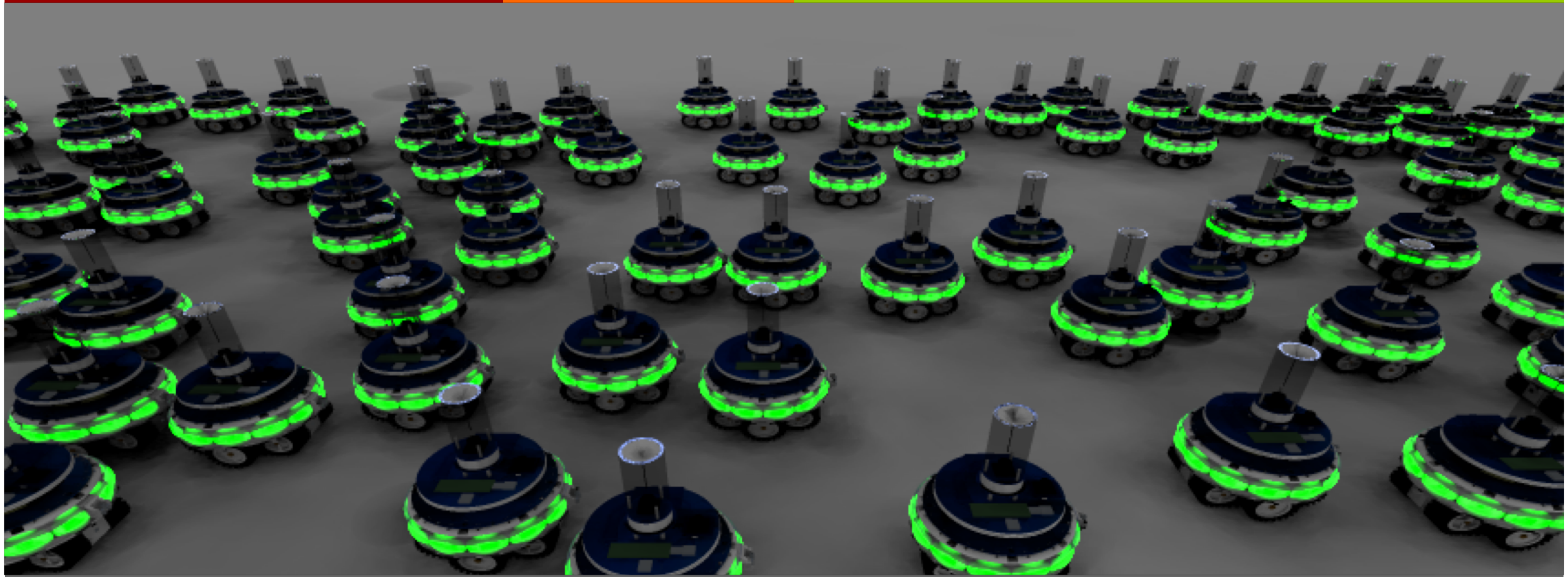
Multi-Robot Systems and Robot Swarms

Lenka Pitonakova :: Nov 2018



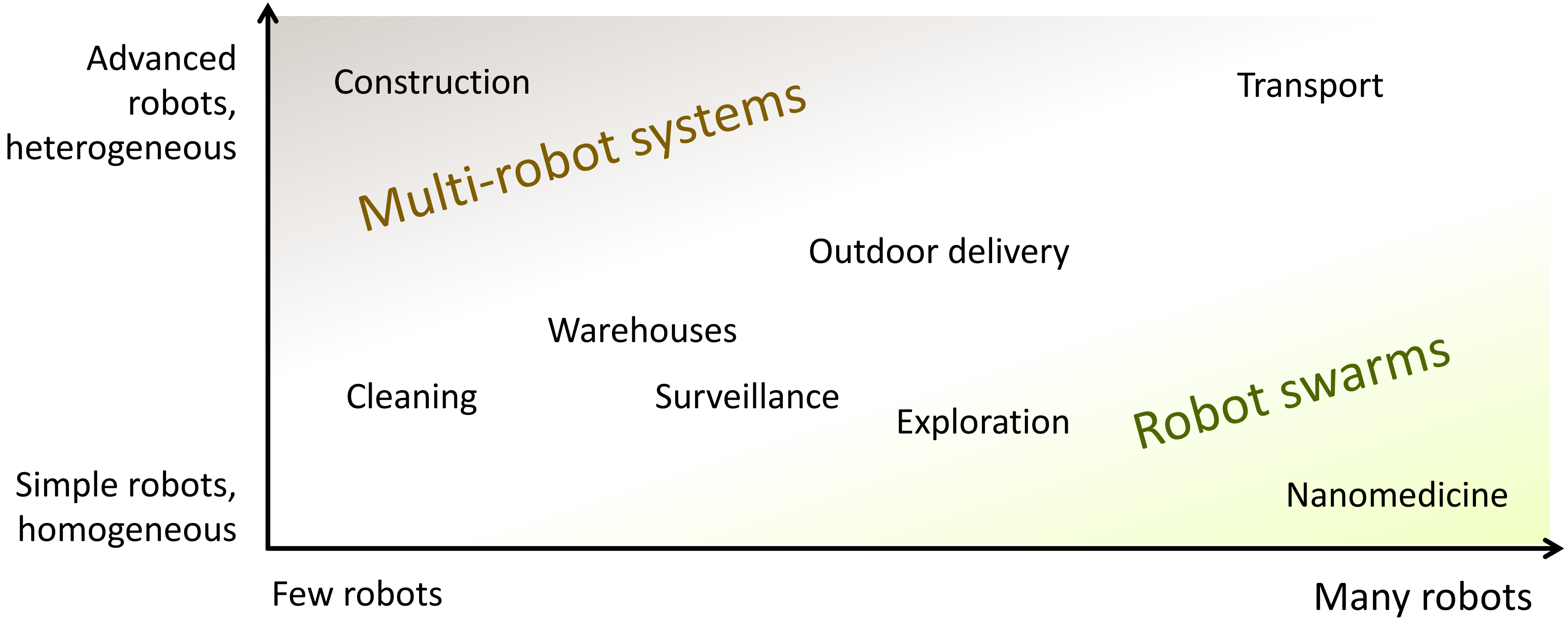
What are they?

- **Delivery robots** in warehouses, hospitals
  - Structured, relatively predictable environments
  - Communication between all robots possible
  - Relatively well-structured environments
  - “Easy” to program and predict

Amazon Kiva

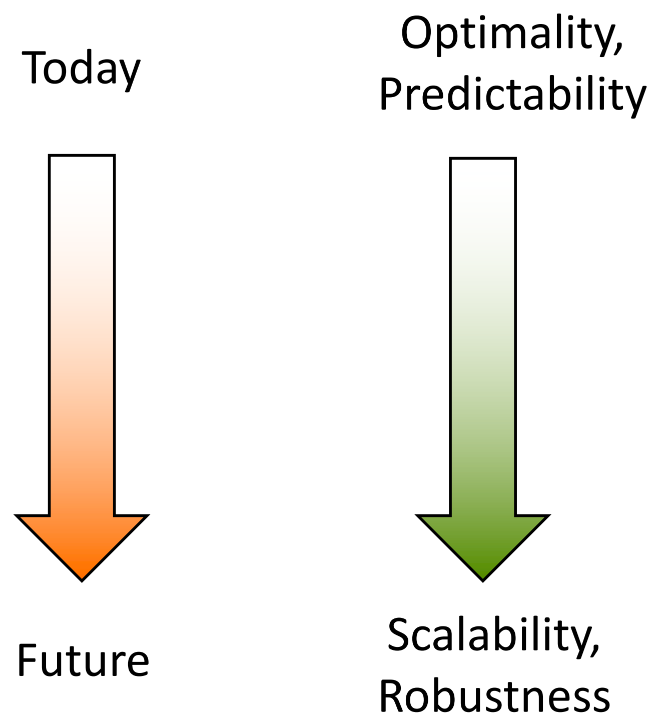
Techi Medic

Potential tasks



Controllers

- **Centralised**
  - Global knowledge and planning
- **Distributed**
  - Local knowledge, global planning
  - E.g. auction-based task allocation (cost bidding) through a facilitator
- **Decentralised**
  - Local knowledge and interactions, local planning
  - Often bio-inspired



Swarm robotics

- Decentralised systems, making use of **emergence**
  - System-level behaviour from local actions and interactions
  - Studied for their potential for robustness, scalability, autonomy
- Topics:
  - **Collective foraging**
  - **Collective construction**
  - **Algorithm design**

Emergence

- **Social insects:** Limited individual knowledge and capabilities
- Colonies able to perform **complex tasks**: Trail formation, food source selection, construction, farming

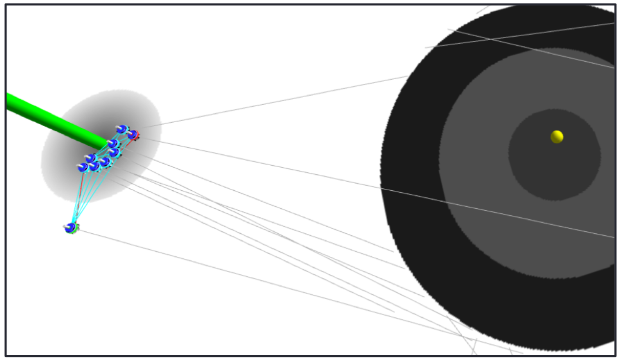


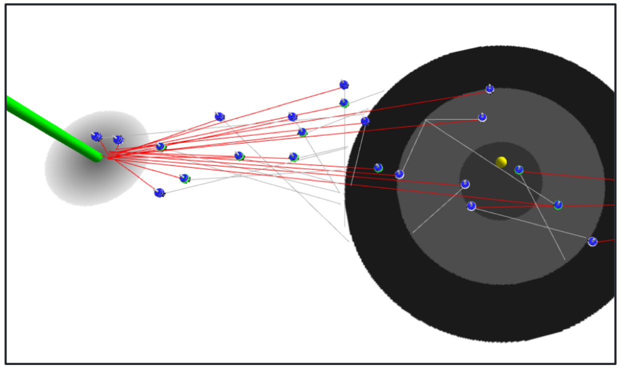
- Growth of complexity in a **‘bottom-up’ fashion**
  - Local behaviour -> global (system-level) behaviour
  - An individual insect does not know the overall plan
- System-level behaviour is **greater than sum of its parts**
  - Work + Extra “stuff”: Information, interactions that affect work



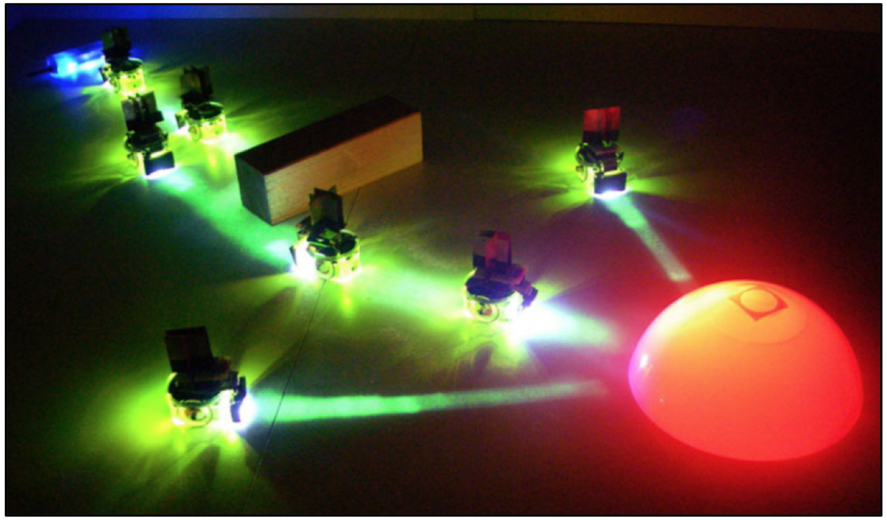
Collective foraging

- **Searching** for “food” in an unknown environment
- “Food” is either **consumed** or **brought back** to “nest”
- Paradigm for
  - Resource collection
  - Warehouse / customer servicing
  - Search and rescue
  - Toxic waste clean-up, …
- Studying various strategies, how they could be applied to various tasks, how robust they are,...



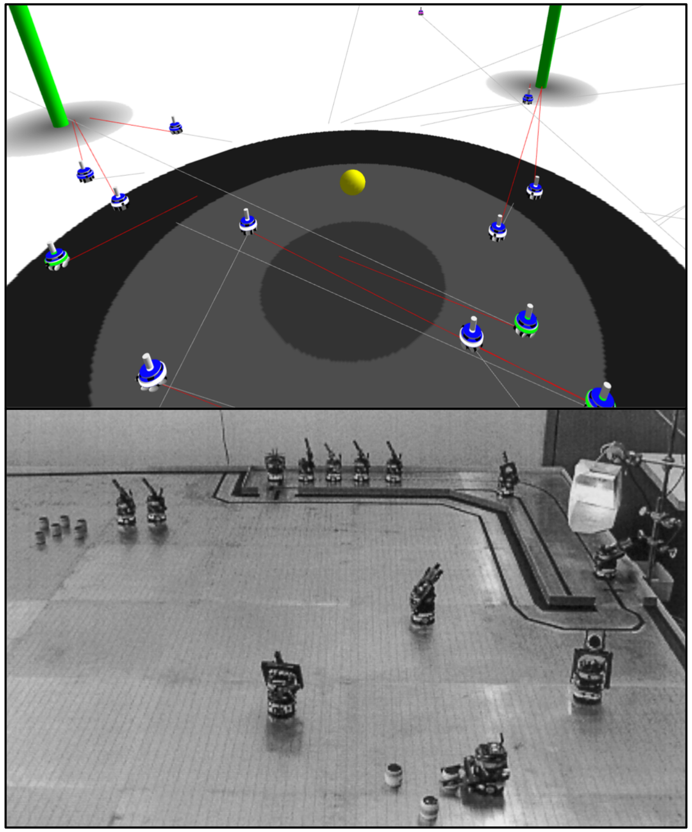


- **Ant inspired**
  - Pheromone trails leading to different food sources, shorter paths and paths to better quality resources get reinforced
  - Unused paths evaporate
  - Path projection in a semi-virtual environment
    Sugawara, K., et al. (2004). Proceedings of IROS 2004, 3074–3079.
  - Robots or RFID tags as pheromone repositories
    Hrolenok, B., et al. (2010). Proceedings of AAMAS 2010, 1197–1204.
  - Robots depositing chemicals
    Fujisawa, R., et al. (2014). Swarm Intelligence, 8(3), 227–246.

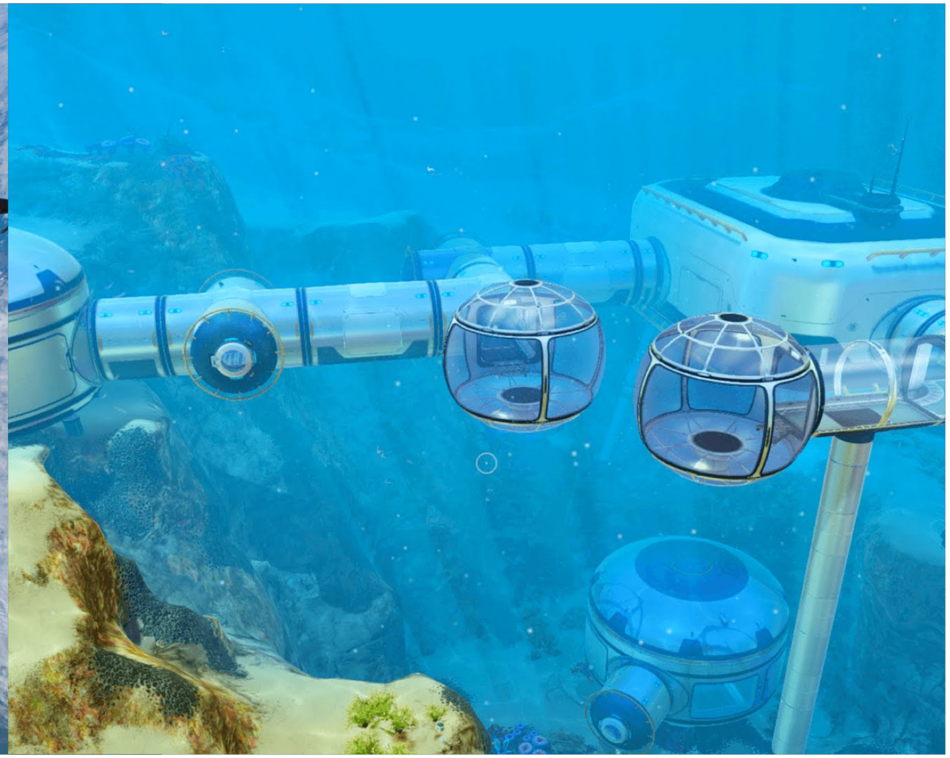


- **Bee inspired**
  - Robots “waggle” dance in the “nest” to recruit to food sources
  - Dance time proportional to food source quality -> selection of more profitable sources

  - Mostly agent-based simulations
    Reina, A., et al. (2015). PloS One, 10(10), e0140950.
    Pitonakova, L., Crowder, R., & Bullock, S. (2018). Swarm Intelligence, 12(1), 71–96.
  - Some implementations on robots
    Krieger, M. J. B., & Billeter, J.-B. (2000). Robotics and Autonomous Systems, 30(1–2), 65–84.

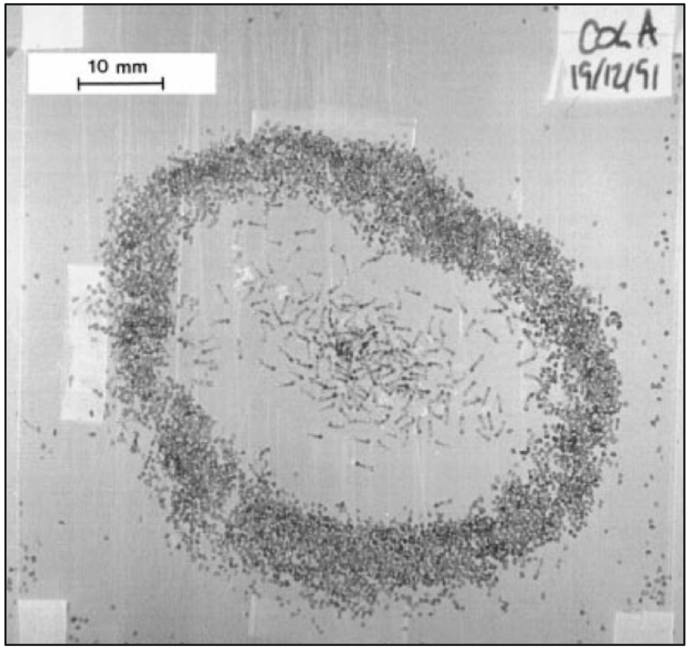


Collective construction

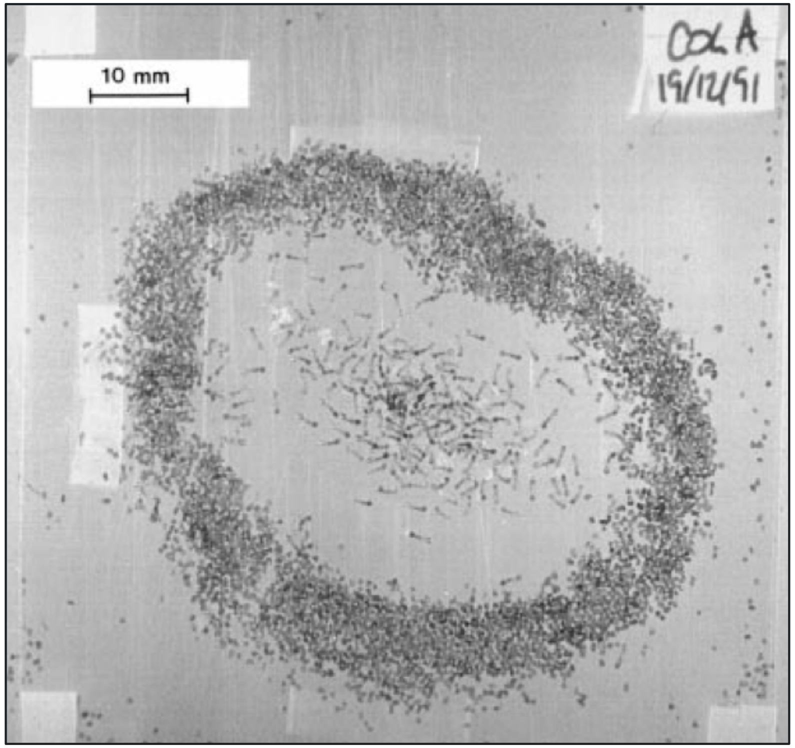


- **Termite inspired**: Pheromone trails and deposits
- **Wasp inspired**: Using built structure
- **Ant inspired:** Mixture of the above

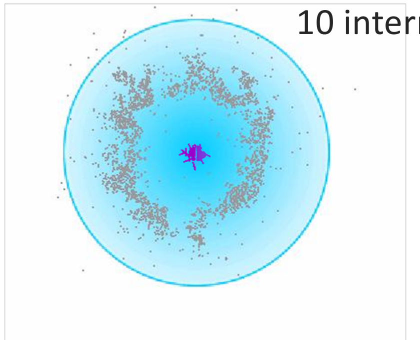
Stigmergy
(Indirect communication through the environment)



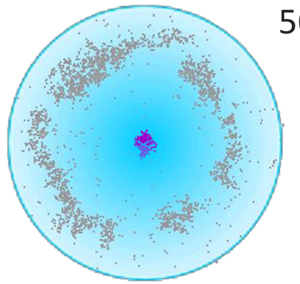
“Controlling ant-based construction”



- Agent-based model
  - “Internal” and “external” ants with individual behaviours
  - Brood pheromone cloud
- Sensors: Pheromone, dirt pellet pushing

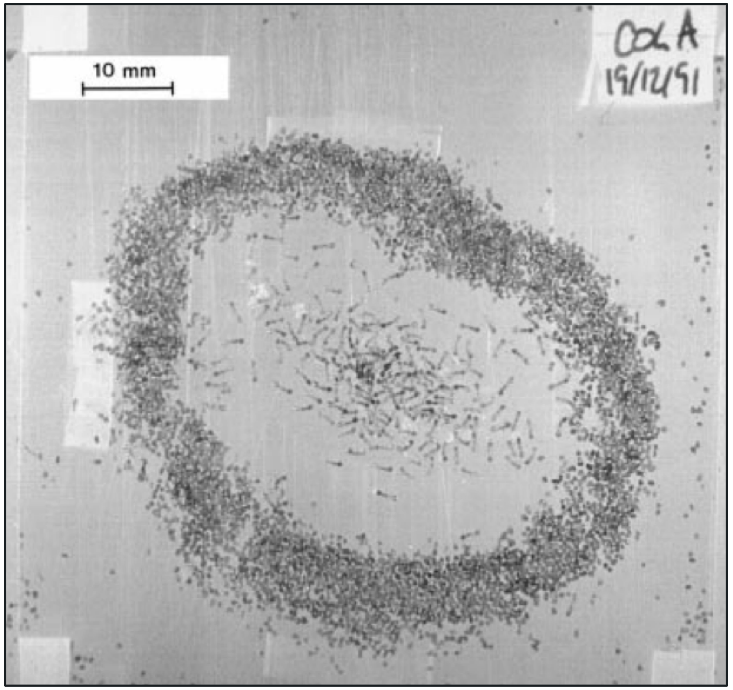


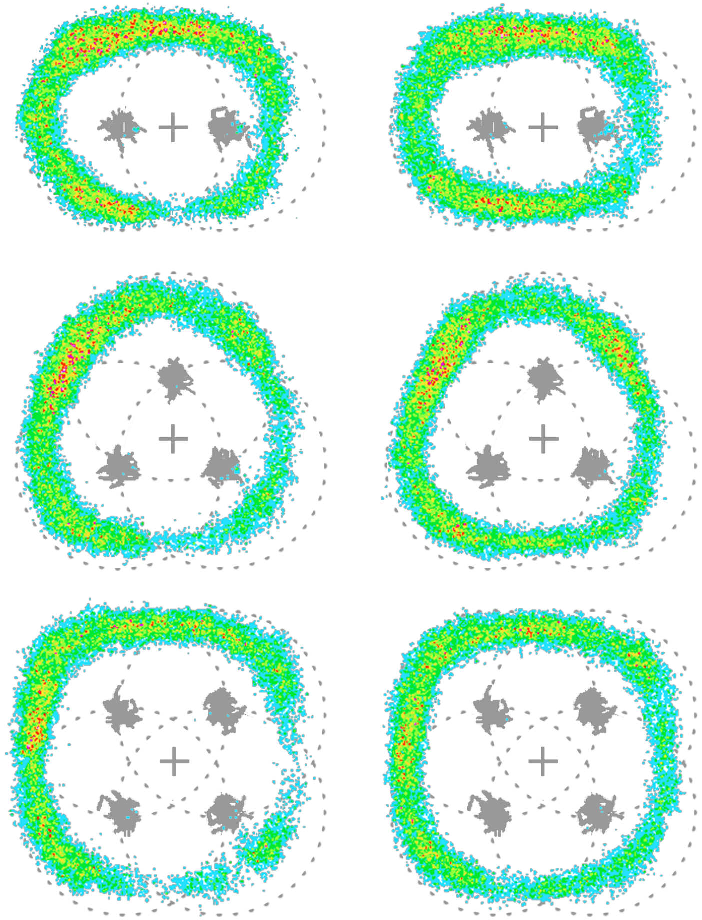
10 internal ants



50 internal ants

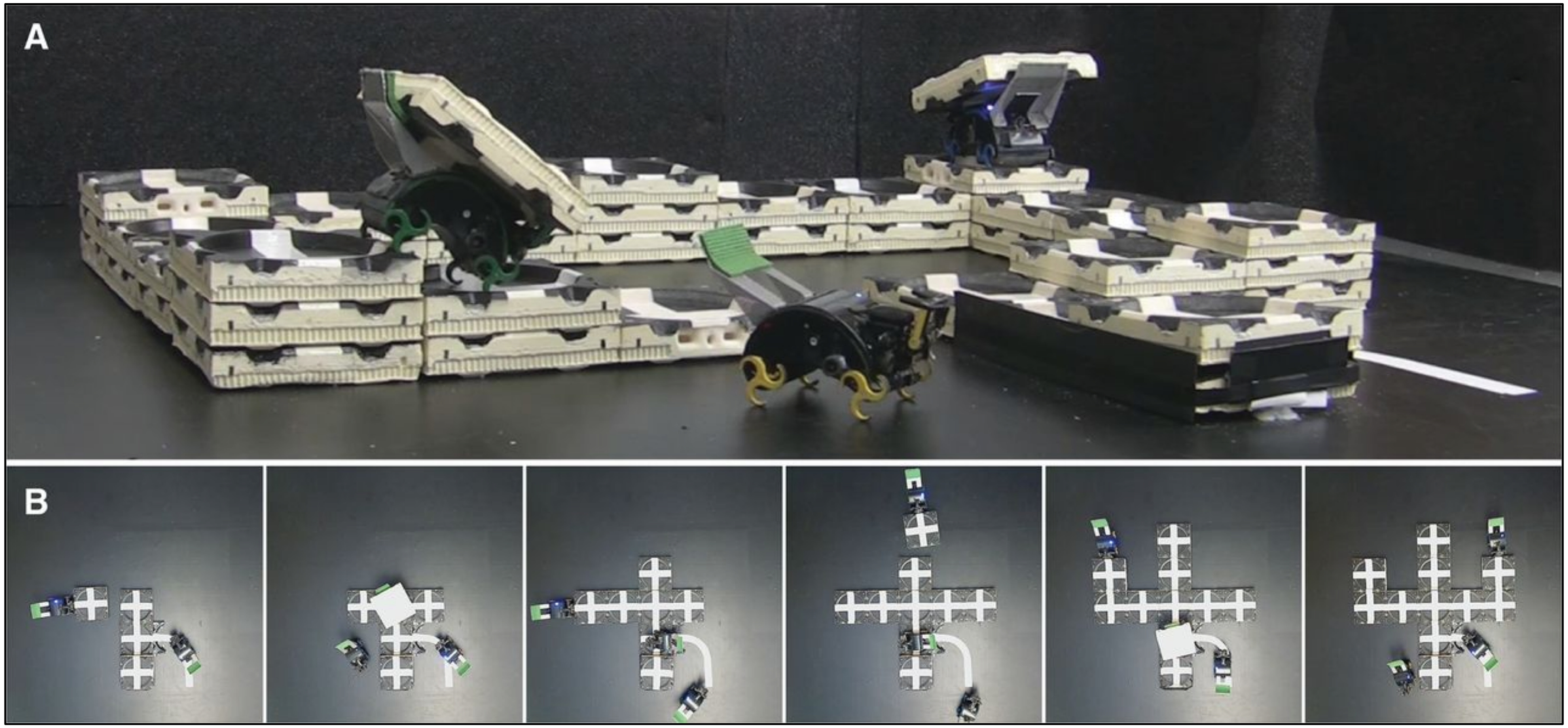
- **Can we build different shapes, unseen in nature?**
- Yes! By using multiple brood clusters
  Pitonakova, L., & Bullock, S. (2013). Proceedings of ECAL 2013, 151–158.



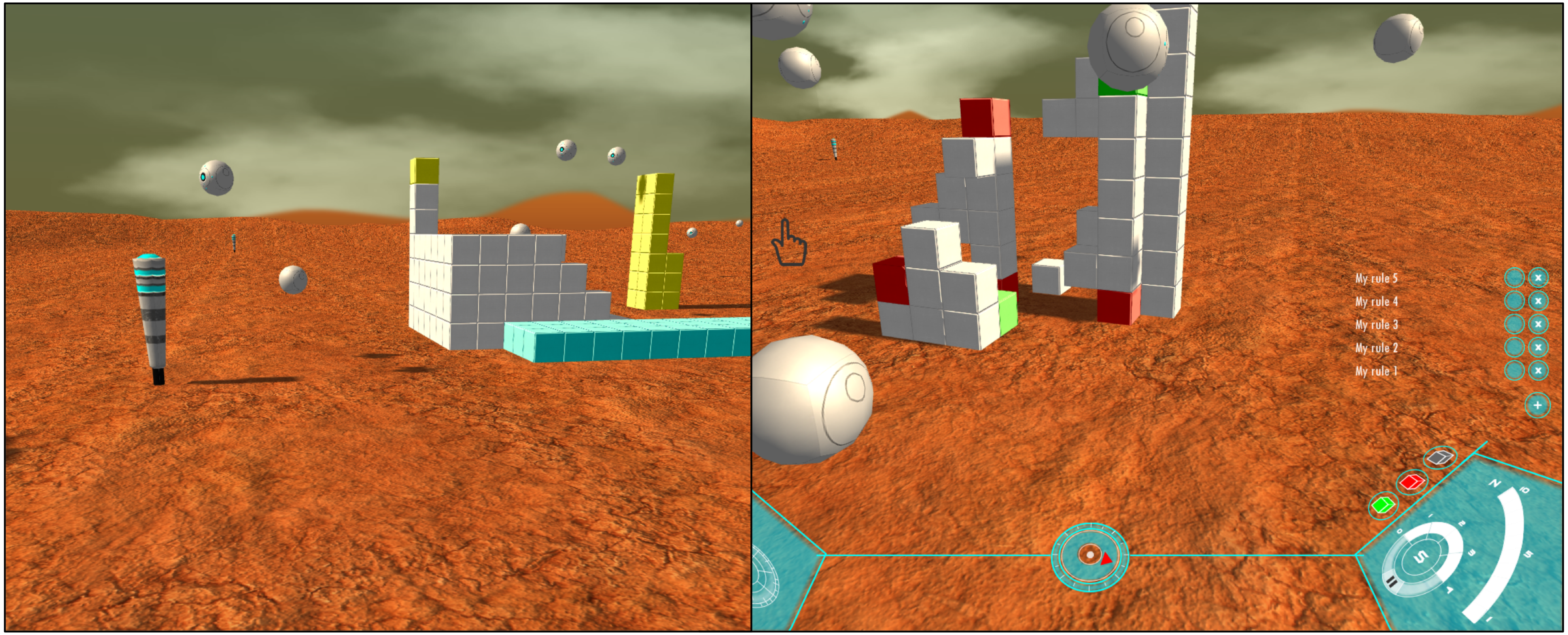


- **TERMES** (Harvard University): 3D construction with robots

  Petersen, K., Nagpal, R., & Werfel, J. K. (2011). Science and Systems VII. Ca: MIT Press.



- **The Hive Mind:** Try programming a robot swarm yourself!
  http://thehivemind.lenkaspace.net



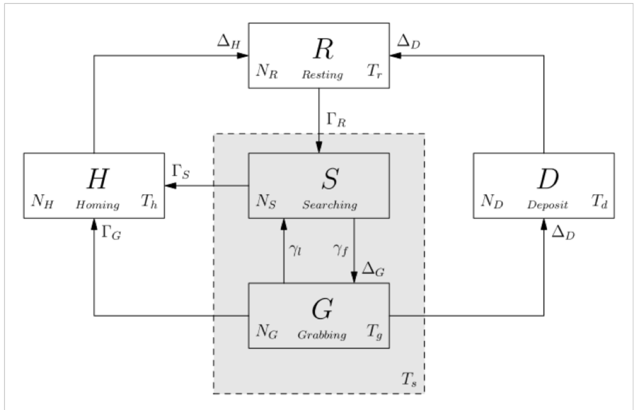
Swarm algorithm design

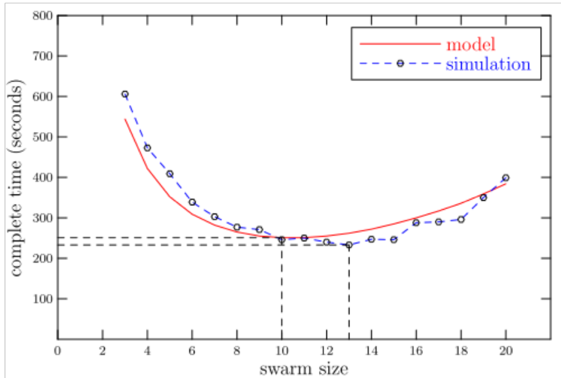
- **How do we program individual robots to achieve desired global behaviour?**
  - Inherent heterogeneity (even in “homogeneous” swarms)
  - Limited local information
  - Dynamic environmens
  - Emergence of undesirable / unpredicted outcomes
- **How do we understand our design decisions?**
  - Information?
  - Effect of robot actions on collective behaviour?

- **Probabilistic Finite State Machines, Macroscopic models**
  - Identify agent **states** and **state transition rates**

$$\Delta_H(k+1) = \Gamma_S(k+1) + \Gamma_G(k+1)$$
$$\Delta_D(k+1) = \left[\Delta_G(k-T_g) - \Omega_G(k-T_g)\right]\Lambda_G(k;T_g)$$
$$\Delta_G(k+1) = \gamma_f M(k) N_S(k)$$

  - Numerical simulation to find the effect of parameters on collective performance
  - Verify PFSM model through a few agent-based simulations

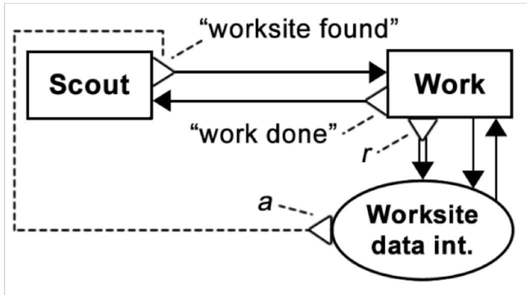




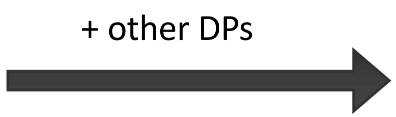
Liu, W., & Winfield, A. F. T. (2010). The International Journal of Robotics Research, 29(14), 1743–1760.

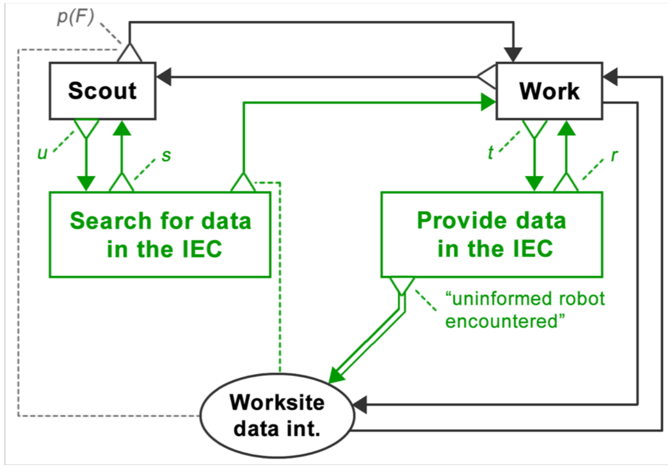
Reina, A., Miletitch, R., Dorigo, M., & Trianni, V. (2015). Swarm Intelligence, 9(2), 75–102.

- **Design patterns**
  - **Modules** of robot behaviour that can be **combined** (using rules) into robot control algorithms



"Broadcaster" DP



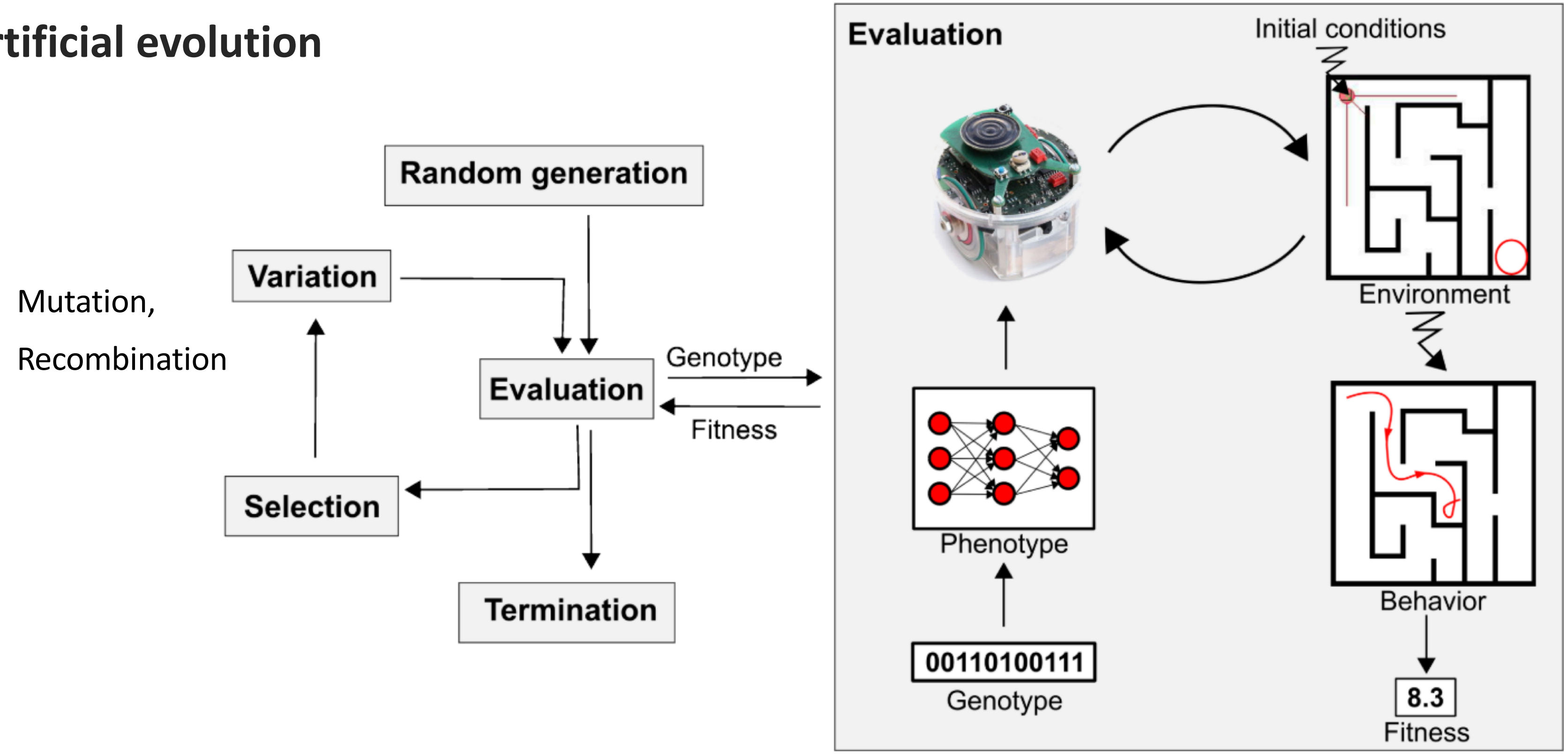


  - Define properties (important parameters, constraints, effects on collective performance, ...) e.g. through experimentation

Pitonakova, L., Crowder, R., & Bullock, S. (2018). Frontiers in Robotics and AI. DOI: 10.3389/frobt.2018.00047

Fernandez-Marquez, J. L., et al. (2013). Natural Computing, 12(1), 43–67.

- **Artificial evolution**



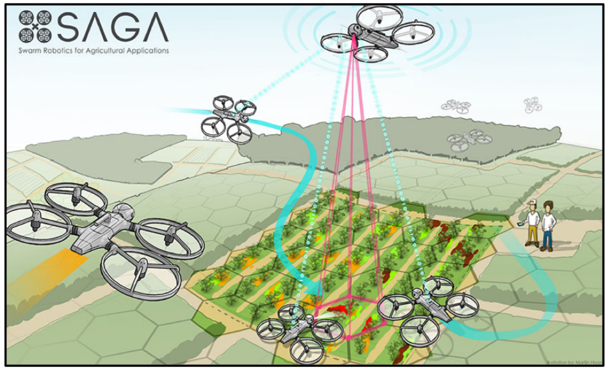
Doncieux, S., et al. (2015). Frontiers in Robotics and AI, 2(4), DOI: 10.3389/frobt.2015.00004.

Ferrante, E., et al. (2015). PLoSComputational Biology, 11(8), e1004273.

- Macroscopic models, Design patterns and Artificial evolution are NOT mutually exclusive!
  - D. P. based on macroscopic model analysis
  - Evolution to optimise parameters in PFSM or design patterns
  - PFSM based on multiple design patterns
  - ...

The future of swarms

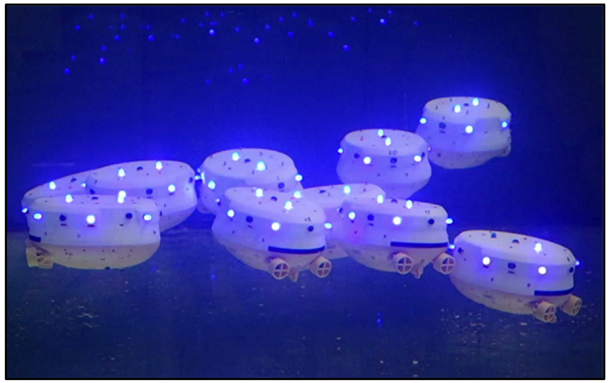
- Automated warehouses, agriculture, ... (boring, hard work)



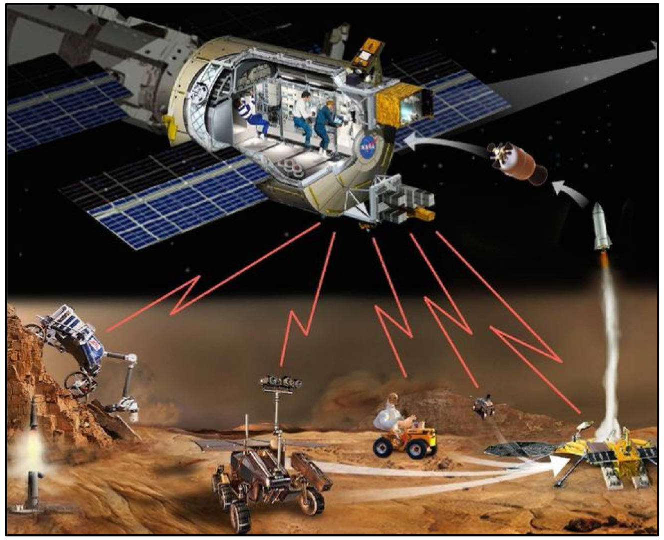
- Package delivery (coordination problem: robots, people, ...)

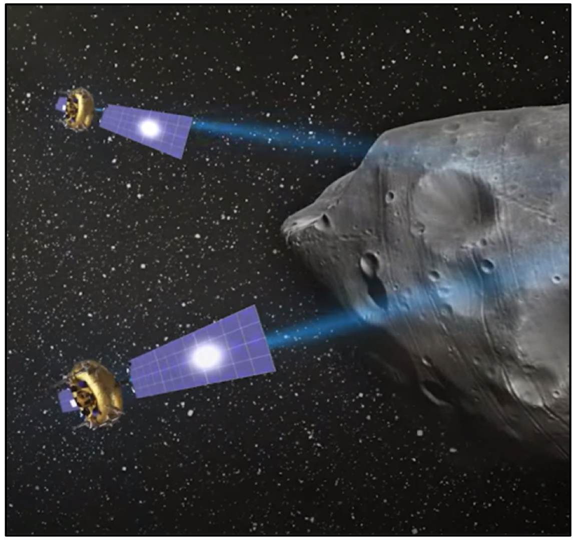
- Autonomous transport, including on-demand

- Dangerous / difficult environments: clean-up of toxic waste, cave exploration, underwater data collection, ...



- Space: Satellite and base construction, exploration, terraforming, asteroid mining





Further reading