Framsticks
Fuzzy Control

Maciej Hapke and Maciej Komosinski. Evolutionary design of interpretable fuzzy controllers. *Foundations of Computing and Decision Sciences*, 33(4):351-367, 2008. [view pdf]

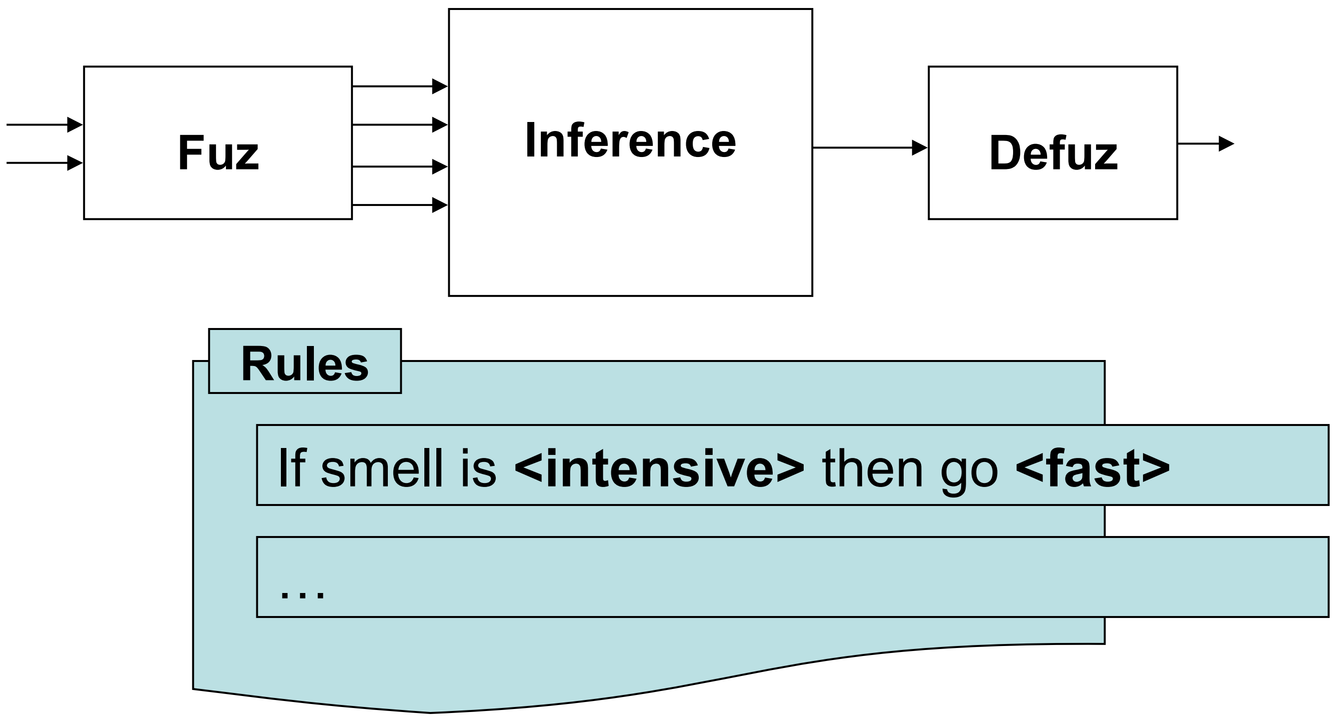
in cooperation with *Dawid Waclawski*

Observations & motivations

- Observations:
  - framsticks move in a way similar to those evolved in the nature – e.g. virtual lizard, water snake
  - the simulation confirms that real evolution makes bodies of different structures move optimally
- Questions about the reasons:
  - why creatures behave in such a way
  - what caused such development of B&B
- This knowledge is hidden in the brain
- A trial to explain evolution

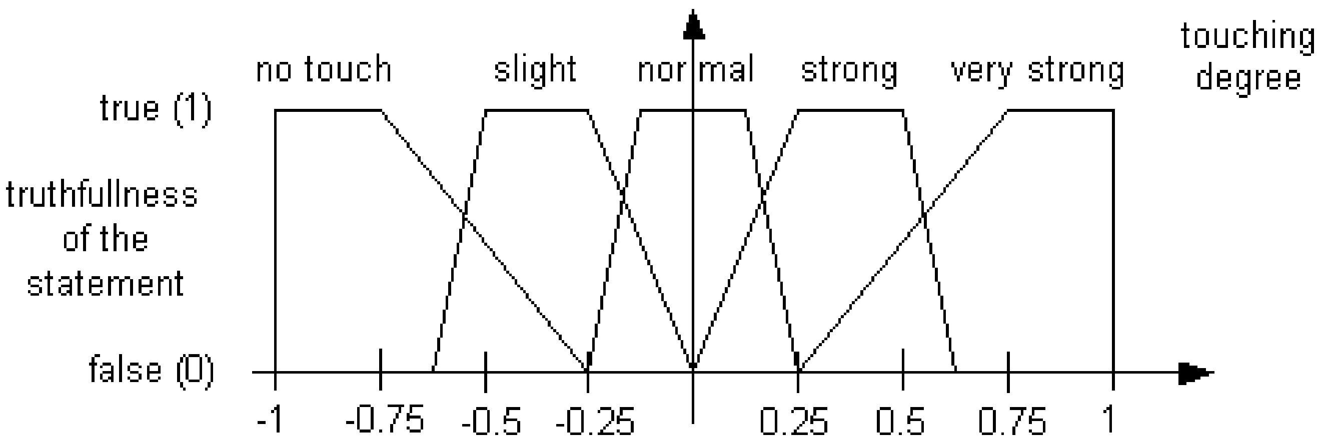
Knowledge representation

- ANN ?
- Fuzzy system



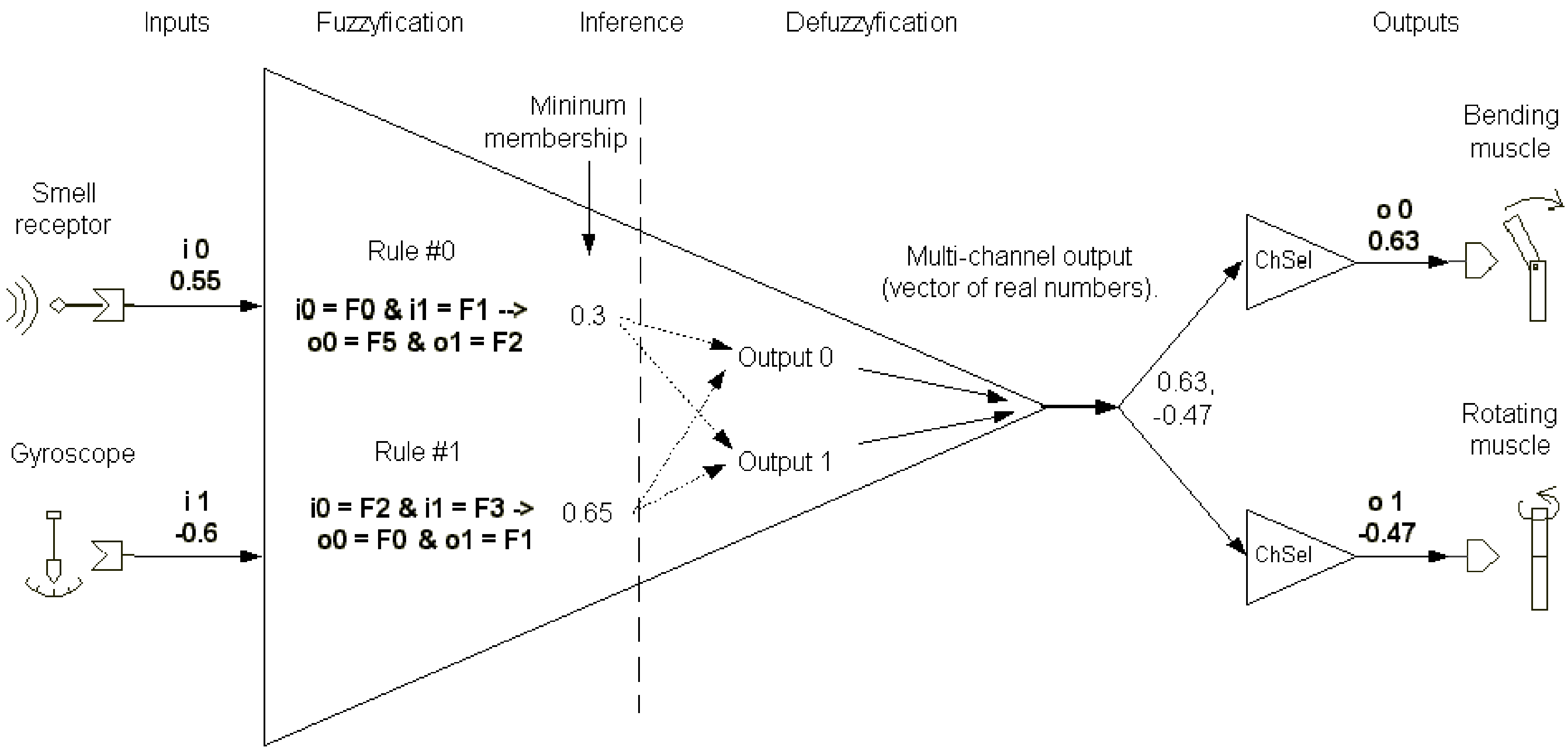
Fuzzy variables

- Example - touch sensor
- Normalized variable domain



Fuzzy “neuron”

- Fuzzy system representation
- Mamdani approach



Evolutionary encoding of FS

- Fuzzy “neuron” genotype sections

Def	Fuzzy sets	Fuzzy rules

```
n:d="Fuzzy:ns=4, nr=2,
fs=-0.1647;-0.1526;-0.0087;0.0631;
-1.0000;-0.8774;-0.7725;-0.6767;
0.0087;0.2308;0.3585;0.4806;
0.0110;0.1664;0.2362;0.2718;
fr=0;3;1;0;2;0:0;2;3;1;2;1;1;3/
2;0;0;2;1;2:3;1;2;0;1;2;0;0/"
```

Example

The example of a fuzzy rule-based system with two inputs (x0, x1), two outputs (y0, y1), two rules (R0, R1) and five fuzzy sets (F0 .. F4) can be described as follows:

F0={-0.35; 0.05; 0.4; 0.65}

F1={-1; -0.8; -0.8; -0.35}

F2={0.2; 0.5; 0.7; 0.8}

F3={-0.65; -0.5; -0.3; 0.1}

F4={0.4; 1; 1; 1}

R0: IF x0 is F0 AND x1 is F1 THEN y0 is F5 AND y1 is F2

R1: IF x0 is F2 AND x1 is F3 THEN y0 is F0 AND y1 is F1

Evolutionary operators

Mutation

- Add/remove a fuzzy set
- Add/remove a fuzzy rule
- Add/remove an input/output

Evolutionary operators
Crossover

- One/multiple crossing points
- Inheritance
  - Two parents/one descendant
  - Parents may be of different length
  - Crossover
    - Draws # of rules
    - For each rule
      - Randomly chooses a pair of rules from p1 and p2
      - Draws # of inputs and outputs
      - Copies inputs and outputs

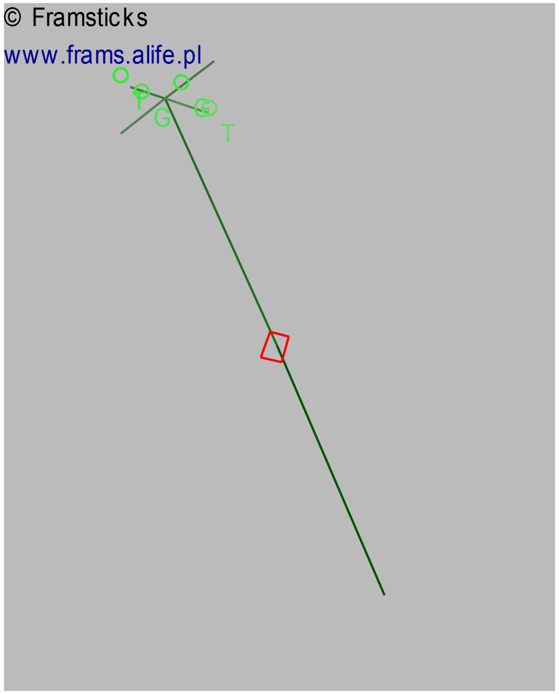
Experiment design

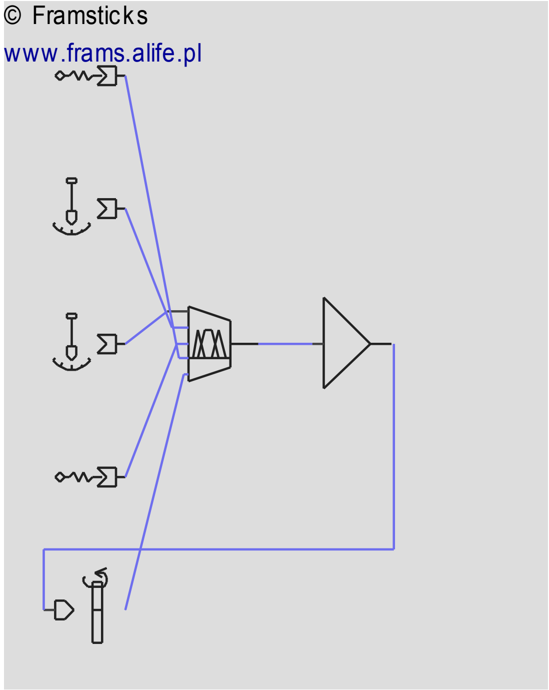
- Goal: to evolve only “fuzzy brain”
- Fixed body structure (parts, joints)
- Fixed # of receptors
- Variable # of fuzzy sets
- Variable # of fuzzy rules

Experiments

Stand-up agent

- Inputs: 2 gyroscopes, 2 touch sens.
- Output: muscle





Experiment

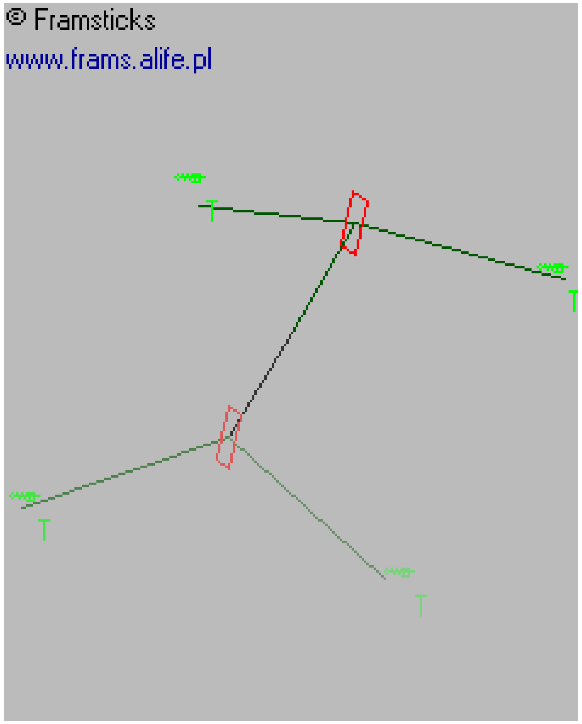
Stand-up agent

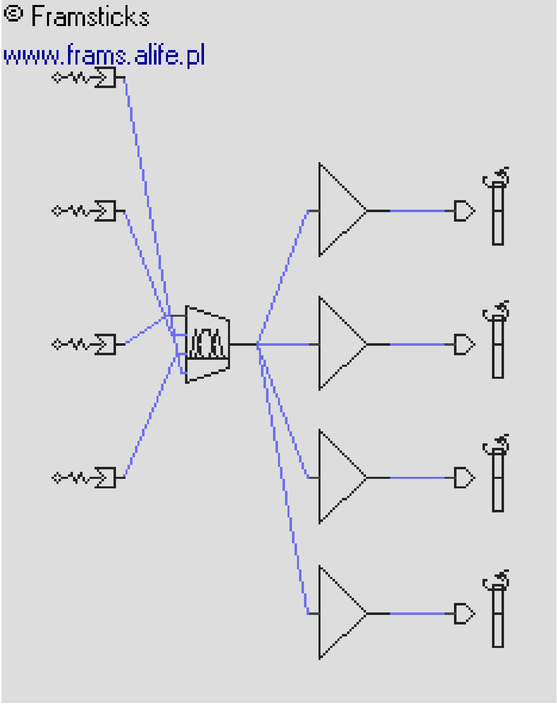
- Fitness function: maximize the average height
- The goal of a FS: to force the agent to stand up
- Two example creatures chosen from the population

Experiments

Walker

- 4 inputs: touch receptors,
- 4 outputs: rotating muscles
- Fitness function: velocity





A movie

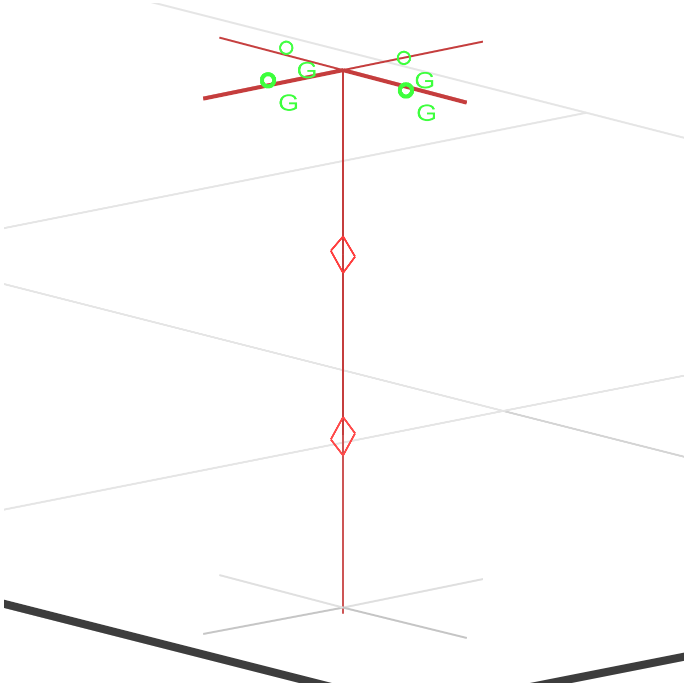
Walker

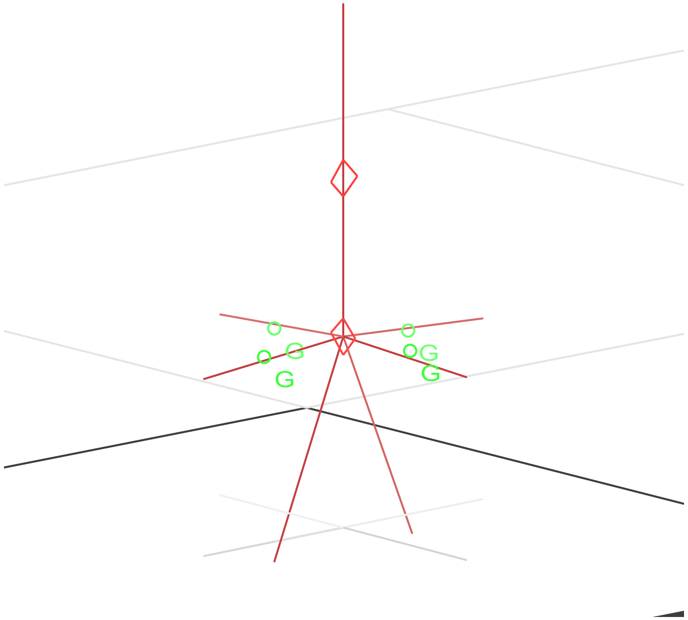
Conclusions

- Walker’s behavior
  - Slightly jumps by means of back legs
  - Runs all around, fitness function does not imply straight running
- Two fuzzy rules are enough

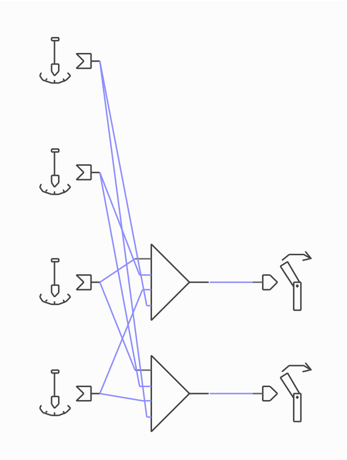
Inverted pendula problem

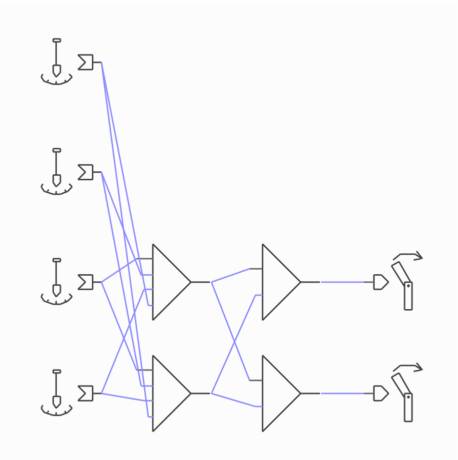
- Modified: active and elastic

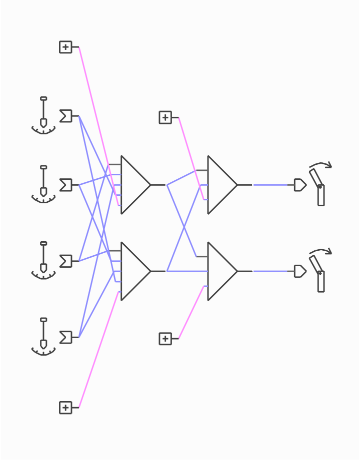


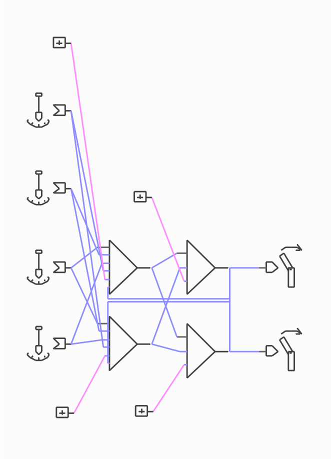


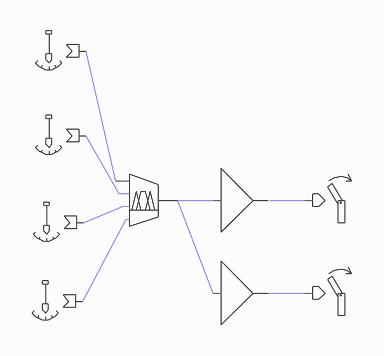
Comparison with NN control



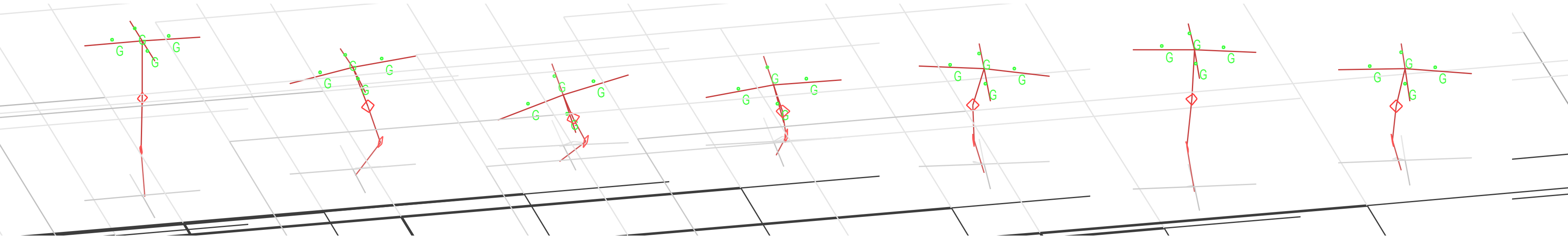




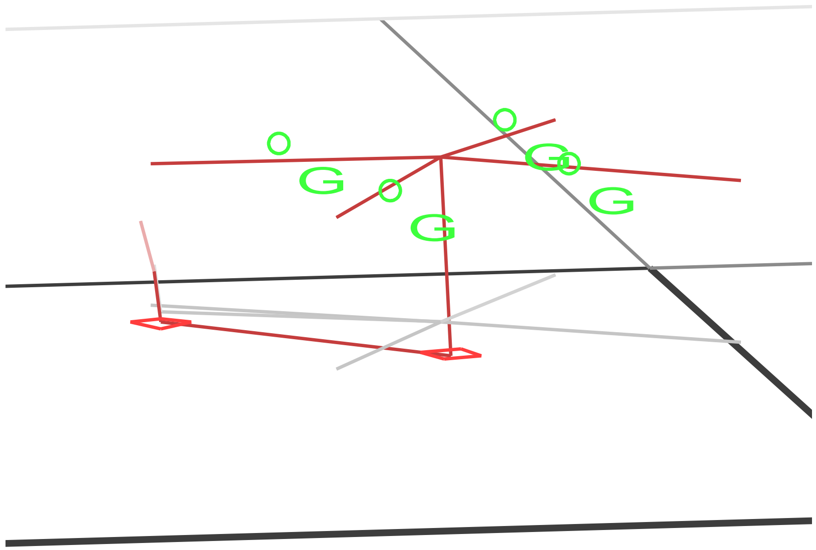


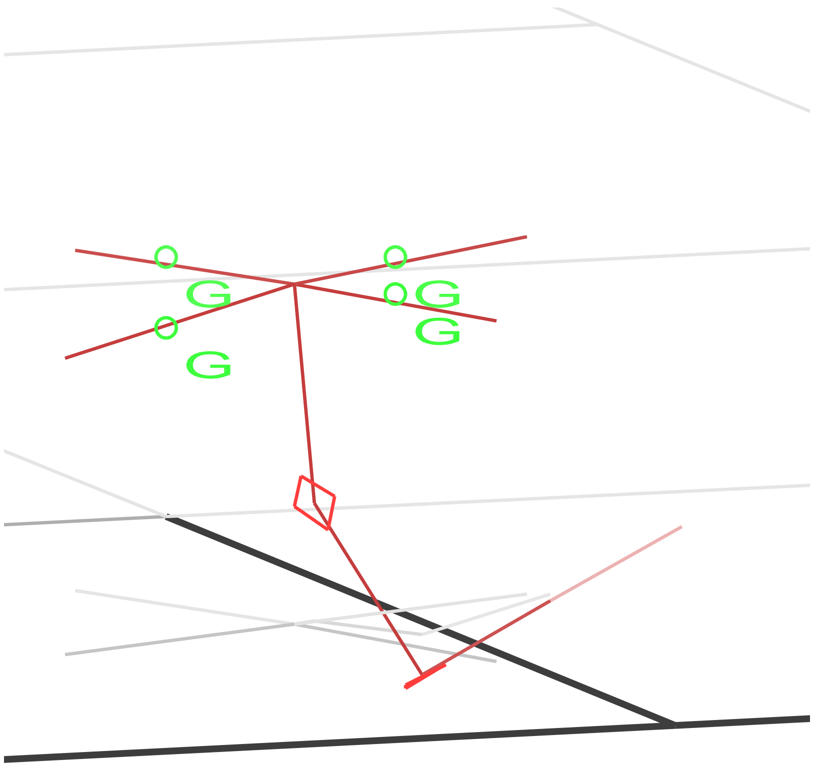


Evolved balancing behavior



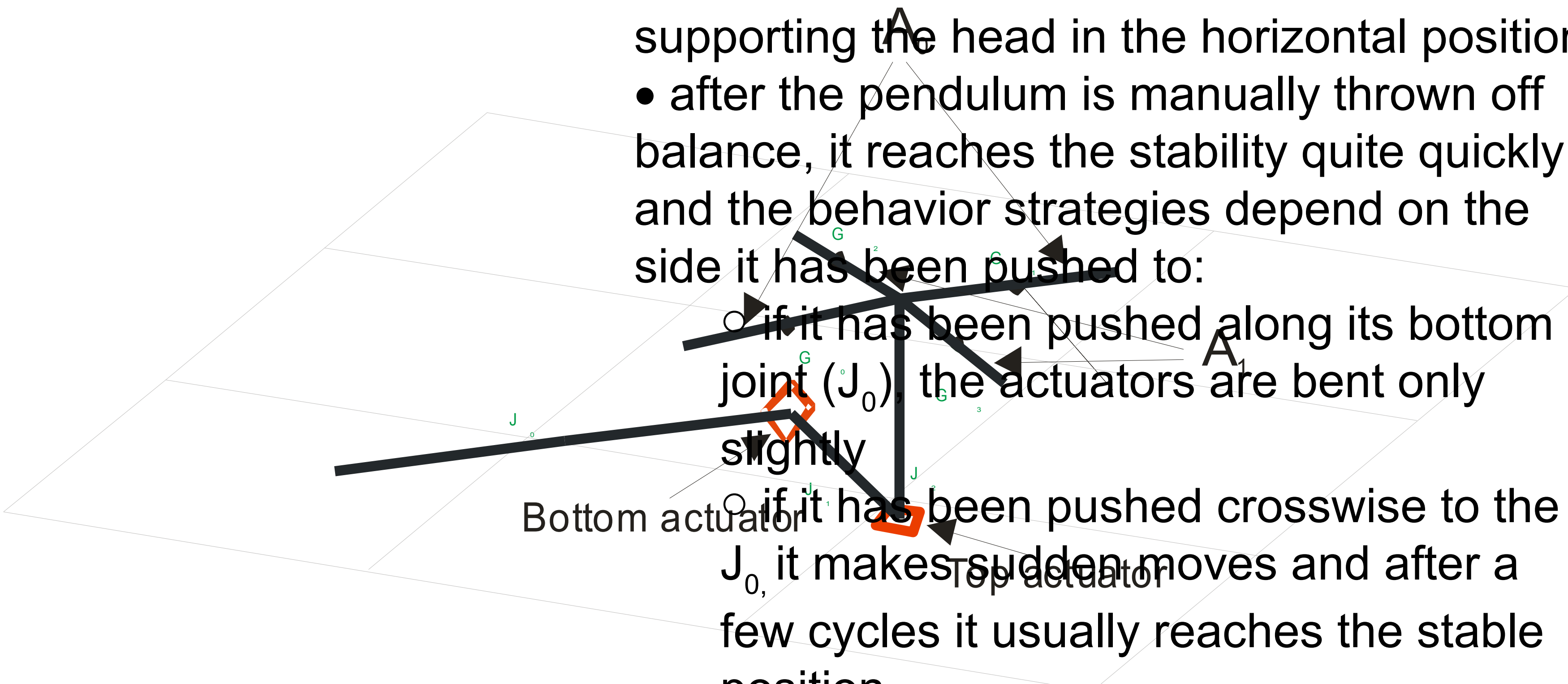
Problems:
elasticity and perceptual aliasing





Understanding evolved fuzzy rules

- in the stable position, J_0 and J_1 lie down on the ground, while J_2 stands upright supporting the head in the horizontal position
- after the pendulum is manually thrown off balance, it reaches the stability quite quickly and the behavior strategies depend on the side it has been pushed to:
  - if it has been pushed along its bottom joint (J_0), the actuators are bent only slightly
  - if it has been pushed crosswise to the J_0, it makes sudden moves and after a few cycles it usually reaches the stable position
  - if the pendulum falls upside down, the fuzzy system is unable to make it stand straight.



Understanding evolved fuzzy rules

Each fuzzy system has four inputs and two outputs. Input signals `s0`, `s1`, `s2`, `s3` come from four sensors. Based on their values, the fuzzy system sends two outputs signals for actuators: `bend_bottom` and `bend_top`. Input and output fuzzy variables are defined in the normalized domain [-1, 1]. Input linguistic variables **`upright`**, **`leveled`** and **`upside_down`** are defined as follows: (-1, -1, -1, 0), (-1, 0, 0, 1) and (0, 1, 1, 1), while the outputs characterizing bending directions are expressed by linguistic variables **`right`** (-1, -1, -1, 0), **`none`** (-1, 0, 0, 1) and **`left`** (0, 1, 1, 1).

Understanding evolved fuzzy rules

```
1. s2=leveled and s0=leveled      => bend_bottom=left and bend_top=left
2. s3=leveled and s1=upside_down  => bend_top=left
3. s1=upright                     => bend_bottom=left and bend_top=left
4. s3=upside_down                 => bend_bottom=right and bend_top=left
5. s1=upside_down                 => bend_bottom=left and bend_top=none
```

- The pairs of sensor signals (s0, s1) and (s2, s3) never come together in a single premise of the rule. It is because the optimization process discovered a property of the pendulum structure: the signals from these equilibrium sensor pairs are almost the same. This is the consequence of placing sensors (G_0, G_1) and (G_2, G_3) on the same arms, respectively.
- See text for detailed explanation and analysis of each rule.

Conclusions

- Successful (evolutionary) simplification of the fuzzy system (from 20 rules to 5 rules)
- both evolution of neural and fuzzy controllers for active inverted pendulum lead to similar pendulum behaviors
- NNs easier to optimize
- verified ability to extract knowledge from the fuzzy control system