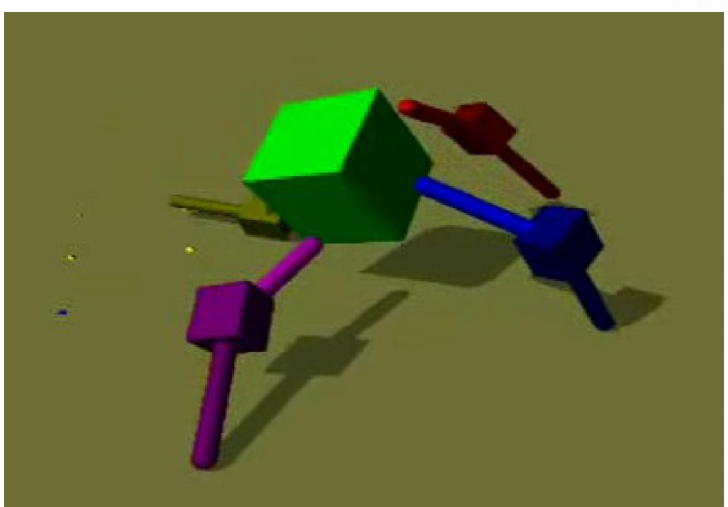
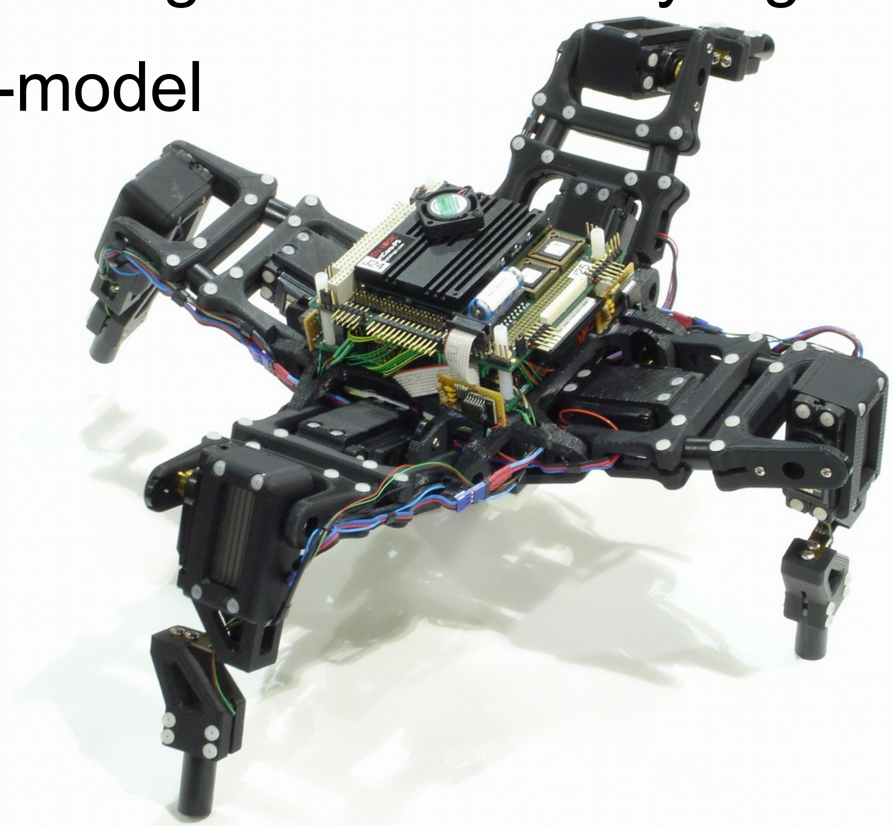
A Self-Modeling Quadruped Robot

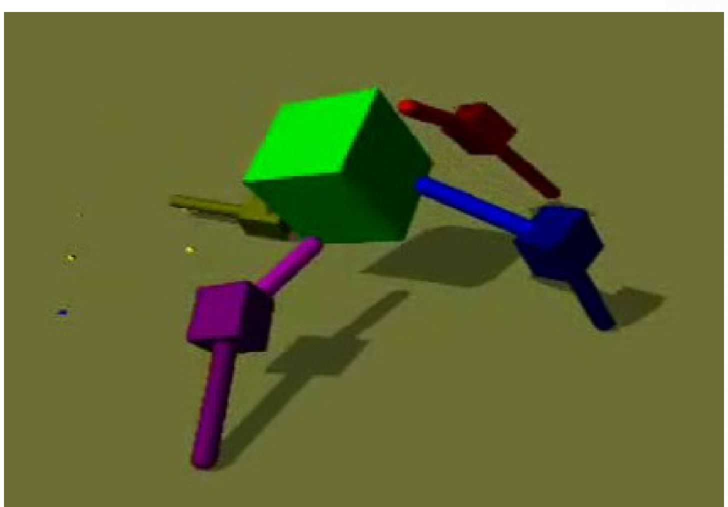
- Josh Bongard, Victor Zykov, and Hod Lipson, "Resilient machines through continuous self-modeling", *Science*, 314, pp. 1118-1121, 2006.
- "Starfish" robot autonomously learns about its own body
- Develops internal **self-model** using an evolutionary algorithm
- Learns to walk based on self-model
- Can recover from damage

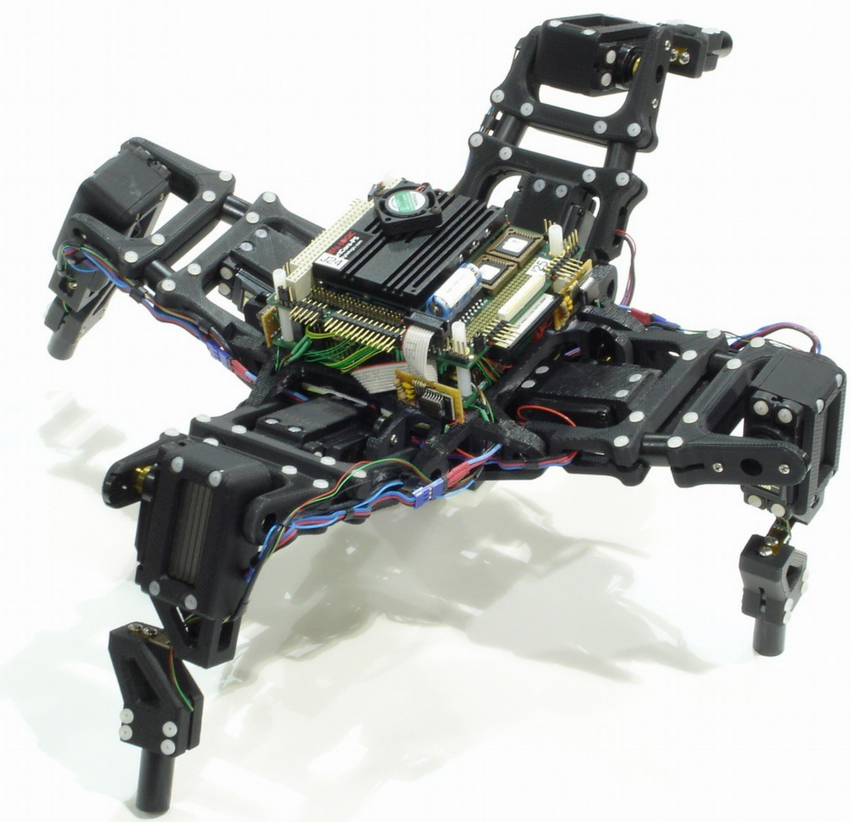




A Self-Modeling Quadruped Robot

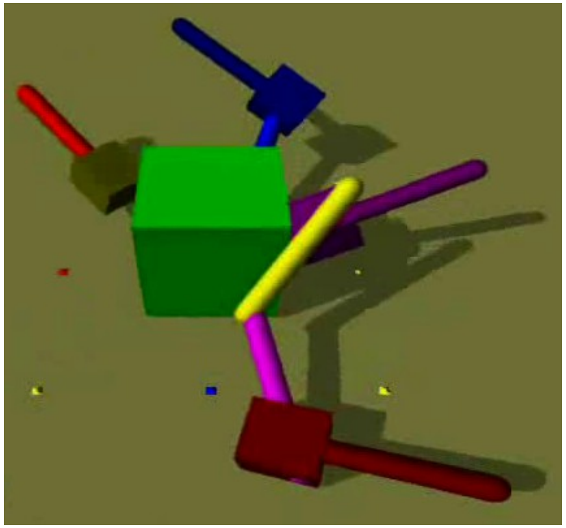
- 9 body parts:
  - central body, 4 legs, 2 parts per leg
- 2 body tilt sensors (left-right, forward-back)
- 8 motorized joints
- 8 joint angle sensors



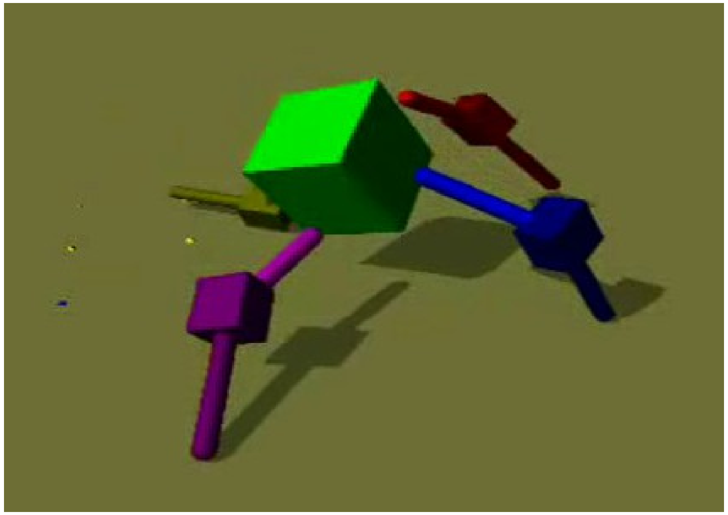


Self-Models

- Robot knows it has 9 body parts, but does NOT know which part is attached to which
- A self-model consists of **16 numerical parameters** that specify how the parts are attached to each other
- Robot maintains 15 competing self-models internally



A poor self-model



A good self-model

Stage I: Learning About Itself

(a) 15 internal self-models are randomly created

Stage I: Learning About Itself

Physical Action	Observed Result
action 1	*result* 1

(a) 15 internal self-models are randomly created

(b) Robot performs a randomly chosen motor action

Stage I: Learning About Itself

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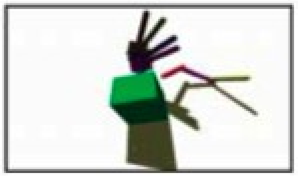
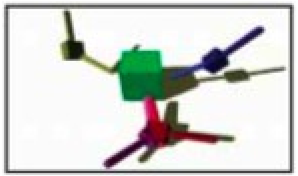
(a) 15 internal self-models are randomly created

(b) Robot performs a randomly chosen motor action

(c) Self-models evolve for 200 cycles. Fitness: ability to predict observed results of robot's actions so far





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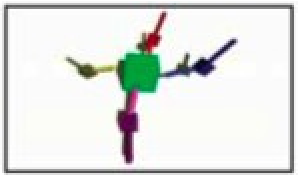


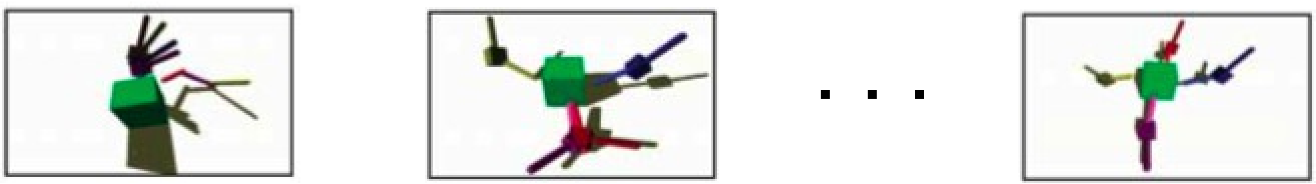
Stage I: Learning About Itself

Physical Action	Observed Result
action 1	*result* 1
***action* 2**	

(a) 15 internal self-models are randomly created

(b) Robot performs a randomly chosen motor action

(c) Self-models evolve for 200 cycles. Fitness: ability to predict observed results of robot's actions so far



(d) A new action is chosen that **maximizes disagreement** among the models about that action's predicted effect

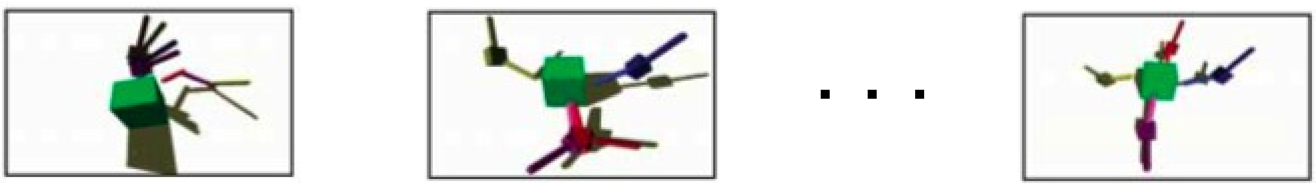
Stage I: Learning About Itself

Physical Action	**Observed Result**
action 1	*result* 1
***action* 2**	***result* 2**

(a) 15 internal self-models are randomly created

(b) Robot performs a randomly chosen motor action

(c) Self-models evolve for 200 cycles. Fitness: ability to predict observed results of robot's actions so far



(d) A new action is chosen that **maximizes disagreement** among the models about that action's predicted effect

(e) Robot performs the action and observes the result

Stage I: Learning About Itself

Physical Action	Observed Result
action 1	*result* 1
action 2	*result* 2

(a) 15 internal self-models are randomly created

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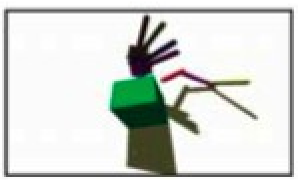

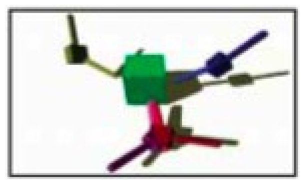

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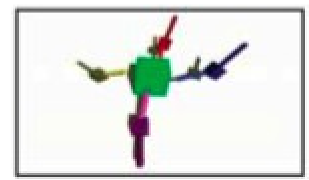


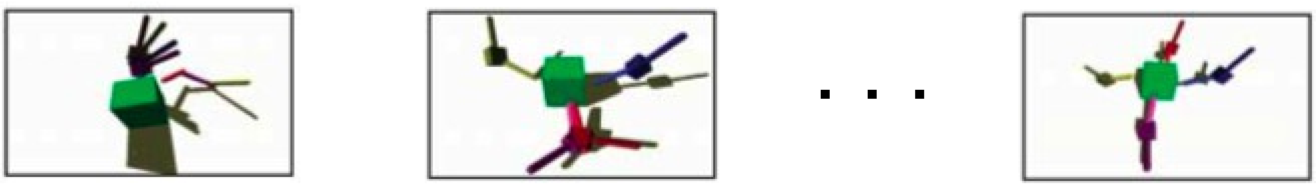
Stage I: Learning About Itself

Physical Action	Observed Result
action 1	*result 1*
action 2	*result 2*
action 3	

(a) 15 internal self-models are randomly created

(b) Robot performs a randomly chosen motor action

(c) Self-models evolve for 200 cycles. Fitness: ability to predict observed results of robot's actions so far



(d) A new action is chosen that **maximizes disagreement** among the models about that action's predicted effect

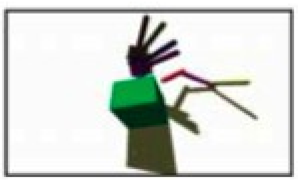
Stage I: Learning About Itself

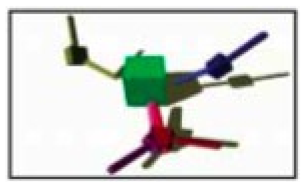
Physical Action	**Observed Result**
action 1	*result 1*
action 2	*result 2*
action 3	***result 3***

(a) 15 internal self-models are randomly created

(b) Robot performs a randomly chosen motor action

(c) Self-models evolve for 200 cycles. Fitness: ability to predict observed results of robot's actions so far





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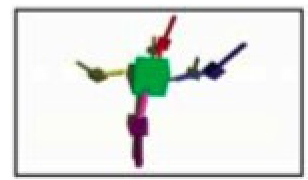


(d) A new action is chosen that **maximizes disagreement** among the models about that action's predicted effect

(e) Robot performs the action and observes the result

Stage I: Learning About Itself

Physical Action	Observed Result
action 1	*result* 1
action 2	*result* 2
action 3	*result* 3
. . .	. . .

(a) 15 internal self-models are randomly created

(b) Robot performs a randomly chosen motor action

(c) Self-models evolve for 200 cycles. Fitness: ability to predict observed results of robot's actions so far

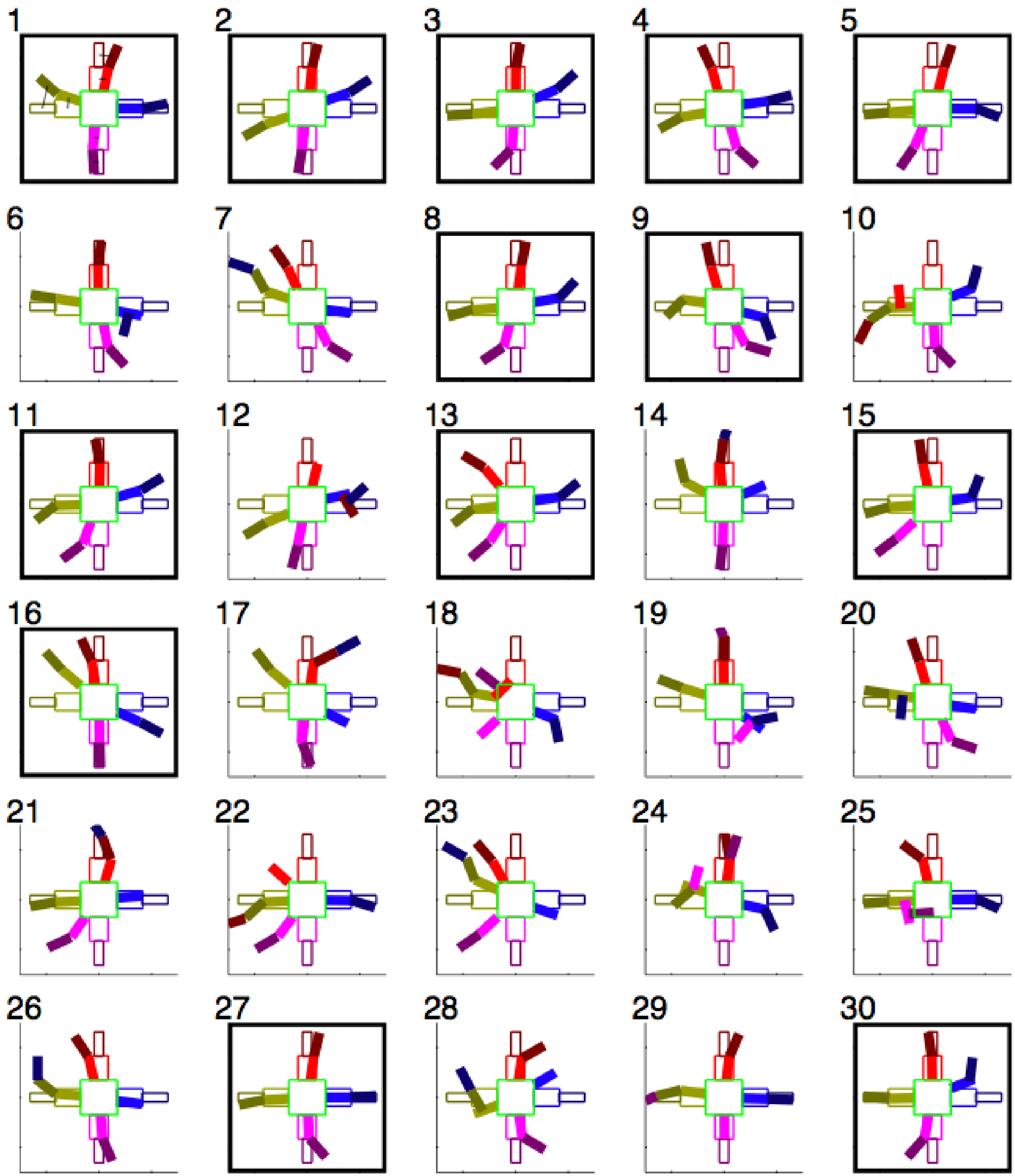
(d) A new action is chosen that **maximizes disagreement** among the models about that action's predicted effect

(e) Robot performs the action and observes the result

Steps (c)-(e) are repeated for 16 different exploratory actions

Stage I: Results

30 independent experiments were performed



13 of them (43%) produced a self-model with the correct topology

Average model inaccuracy: 7.3 cm

Model-Driven Learning Disabled: Baseline 1

(a) 15 internal self-models are randomly created

(b) Robot performs 16 randomly chosen motor actions

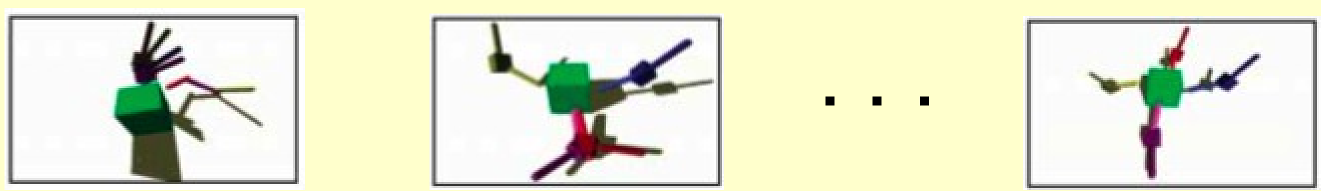
Physical Action	**Observed Result**
action 1	*result* 1
action 2	*result* 2
action 3	*result* 3
action 4	*result* 4
. . .	. . .
action 16	*result* 16

Model-Driven Learning Disabled: Baseline 1

(a) 15 internal self-models are randomly created

(b) Robot performs 16 randomly chosen motor actions

(c) Self-models evolve **based on all 16 actions together**.
Fitness: ability to predict observed results of actions.



Physical Action	**Observed Result**
action 1	*result* 1
action 2	*result* 2
action 3	*result* 3
action 4	*result* 4
. . .	. . .
action 16	*result* 16

Results: Baseline 1

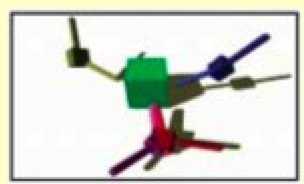
- As before, 30 independent experiments were performed
- Only 7 of them (23%) produced a topologically correct self-model, compared to 43% with model-driven learning enabled
- Average model inaccuracy was 9.6 cm, compared to 7.3 cm with model-driven learning enabled
- Interleaving exploratory motor actions chosen on the basis of the evolving self-models significantly improves model synthesis, compared to randomly choosing all exploratory actions first, and then modeling.

Model-Driven Learning Disabled: Baseline 2

(a) 15 internal self-models are randomly created

(b) Robot performs a randomly chosen motor action

(c) Self-models evolve for 200 cycles. Fitness: ability to predict observed results of robot's actions so far



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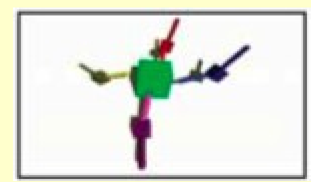


(d) A new action is **chosen randomly**

(e) Robot performs the action and observes the result

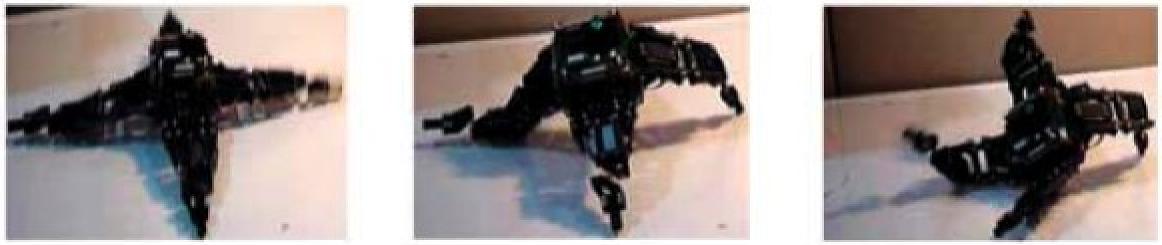
Steps (c)-(e) are repeated for 16 different exploratory actions

Results: Baseline 2

- As before, 30 independent experiments were performed
- Only 8 of them (26%) produced a topologically correct self-model, compared to 43% with model-driven learning enabled
- Average model inaccuracy was 9.7 cm, compared to 7.3 cm with model-driven learning enabled
- Interleaving exploratory motor actions chosen on the basis of the evolving self-models, compared to interleaving random exploratory actions, significantly improves model synthesis.

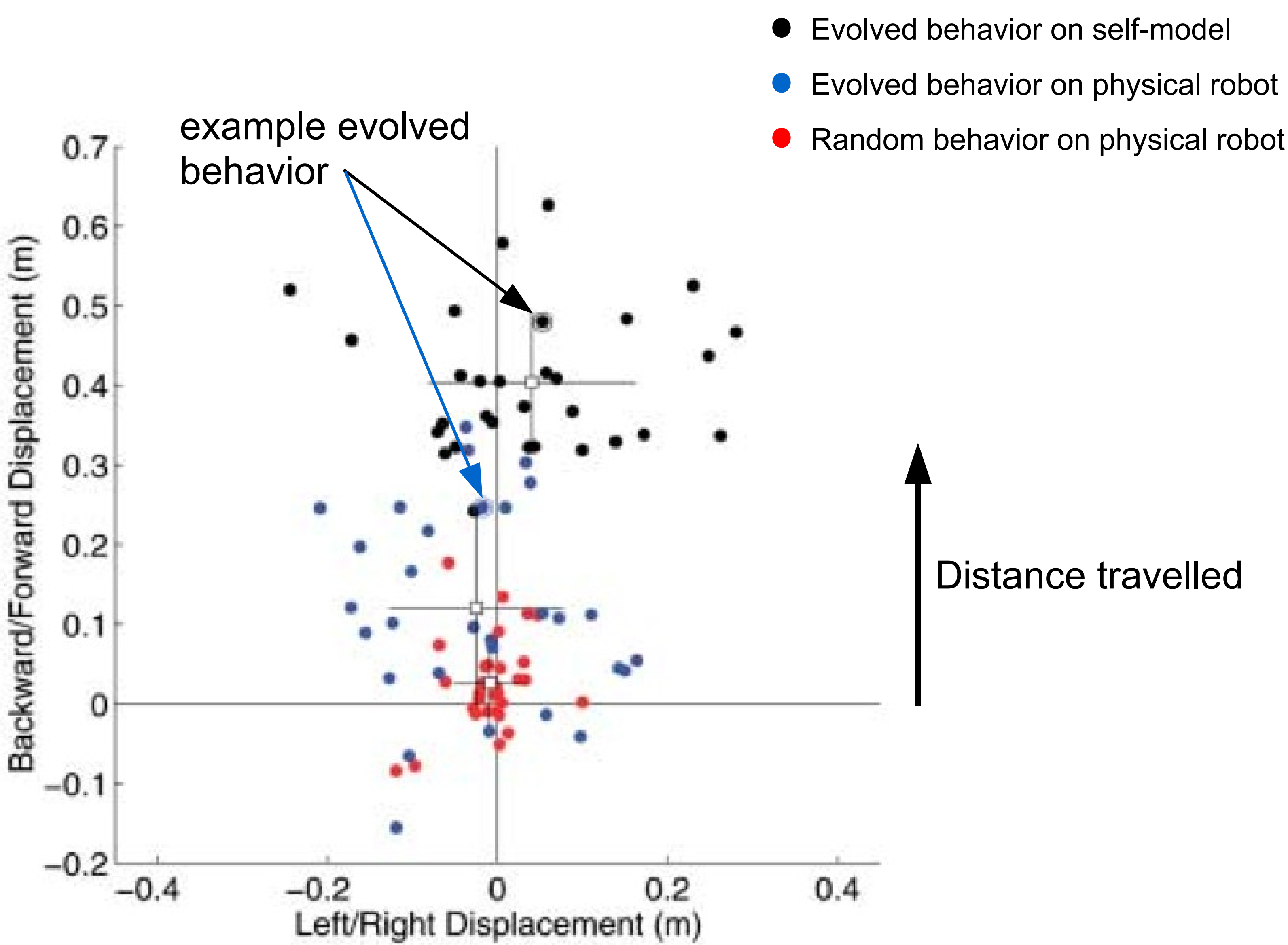
Stage II: Learning To Walk

- Start with the most accurate **self-model** generated in Stage I
- Use an **evolutionary algorithm** to evolve behaviors
  - a behavior is a set of numbers specifying a temporal sequence of joint angles
  - fitness of a behavior: how far does it cause the self-model to move forward in simulation?
- Test the **best evolved behavior** on the physical robot

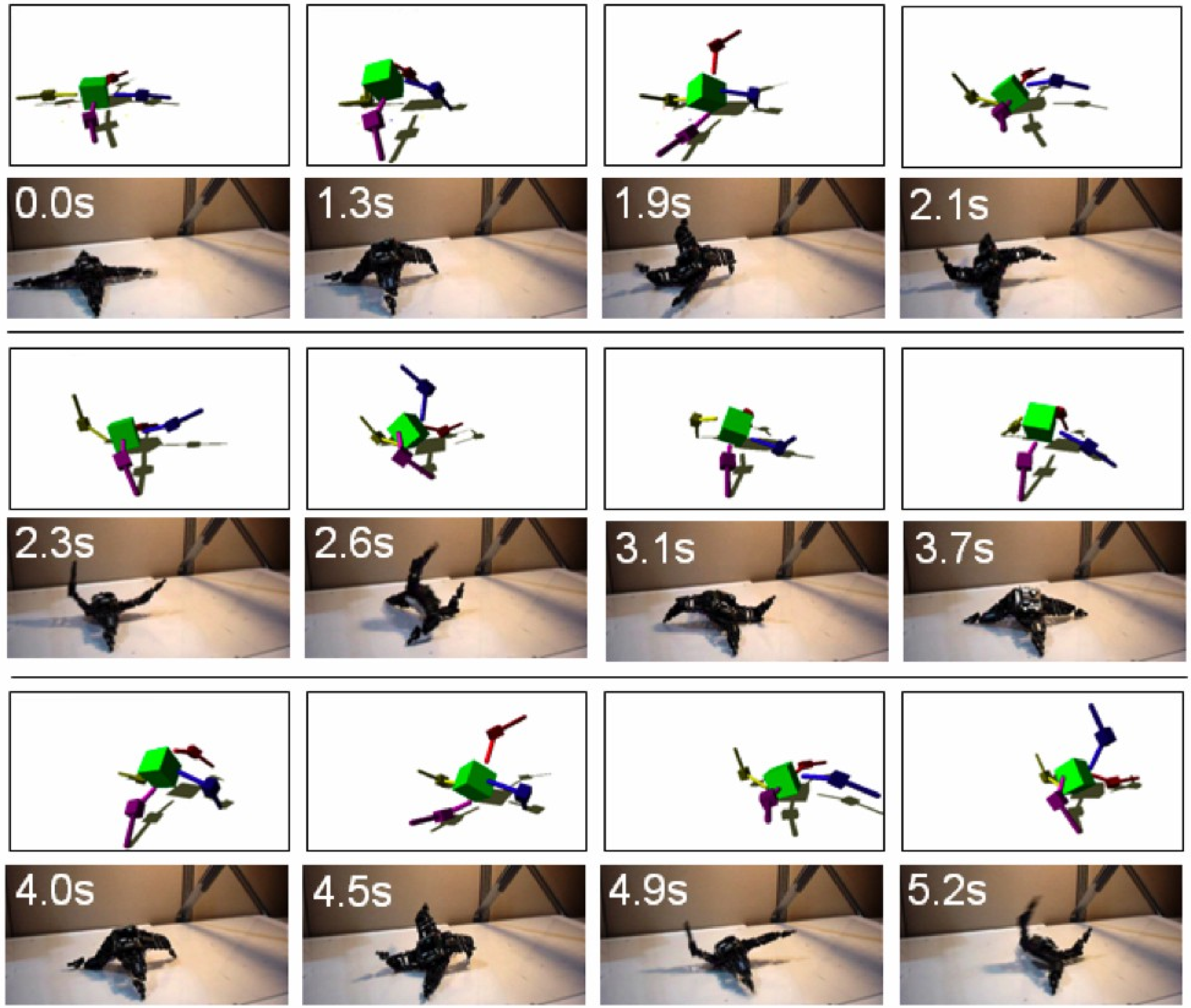


- Repeat **30 times**, starting from different random populations of behaviors but using **the same self-model** in each case

Stage II: Results

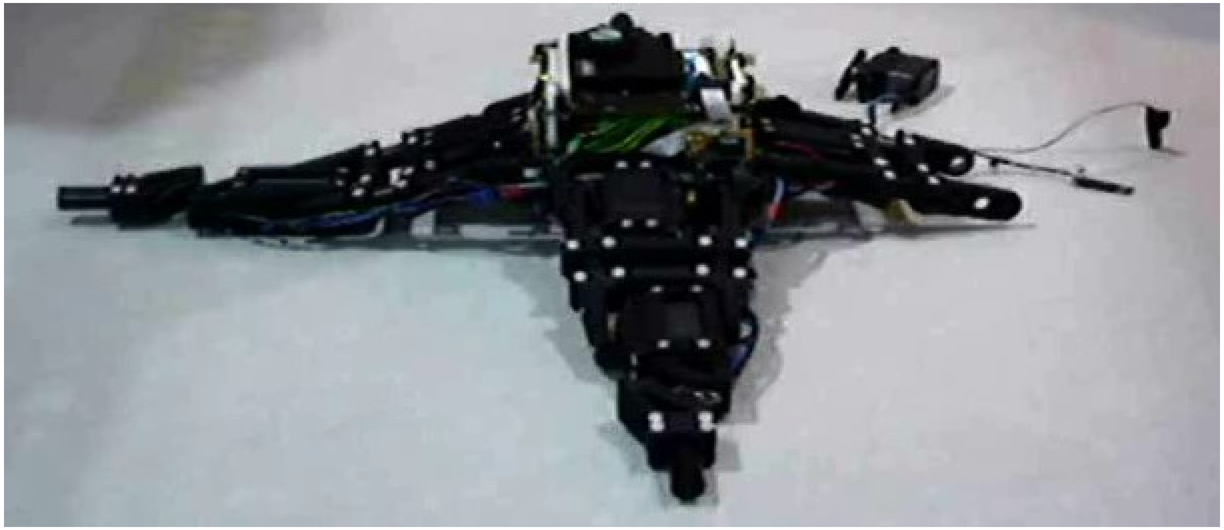


Stage II: Results



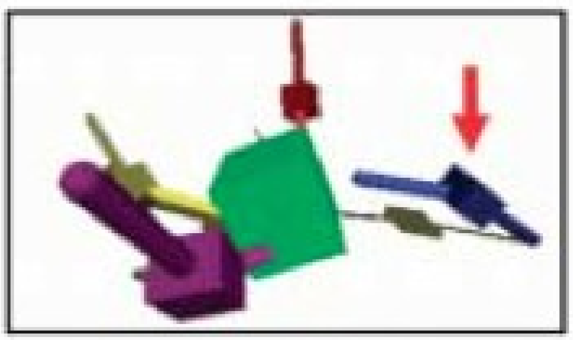
Damage Recovery

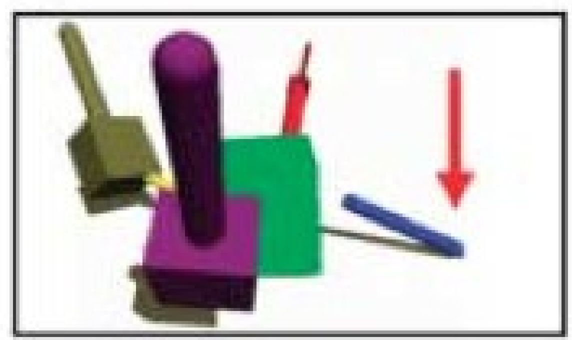
- If the robot becomes damaged, self-modeling and experimentation recommence with the best model so far



Damage Recovery

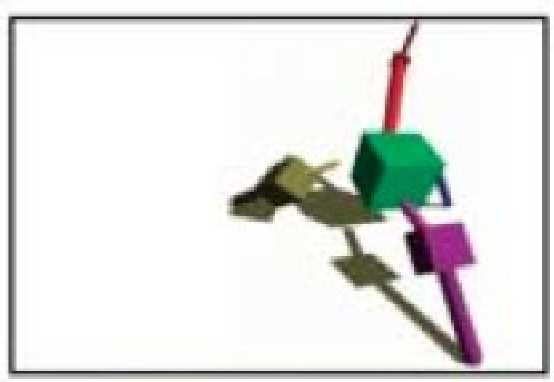
- If the robot becomes damaged, self-modeling and experimentation recommence with the best model so far
- The EA varies the relative sizes of leg parts within models until a new, more accurate self-model emerges



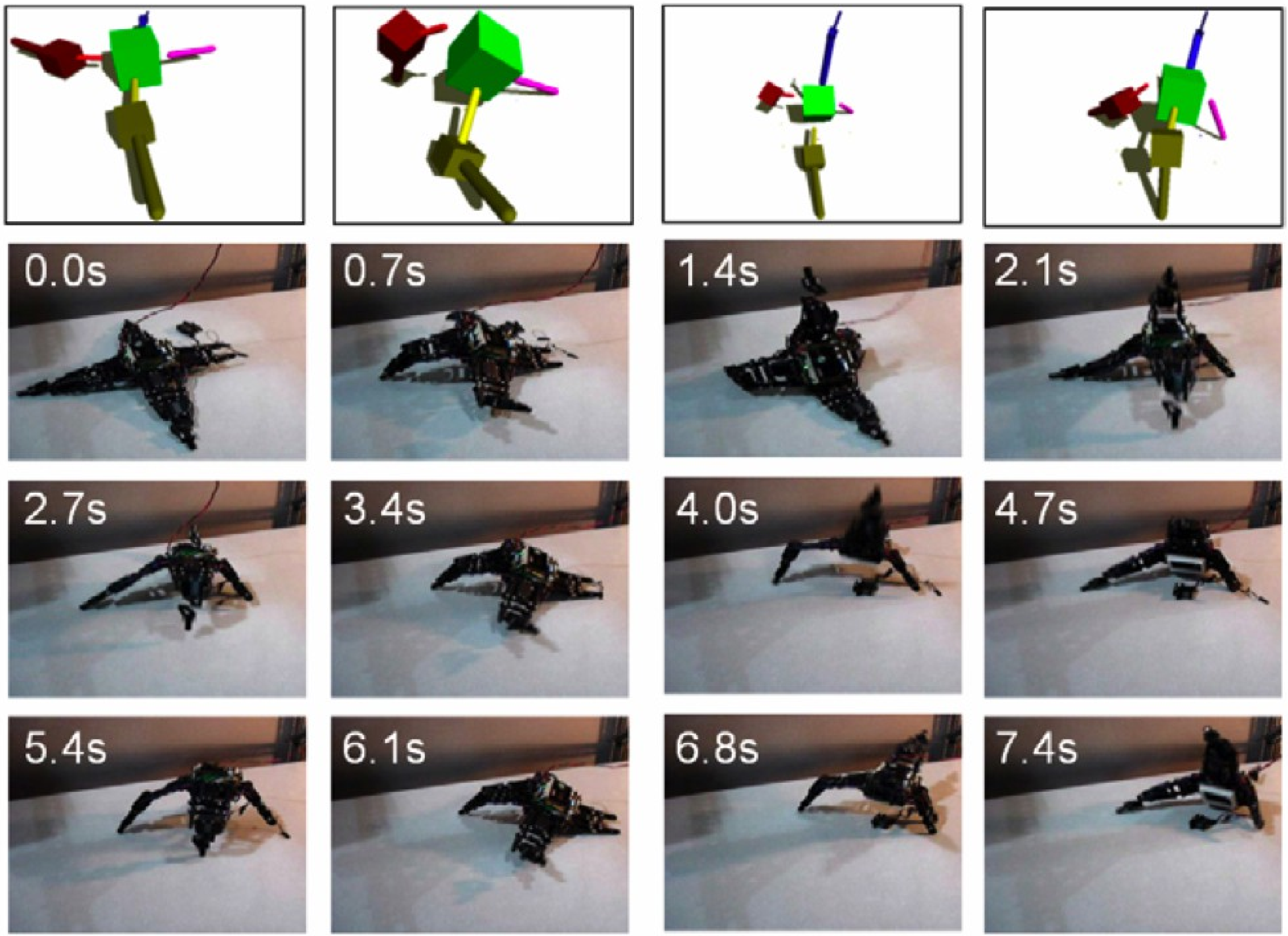


Damage Recovery

- If the robot becomes damaged, self-modeling and experimentation recommence with the best model so far
- The EA varies the relative sizes of leg parts within models until a new, more accurate self-model emerges
- The new, improved self-model is used to synthesize a new walking behavior



Damage Recovery: Results



Feelin' Good!