Evolving Dynamic Gaits with Aibo

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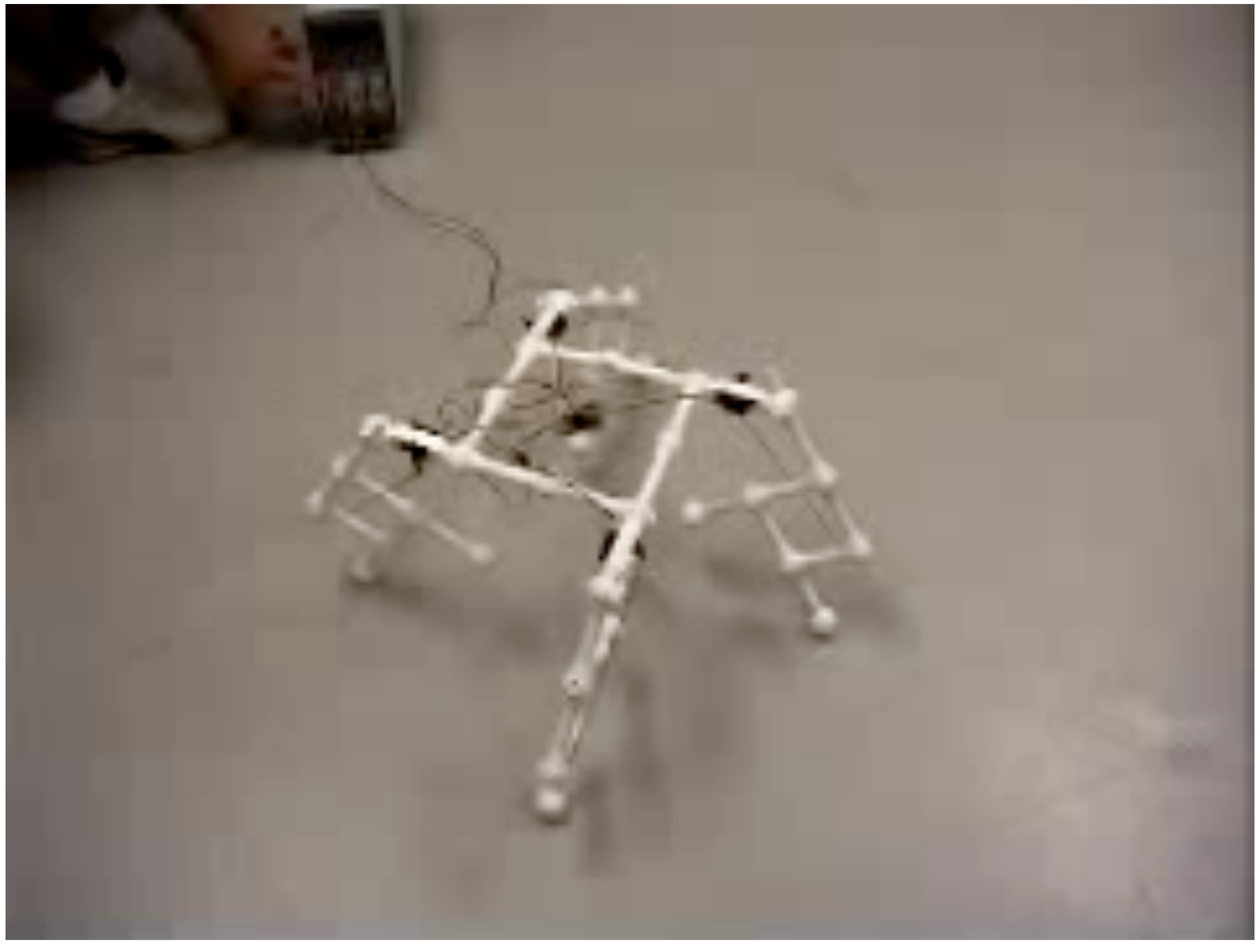
Introduction

Developing locomotion controllers for legged robots has been studied for over 20 years.

Most work has focused on:

- Static gaits.
- Manually designed gaits.

- Designing by hand can be challenging:



Here I describe my work in using Evolutionary Algorithms to autonomously acquire (evolve/learn) gaits.

Outline

- Intro to Evolutionary Algorithms.

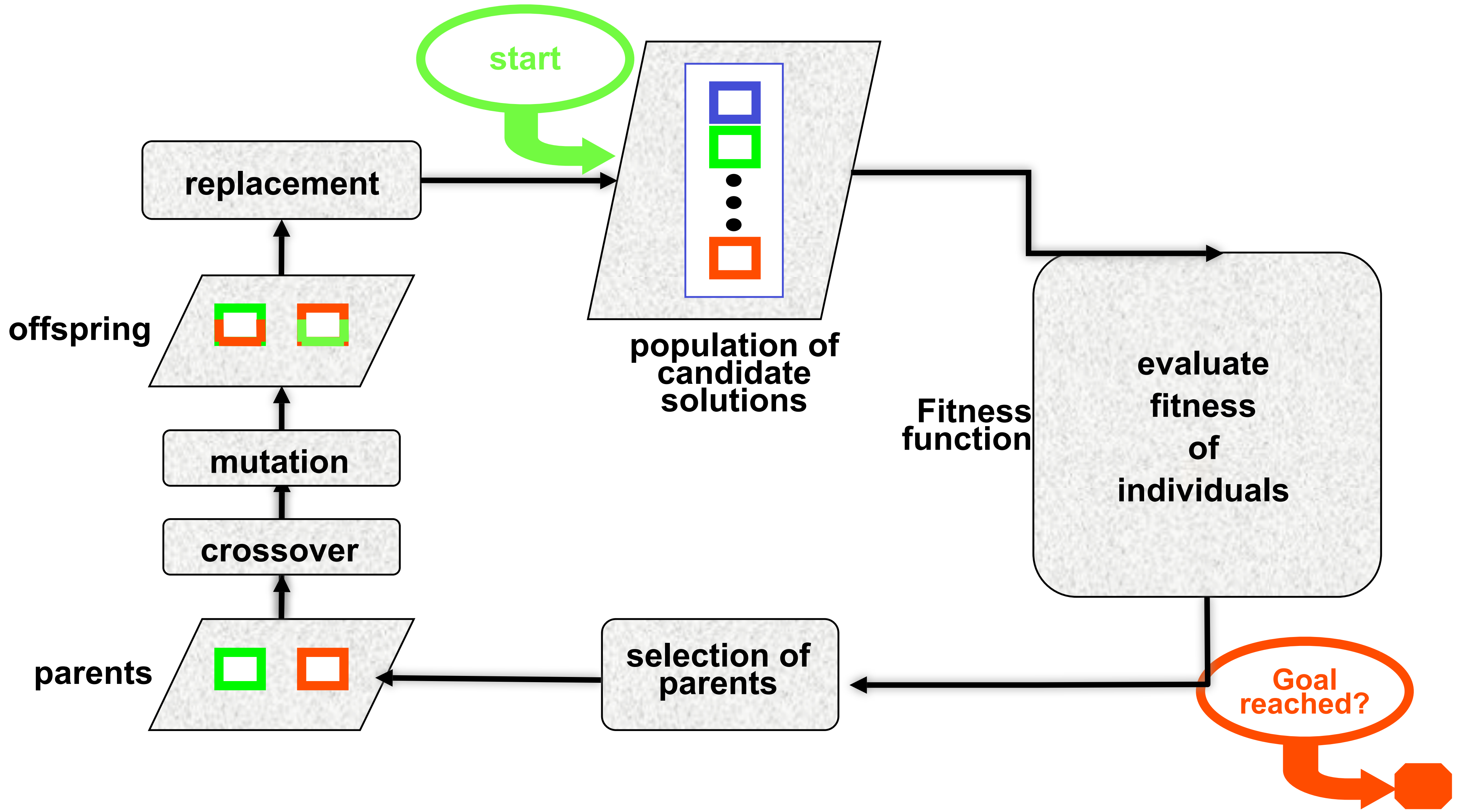
- Evolving pace & trot on DRX-600.
- Evolving gait-type and robustness on Aibo.

- Evolving static gaits in simulation.
- Evolving higher level behaviors in simulation.

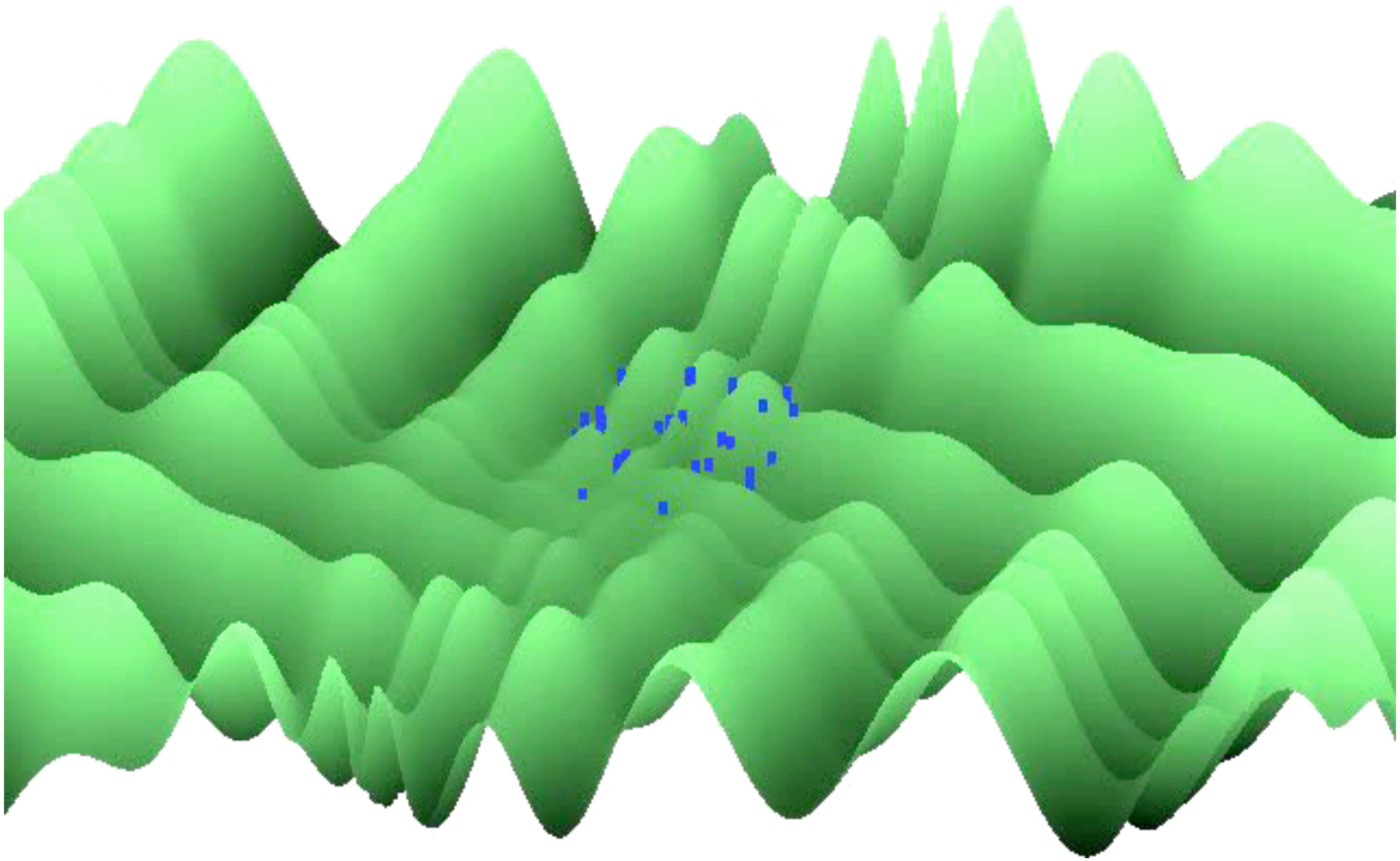
Part I: Evolutionary Algorithms

Evolutionary Algorithms (EAs)

- A family of stochastic, population-based search algorithms.
- Inspired by neo-Darwinism.



Example EA



- Maximize f(x, y):
  - f() is the rotated F101 function.
  - Using a standard Evolutionary Algorithm (EA).

Uses of EAs

Evolutionary Algorithms become more and more useful with the continuing increase in computer power.

Many application areas:

- Analog (and digital) circuits.
- Antennas.
- Engineering design.
- MEMS devices.
- Neural Networks (optimize topology and/or weights).
- Parameter optimization (multi-modal, non-differentiable).
- Topological Design
- ...

Evolving Antennas

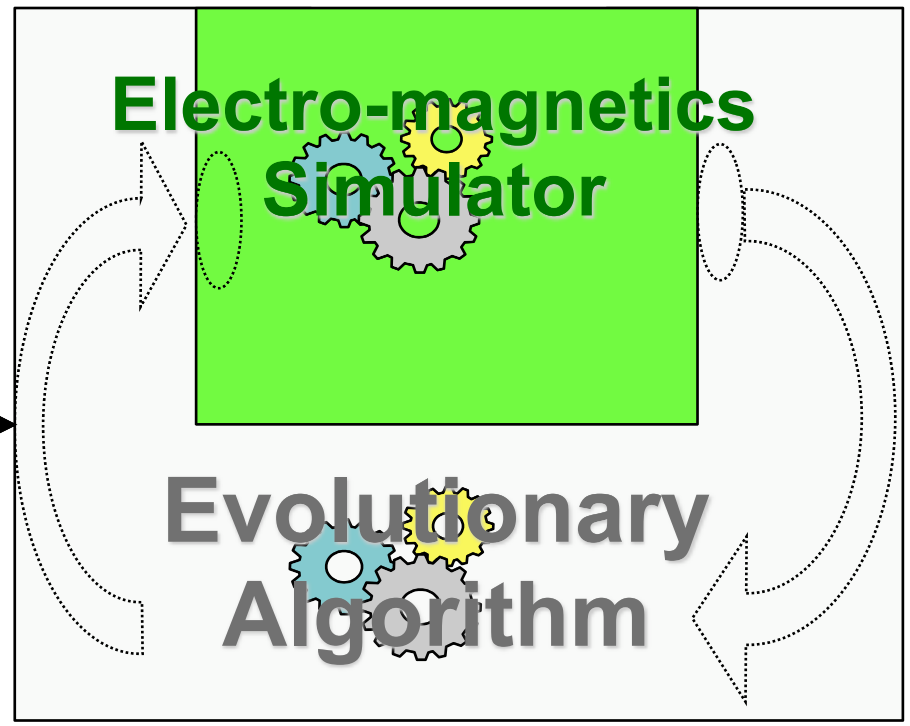
- Transmit Frequency: 8470 MHz
- Receive Frequency: 7209.125 MHz
- Antenna RF Input: 1.5W = 1.76 dBW = 31.76 dBm
- VSWR: < 1.2 : 1 at the antenna input port at Transmit Freq, < 1.5 : 1 at the antenna input port at Receive Freq
- Antenna Gain Pattern: Shall be 0 dBic or greater for angles 40 <= theta <=80; 0 <= phi <= 360
- Antenna pattern gain (this shall be obtained with the antenna mounted on the ST5 mock-up) shall be 0.0 dBic (relative to anisotropic circularly polarized reference) for angles 40 <= theta <=80; 0 <= phi <= 360, where theta and phi are the standard spherical coordinate angles as defined in the IEEE Standard Test

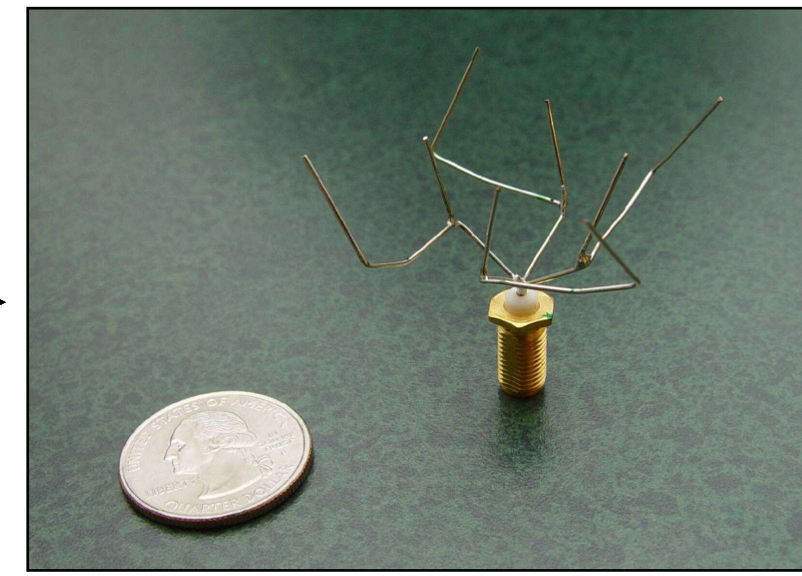
Requirements

- Antenna Input Impedance: 50 ohms at the antenna input port
- Magnetic dipole moment: < 60 mA-cm^2
- Grounding: Cable shields of all coaxial inputs and outputs shall be returned to RF ground at the transponder system chasis. The cases of all comm units will be electrically

Small Amount of E/M Expertise

Small Amount of EA Expertise

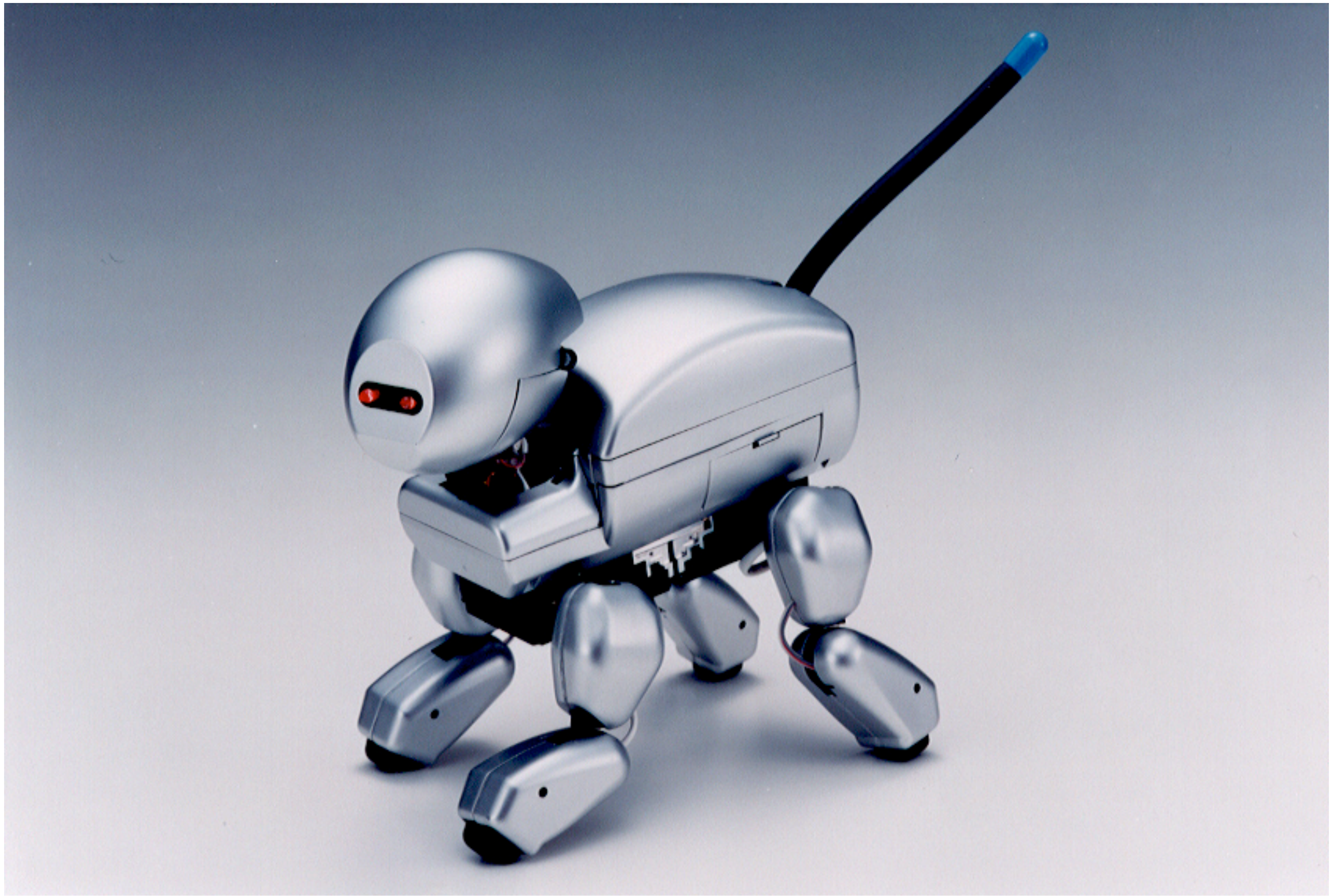




- Evolutionary Design Engine:
  - –Parallel, any Unix.
  - –Uses NEC4.
- Beowulf cluster of over 80 processors.

Result: Evolved Antenna

Part II:
Evolving Gaits with the DRX-600



DRX-600

DRX-600: 6th generation quadruped robot by Sony.

- Engineers designed and built the robot.
- Developed a locomotion module, with a parameterized gait equation.
- Came up with various walking/crawling gaits.

Problem => *Could not make it run*.

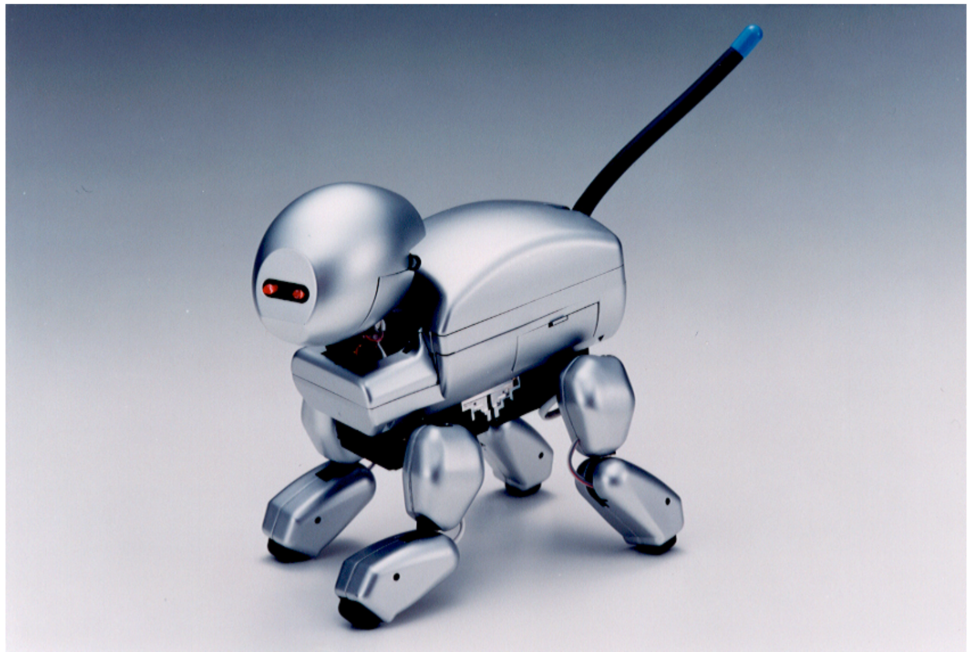
Solution: Autonomously acquire a dynamic gait using an **Evolutionary Algorithm.**

This was the *first autonomous acquisition of a dynamic gait* on a quadruped robot.

DRX600 Hardware Platform

DRX600 / OPEN-R Prototype:

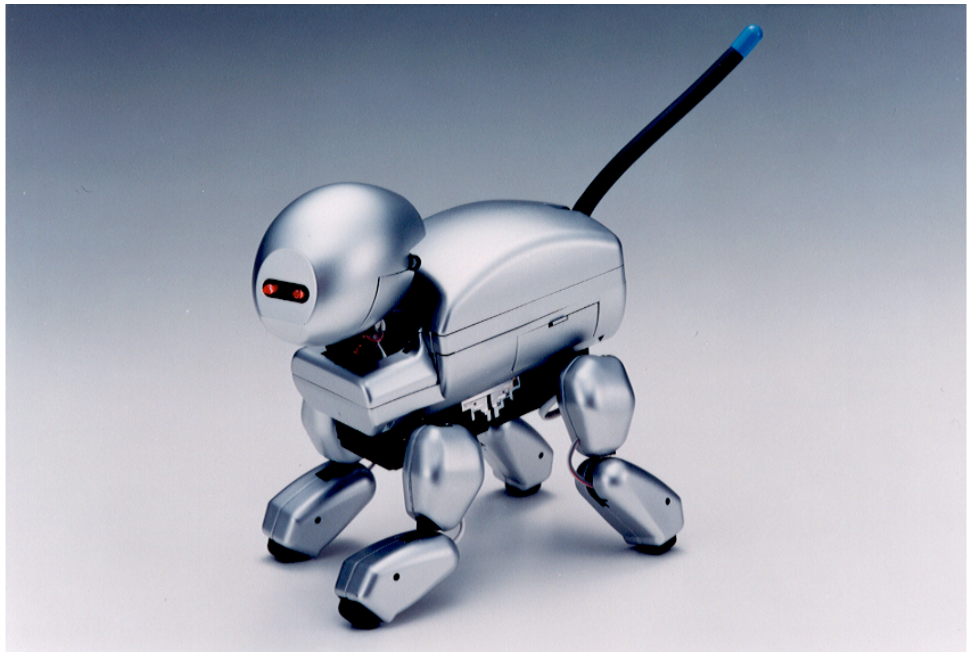
- 6th generation entertainment robot by Sony.
- onboard CPU.
- micro-camera unit (MCU).
- position-sensitive device (PSD).
- stereo microphones.
- gyroscope & accelerometers.
- 5 touch sensors (top of head, bottom of each foot).
- 4 legs, each with 3 DOF.
- Head: 3 DOF.
- Tail: 1 DOF.



DRX600 Locomotion Module

Locomotion Module (LM):

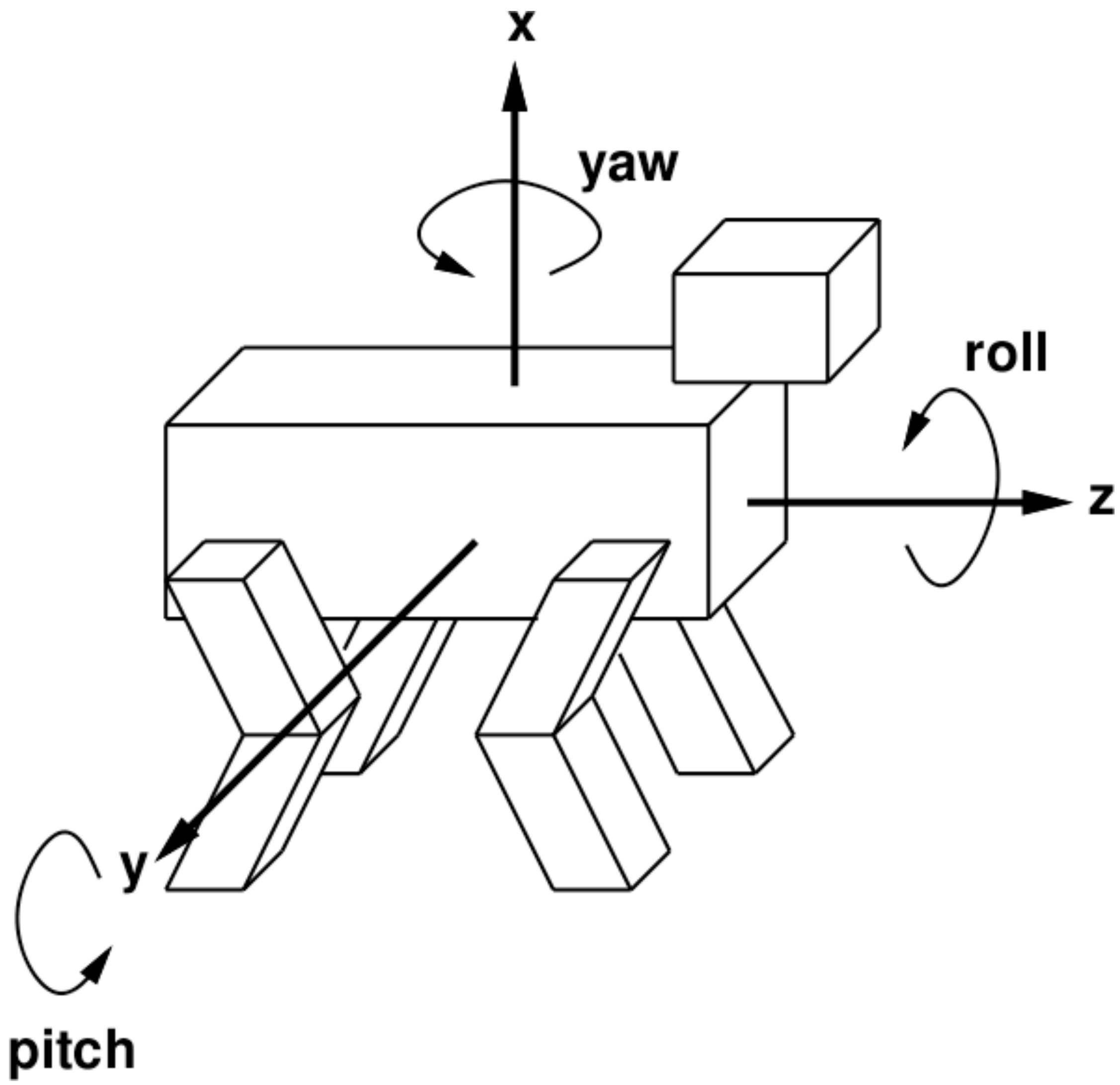
- The software module which controls gaits.
- Gaits are specified by a vector of real-valued parameters.
- LM uses a mathematical function of sines and cosines to then create a cyclic motion of the bottom of each leg.
- Actuators are controlled by a special ASIC chip.
- Every 8ms the LM sets the target joint position and PID gain value and the ASIC chip calculates the output to the motor to make its position error 0.



Developing/evolving a gait consists of creating a *set of parameter values* for the LM.

DRX-600 Gait Parameters

- LM has 61 parameters.
- Reduced to 20 params for the EA.



parameter	unit	initial range
body center x	mm.	85 - 95
body center z	mm.	-5 - 5
body pitch	degrees	-5 - 5
all legs y	mm.	5 - 25
front legs z	mm.	24 - 40
rear legs z	mm.	15 - 29
step length	n.a.	80 - 220
swing height	mm.	15 - 29
swing time	ms.	200 - 400
swing mult.	n.a.	1.5 - 2.5
switch time	ms.	500 - 900
ampl. body x	mm.	-2 - 2
ampl. body y	mm.	0 - 20
ampl. body z	mm.	-2 - 2
ampl. yaw	degrees	-2 - 2
ampl. pitch	degrees	-3 - 3
ampl. roll	degrees	-3 - 3
min. gain	n.a.	25 - 175
shift	degrees	60 - 120
length	degrees	90 - 150

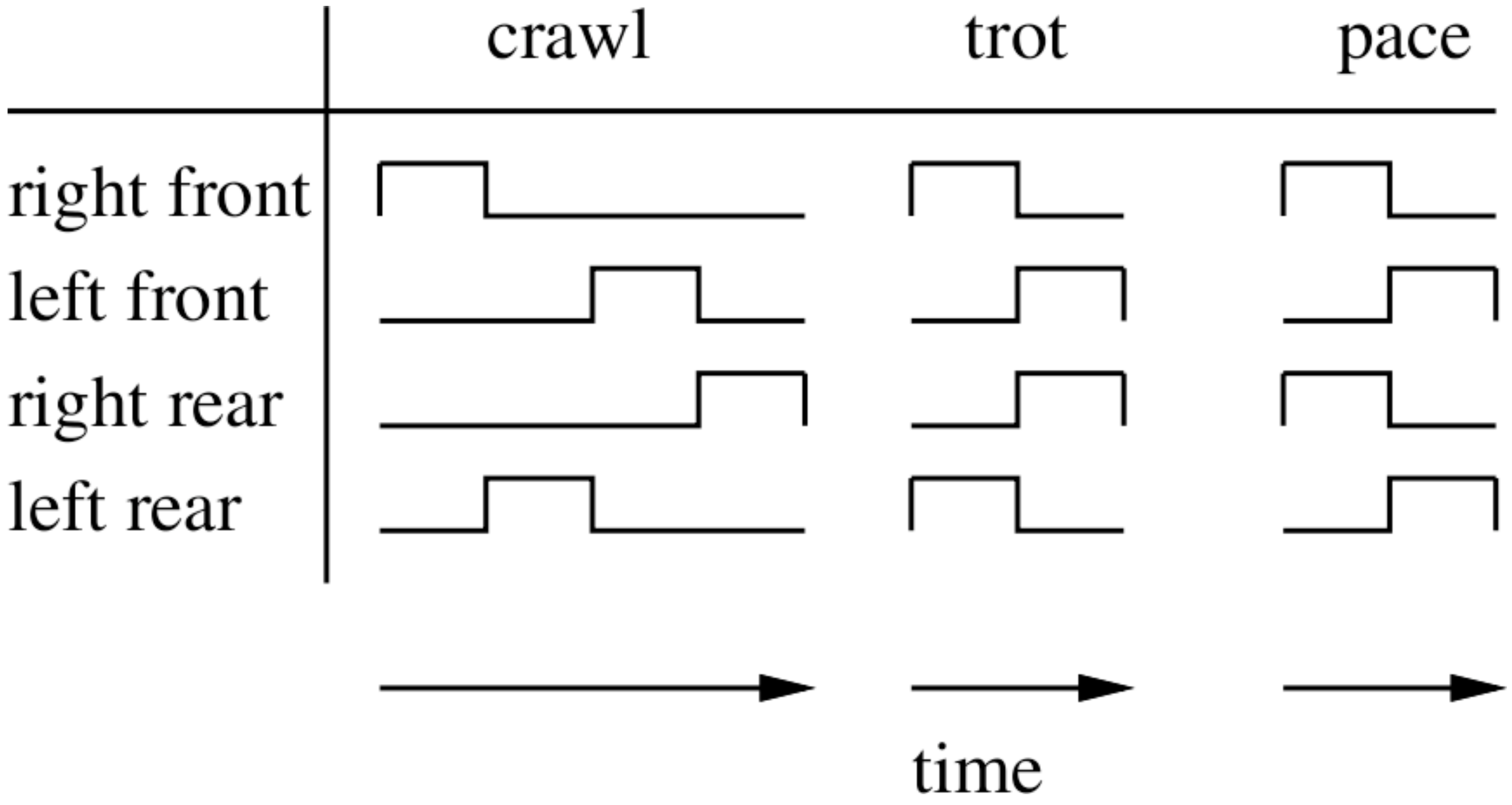
Evolving Gaits

- They had manually created some non-dynamic gaits:
  - Crawl: 5m/min; and a Fast-Crawl: 6 m/min.
- A hand-coded pace gait was developed but did not work well:
  - Sometimes moved backwards.
- Could not hand-code a trot gait.

Objective:

- Evolve/learn a dynamic gait.
- Initially constructed a basic EA with a human in the loop.
  - Human measured distance traveled and entered it into the computer.
- Wanted to setup a system for autonomous gait acquisition by using the robot's own sensors for evaluation.

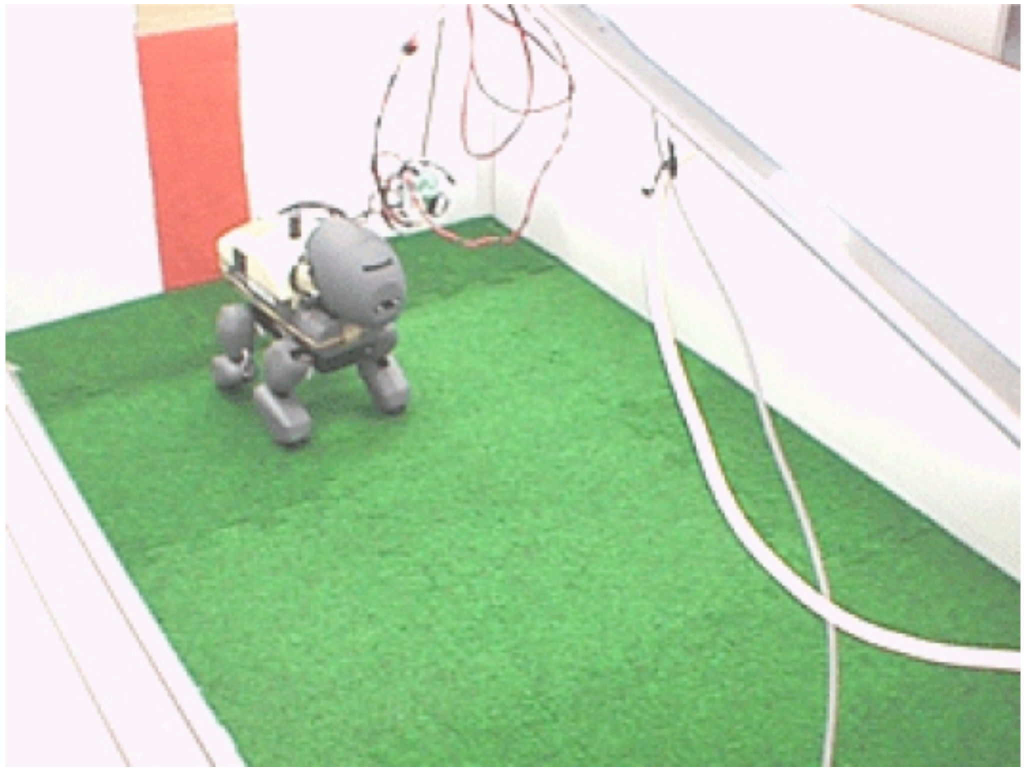
Quadruped Gaits



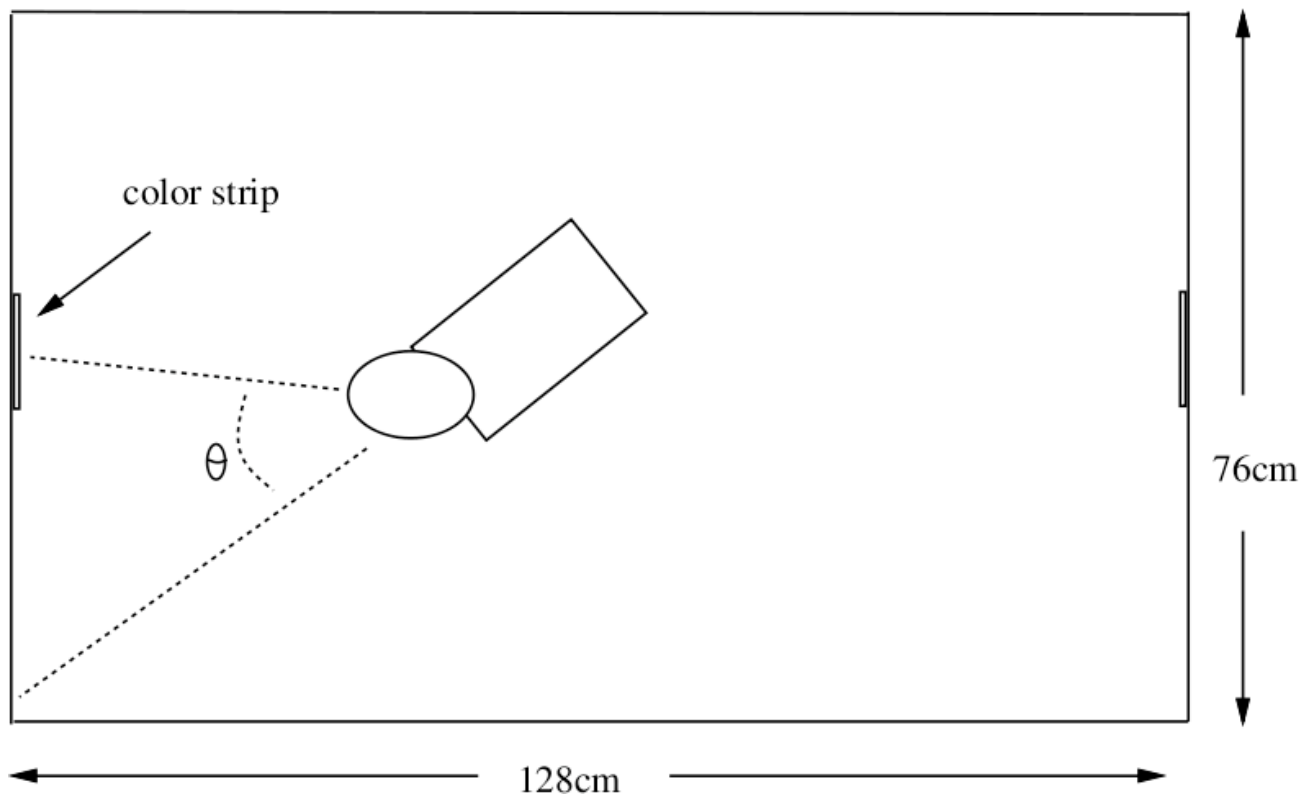
- We wanted to produce both a trot and a pace gait.
- Type of gait is determined by relative phase offsets of the four legs.

Overview of Evolutionary Setup

- Evolution takes place inside a rectangular “pen”.
  - Two color strips on opposite sides.
  - EA is run using robot’s onboard CPU.
  - Robot evaluates itself with its own sensors.
- A set of cables is connected to the robot from a pole above the pen.
  - Electricity and data.

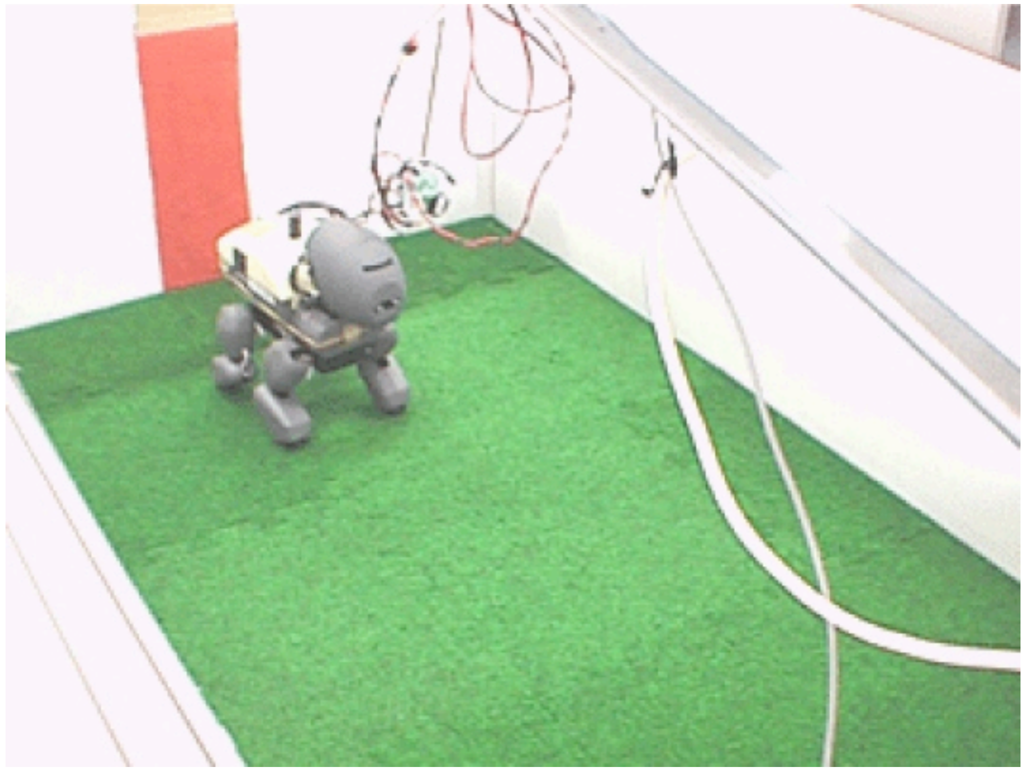


- Evaluation of a gait consists of:
  - Center on a color strip.
  - Measure distance.
  - Run forward.
  - Measure distance.
  - Calculate average velocity.
  - Turn around and repeat.



Centering on Color Strip

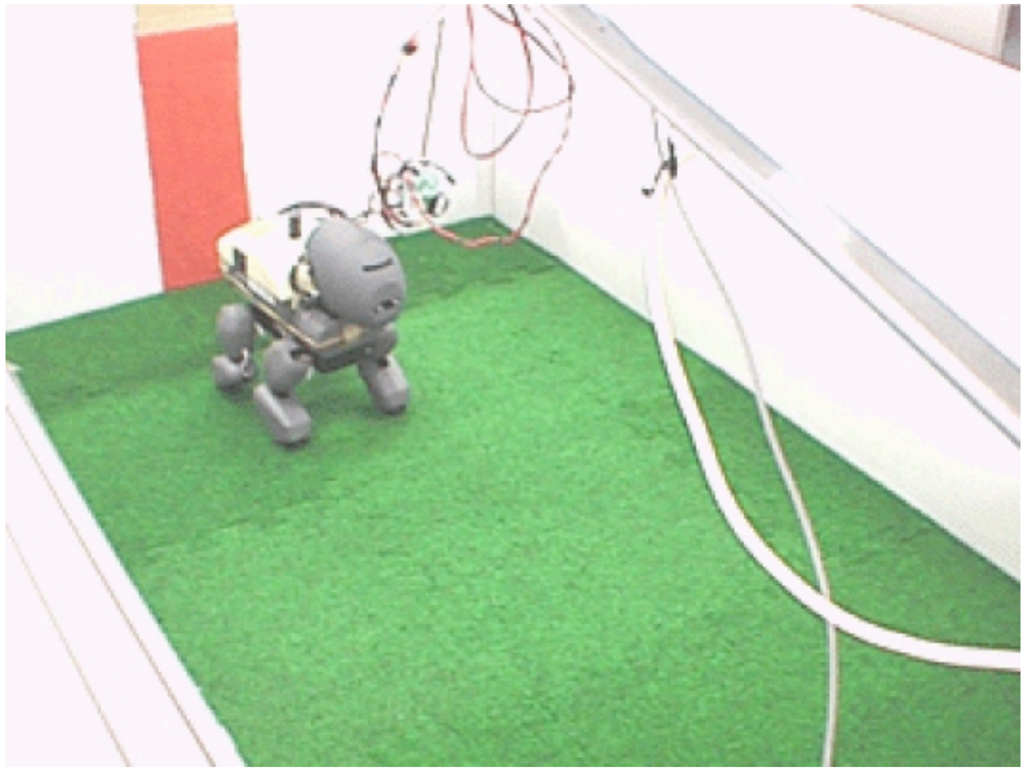
- Robot has a Micro-Camera Unit:
  - 362x492 pixels.
  - 8 Color detection tables (CDTs).
  - Used one CDT for each color strip.



- Using a hand-coded, crawl gait, robot turns left/right until body is centered on the desired color strip:
  - Tolerance is +/- 6 degrees.

Calculating Distance

- Robot has a Position Sensitive Device (PSD):
  – Infrared sonar sensor.
  – Accurate from 10 to 80cm.

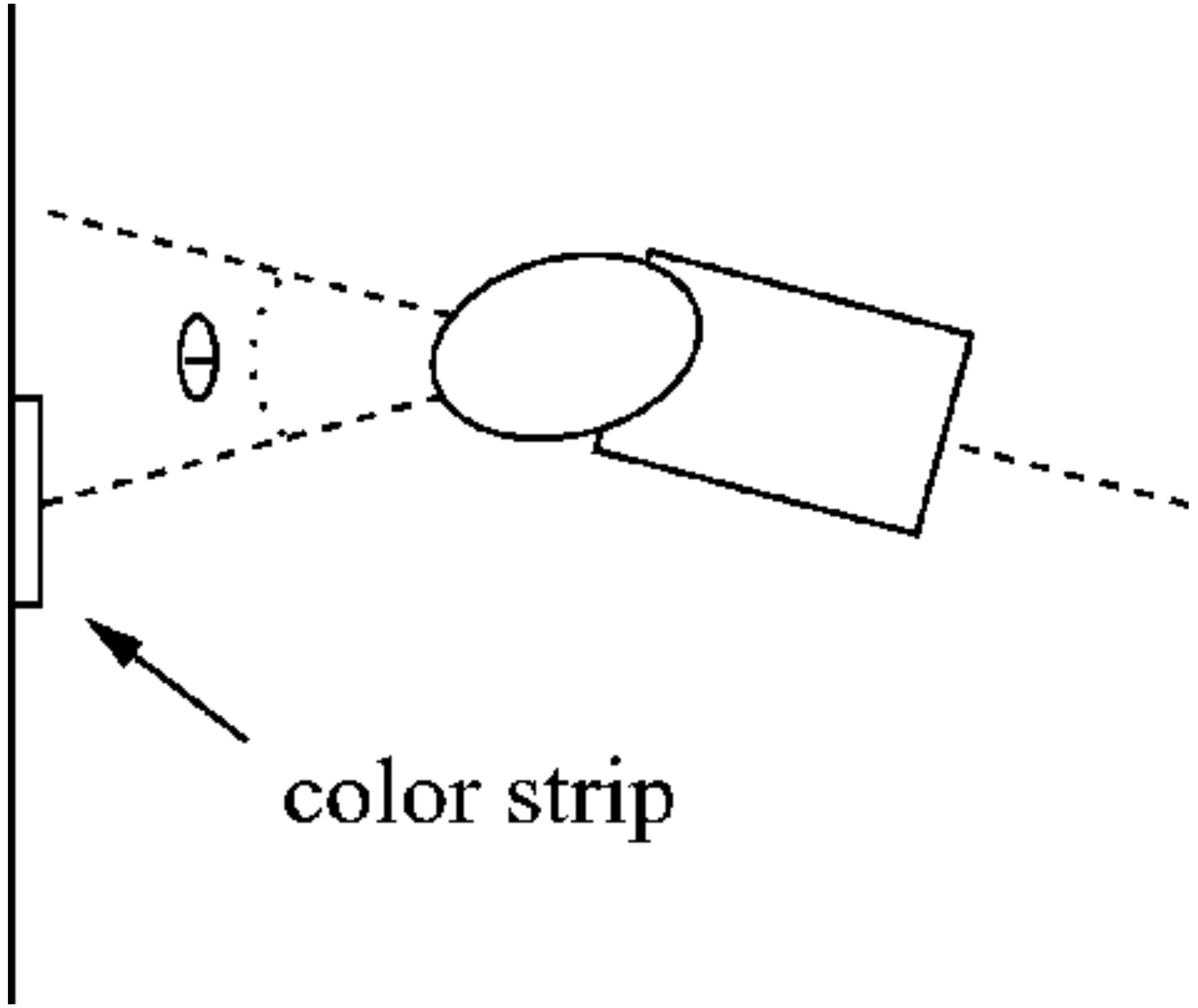


- Built a lookup table of PSD sensor values:
  – Taken at 5cm intervals.
  – Averaged over two hundred readings.

- To measure distance:
  – Take average of three, sequential PSD readings.
  – Calculate distance with the lookup table, using linear-interpolation between sensor-distance values.

Scoring a Gait

- Once centered on a color strip the robot runs:
  - 7s.
  - or within 20cm of a wall.
- The fitness function for scoring a gait rewards for:
  - High velocity.
  - Straightness.
- Straightness is based on a measure of angle between robot and the color strip.
  - Robot pans its head until it is centered on the color strip.
  - Angle to color strip is the angle the head has turned.



Scoring a Gait

$$\text{score} = v(d_{\text{start}}, d_{\text{stop}}, \text{time}) \times s(\theta, d_{\text{stop}})$$

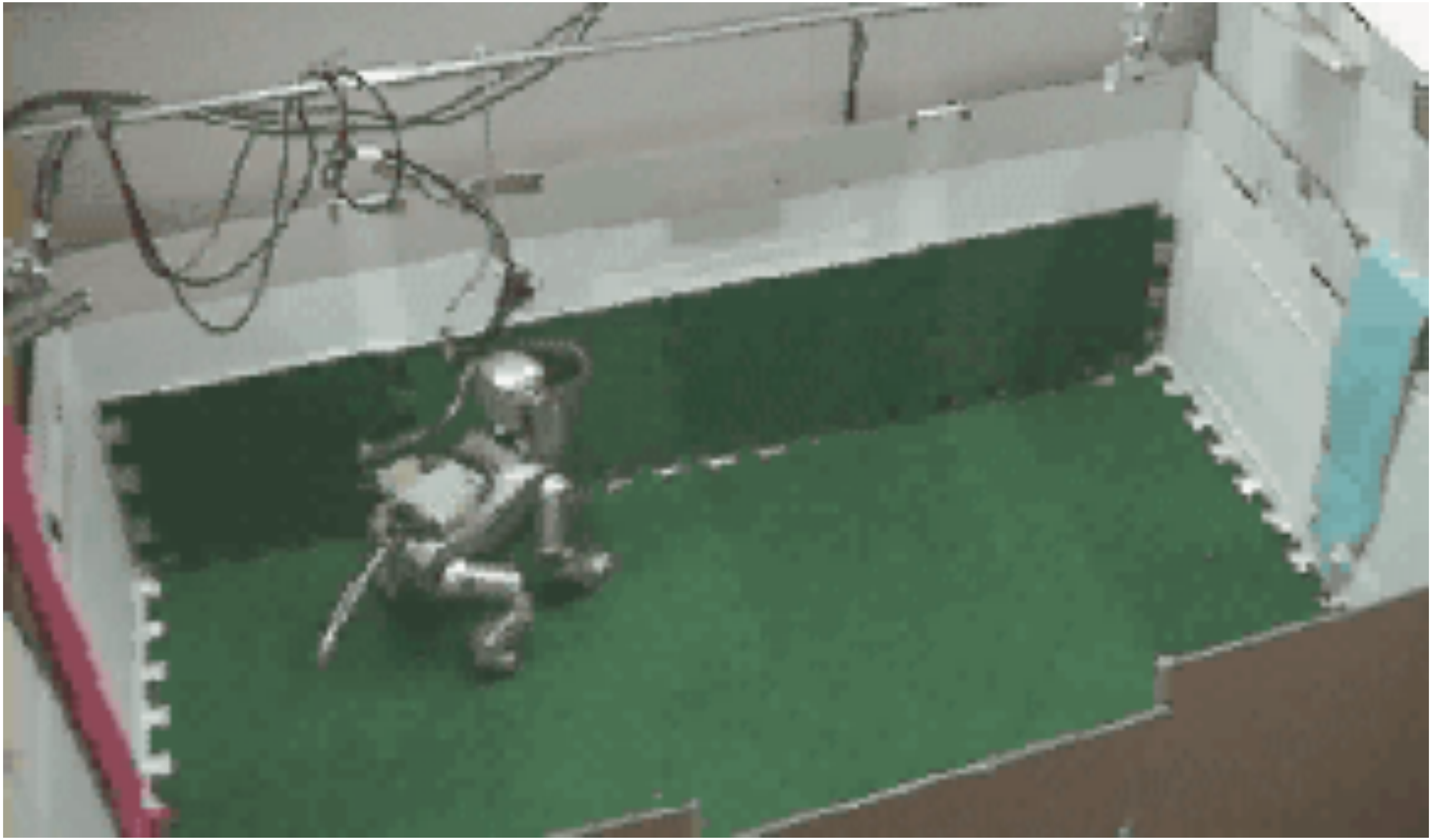
$$v(d_{\text{start}}, d_{\text{stop}}, \text{time}) = \frac{d_{\text{start}} - d_{\text{stop}}}{\text{time}}$$

$$s(\theta, d_{\text{stop}}) = \frac{d_{\text{stop}}\left(f(\theta) - 1\right) + 80 - 10 f(\theta)}{70}$$

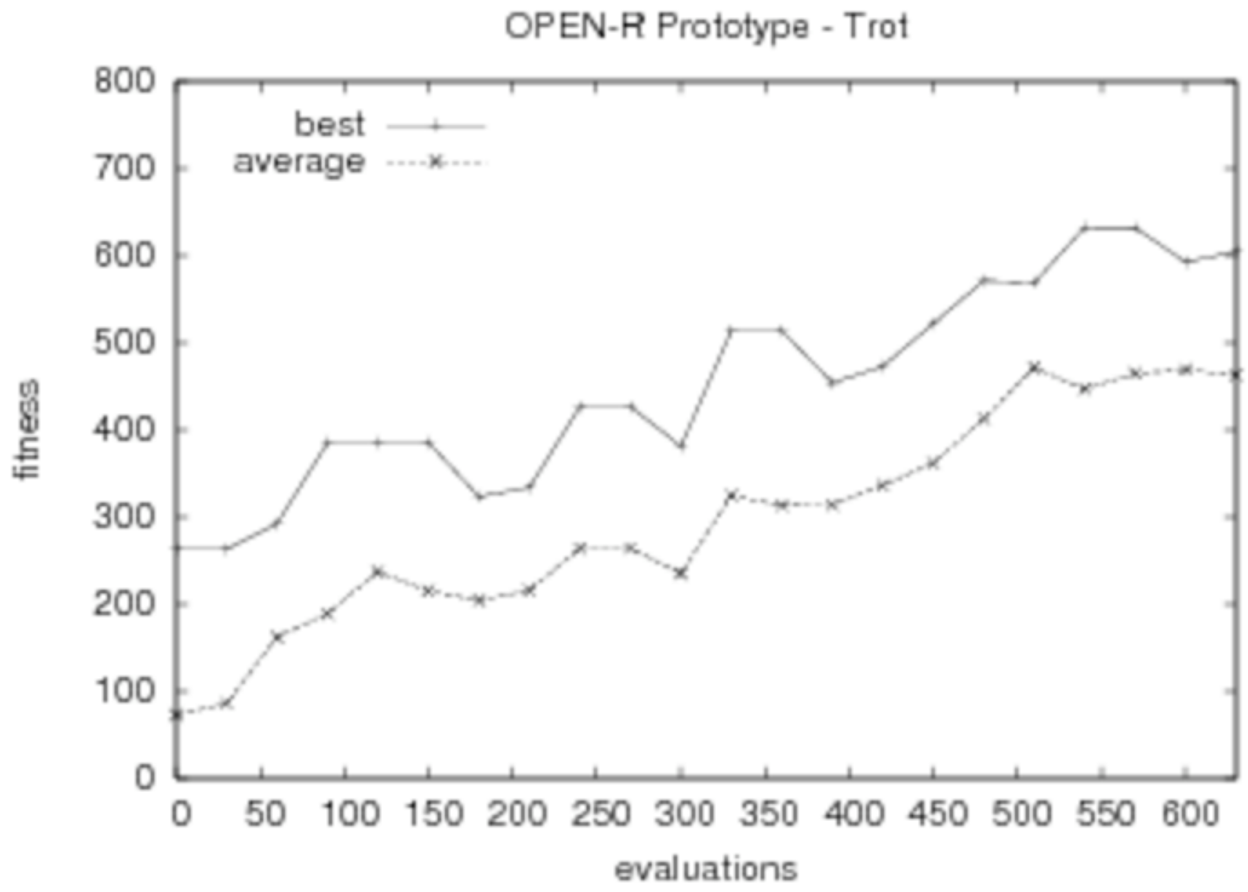
$$f(\theta) = 1 - \frac{|\theta|}{90^\circ}.$$

- Scoring a gait is a function of velocity and straightness.
  - v(): standard method for calculating velocity.
  - s(): a measure of straightness.
    - s() = 1 when the angle to the color strip is 0.
    - s() = 0 when the angle to the color strip is 90 degrees.

Example Gait Evaluation

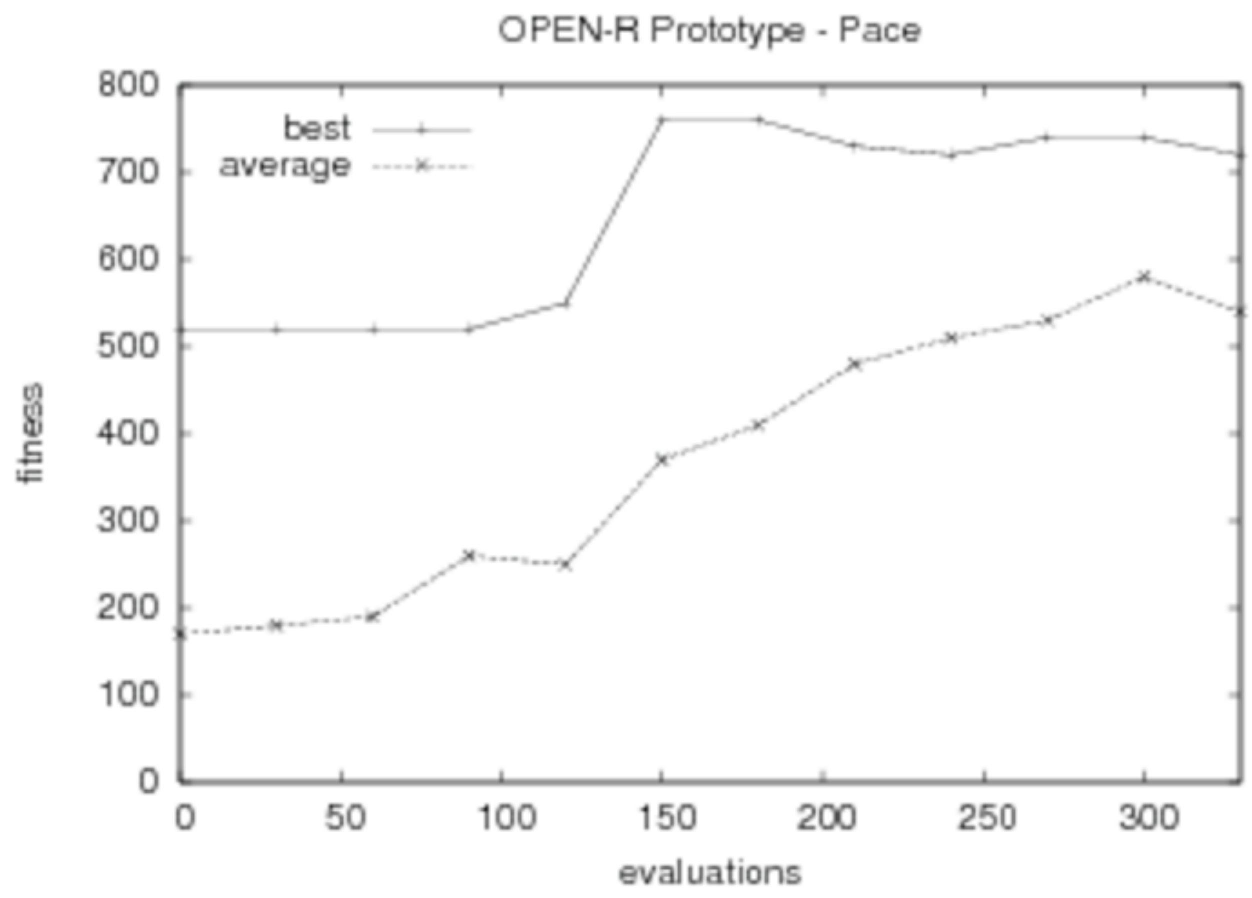


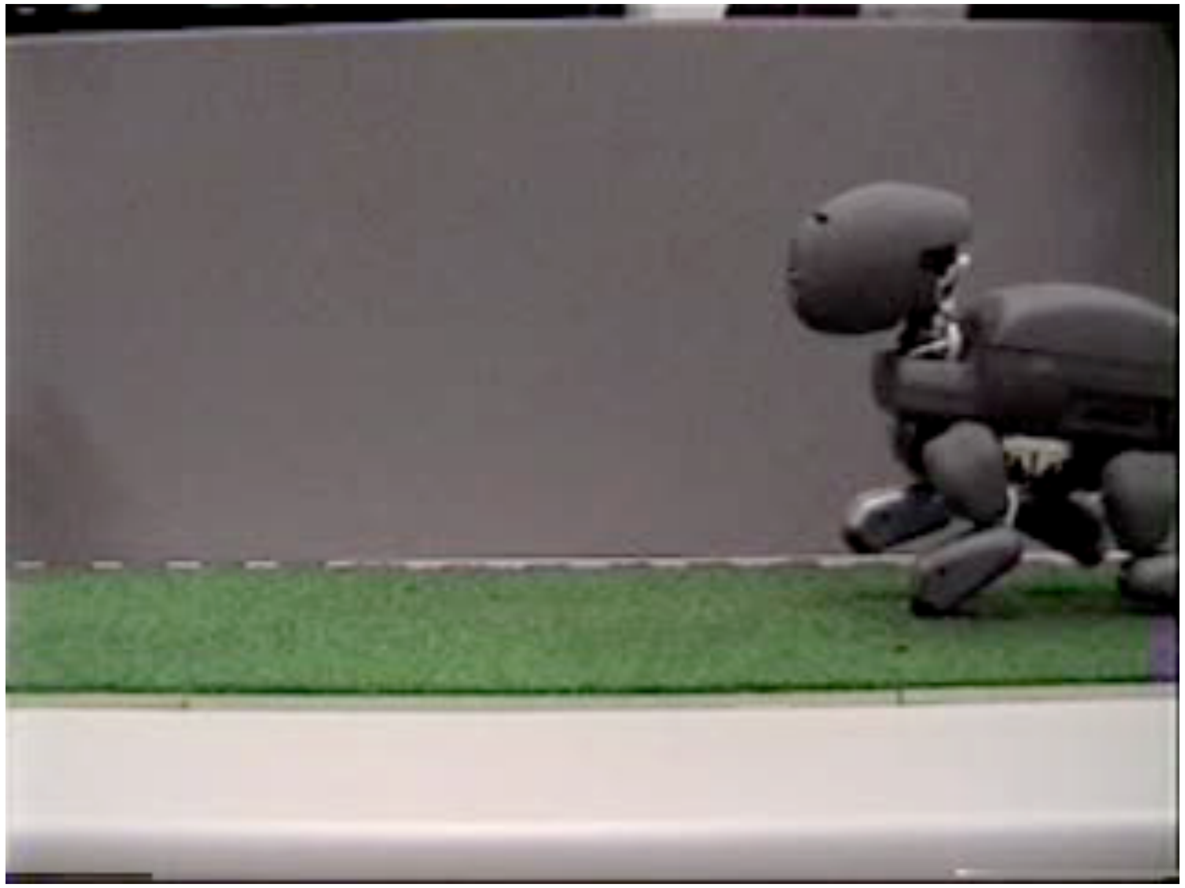
Best Evolved Trot Gait



– Used a steady-state EA with a population of 30 individuals.
– First 30 randomly generated individuals were valid.
– Evolution ran for 21 generations (over 600 evaluations).
– Best evolved individual: fitness 6.3, speed of 6.5 m/min.
  - 26 body-lengths / min.

Best Evolved Pace Gait





- 84 random individs needed to create initial pop of 30 individuals:
  - Gaits params that caused robot to fall were "invalid".
- Evolution ran for 11 generations (330 evaluations).
- Best evolved individual: fitness 7.6, speed of 10.2 m/min.
  - 40 body-lengths / min.

Best Evolved Gait Params

parameter	unit	initial range	best trot	best pace
body center x	mm.	85 - 95	82.7	89.2
body center z	mm.	-5 - 5	6.2	-2.0
body pitch	degrees	-5 - 5	-11.3	3.2
all legs y	mm.	5 - 25	10.6	10.0
front legs z	mm.	24 - 40	24.7	25.0
rear legs z	mm.	15 - 29	24.3	25.3
step length	n.a.	80 - 220	152	182
swing height	mm.	15 - 29	19.6	29.5
swing time	ms.	200 - 400	421	222
swing mult.	n.a.	1.5 - 2.5	2.4	1.7
switch time	ms.	500 - 900	799	617
ampl. body x	mm.	-2 - 2	0.6	-0.4
ampl. body y	mm.	0 - 20	10.3	5.1
ampl. body z	mm.	-2 - 2	0.7	-1.3
ampl. yaw	degrees	-2 - 2	-2.9	1.6
ampl. pitch	degrees	-3 - 3	-0.4	3.7
ampl. roll	degrees	-3 - 3	2.2	0.4
min. gain	n.a.	25 - 175	103	101
shift	degrees	60 - 120	64	125
length	degrees	90 - 150	117	103

Part II: Summary

- Evolve trot and pace gaits for DRX-600.
  - Gaits consisted of a set of parameters for the Locomotion Module.
  - Could not hand-code a dynamic gait.
  - Best hand-coded gait: 6m/min.
- EA setup:
  - Robot was fully autonomous.
  - Ran back-and-forth in a pen evaluating itself.
- Best evolved gaits:
  - Trot: 6.5m/min; 26 body-lengths/min.
  - Pace: 10.2m/min; 40 body-lenths/min.
- **First autonomous acquisition of a dynamic gait on a quadruped robot.**

Part III: Evolving Robust Gaits for Aibo

Aibo

Aibo (ERS-110):

- 7th generation quadruped robot by Sony.
- This model was intended to be sold to consumers.

Problems:

- Mass manufacturing resulted in variances between different robots.
- Robots would be used on a variety of surface types.

=> ***Needed to increase robustness***.

Objective: Modify evolutionary system to reward for a more robust gait.

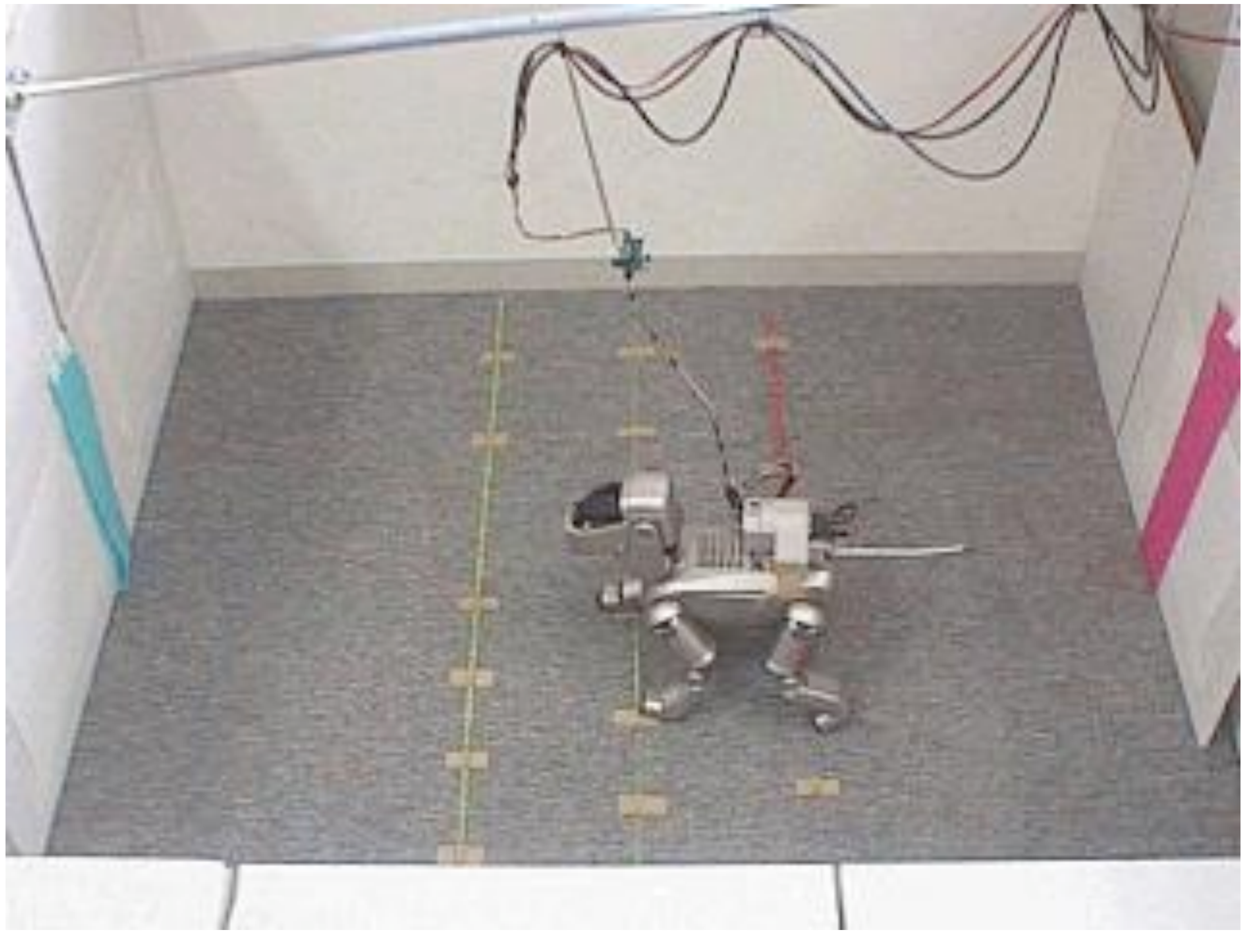
Also interested in evolving gait type.

Biasing for Robust Gaits

- Static gaits transferred relatively well.
- Dynamic gaits did not:
  - Tended to have a foot catch on the ground.

Approach:

- Put pressure to evolve gaits with more clearance.
- Plastic rods were placed in the pen as obstacles.
- Gaits which had higher steps would be likely to score better.



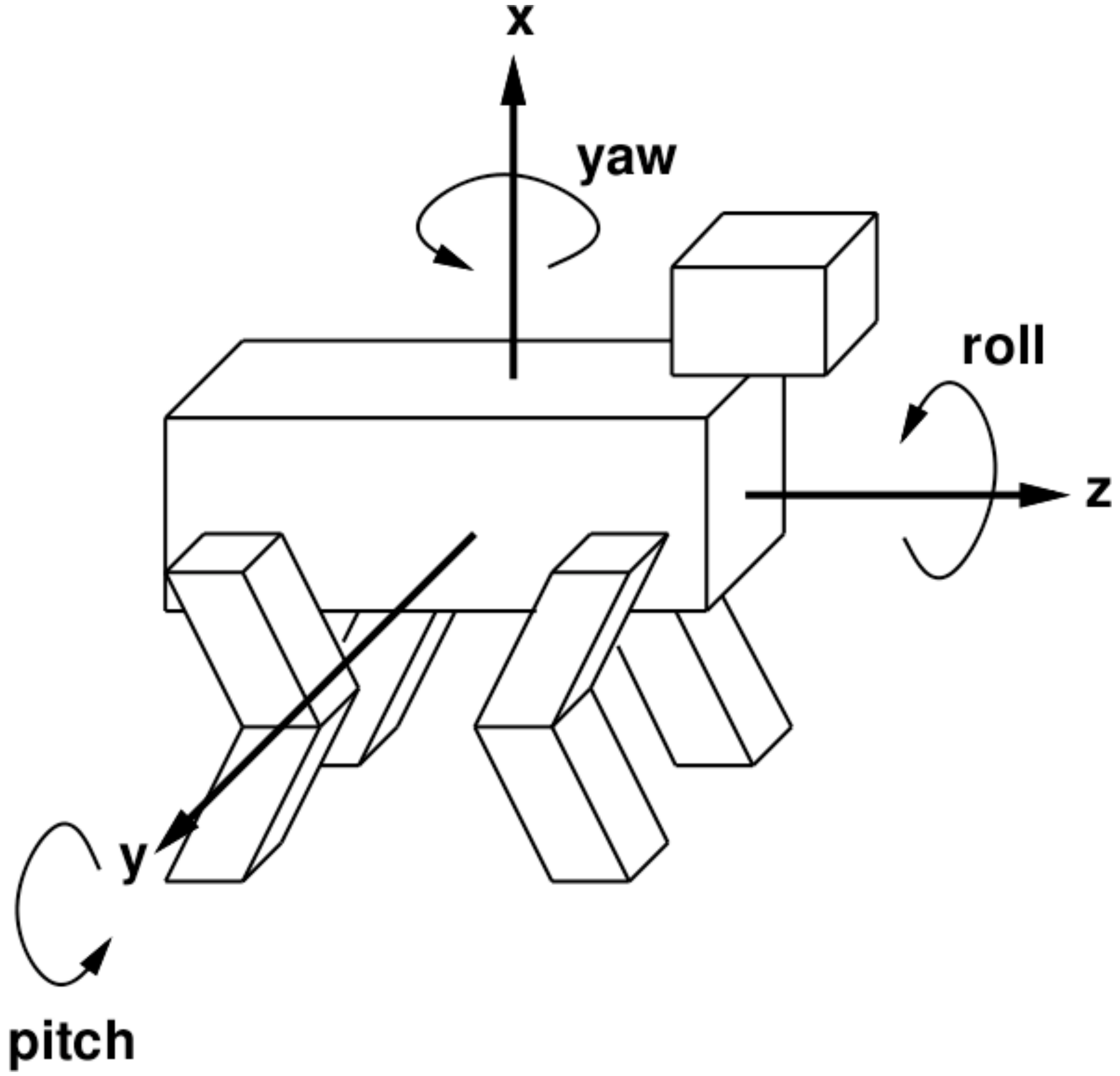
Evolving Gait Type

- With the DRX-600, gait type was preset (trot or pace) and fixed. Here, we wanted to evolve the gait type.
- Parameterized gait type with 2 parameters:
  - **L-R**: phase offset between Left and Right legs.
  - **F-H**: phase offset between Fore and Hind legs.
- Right Foreleg starts at a phase offset of 0.
- Left Foreleg starts at phase offset of: **L-R**.
- Right Hindleg starts at phase offset of: **F-H**.
- Left Hindleg starts at phase offset of: **L-R + F-H**.

Parameter	Crawl	Trot	Pace	Skip
L-R	0.5	0.5	0.5	0.0
F-H	0.75	0.5	0.0	0.5

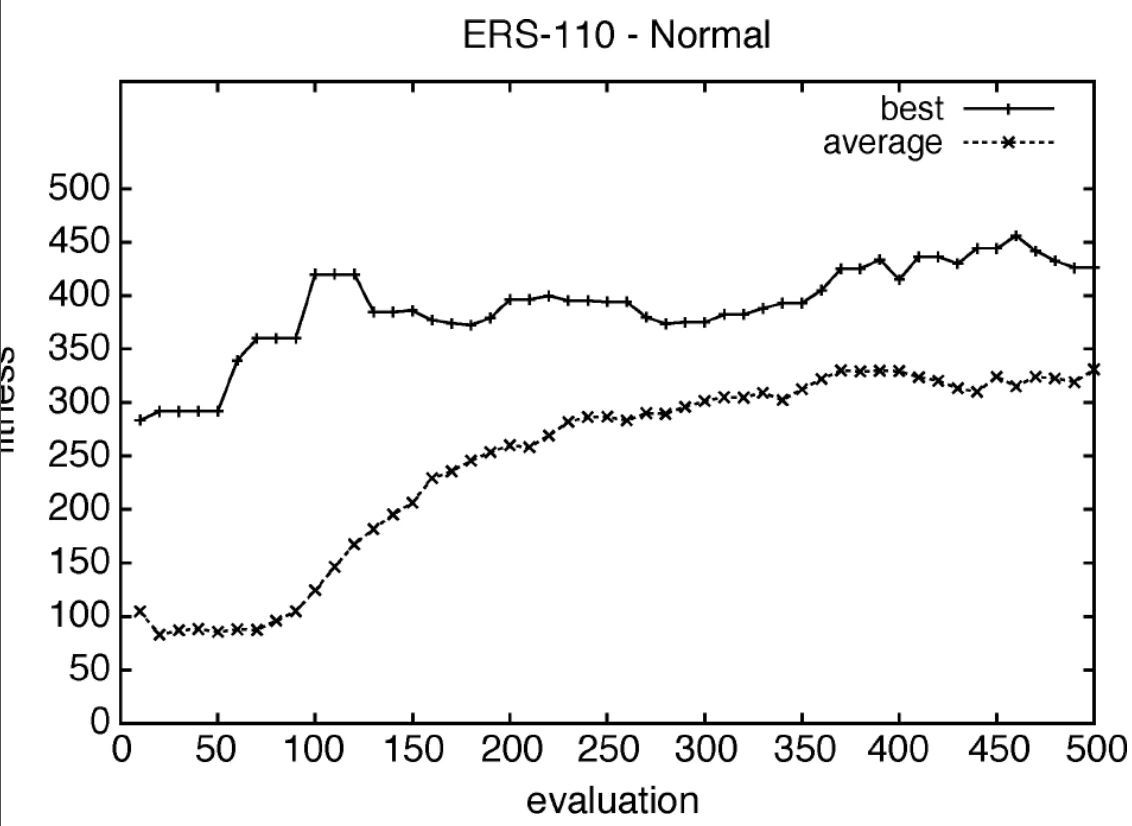
Aibo Gait Parameters

- 21 params for the EA.



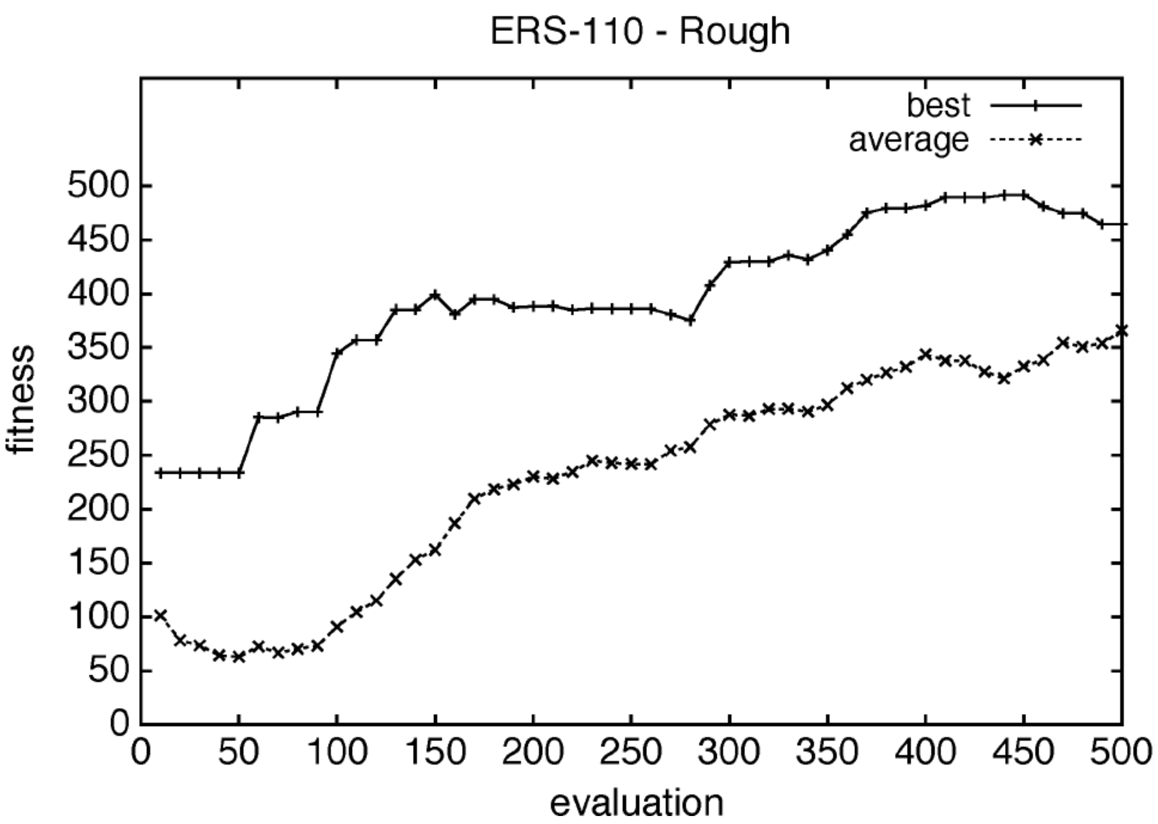
parameter	unit	initial range
body center x	mm.	105 - 125
body center z	mm.	-10 - 10
body pitch	degrees	-10 - 10
posture center x	mm.	0 - 20
all legs y	mm.	-5 - 15
front legs z	mm.	10 - 30
rear legs z	mm.	-5 - 15
step length	n.a.	60 - 100
swing height front	mm.	25 - 45
swing height rear	mm.	25 - 45
swing time	ms.	460 - 540
swing mult.	n.a.	3 - 5
switch time	ms.	500 - 900
ampl. body x	mm.	-10 - 10
ampl. body y	mm.	-25 - -5
ampl. body z	mm.	-20 - 0
ampl. yaw	degrees	-10 - 10
ampl. pitch	degrees	-10 - 10
ampl. roll	degrees	-5 - 15
L-R	n.a.	0.25 - 0.5
F-H	n.a.	0.5 - 0.75

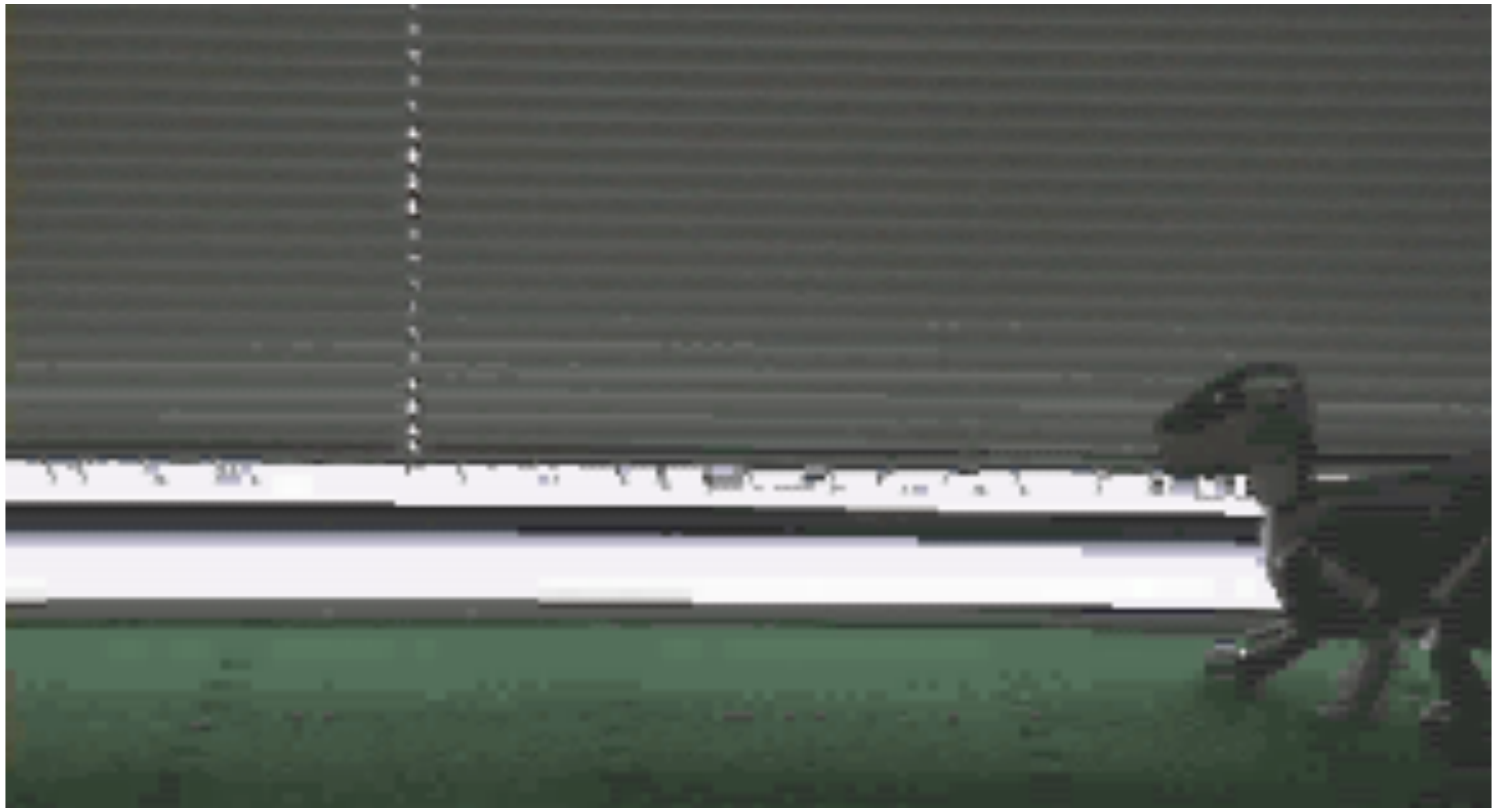
Evolution without Rods



- For comparison, evolved gaits on surface both with and without the rods.
- Population size of 30 individuals.
- 3 separate evolutionary runs of 500 evaluations each.
- 25 hours total to run.

Evolution with Rods





- Individuals in initial population would tend to catch a foot on the rod and fall over.
- Eventually the population evolved to lift their feet over the rods.
  - Contrast this to gaits evolved on the unobstructed surface which did not take high steps and were not as good.

On Different Surfaces

- To evaluate robustness we tested gait parameters on:
  - 4 different surface types.
  - Used 3 different ERS-100 robots.

Surface	Regular Carpet	Obstructed Carpet
office carpet	387 cm/min.	600 cm/min.
Robocup	369 cm/min.	598 cm/min.
tatami	369 cm/min.	576 cm/min.
wood	387 cm/min.	443 cm/min.

- In all four cases, gait parameters evolved on the obstructed carpet (with rods) was faster.

Gait for Consumer Version of Aibo

- Instead of starting an EA with a random population, an alternative is to *seed* the population with copies of the best individual from a previous run.
- Here we *seeded* a population with the best individual from the original experiments.
  - A *small perturbation* was added to the parameter values to give some genetic variation in the pop.
- After more evolution, a trot gait with a speed of **9m/min** was evolved.
- This evolved gait passed the Quality Assurance department and was used on the consumer version of the first Aibo.

Gait for Consumer Version of Aibo

parameter	unit	initial range	best gait
body center x	mm.	105 - 125	110.1
body center z	mm.	-10 - 10	-4.8
body pitch	degrees	-10 - 10	6.5
posture center x	mm.	0 - 20	-1.8
all legs y	mm.	-5 - 15	7.4
front legs z	mm.	10 - 30	21.5
rear legs z	mm.	-5 - 15	18.5
step length	n.a.	60 - 100	124.4
swing height front	mm.	25 - 45	36.5
swing height rear	mm.	25 - 45	44.1
swing time	ms.	460 - 540	503
swing mult.	n.a.	3 - 5	3.0
switch time	ms.	500 - 900	974
ampl. body x	mm.	-10 - 10	-1.8
ampl. body y	mm.	-25 - -5	-10.0
ampl. body z	mm.	-20 - 0	-13.6
ampl. yaw	degrees	-10 - 10	0.9
ampl. pitch	degrees	-10 - 10	-0.5
ampl. roll	degrees	-5 - 15	4.5
L-R	n.a.	0.25 - 0.5	0.48
F-H	n.a.	0.5 - 0.75	0.67

Part III: Summary

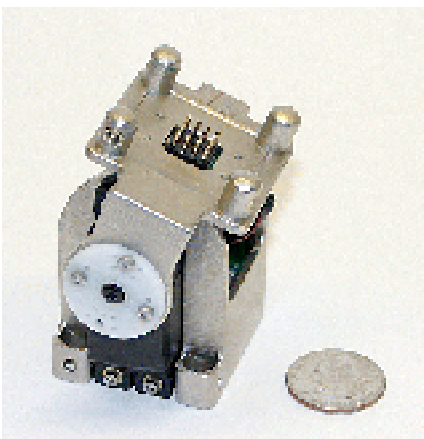
- Modified system to evolve gaits for AIBO:
  - Evolved for Robustness.
    - Evolved on surface with obstacles.
  - Evolved Gait Type:
    - Added parameters for phase-offset (L-R, F-H).
- Evolutionary Results:
  - Evolution on rough surface produced best results.
- Further Evolution:
  - Seeded a subsequent run with best evolved gait.
  - Evolved trot gait: 9m/min.
  - **Gait was used on consumer version of Aibo.**

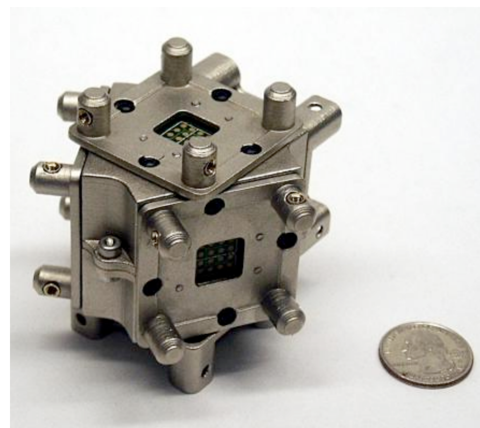
Part IV: Evolution in Simulation

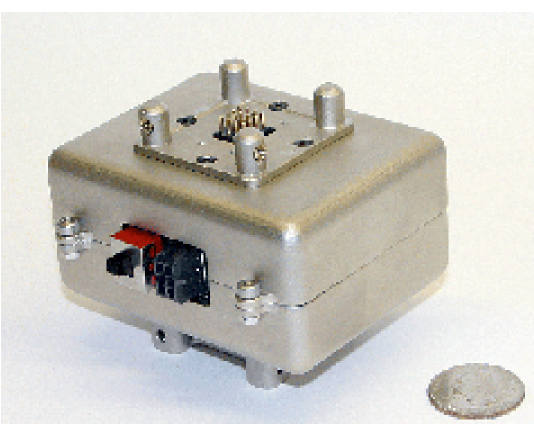
Evolving Gaits in Simulation

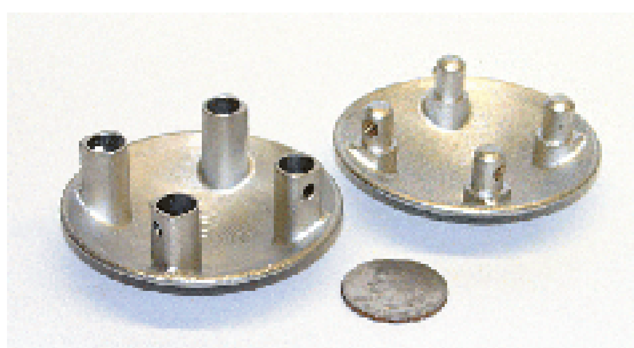
- Evolving on a physical robot has limitations:
  - Requires a working robot.
  - Goes in real-time.
  - May damage the robot.
  - Requires sophisticated sensors or experimental environment.
- Evolve gaits in simulation and transfer to physical robot.
  - Open-source physics engines are available.
  - Should be do-able for static gaits ...

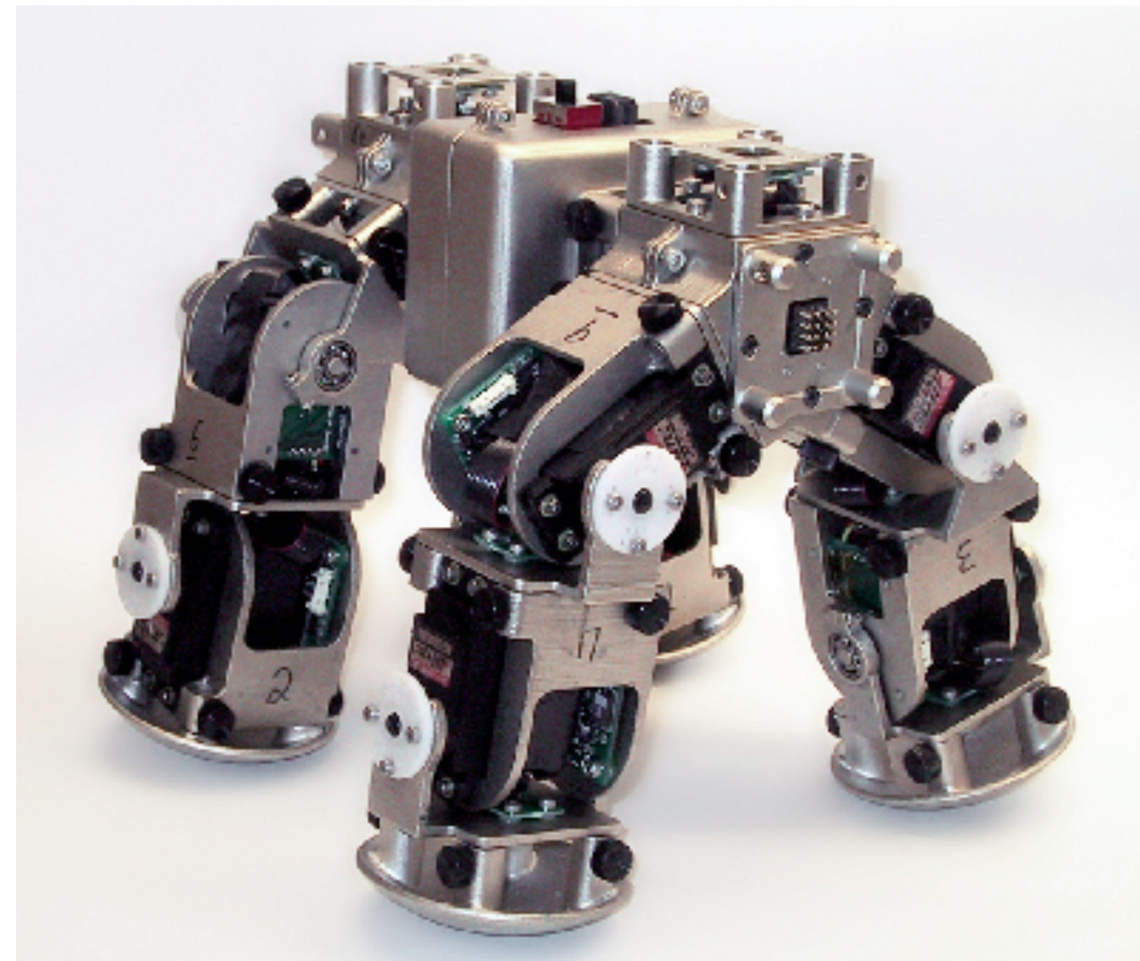
Robot Hardware









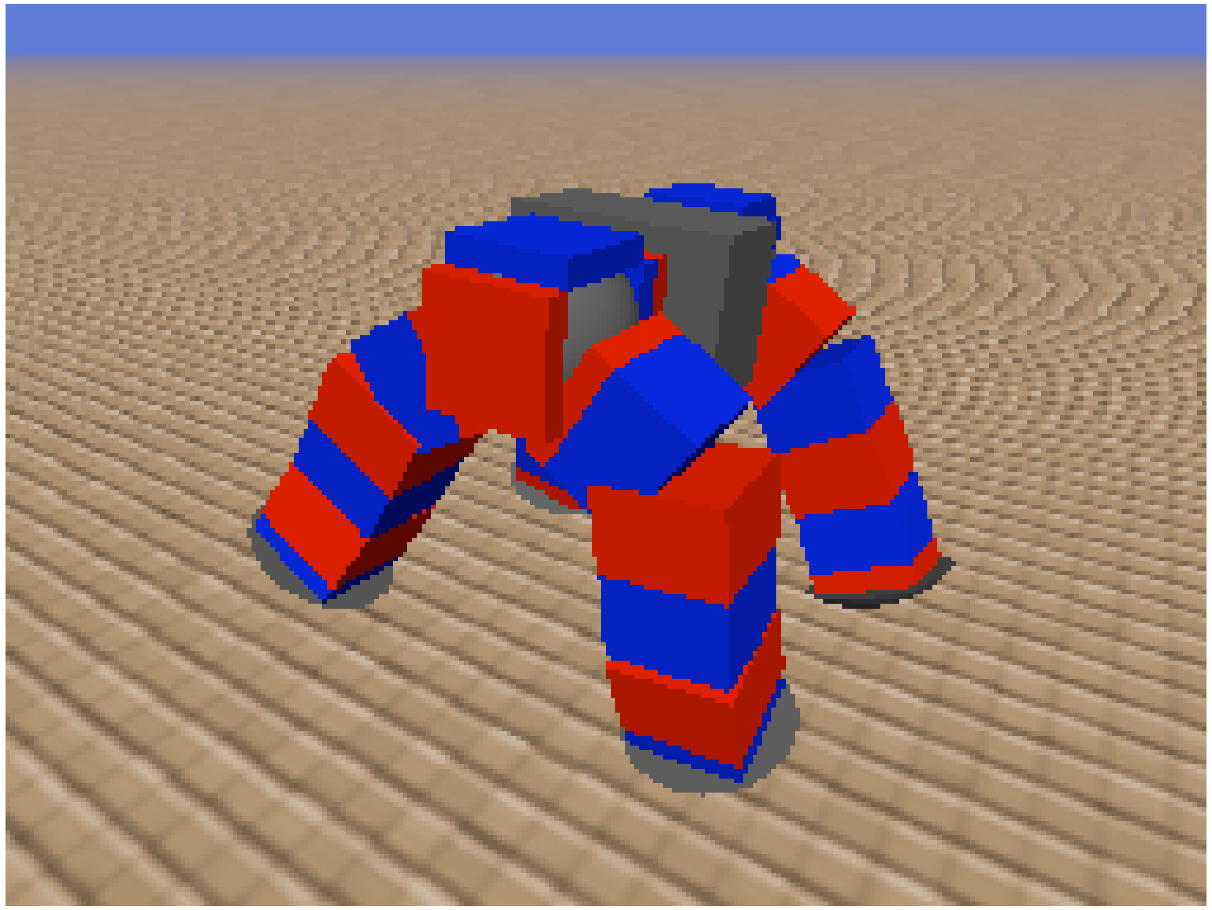


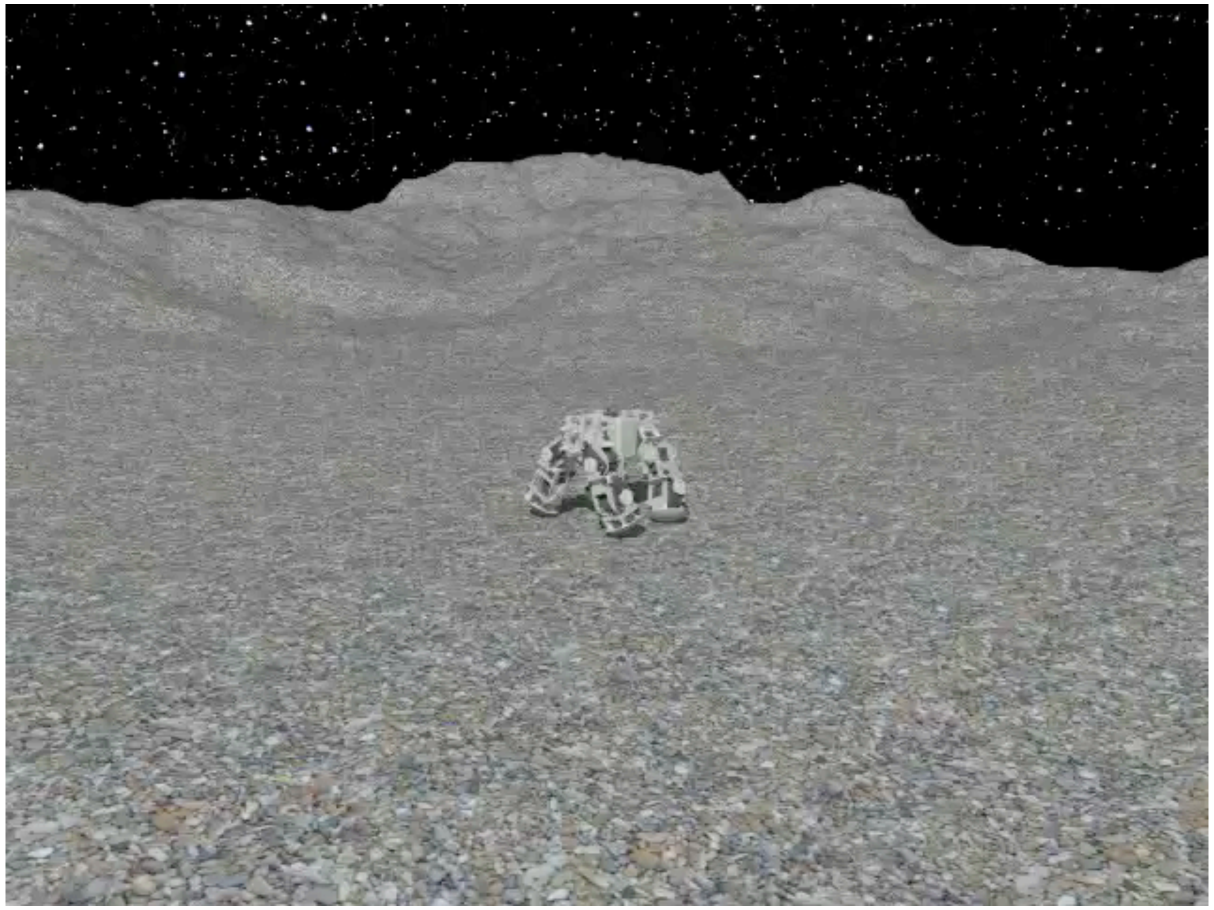
- Configured a quadruped using our modular robotic system.
- MR system was designed and built by Matt Hancher.

Compared with other Mod Robots

NASA's MR; Murata's M-Trans; Rus's Crystalline and Molecule; Yim's Polybots and Zykov's Molecubes.

Simulation and Hand-design Gait



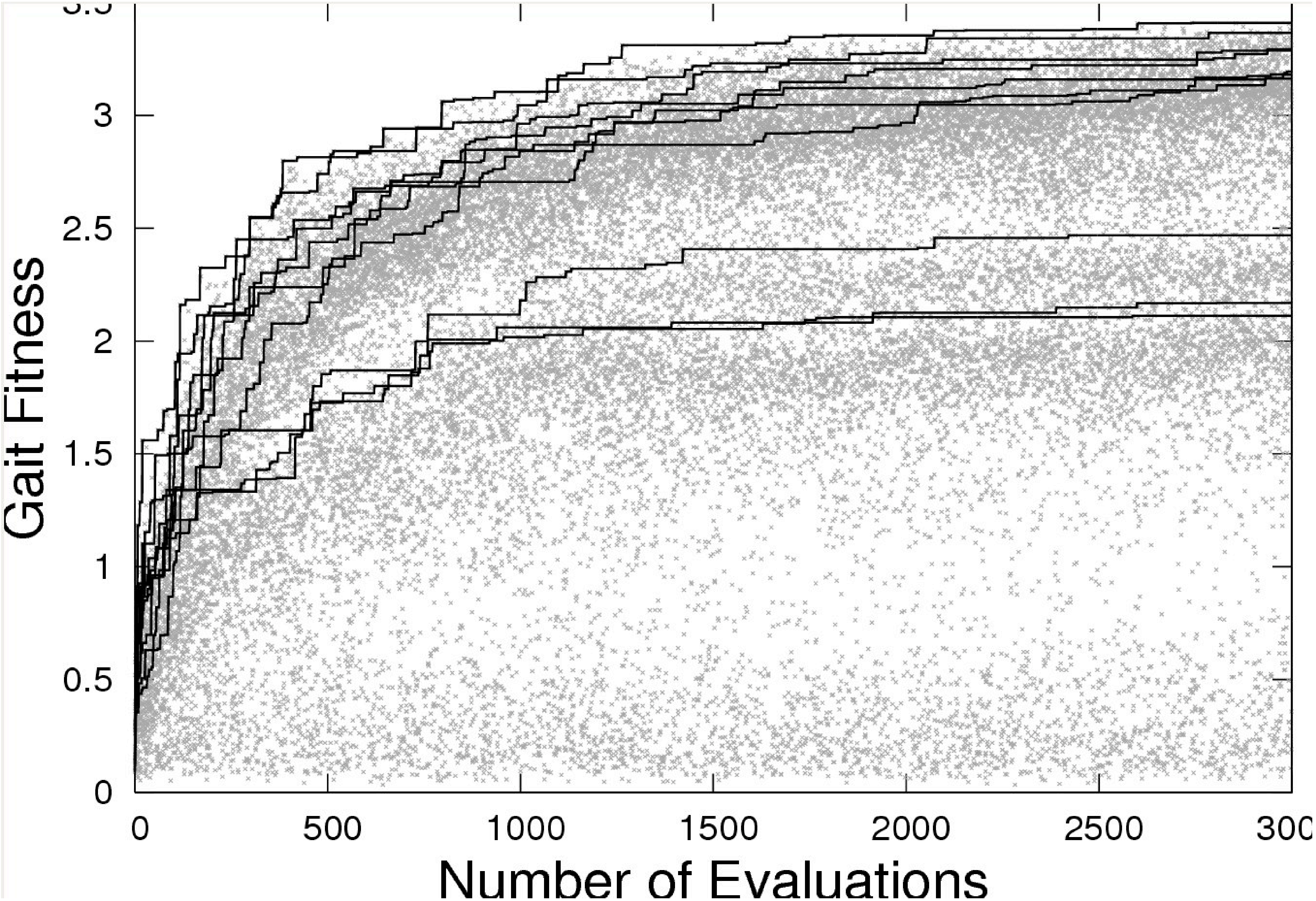


- (Left) Simulation uses Open Dynamics Engine (ODE).
- (Right) Hand designed gait running in simulation.

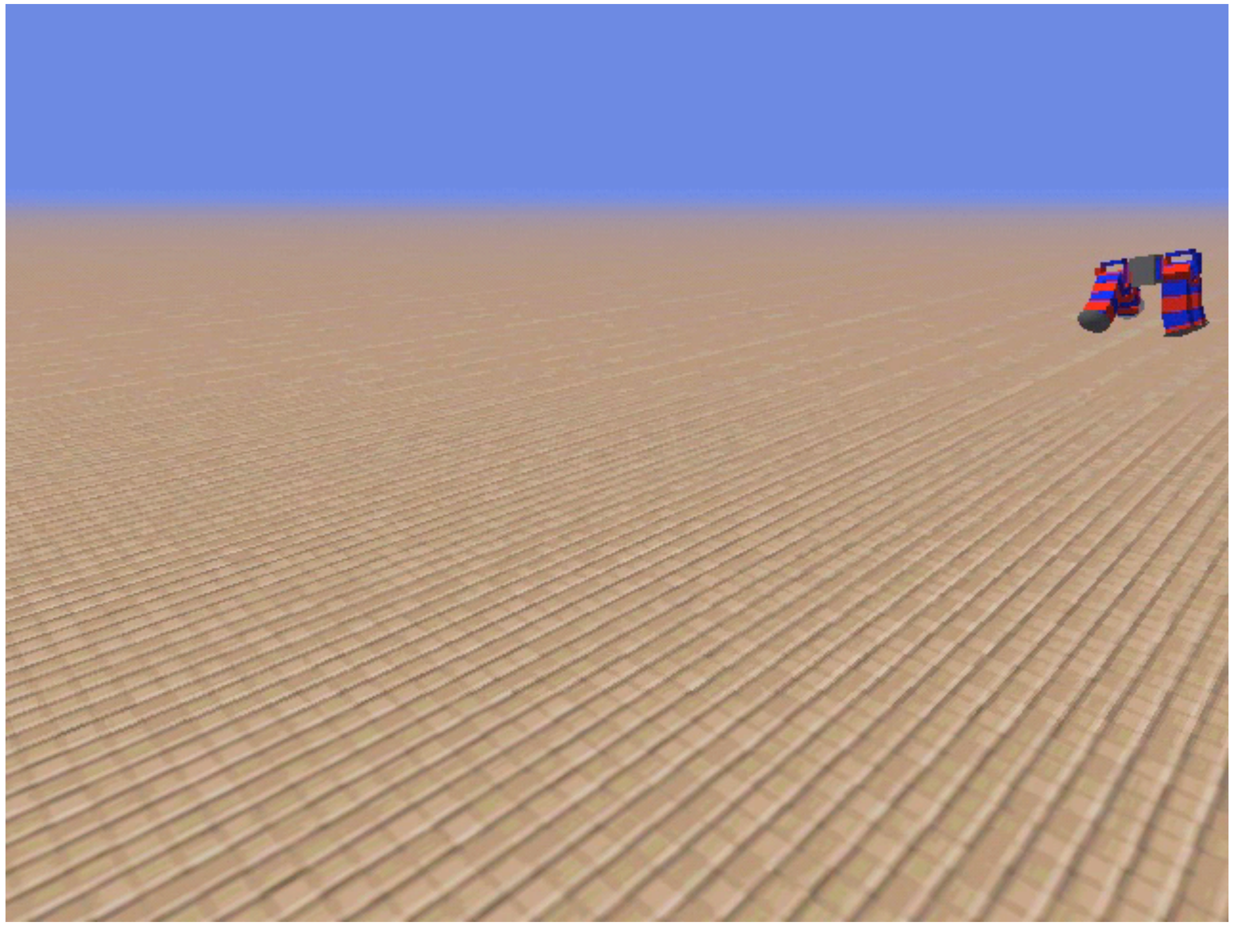
Experimental Setup

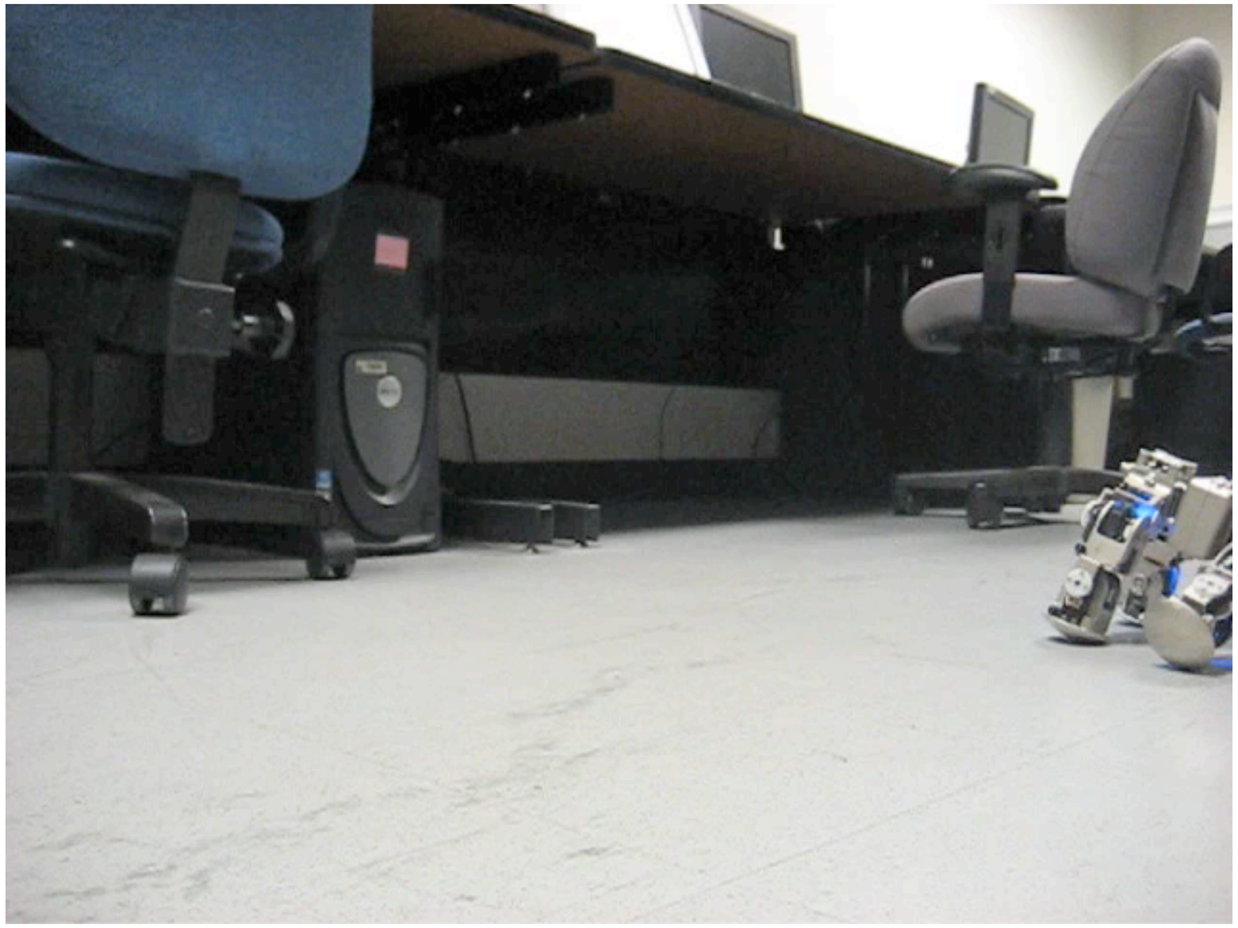
- Oscillator controller:
  - Each joint is parameterized by the first 3 Fourier basis coefficients.
- EA:
  - Steady-state EA.
  - Population size of 4.
  - Mutation rate decreases over the course of the run.
- Evaluation:
  - Gait is evaluated in simulation for 10s.
  - Fitness is ratio of distance / energy.

Evolutionary Results



Best Evolved Gait





Part V: Evolving Higher-level Behaviors

Motivation

- Evolving high-level behaviors:
  - Would take much longer than evolving gaits (1000x?).
  - Harder to do with robot's sensors.
  - Require more sophisticated experimental environment.
- Solution:
  - Evolve in simulation.
- Simulate at a high-level:
  - Abstract away details of leg movement.
  - Use a fairly simple robot simulator.

Evolve Ball-chasing

- Evolve ball-chasing.
- Controller is a recurrent neural network.
  - 12 inputs, 20 hidden units, 7 outputs.

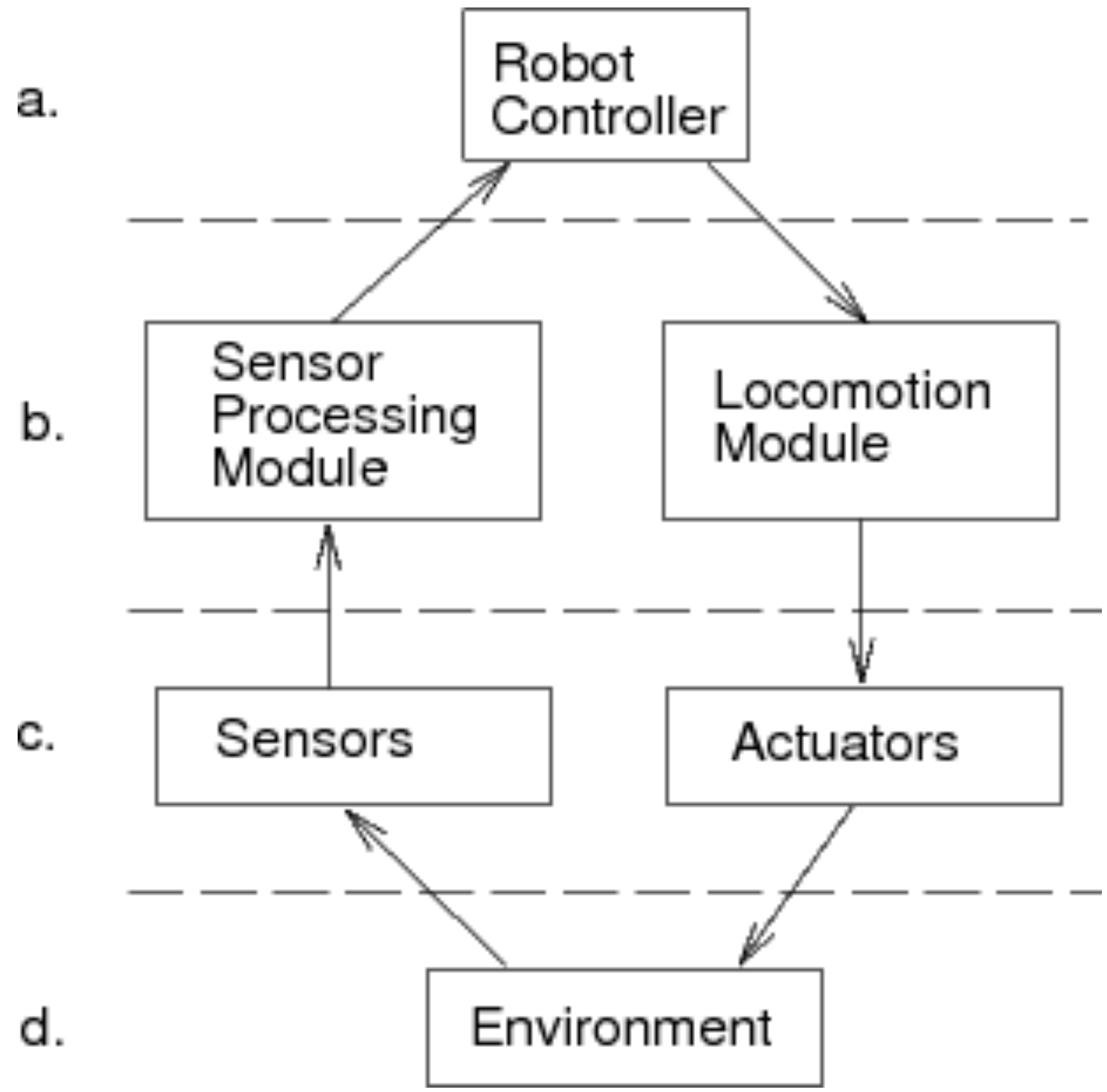
- Inputs:
  - 0. Tilt angle of neck.
  - 1. Pan angle of neck.
  - 2. Distance (PSD).
  - 3-7: Previous step.
  - 8. (boolean) Is ball visible?
  - 9. Size of ball in CDT.
  - 10 Tilt angle to ball.
  - 11. Pan angle to ball.

- Outputs:
  - 0. Stop.
  - 1. Step forward.
  - 2. Turn left.
  - 3. Turn right.
  - 4. Step front left.
  - 5. Step front right.
  - 6. Head position.

Simulator Implementation

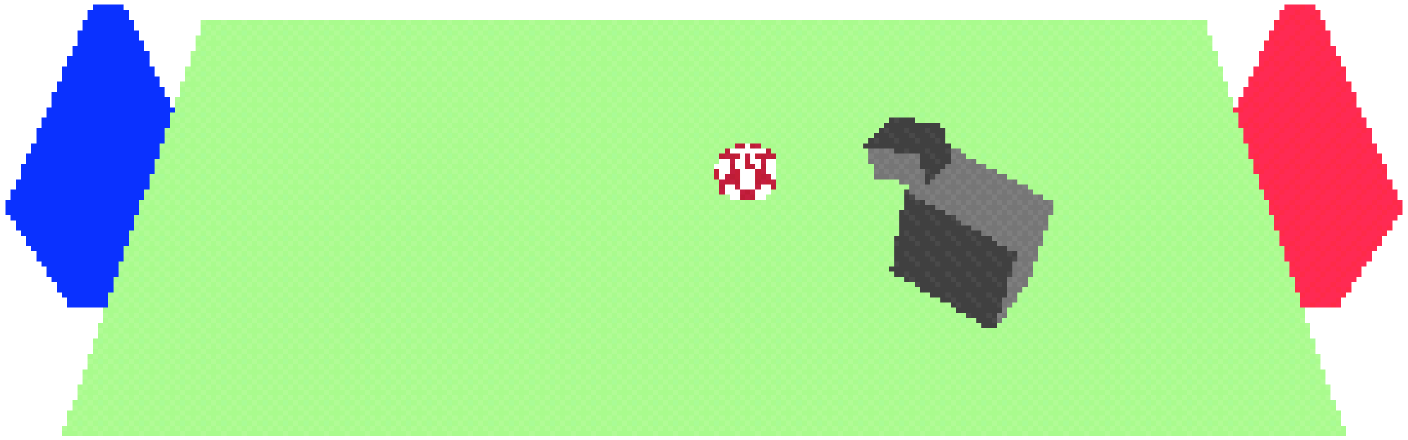
- Input:
  - From CDT:
    - Angle to object.
    - Size of object.
  - From PSD.

- Output:
- High-level move command.
- Head position..



Simulator Details

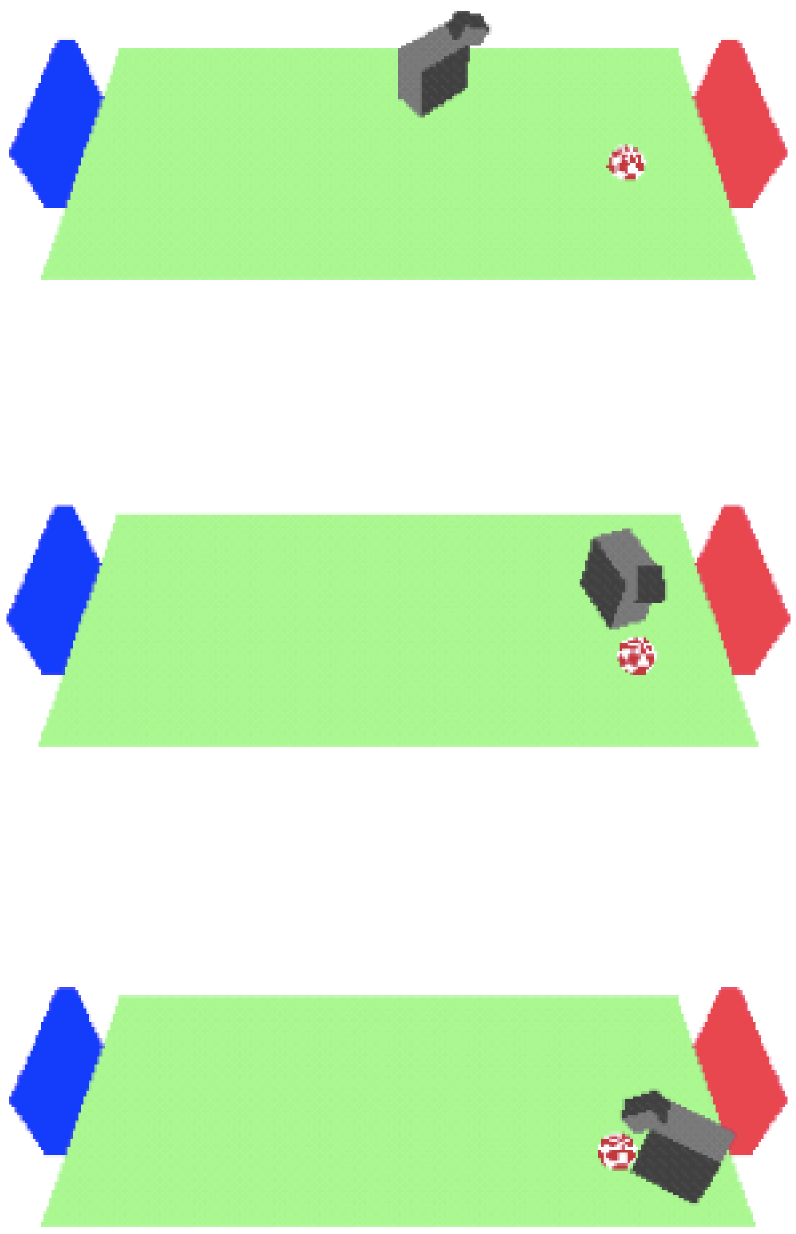
- Classical physical dynamics of rigid bodies:
  - Sensor error of +/- 10%.
    - Error set randomly at start of each trial.
    - This creates **unreliability** and not **noise**.



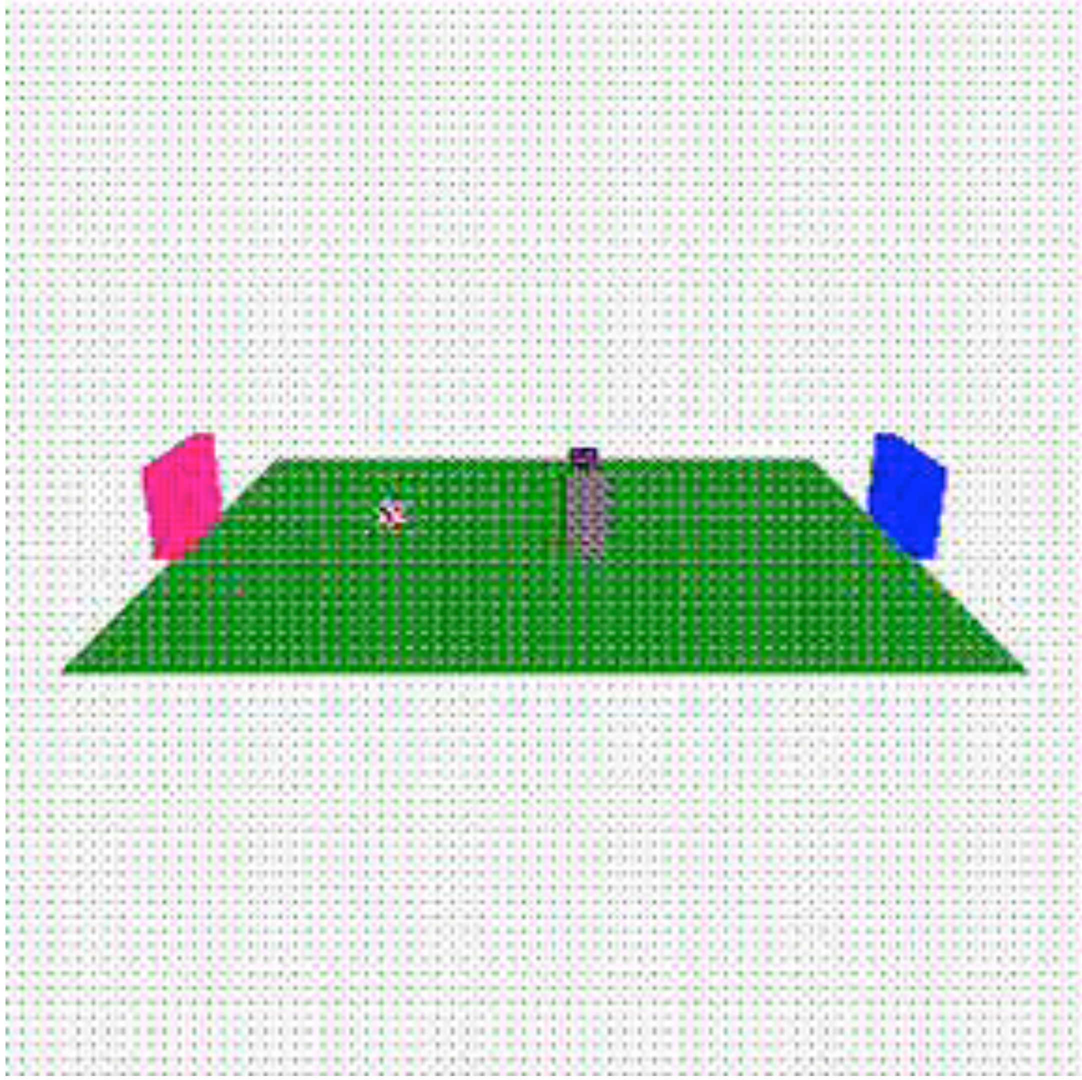
- Simulator is:
  - **11700** times faster than real time.
  - **4500** times faster when controller is included.

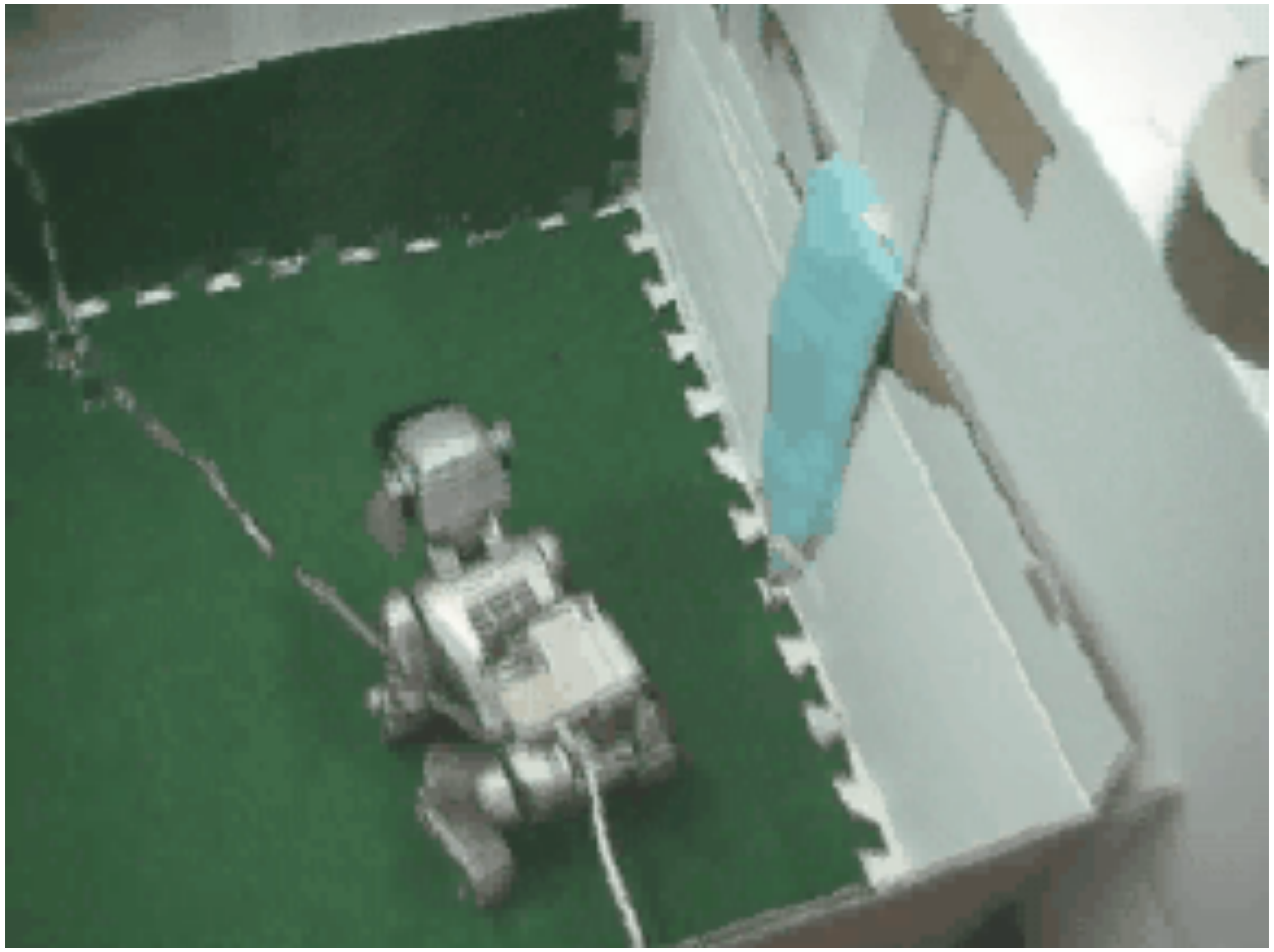
Results

- Evolving ball chasing:
  - Population size of 60.
  - Evolved for 100 generations.
  - Each evaluation:
    - 12 tries with random ball and robot locations.
    - 21 minutes (simulated) for each try.
  - Fitness is the distance the ball is moved.



Evolved Ball Chasing



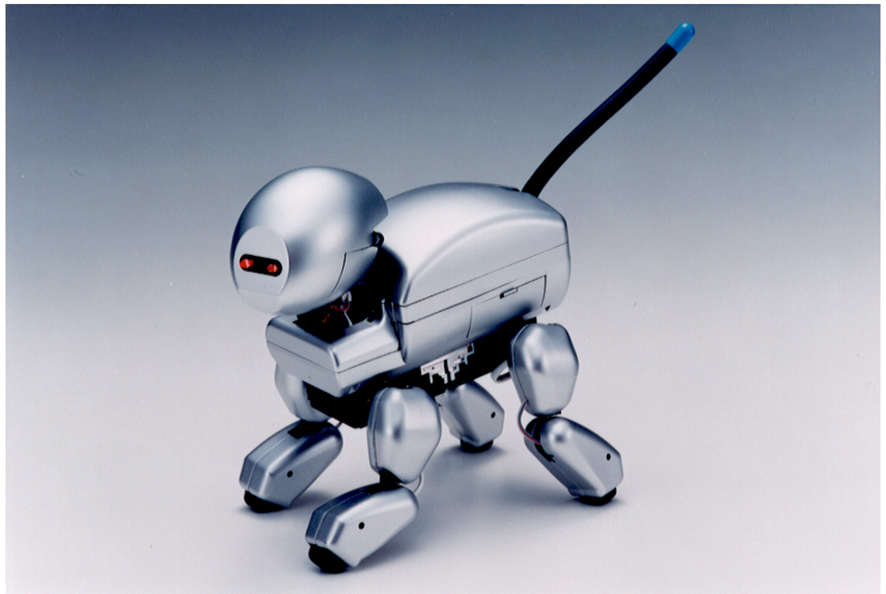


Part V: Summary

- Simulated Aibo:
  - Modeled at a high-level.
  - Speedup of 4500x to 11700x faster.
- Evolved a neural-controller for ball chasing.
  - Recurrent neural network.
  - 12 inputs, 20 hidden units, 7 outputs.
- Evolved RNN was transferred to an actual Aibo.

Conclusion

- Evolved pace and trot on DRX-600
  - Trot: 6.5m/min; Pace 10.4m/min.
  - *First autonomous acquisition of a dynamic gait with a quadruped robot.*
- Evolved robust gaits for Aibo:
  - 9m/min.
  - Used on consumer version of Aibo.
- Evolved static gait in simulation.
  - Simulated on ODE for a modular robot.
- Evolved ball-chasing:
  - High-level simulator: 4500x - 11700x faster.
  - Used recurrent neural networks.



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