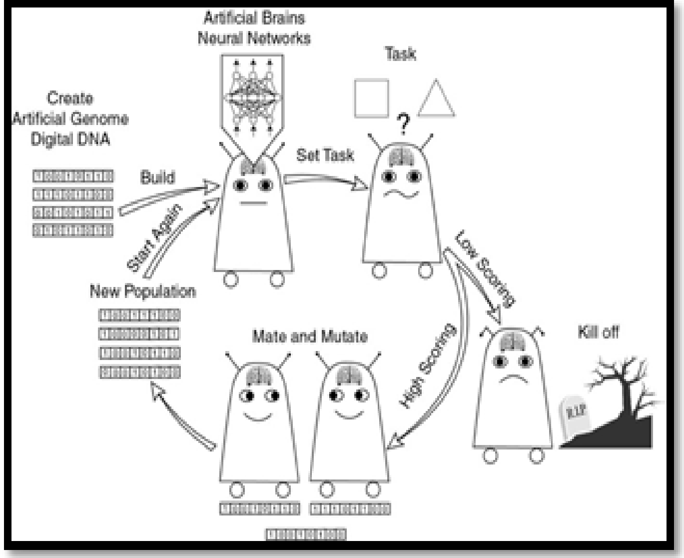
NTNU
Norwegian University of Science and Technology

Lecture 10

Evolutionary Robotics

Kazi Shah Nawaz Ripon and Pauline Haddow



Outline

- Evolutionary Robotics (ER)
- Classic ER System
- EA in Robotics
  - Evolving Gaits in a Walking Biped Robot Controller
  - Co-Evolving Morphology and Control
- Swarm Robotics
- ChIRP: Cheap Interchangeable Robotic Platform for Swarm Robotics

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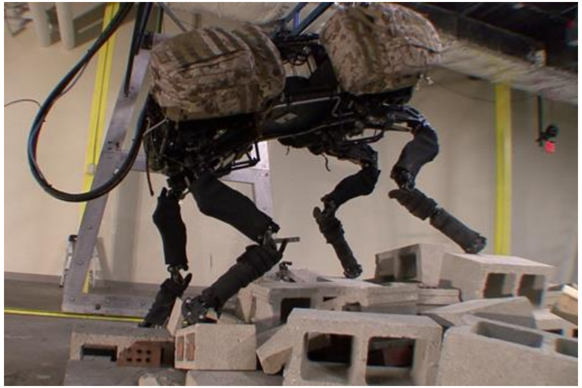
Evolutionary Robotics (ER)

Taking a biologically inspired approach to the design of autonomous, adaptive system.



Evolutionary Robotics (ER)

- ER aims to evolve autonomous robot controllers (i.e. robot brains) as well as robot morphologies (i.e. robot bodies) in a way that does not require direct programming by humans.

- The primary advantage is to produce controllers or even whole robots that are capable of functioning **in environments that humans do not understand well**.

- The long-term goal of ER is to create general, robot-generating algorithms.

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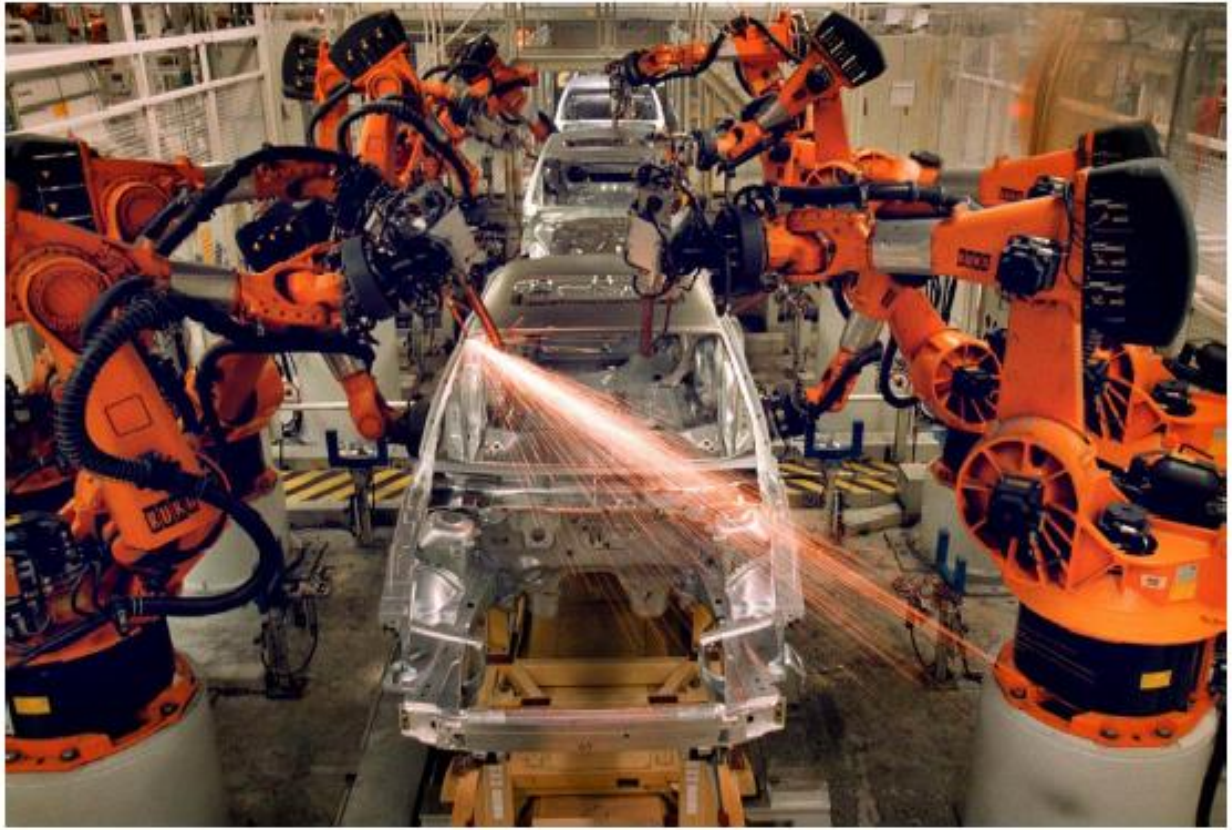
Evolutionary Robotics (ER)

- Morphology and control architecture are closely interdependent, and any change in one is likely to have a large influence on the functioning of the others.
- Most fields related to robotics are focused on one specific robot feature or functionality while ignoring the rest.
- ER is an alternative point of view in which the robot, its environment, and all interactions among its components are studied as a whole.

Motivations

- Machine learning algorithms usually require a set of training examples consisting of both a hypothetical input and a desired answer.
- In many robot learning applications the desired answers (an action for the robot to take) are usually not known explicitly a priori.
- EAs are natural solutions to this sort of problem, as the fitness function need only encode the success or failure of a given controller.

Current Robots



Future Scenarios

7

Autonomous vs Adaptive

Autonomous yet non-adaptive machines:

- Industrial robots.
- They execute the same sequence of actions repeatedly.

Adaptive yet non-autonomous machines:

- Unmanned drones.
- They exhibit the adaptive capabilities of their remote human operators.

- To date, the only force known to be capable of producing fully autonomous as well as adaptive machines is biological evolution.

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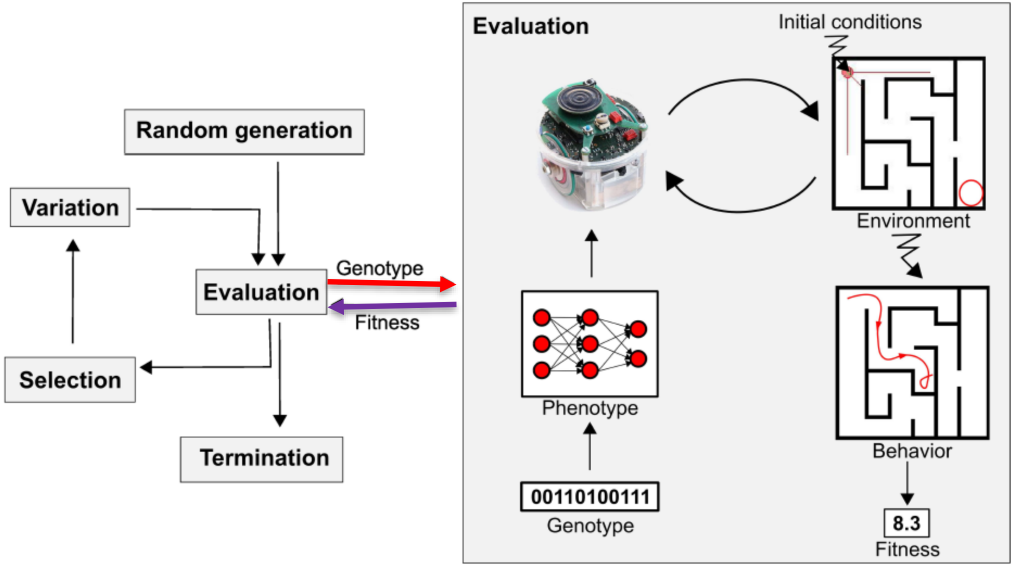
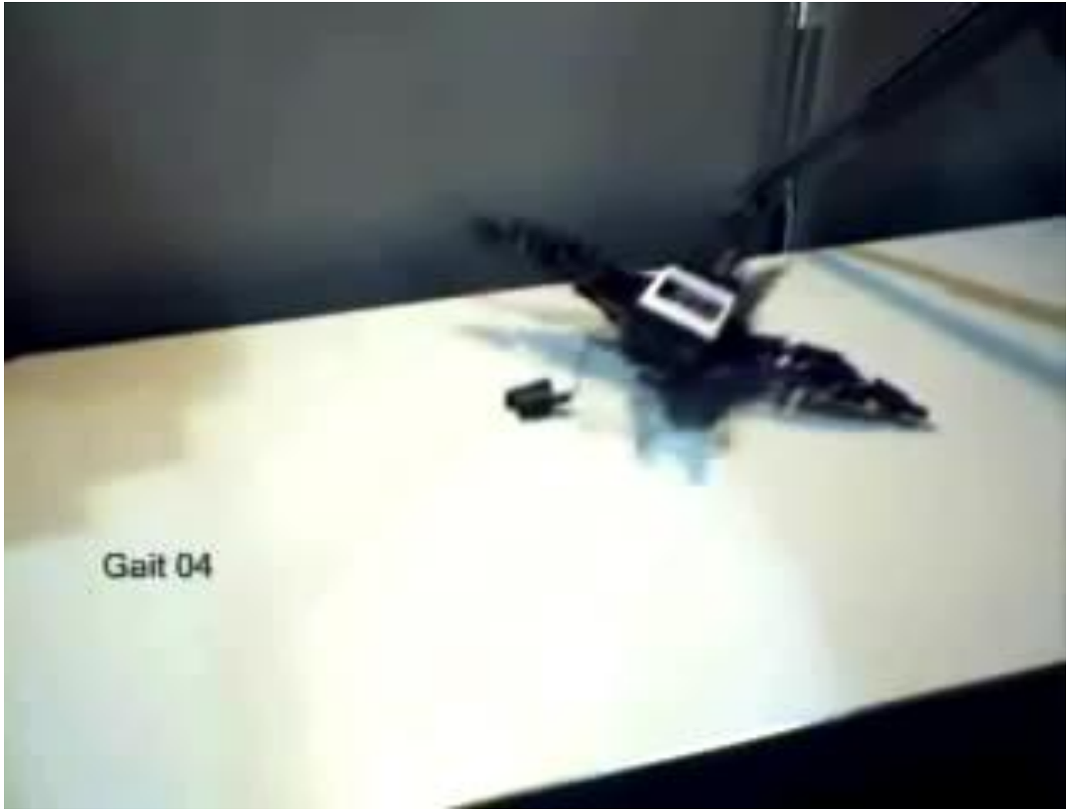
Classic ER System



- The evaluation component takes a genotype from the evolutionary component as input and returns the fitness value of the corresponding robot as output.

Why ER Does Have The Potential For Dramatic Impact?



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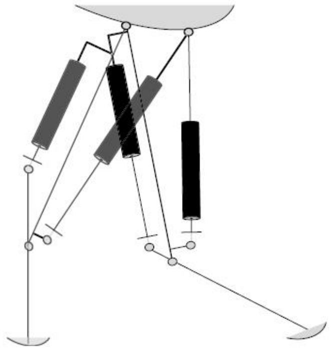
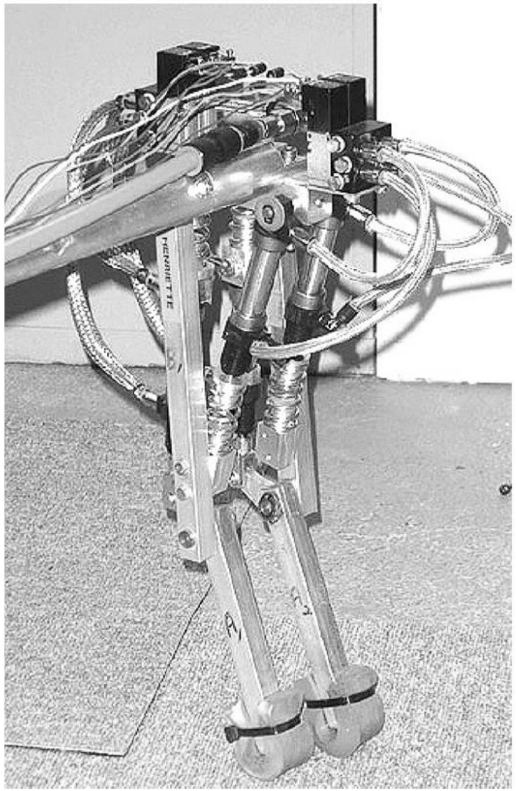
Evolving Gaits in a Walking Biped Robot Controller



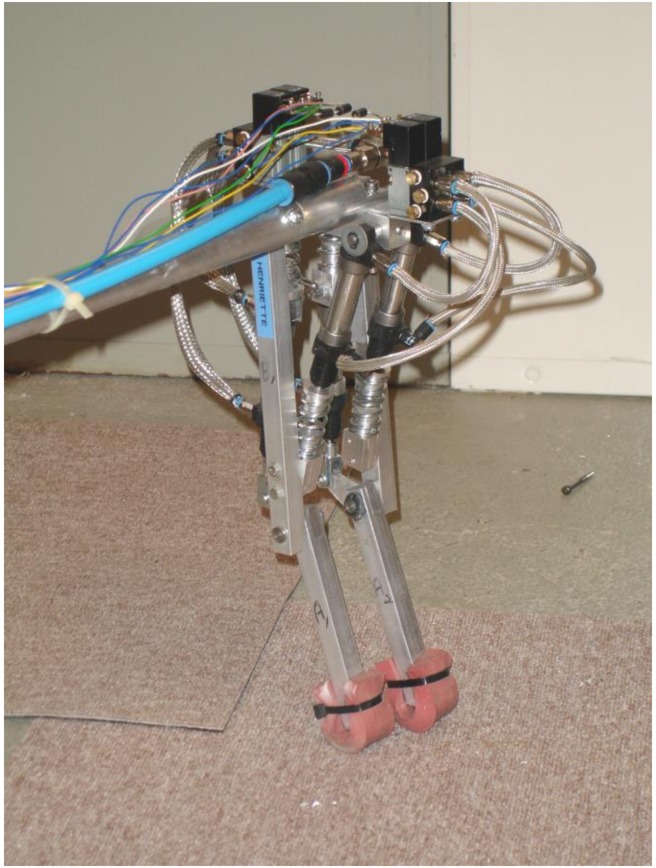


Evolving Gaits in a Walking Biped Robot Controller

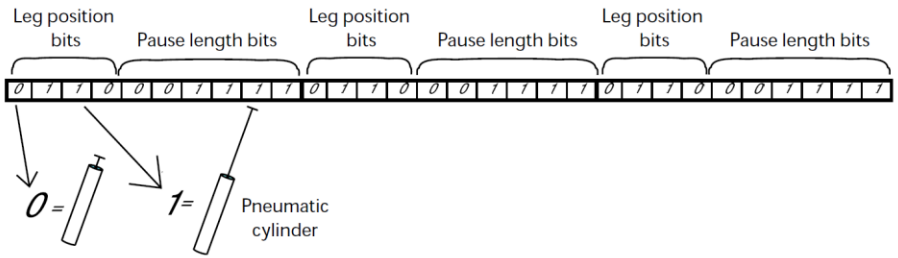
- This research used an EA for evolving gaits in a walking biped robot controller.
- The focus is **fast learning in a real-time environment**.
- The robot was a two-legged biped with binary operated pneumatic cylinders.
- The goal was to find the most efficient gait with respect to speed.

L. M. Garder and M. E. Høvin, **Robot Gaits Evolved by Combining Genetic Algorithms and Binary Hill Climbing.**

The Robot Hardware



Chromosome Encoding



- Each gait is coded by a 30 bit chromosome.
- The chromosome represents 3 body positions each followed by a variable pause.
- 2 cylinders can move a single leg to 4 different positions, and 2 legs with 4 cylinders can hold 16 different positions.
- 3 following positions with 6 bits pauses in between make a search space of $2^{30} = 1073741824$ different gaits.

Pauses

- A gait is composed of leg positions and pauses.
- The most efficient gaits with respect to forward speeds are gaits dominated by jumping movements.
- In a jumping movement the pause length between each leg kick is outmost critical as the robot may stumble if the timing of the leg kick is just slightly wrong.

Fitness Function

- The fitness of each chromosome (gait) is a function of the forward speed of the robot caused by the corresponding chromosome.
- Each gait is repeated 3 times in sequence to reduce the impact caused by the initial leg positions.
- A movement in the backward direction causes the fitness to be zero.

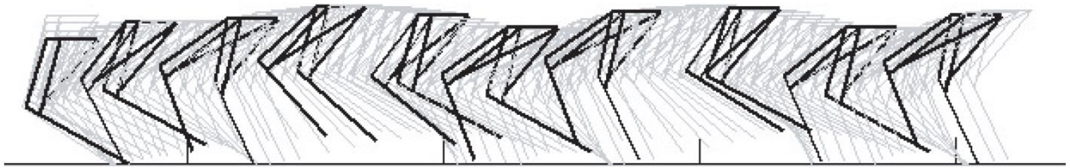
The GA

- The leg position bits are first evolved by simple GA up to generation 8.
- All pause length bits are fixed corresponding to pause lengths of 150ms.
- In generation 8, GA has normally found a decent leg position pattern.
- From generation 9, all leg position bits are fixed.
- In generation 9, all possible combinations of the most significant pause length bits are tested (coarse search) where all other bits are kept fixed.
- With 3 pauses in a chromosome there are 8 possible combinations of the most significant pause bits to be tested.

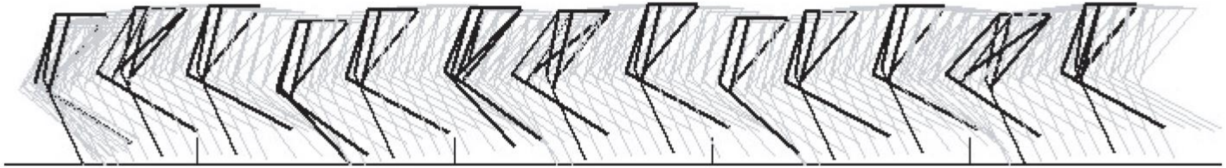
The GA (contd)

- The chromosome with the **highest fitness containing the most successful most significant pause bits** is kept.
- 8 copies of this chromosome are then made forming generation 10.
- In generation 10, all combinations of **the next most significant pause bits** are tested keeping the other bits fixed.
- The chromosome with the highest fitness containing the most successful next most significant pause bits are then kept.
- 8 copies of this chromosome are then made forming generation 11 and so on until **the least significant pause bits** are found in generation 14.
- The search is then terminated.

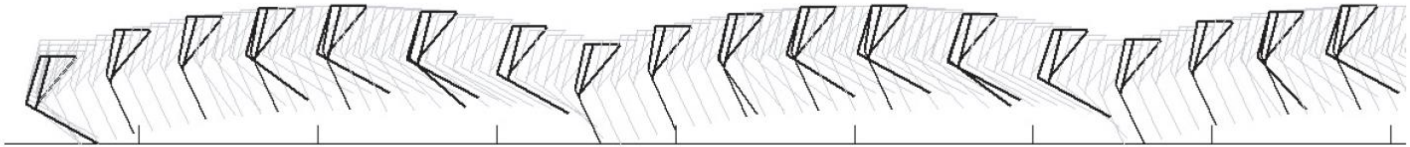
Gaits Obtained



Suboptimal gait based on asymmetric jumping.



Suboptimal gait based on every other one-leg jumping.



Optimal gait based on gaits based on synchronous jumping.

Evolving Gaits in a Walking Biped Robot Controller

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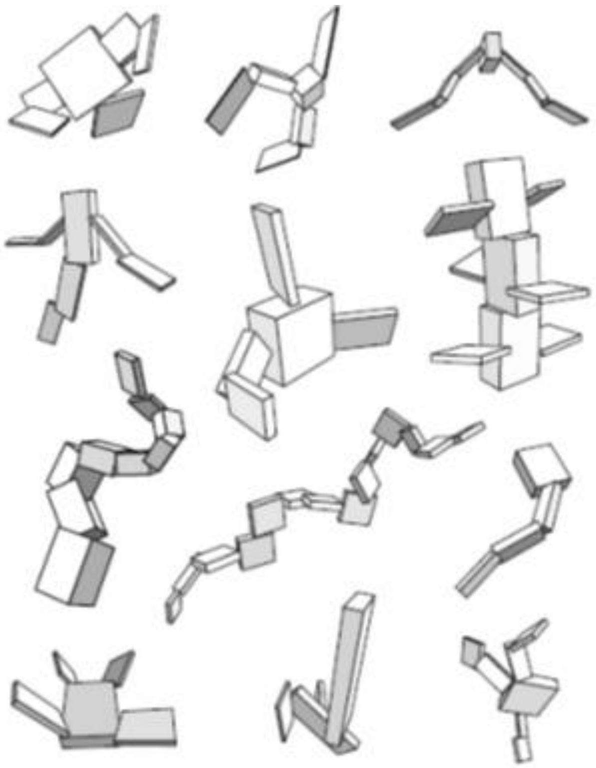
Co-Evolving Morphology and Control



Co-Evolving Morphology and Control

- Morphology and control are interdependent and should therefore be developed together.
    - Evolve the control structure of the robot (as before).
    - But, also co-evolve the morphology (robot body).
- GAs permit virtual entities to be created **without requiring an understanding of the procedures or parameters** used to generate them.
    - It determines the creature morphologies as well as their control systems.

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Evolving Virtual Creatures by Karl Sims

- This work presents a novel system for creating virtual creatures that move and behave in simulated three-dimensional physical worlds.
- The morphologies of creatures and the neural systems for controlling their muscle forces are both generated automatically using GA.
- Different fitness evaluation functions are used to direct simulated evolutions towards specific behaviors such as swimming, walking, jumping, and following.

Co-Evolving Morphology and Control

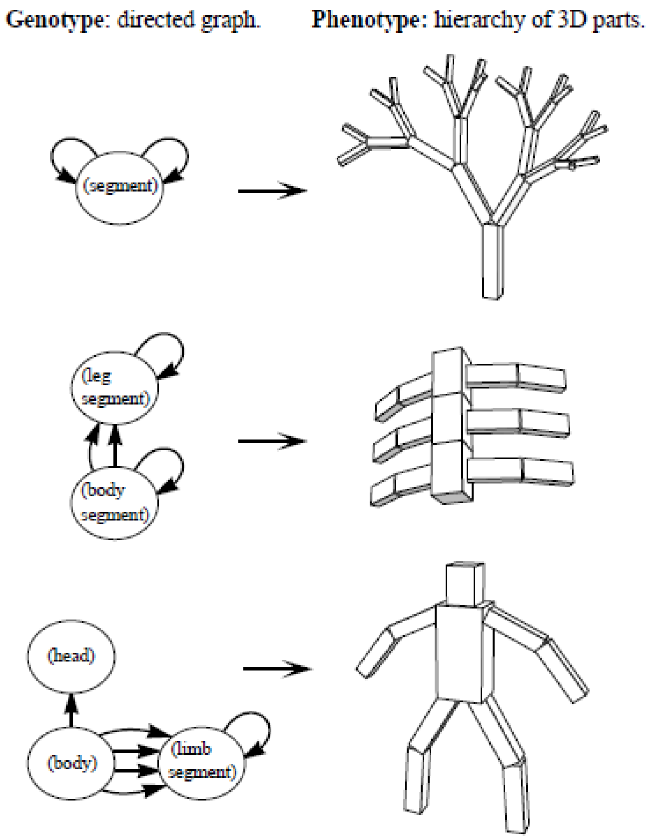
4 min. Video of karl Sims Co-Evolve Creature (1994)

Contributions

- Earlier, control systems were generated for fixed structures that were user-designed.
- In this work, the three-dimensional physical structure of a creature can adapt to its control system, and vice versa, as they **evolve together**.
- The "nervous systems" of creatures are also completely determined by the optimization:
  - the number of internal nodes, the connectivity, and the type of function each neural node performs are included in the genetic description of each creature.
  - These remove the necessity for a user to provide any specific creature information.

Creature Morphology

- Genotype: Directed graph of nodes and connections.
- Phenotype: A hierarchy of articulated three-dimensional rigid parts.



Internal Parameters

- Dimensions
- Joint-type:
  - joint-types: *rigid, revolute, twist, universal, bend-twist, twist-bend*, or *spherical*.
- Joint-limits.
- Recursive-limit.
- A set of local *neurons* is also included in each node.

Initial Population

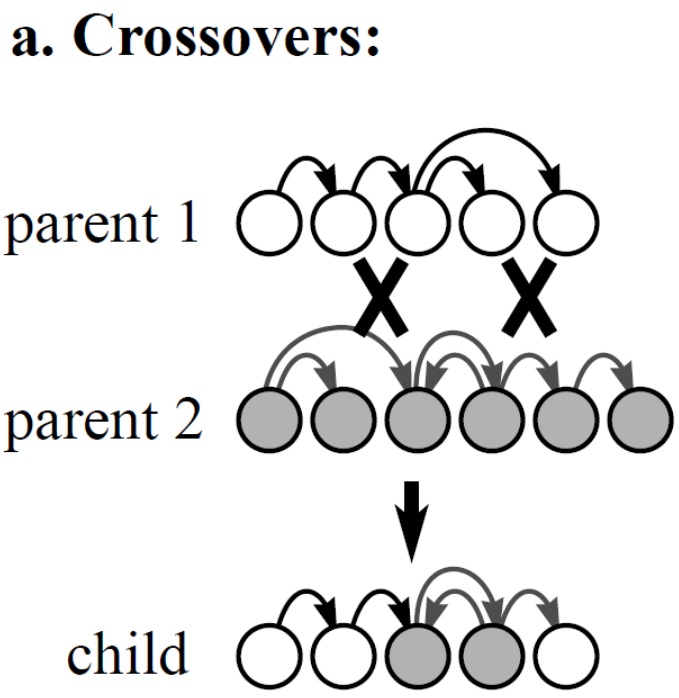
- An evolution of virtual creatures is begun by first creating an initial population of genotypes.

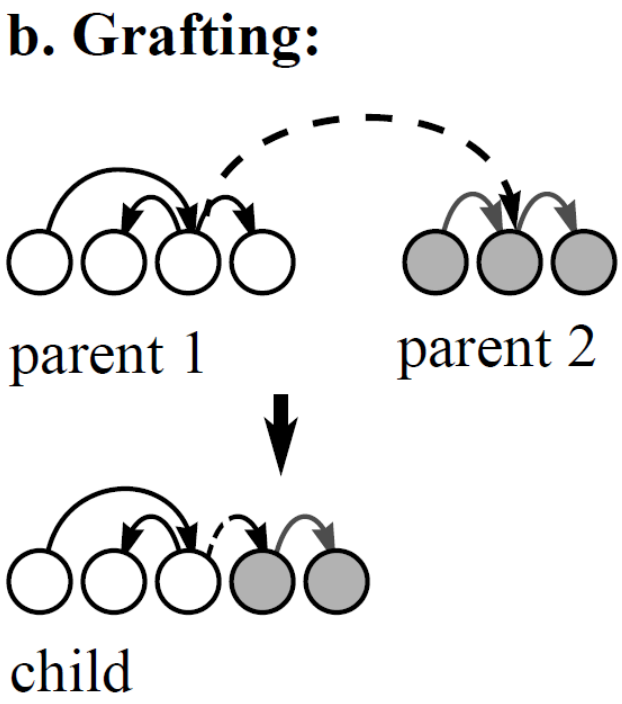
- These initial genotypes can come from several possible sources:
  - new genotypes can be synthesized “from scratch” by random generation of sets of nodes and connections.
  - An existing genotype from a previous evolution can be used to seed the initial population of a new evolution.
  - A seed genotype can be designed by hand.

Mutation of Directed Graph

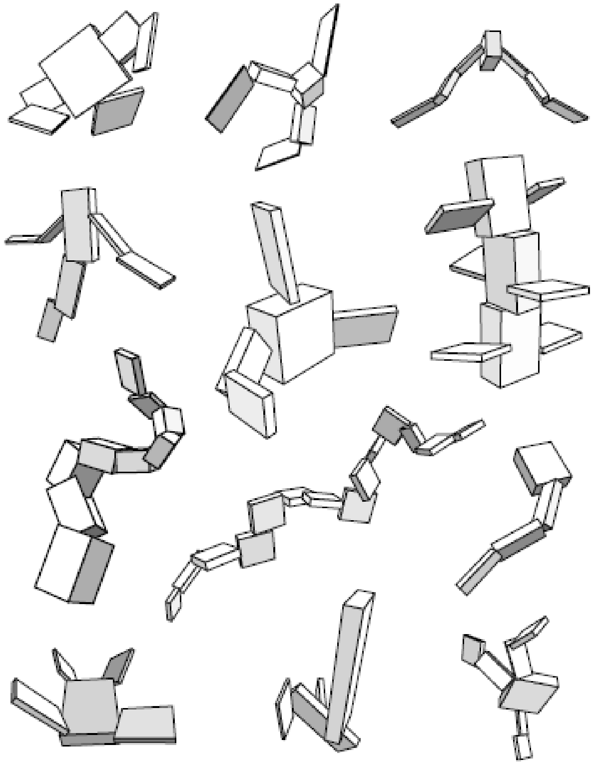
- The internal parameters of each node are subjected to possible alterations.
- A mutation frequency for each parameter type determines the probability that a mutation will be applied to it at all.
  - Boolean values are mutated by simply flipping their state.
  - Scalar values are mutated by adding several random numbers to them for a Gaussian-like distribution so small adjustments are more likely than drastic ones.

Mating Directed Graph



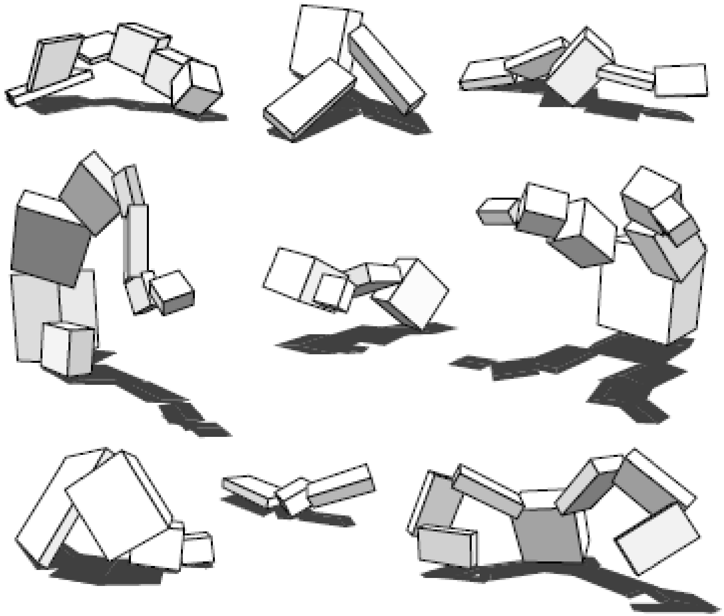


Results



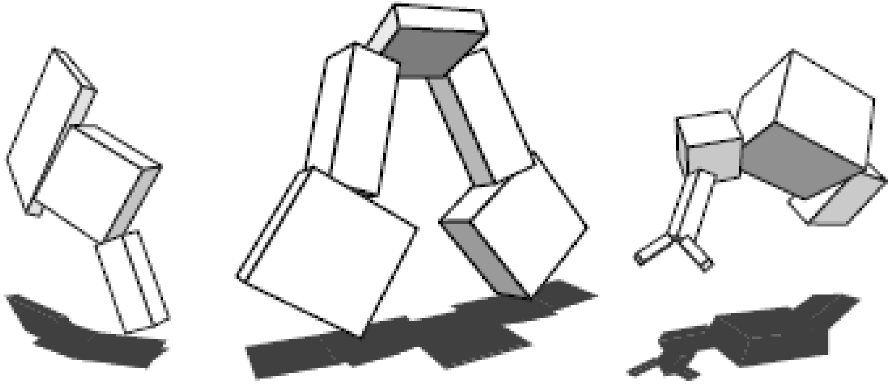
Creatures evolved for swimming.

Results



Creatures evolved for walking.

Results



Creatures evolved for jumping.

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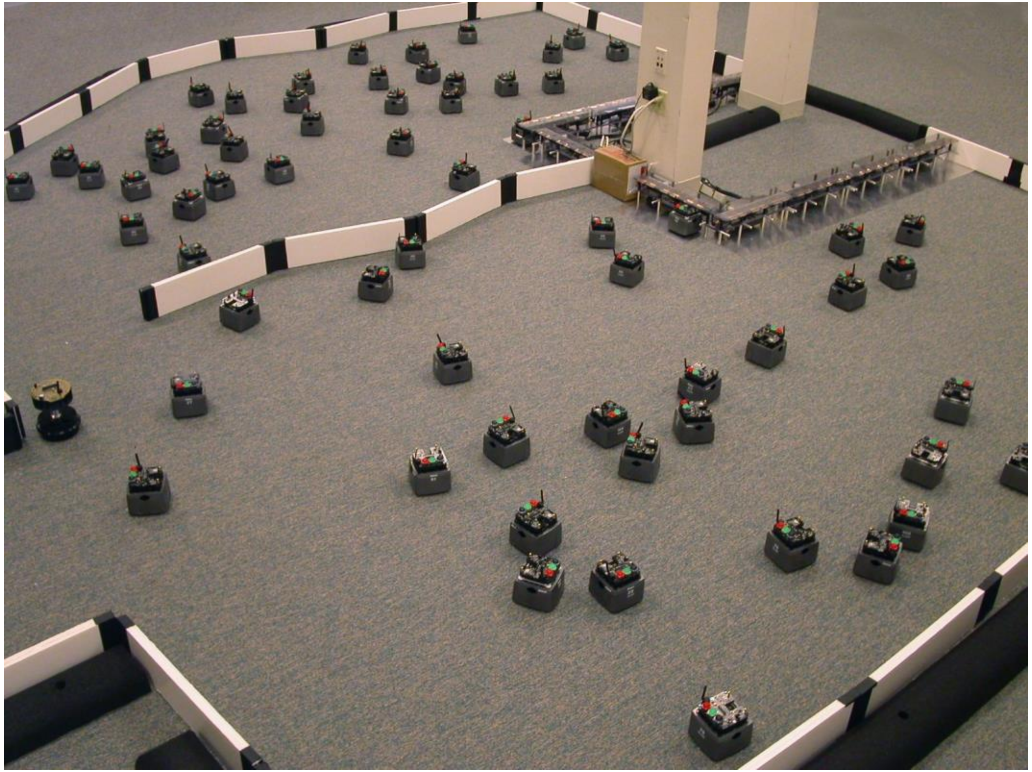
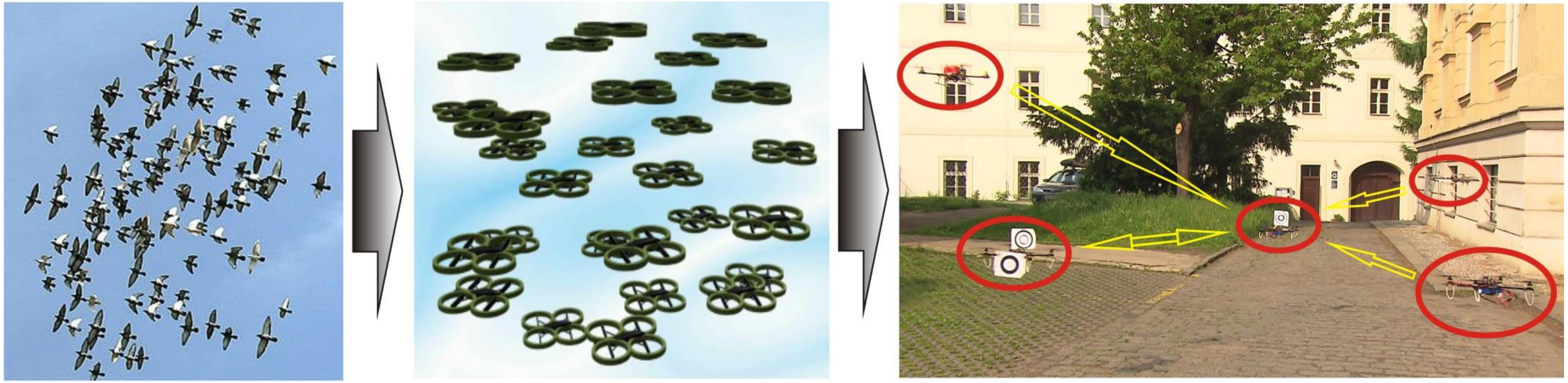


Swarm Robotics

Examples slides are from the book *Bio-Inspired Artificial Intelligence: Theories, Methods, and Technologies* by Dario Floreano and Claudio Mattiussi, MIT Press

Swarm Robotics



- Swarm robotics is the study of how to coordinate large groups of relatively simple robots through the use of local rules.
- It takes its inspiration from societies of insects that can perform tasks that are beyond the capabilities of the individuals.

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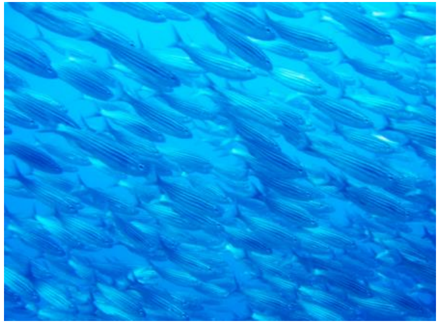
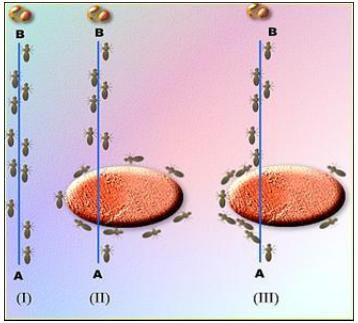
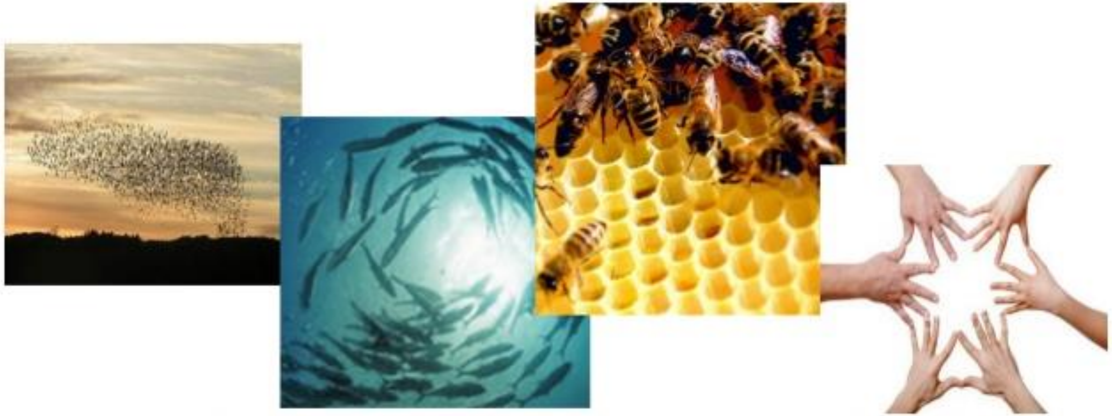
Sources of Inspiration

- Taking a ***swarm intelligence*** approach to robotics.
- A desired **collective behavior** emerges from the interactions among robots and interactions of robots with the environment.





Self-Organization / Stigmergy



Example

(A swarm robotic demonstration using 278 miniature e-puck robots at the Ecole Polytechnique Federale de Lausanne (EPFL) in Lausanne, Switzerland. Robots in the video are all real, not computer generated)

Traditional Robotics

- Traditionally, robotics researchers focus on the development of highly capable and expensive robots.
- Only a few are made.
    - Predator airplanes
- With swarm robotics, the emphasis is on having lots of relatively inexpensive robots.
    - Micro-air vehicles

Swarm Robot / Multi-Robot

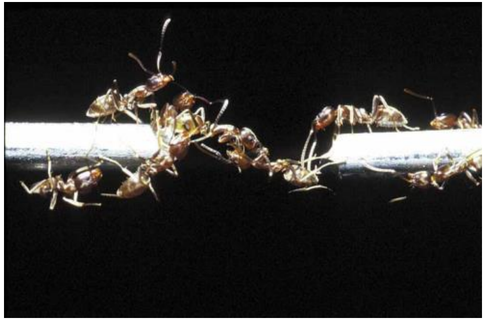
- These concepts are similar in the sense that they require multiple robots that communicate/cooperate.
- Apart from that, their application, and thus their design and implementation differ.
- With swarm robots, each robot to be too stupid to possibly even know why it's doing something (i.e., what is the ultimate goal).
  - Each robot is unable to do anything meaningful.
- In multi-robots, each robot has its own goal.
- Multi-robot systems can be homogeneous and heterogeneous, but swarm systems have to homogeneous.

Characteristics

- Autonomous.
- A large number of units.
- Homogeneous.
- Simple and incapable or inefficient.
- Only local communication.
- Distributed.
- Scalable and robust.

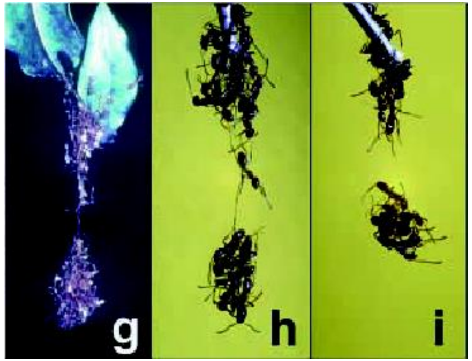
Physical Cooperation of Mobile Individuals

Passing a gap



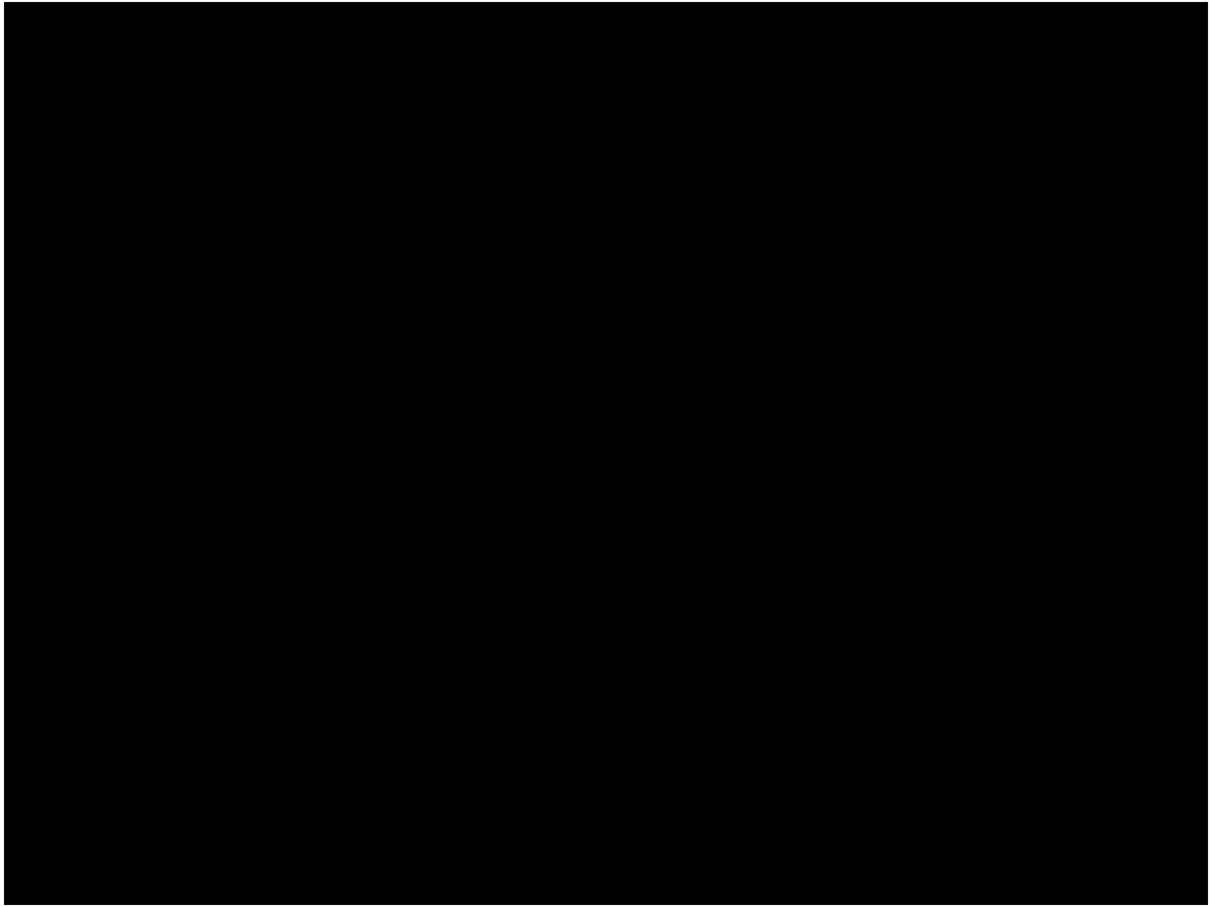
Nest building

Grouped Fall



Plugging potholes in the trail

Physical Cooperation of Mobile Individuals



Simulator

- There exist many mobile robotic simulators available which can be used for swarm-robotic experiments.

- They differ not only in their technical aspects but also in the license and cost.
  - Player/Stage/Gazebo.
  - Webots.
  - Microsoft Robotics Studio.
  - *SwarmBot3D.*

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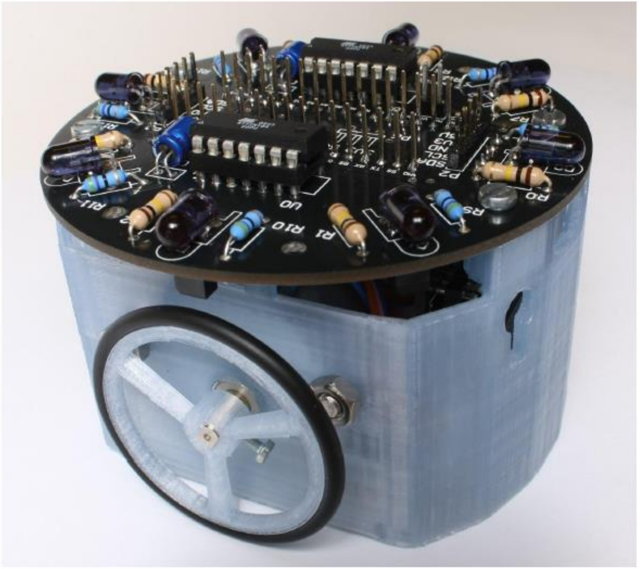
ChIRP: Cheap Interchangeable Robotic Platform for Swarm Robotics

Base

- Stepper motors
- Distance sensors (also communication)
- Resilient to luminosity variations
- Battery (~ 3 hours)
- Based on Arduino Micro
- Boards to control hardware
- 3D printed case



Extension

- Pins on top from Arduino Micro
- Slots for physical extension

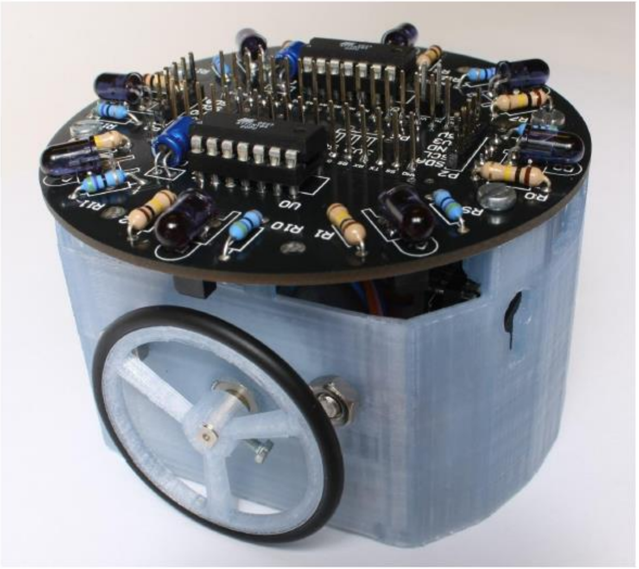
ChIRP: *Continue*

Interface

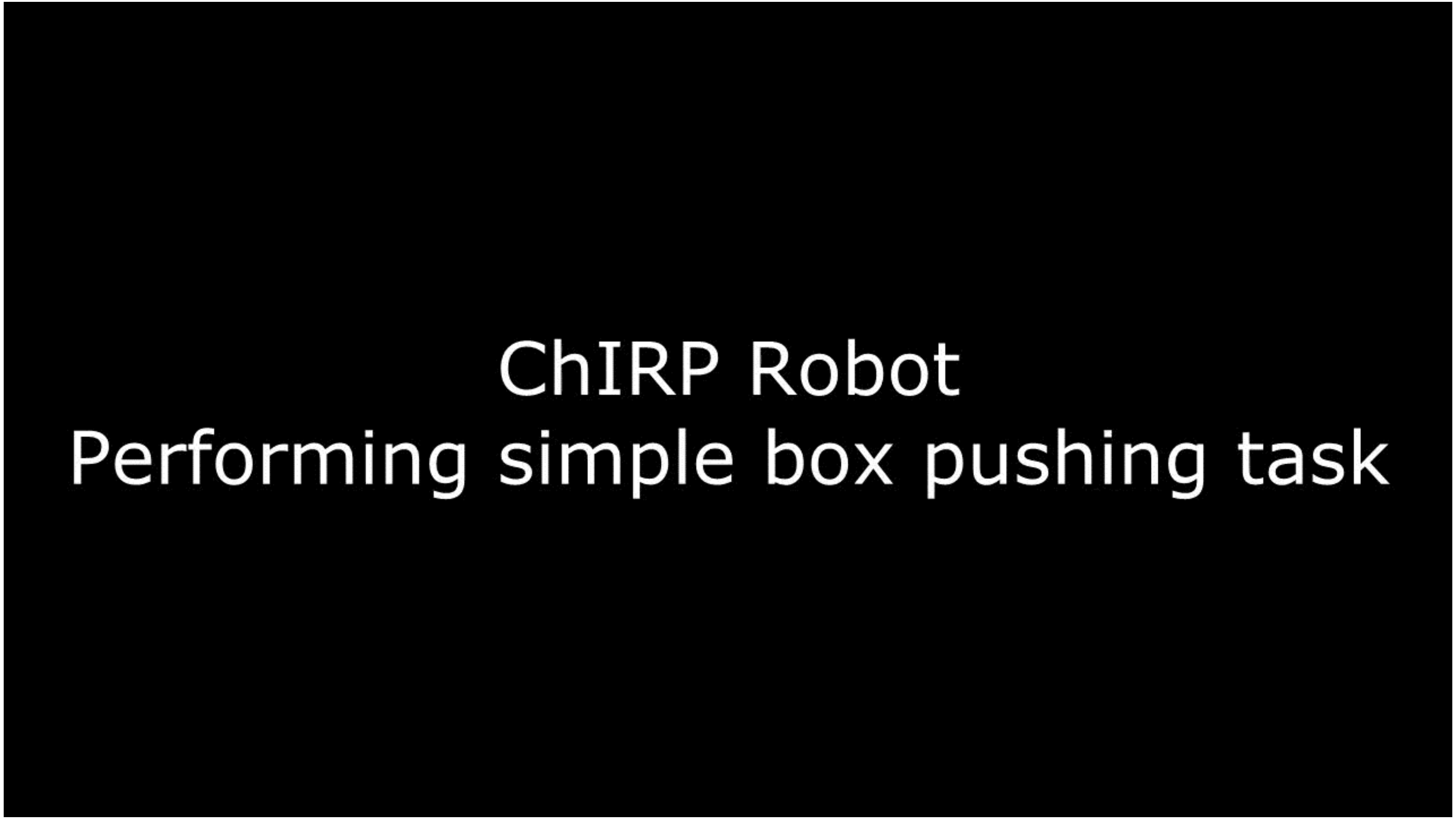
- Programming by USB
- Arduino IDE

Librairies

- Driving the motors
  - Call a function to set the speed
- Using the infra-red as distance sensors
  - Call a function to get the distances
- Using the infra-red as local communication
  - Call a function to get the message
  - Call a function to broadcast a message



ChIRP: *box pushing demo*



Reading

Required Reading:

- Floreano book: chapter 7: 7.4
- Sha, A. (2010). Introduction to Swarm Robotics (NA). *Rapport technique, IEEE Robotics and Automation Society.(Cité page 15.).*

Recommended Reading :

- Bongard, J. C. (2013). Evolutionary robotics. *Communications of the ACM, 56*(8), 74-83.