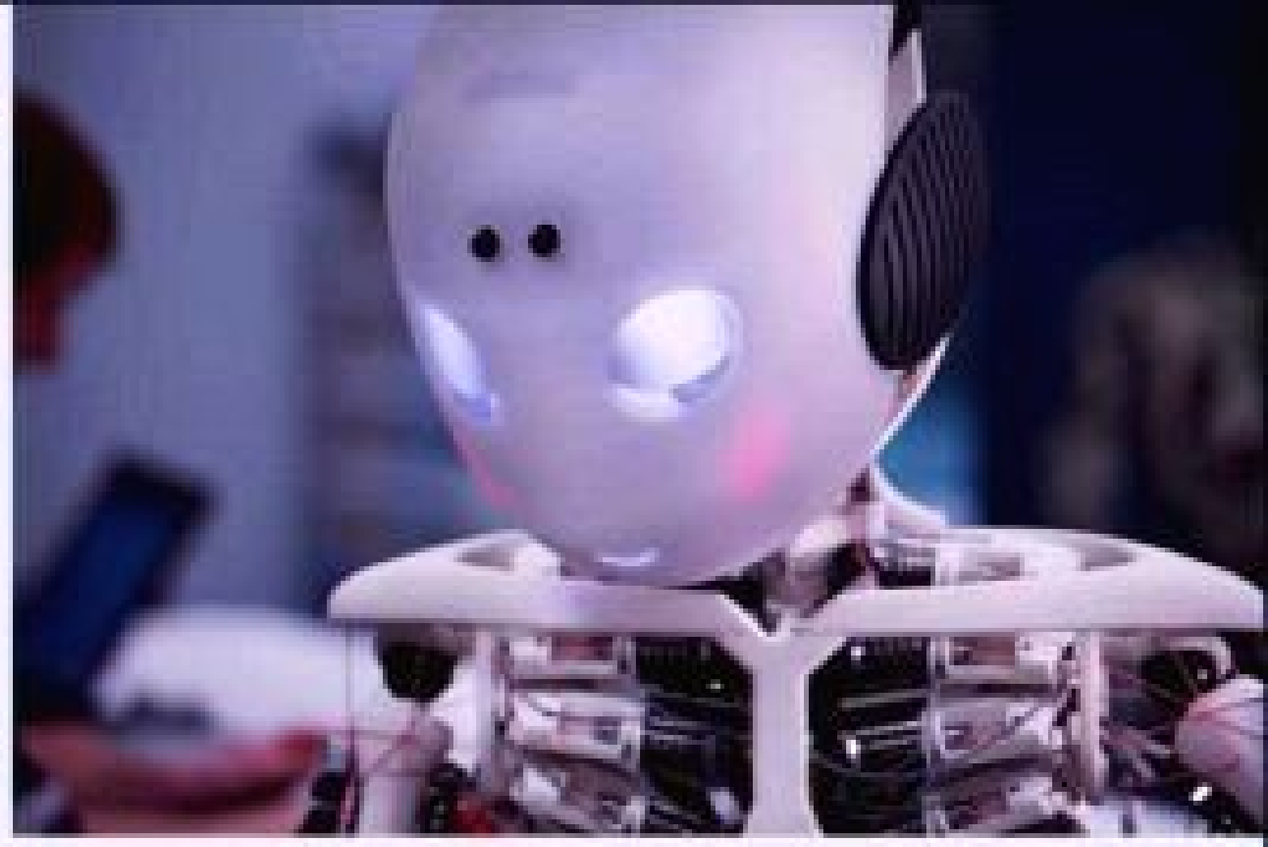
“Soft robotics” — the next generation of intelligent machines



“The four messages of embodiment”

TNG BigTechDay 6, 14 June 2013

Rolf Pfeifer, Artificial Intelligence Laboratory
Department of informatics, University of Zurich
NCCR National Competence Center Robotics, Switzerland

Relation to cognition/ intelligence?

"Why do plants not have brains? The answer is actually quite simple: they don't have to move." Lewis Wolpert, UK

—> evolutionary selectionist pressure on brain development

brain/intelligence always part of complete organism

Cognitive Systems/ Artificial Intelligence — goals

1. Understanding biological systems

animals *humans*

2. Principles, theory

3. Applications

Baxter

vacuum cleaner

robot "bar man"

Engkey

Artificial Intelligence — goals

Slogan: **"Understanding by building"**
(synthetic methdology)

Zurich AI Lab robots

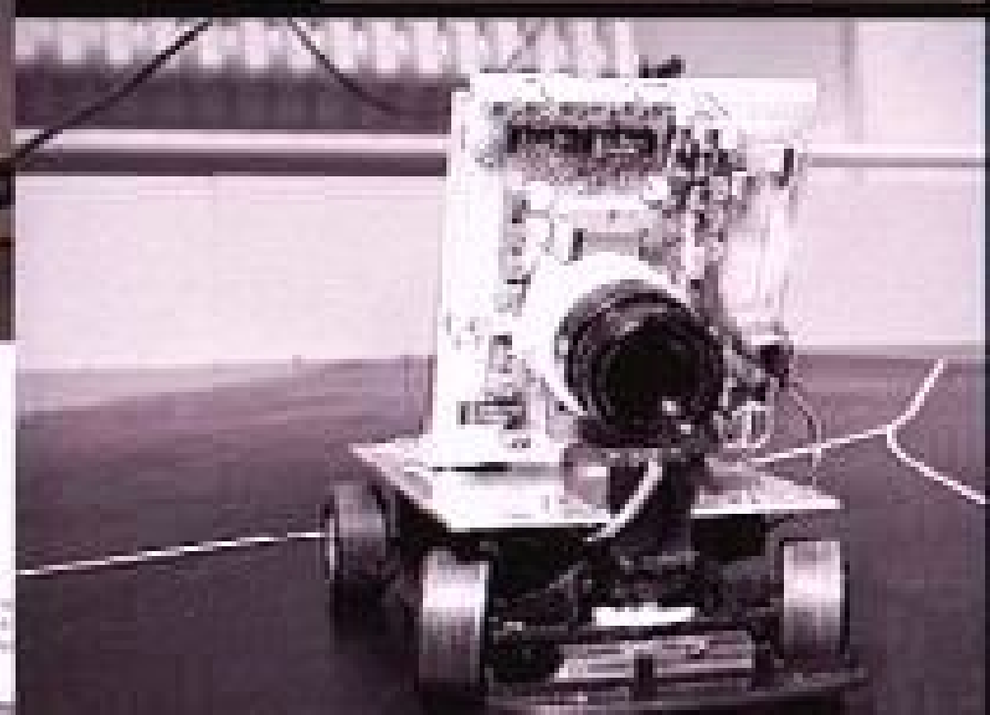
Didabot

Famez

Sita

Rufus T. Firefly

Ms. Gloria Teasdale



robotics

Morpho

Zurich AI Lab robots

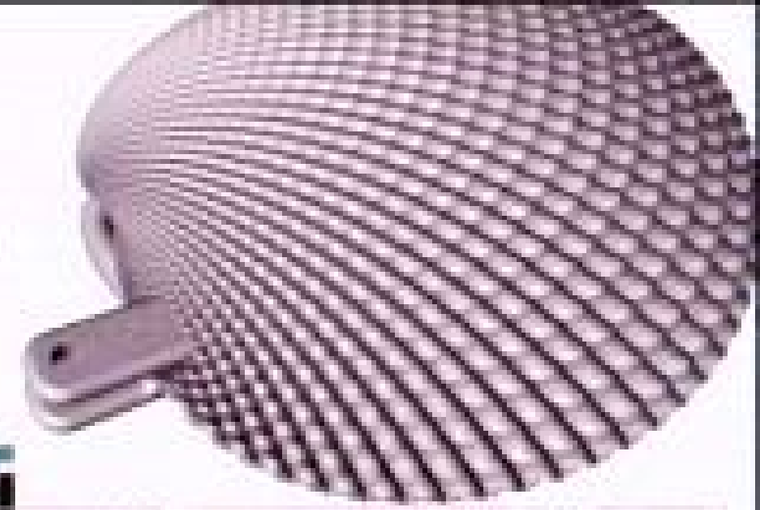
- Amouse
- Sahabotl/II
- Melissa
- Tripp
- Samurai
- Analogrob
- Dexterolator
- Stumpy
- Eyebot
- Mindstorms
- Kheperas
- Mitsubishi
- Forkleg

Zurich AI Lab robots

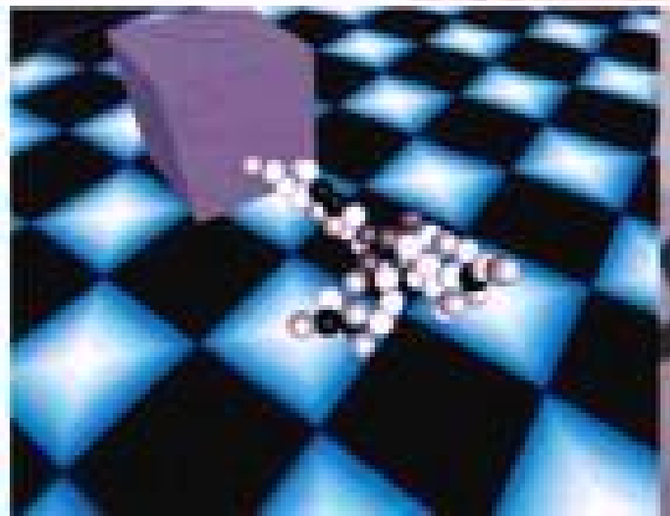
Stumpy, Monkey, Puppy, Min-dog, Wheeled Walker, Mini-Stumpy, Wanda, Dumbo, Rabbit

Zurich AI Lab robots

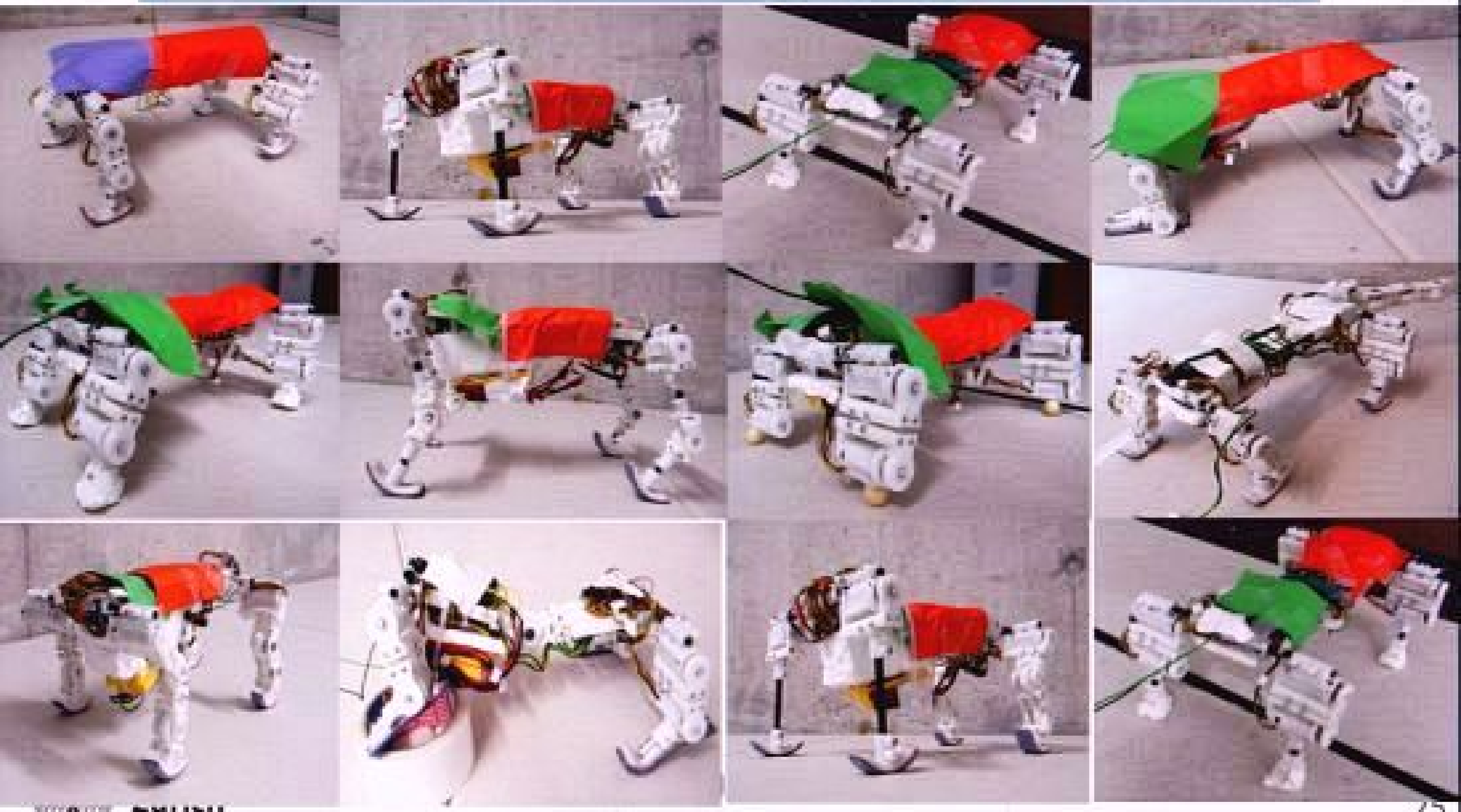


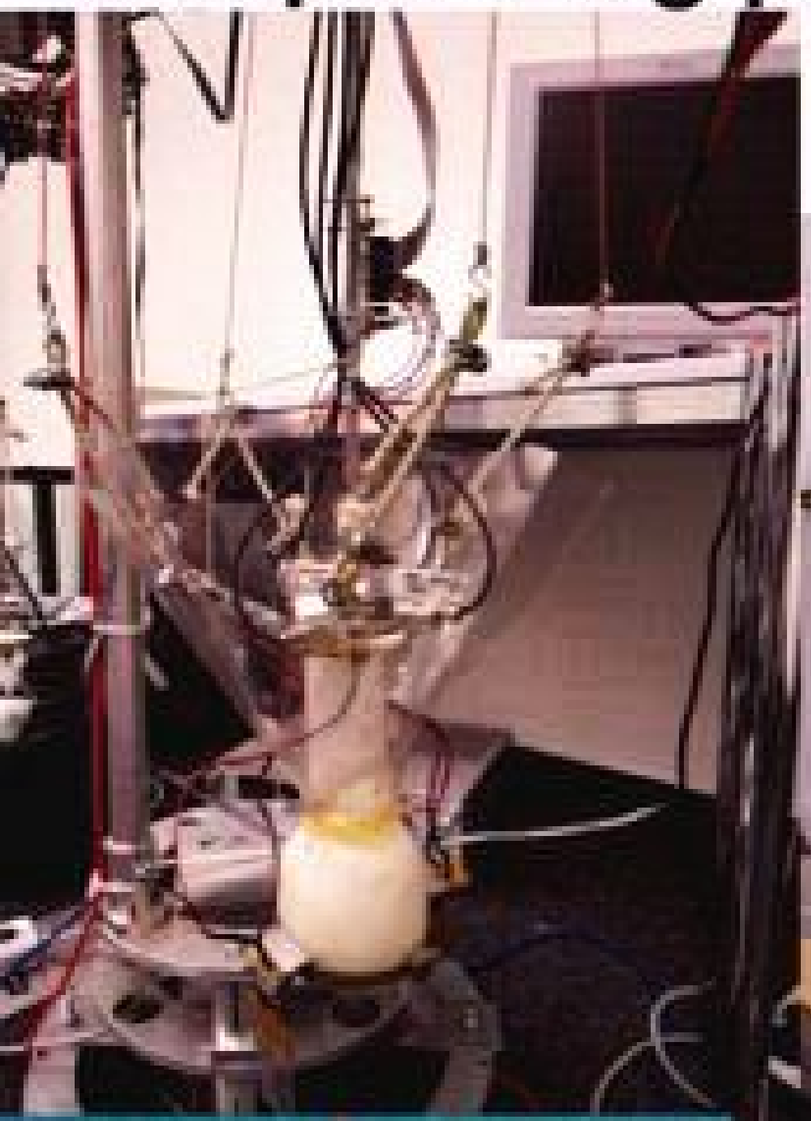


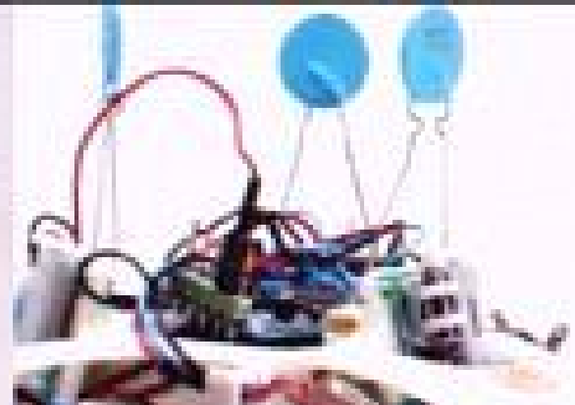



AI Lab Robots
(exploration of morphology)

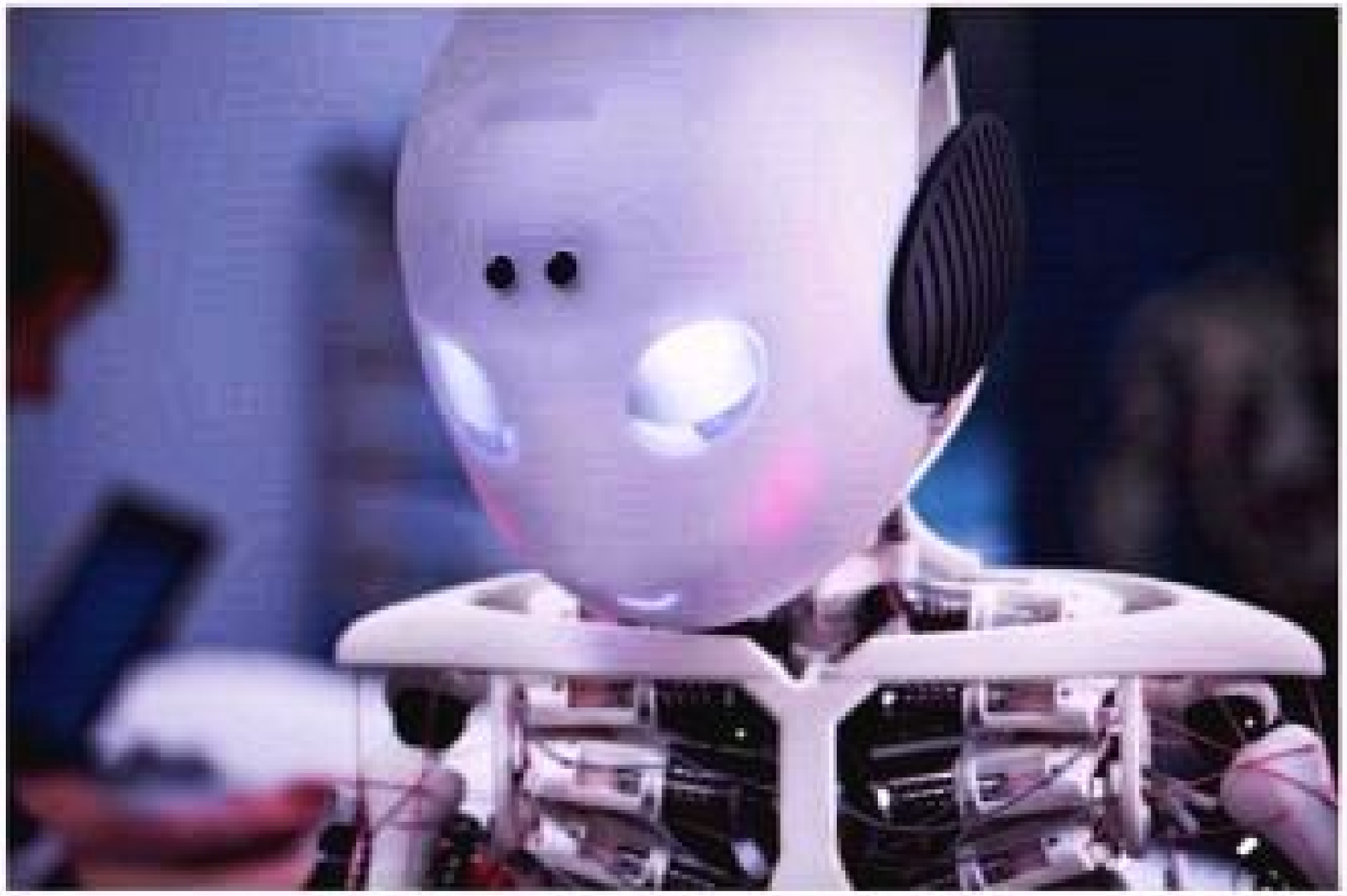


floating; hair-bot; adaptive leg press





Recent development: Roboy



more later

Contents

- introduction and background
- the four messages of embodiment
- the "power of materials"
- summary and conclusions
- the "Roboy" project

Getting into the spirit of embodiment

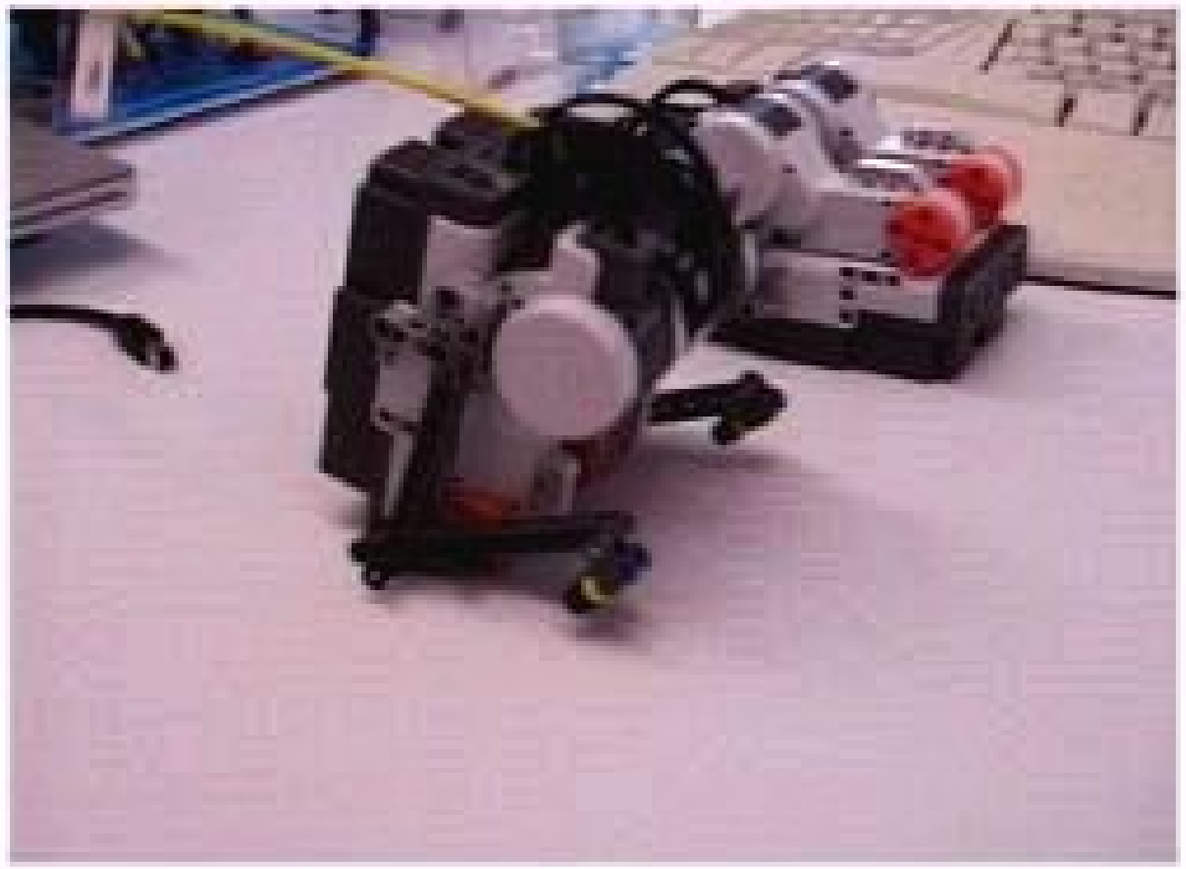
The spirit of embodiment

The spirit of embodiment

The spirit of embodiment

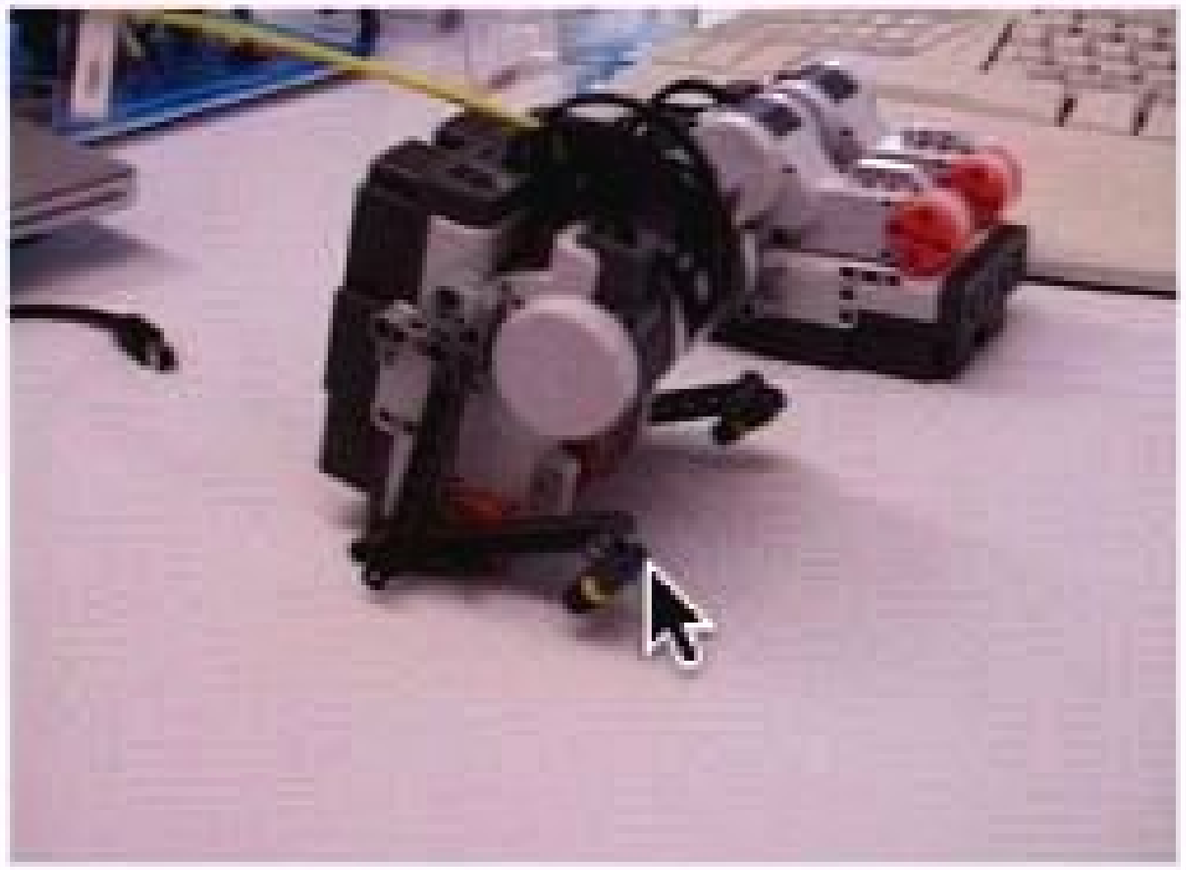
The spirit of embodiment

“Crazy Bird” — Morphology, Control



loosely hanging feet
rubber/plastic

“Crazy Bird” — Morphology, Control



loosely hanging feet
rubber/plastic

behavior of “Crazy Bird”:
only program?

Message 1: Physical embedding

Studying brain (or control) not sufficient: Understanding of

- **embedding of brain into organism**
- **organism's morphological and material properties**
- **environment**

required

Let me be clear

The brain is important!

Let me be clear

The brain is important!

but not the whole story ...

Message 2: Real/ Artificial-constructed worlds

Understanding the differences between

- artificial/constructed worlds (e.g. industrial)

- real worlds (e.g. downtown area, shopping mall, school, home, soccer field)

—> different requirements for robots

industrial environment

- high predictability
- programmability

industrial robots ("hard")

real-world environment

- low predictability
- coping with uncertainty

humans ("soft" to varying degrees)

industrial environment

- high predictability
- programmability

industrial robots ("hard")

real-world environment

- low predictability
- coping with uncertainty

humans ("soft" to varying degrees)

—> no direct transfer of methods

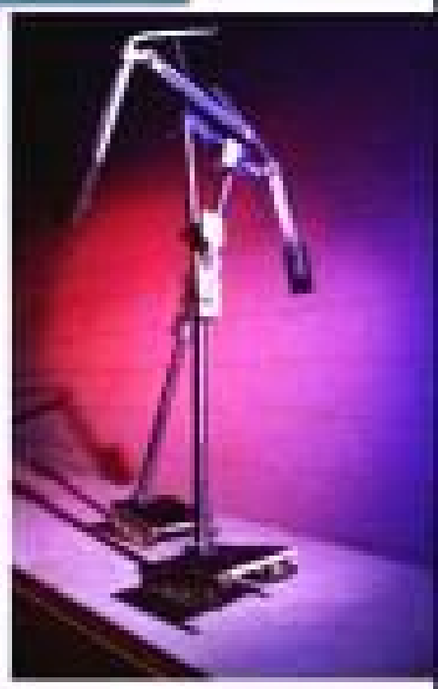
Transfer of methods?

Sony Qrio:
high stiffness
centralized control
conputationally intensive

By comparison: The “Passive Dynamic Walker”

Design and construction:
Ruina, Wisse, Collins: Cornell University
Ithaca, New York

the “brainless” robot: walking without control



Design and construction:
Bendy (Paul, Yokoi, Matsushita),
Tripp (Chandana Paul)

By comparison: The "Passive Dynamic Walker"

Design and construction:
Ruina, Wisse, Collins: Cornell University
Ithaca, New York

the "brainless" robot: walking without control

Design and construction:
Bendy (Paul, Yokoi, Matsushita),
Tripp (Chandana Paul)

By comparison: The “Passive Dynamic Walker”

Design and construction:
Ruina, Wisse, Collins: Cornell University
Ithaca, New York

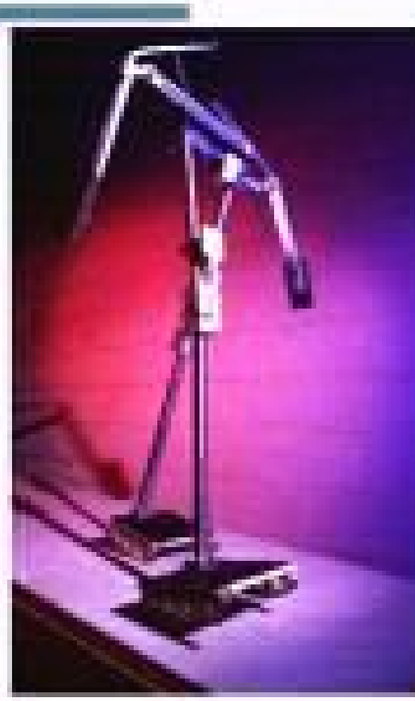
the “brainless” robot: walking without control

Design and construction:
Bendy (Paul, Yokoi, Matsushita),
Tripp (Chandana Paul)

By comparison: The "Passive Dynamic Walker"

Design and construction:
Ruina, Wisse, Collins: Cornell University
Ithaca, New York

the "brainless" robot:
walking without control



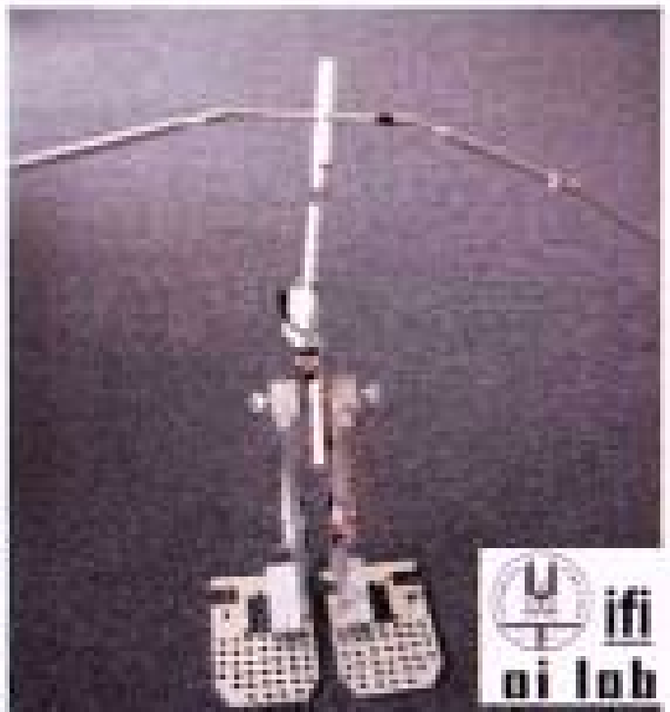
Design and construction:
Bendy (Paul, Yokoi, Matsushita),
Tripp (Chandana Paul)

By comparison: The "Passive Dynamic Walker"

Design and construction:
Ruina, Wisse, Collins: Cornell University
Ithaca, New York

the "brainless" robot:
walking without control

self-stabilization



Design and construction:
Bendy (Paul, Yokoi, Matsushita),
Tripp (Chandana Paul)

Short question

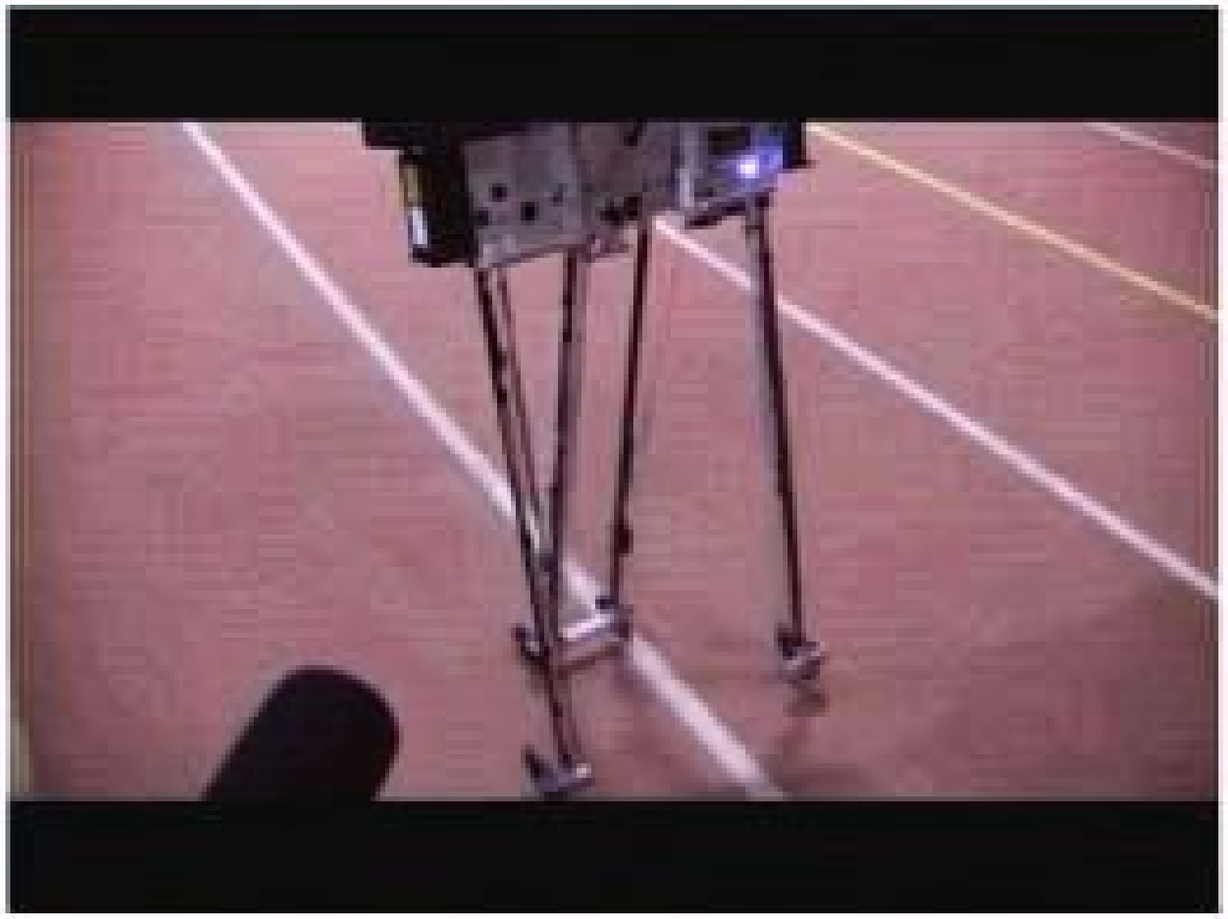
memory for walking?

The Cornell Ranger

design and construction:
Andy Ruina
Cornell University

exploitation of passive dynamics

The Cornell Ranger



design and construction:
Andy Ruina
Cornell University

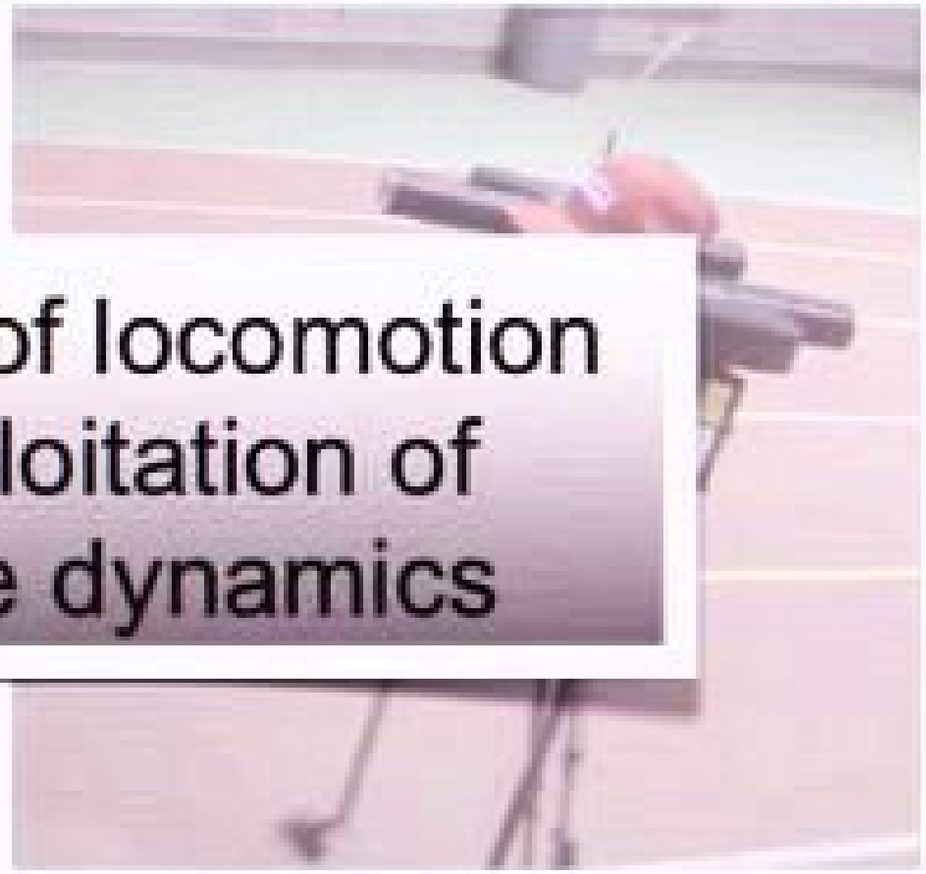
exploitation of passive dynamics

The Cornell Ranger

conception et construction:
Andy Ruina
Cornell University

65km with one battery charge!

The Cornell Ranger



"control" of locomotion by exploitation of passive dynamics

conception
Andy Ruina
Cornell University

65km with one battery charge!

Contrast: Full control

Honda Asimo

Sony Qrio

Message 3: Task distribution

Task distribution between brain (control), body (morphology, materials), and environment

Message 3: Task distribution

Task distribution between brain (control), body (morphology, materials), and environment

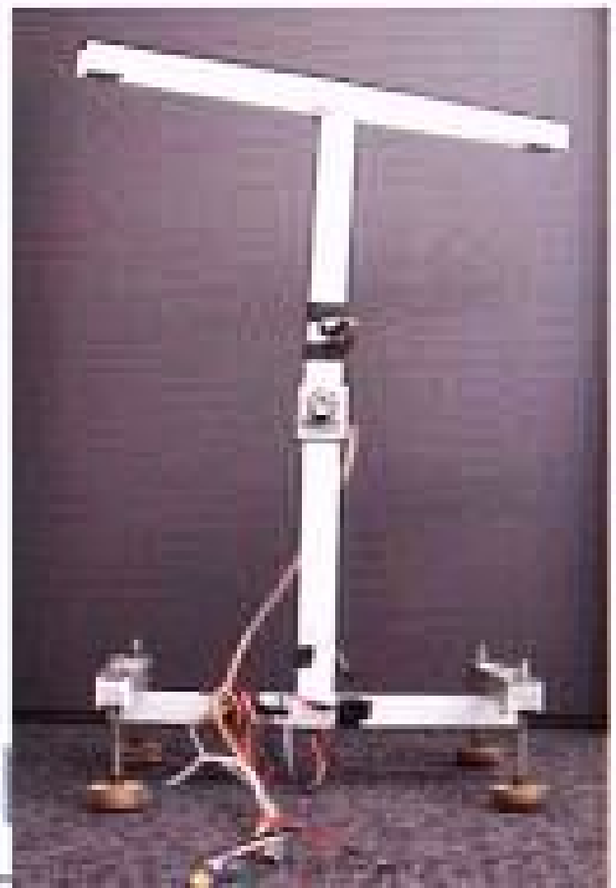
no clear separation between control and hardware (“soft robotics”)

morphological computation

“Stumpy”: task distribution

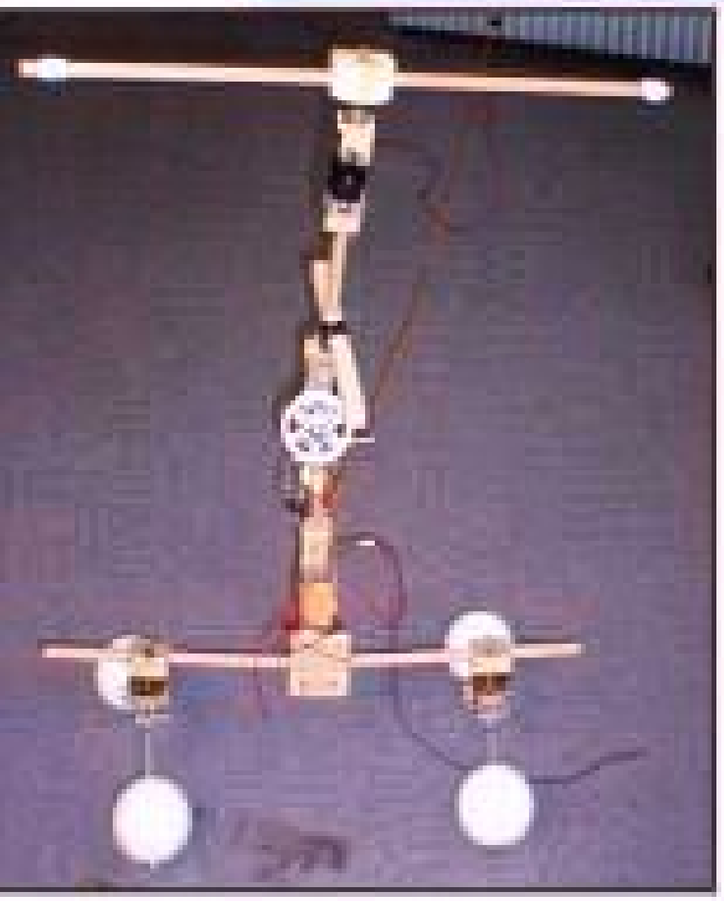
almost brainless: 2 actuated joints
springy materials
surface properties of feet

Design and construction: **Raja Dravid, Chandana Paul, Fumiya Iida**



self-stabilization

“Stumpy”: task distribution



almost brainless: 2 actuated joints
springy materials
surface properties of feet

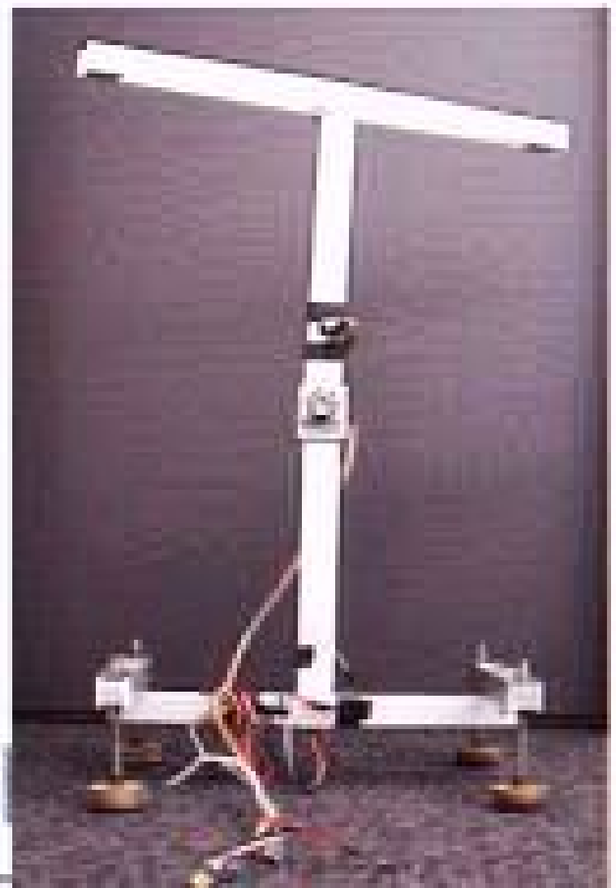
Design and construction: **Raja Dravid, Chandana Paul, Fumiya Iida**

self-stabilization

“Stumpy”: task distribution

almost brainless: 2 actuated joints
springy materials
surface properties of feet

Design and construction: **Raja Dravid, Chandana Paul, Fumiya Iida**



self-stabilization

The dancing robot “Stumpy”

Collaboration with Louis-Philippe Demers, Nanyang Technological University, Singapore

Movie:
Max Lungarella
Raja Dravid
Dynamic Devices and AILab, Zurich

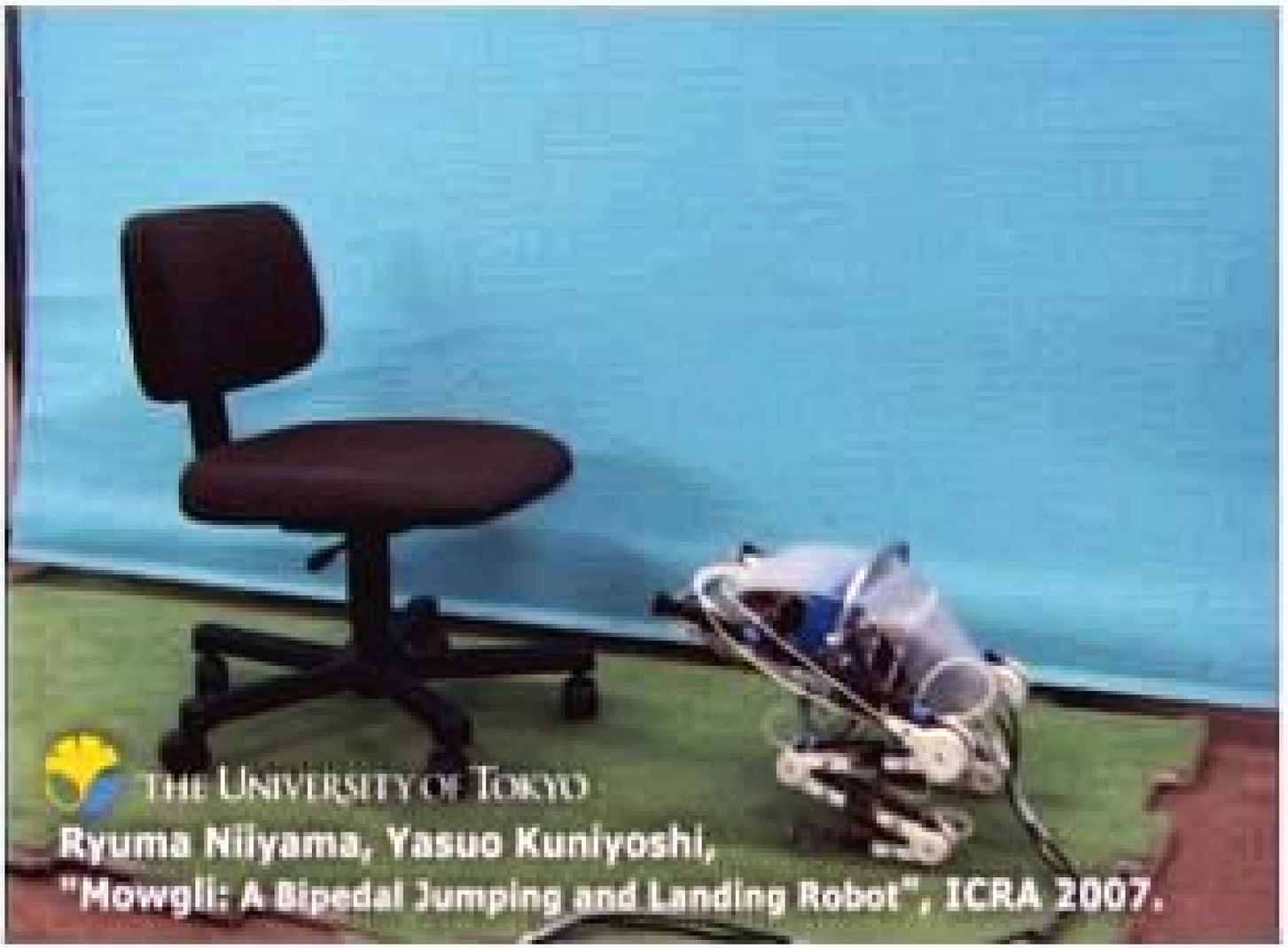
The “robot frog” driven by pneumatic actuators (UTokyo)

Ryuma Niiyama, Yasuo Kuniyoshi,
"Mowgli: A Bipedal Jumping and Landing Robot", ICRA 2007.

Design and construction:
Ryuma Niiyama and
Yasuo Kuniyoshi
University of Tokyo

pneumatic actuators:
compliant materials

The “robot frog” driven by pneumatic actuators (UTokyo)



Design and construction:
Ryuma Niiyama and Yasuo Kuniyoshi
University of Tokyo

pneumatic actuators:
compliant materials

The “robot frog” driven by pneumatic actuators (UTokyo)

Design and construction:
Ryuma Niiyama and Yasuo Kuniyoshi
University of Tokyo

pneumatic actuators:
compliant materials

The “robot frog” driven by pneumatic actuators (UTokyo)

Design and construction:
Ryuma Niiyama and Yasuo Kuniyoshi
University of Tokyo

pneumatic actuators:
compliant materials

Message 3: Task distribution

Task distribution between brain (control), body (morphology, materials), and environment

no clear separation between control and hardware (“soft robotics”)

morphological
computation
re-thinking of “control”
(“orchestration”)

Morphological Computation also: sensory side

- non-homogeneous arrangement of facets in insect eye
- log-polar arrangement of receptors in human retina

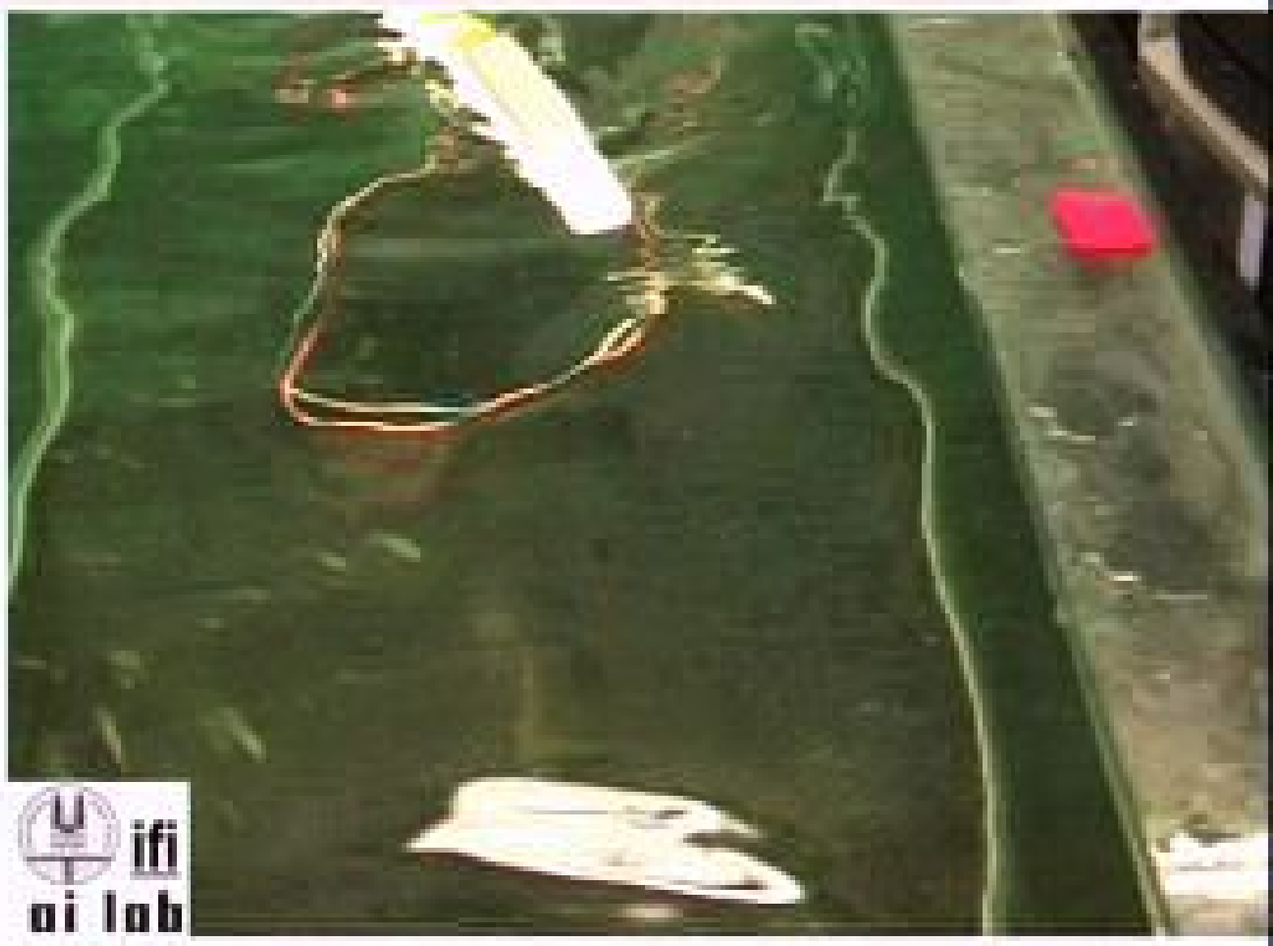
strong contrast to standard cameras

Contents

- introduction and background
- the four messages of embodiment
- **the “power of materials”**
- **summary and conclusions**
- **the “Roboy” project**

The power of materials: The robot fish “Wanda”

design and construction:
Marc Ziegler, AI Lab, UZH



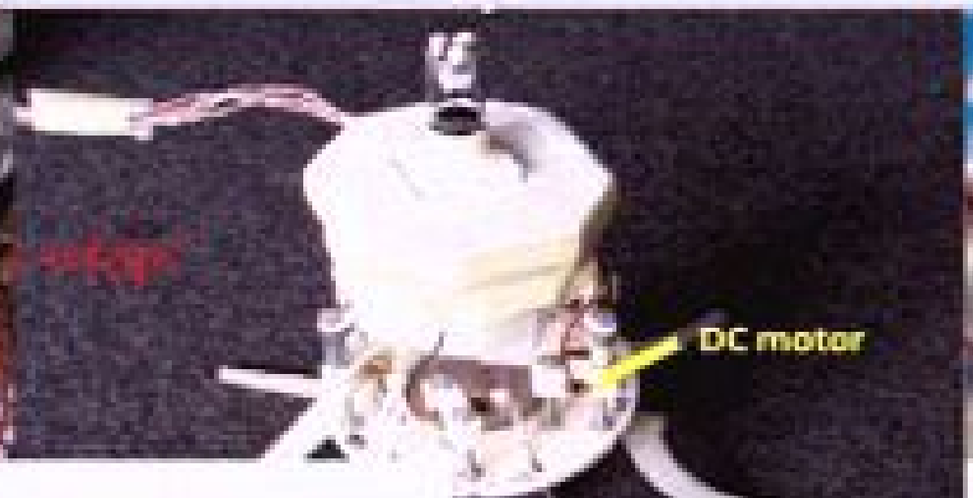
materials

changeable stiffness

maneuverability in 3D space

The Octopus Robot: a paradigmatic case study

Exploiting materials: Octopus (EU Project)



coordinator:
Cecilia Laschi (SSSA)

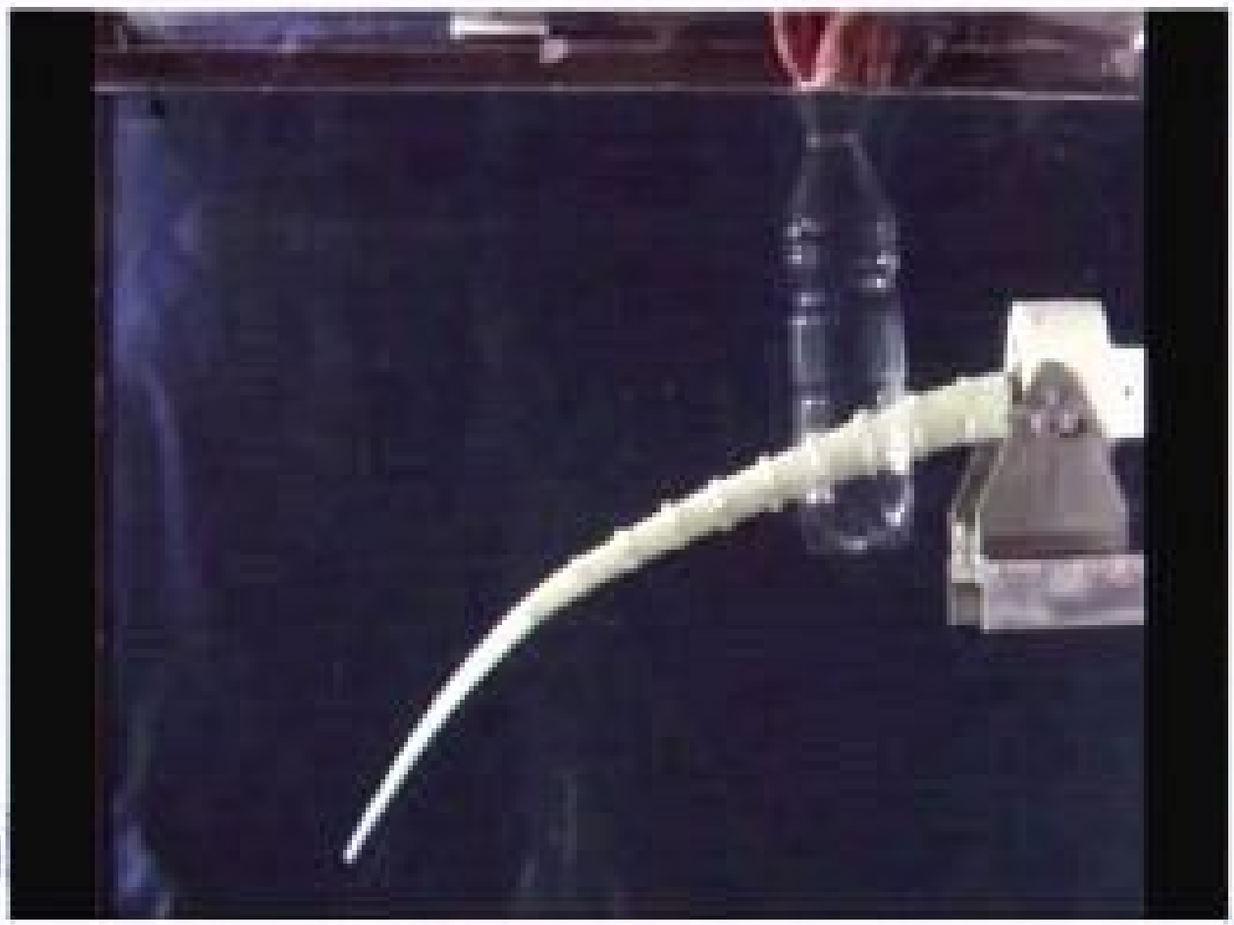
Octopus Arm
Design and construction:

Matteo Cianchetti (SSSA)
Cecilia Laschi (SSSA)
Tao Li (UZH)
Naveen Kuppuswami (UZH)
Kohei Nakajima (UZH)

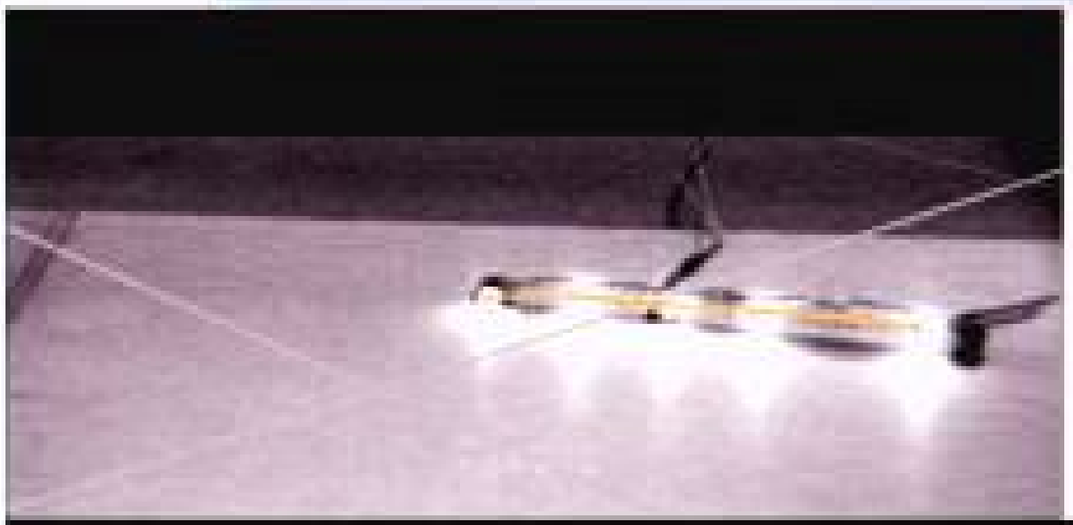
Octopus arm movements

Octopus Arm
Design and construction:

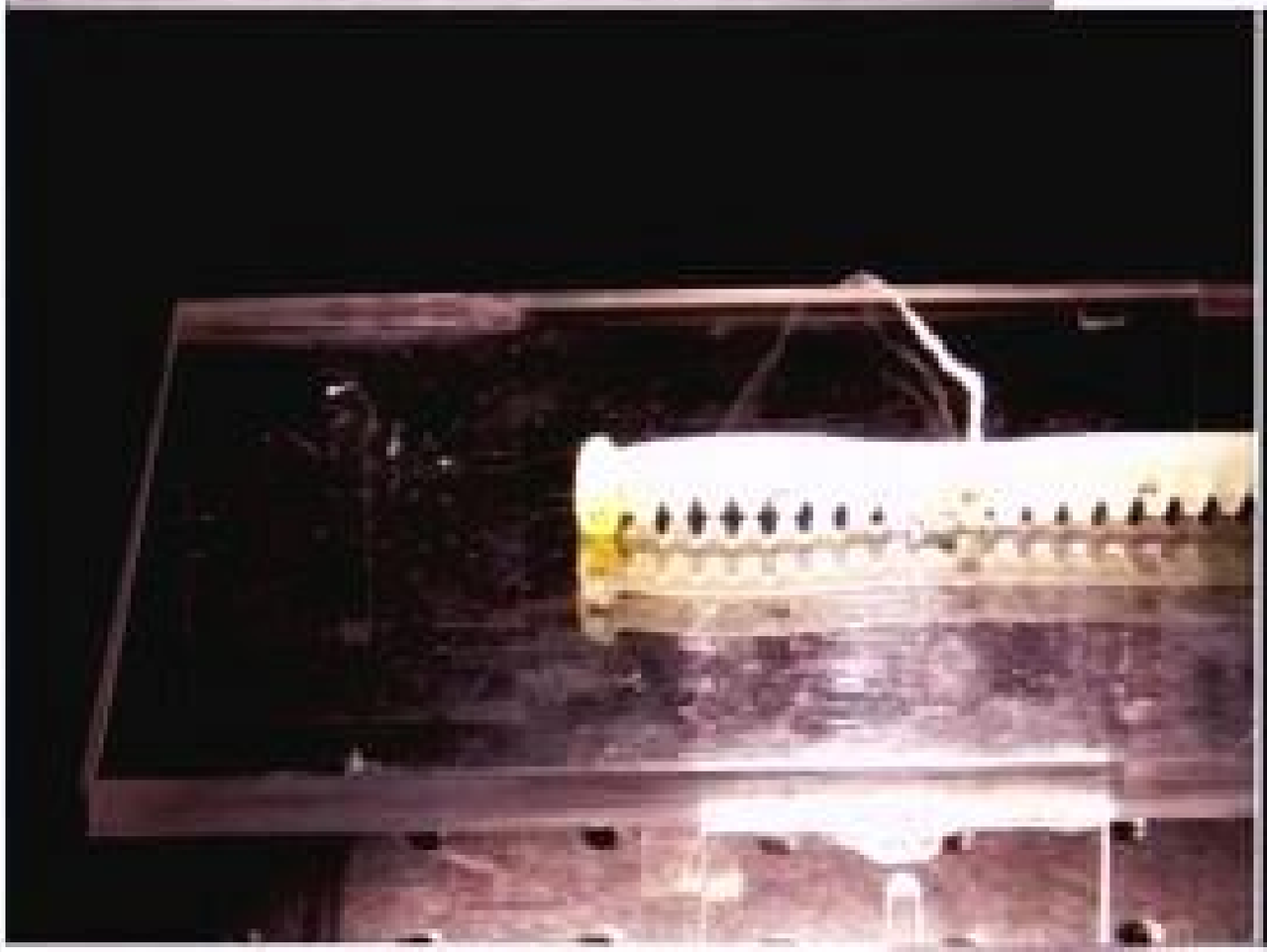
Matteo Cianchetti (SSSA)
Cecilia Laschi (SSSA)
Tao Li (UZH)
Naveen Kuppuswami (UZH)
Kohei Nakajima (UZH)

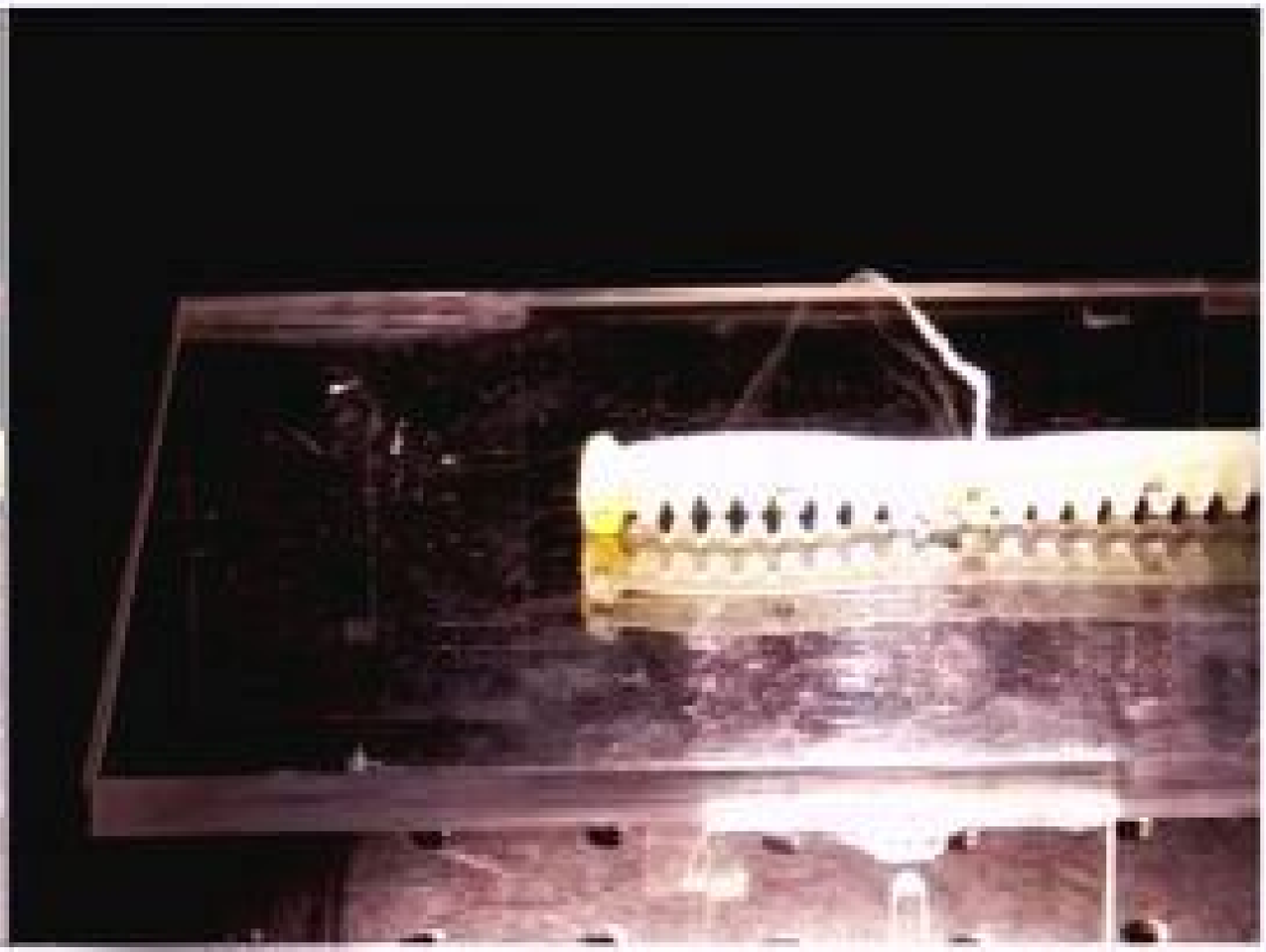


Inching and rolling: GoQBot (Barry Trimmer's caterpillar robots)

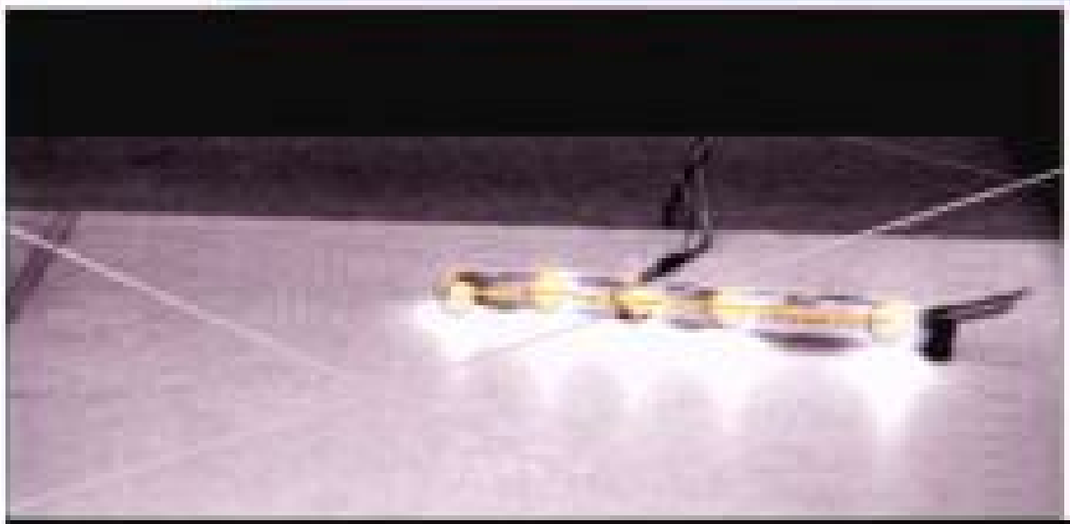


design and construction:
Barry Trimmer, Tuft's University, Boston

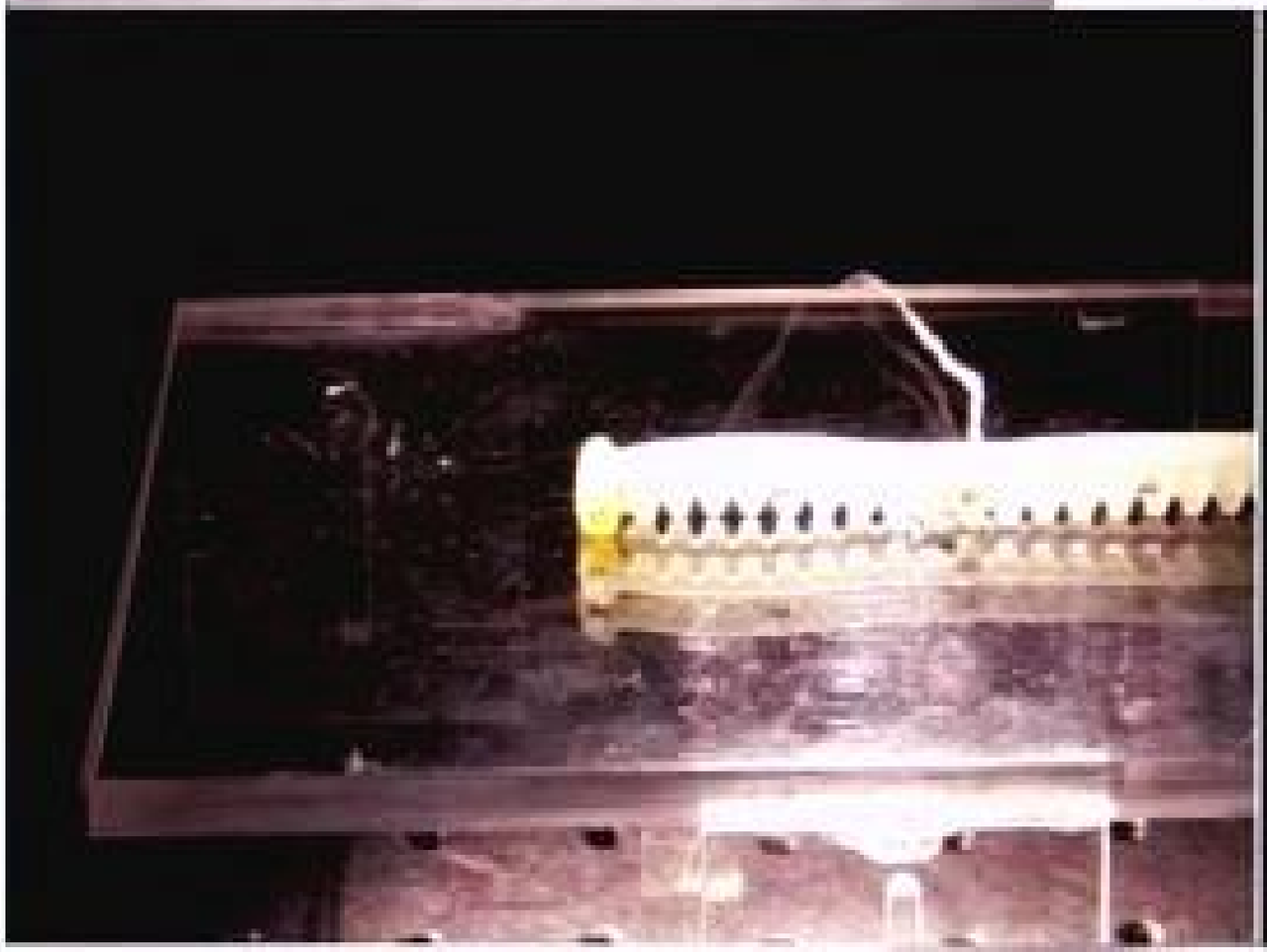


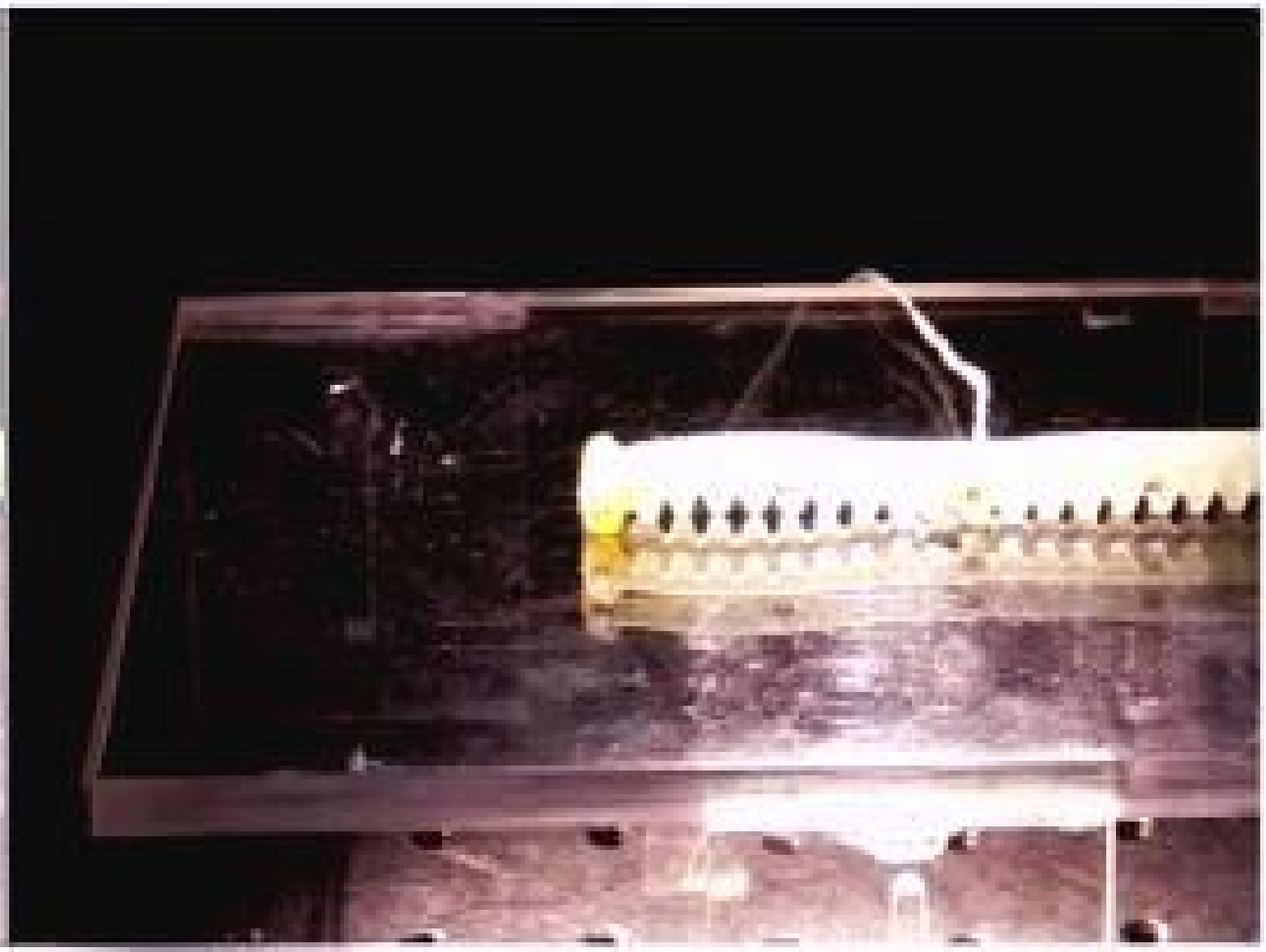


Inching and rolling: GoQBot (Barry Trimmer's caterpillar robots)

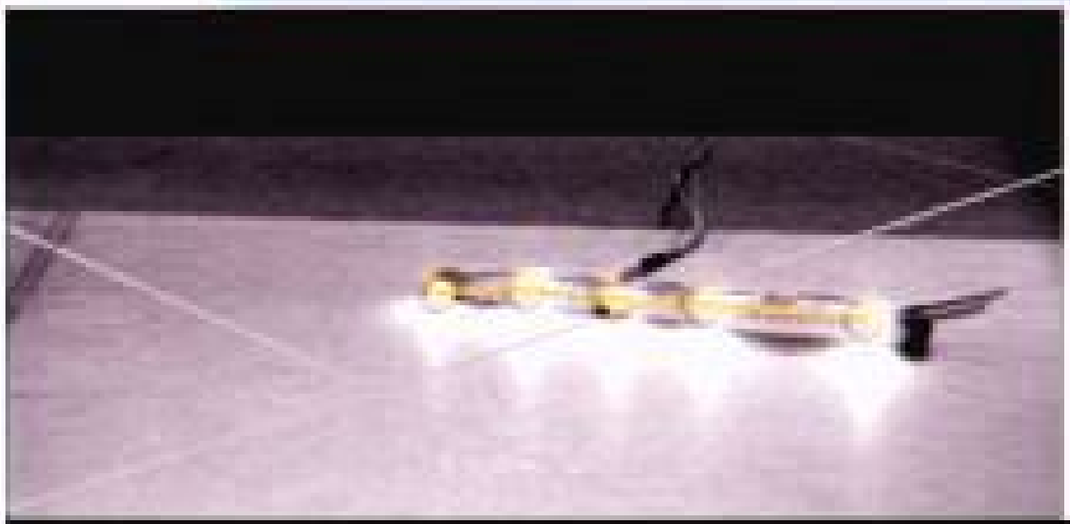


design and construction:
Barry Trimmer, Tuft's University, Boston

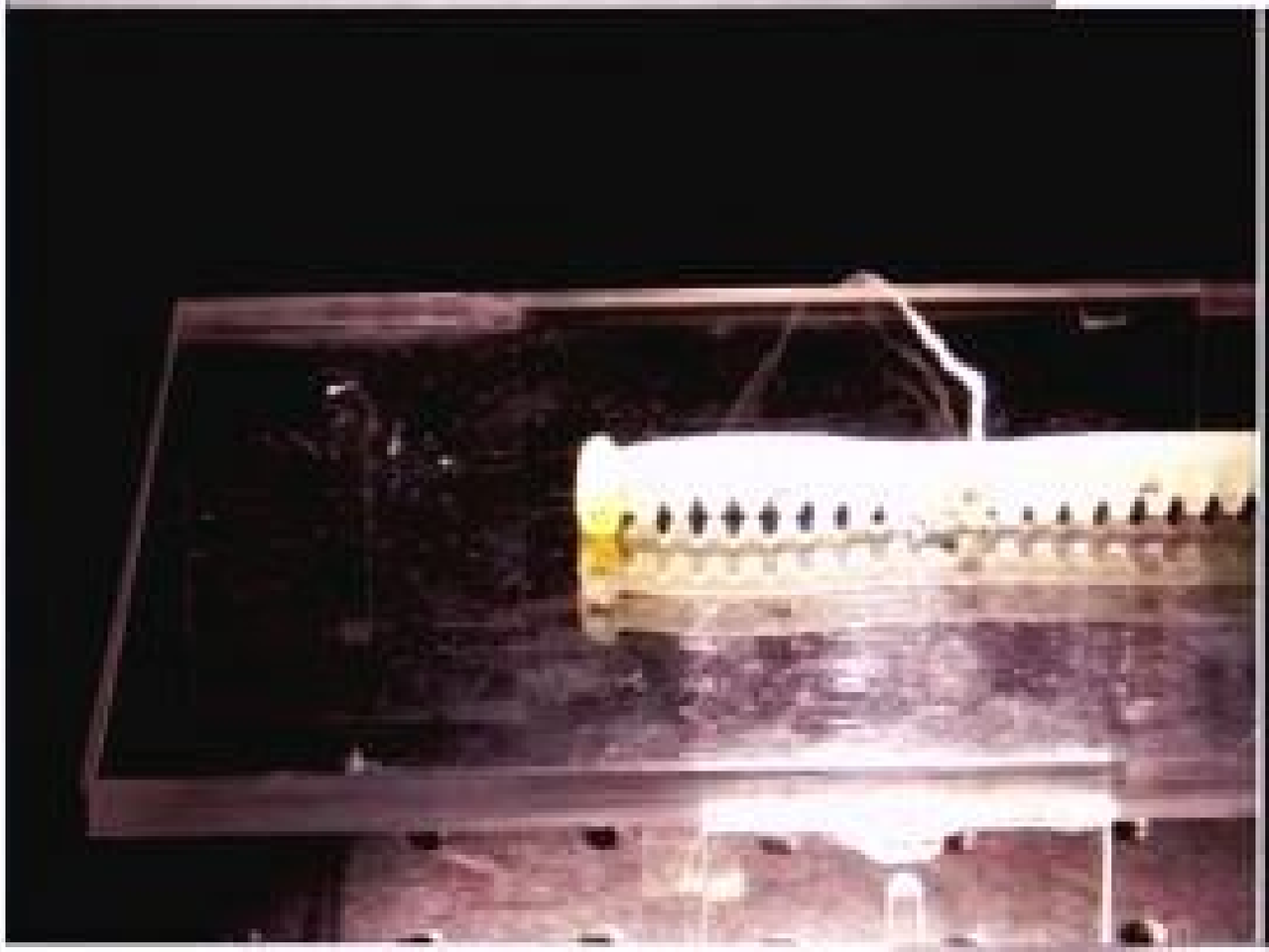


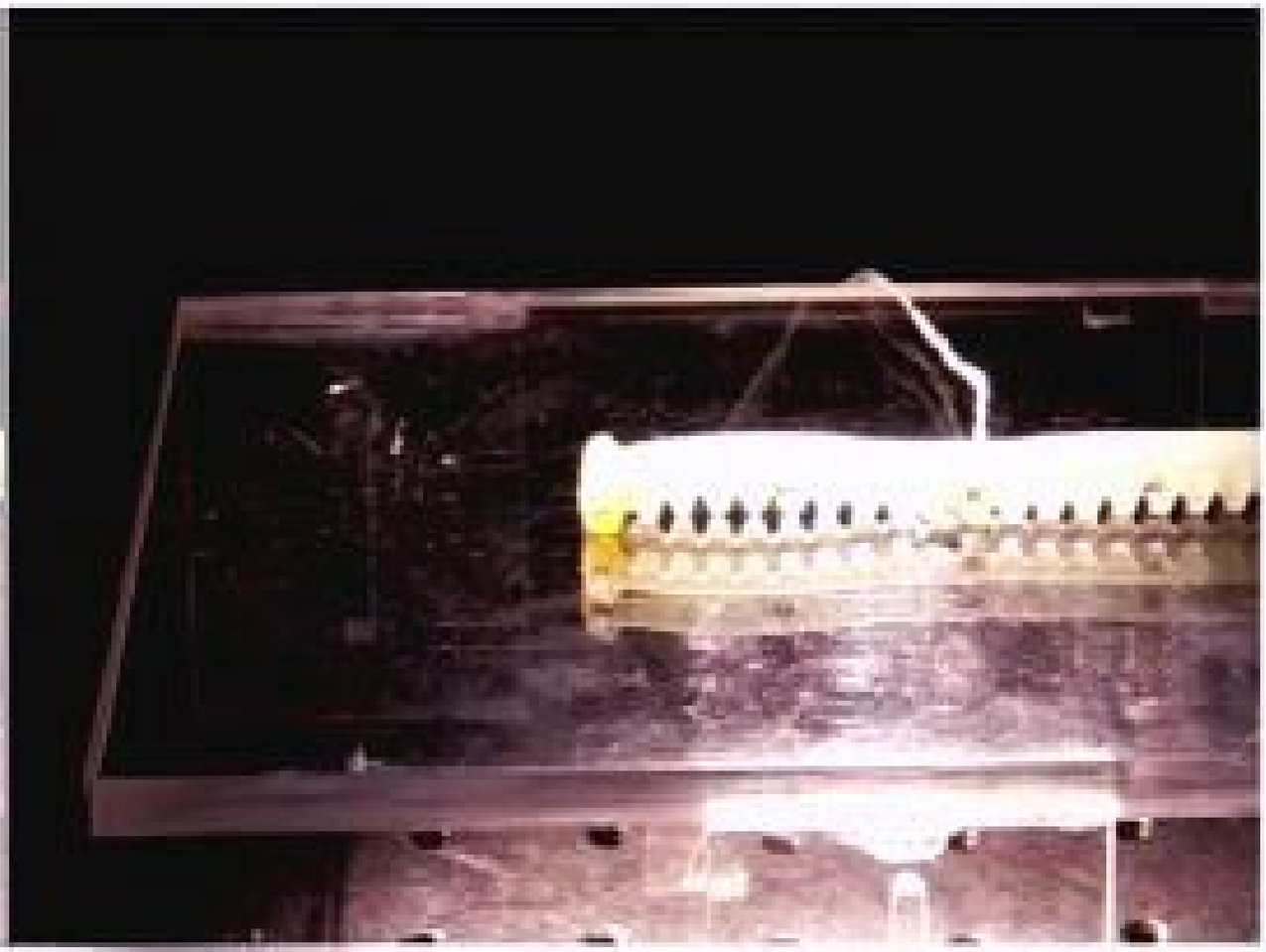


Inching and rolling: GoQBot (Barry Trimmer's caterpillar robots)

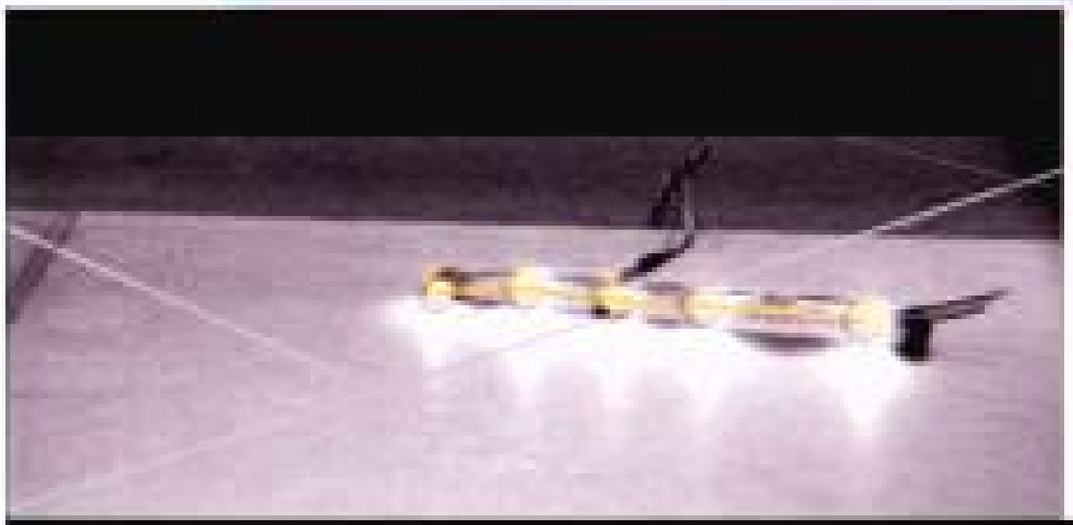


design and construction:
Barry Trimmer, Tuft's University, Boston

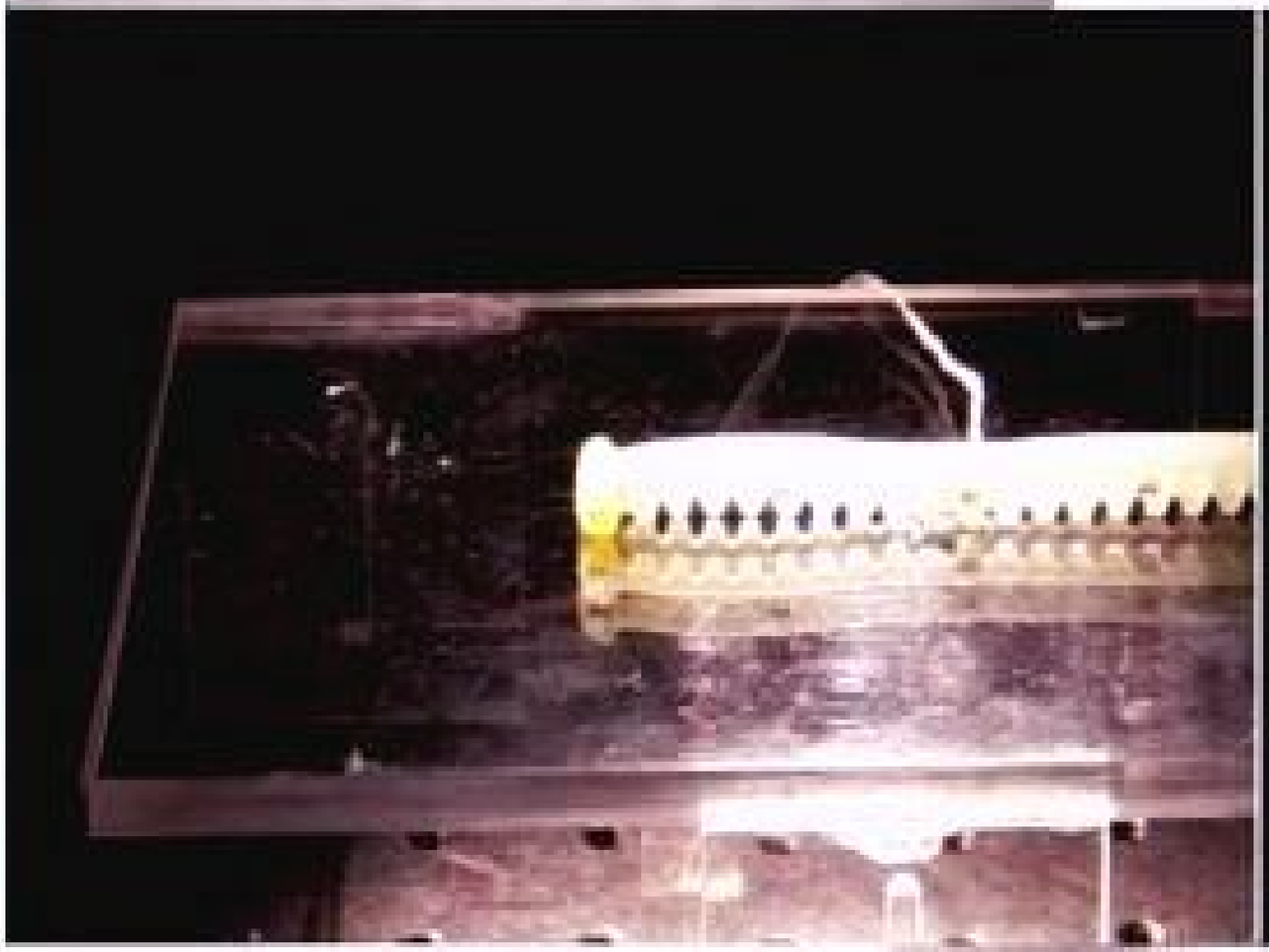


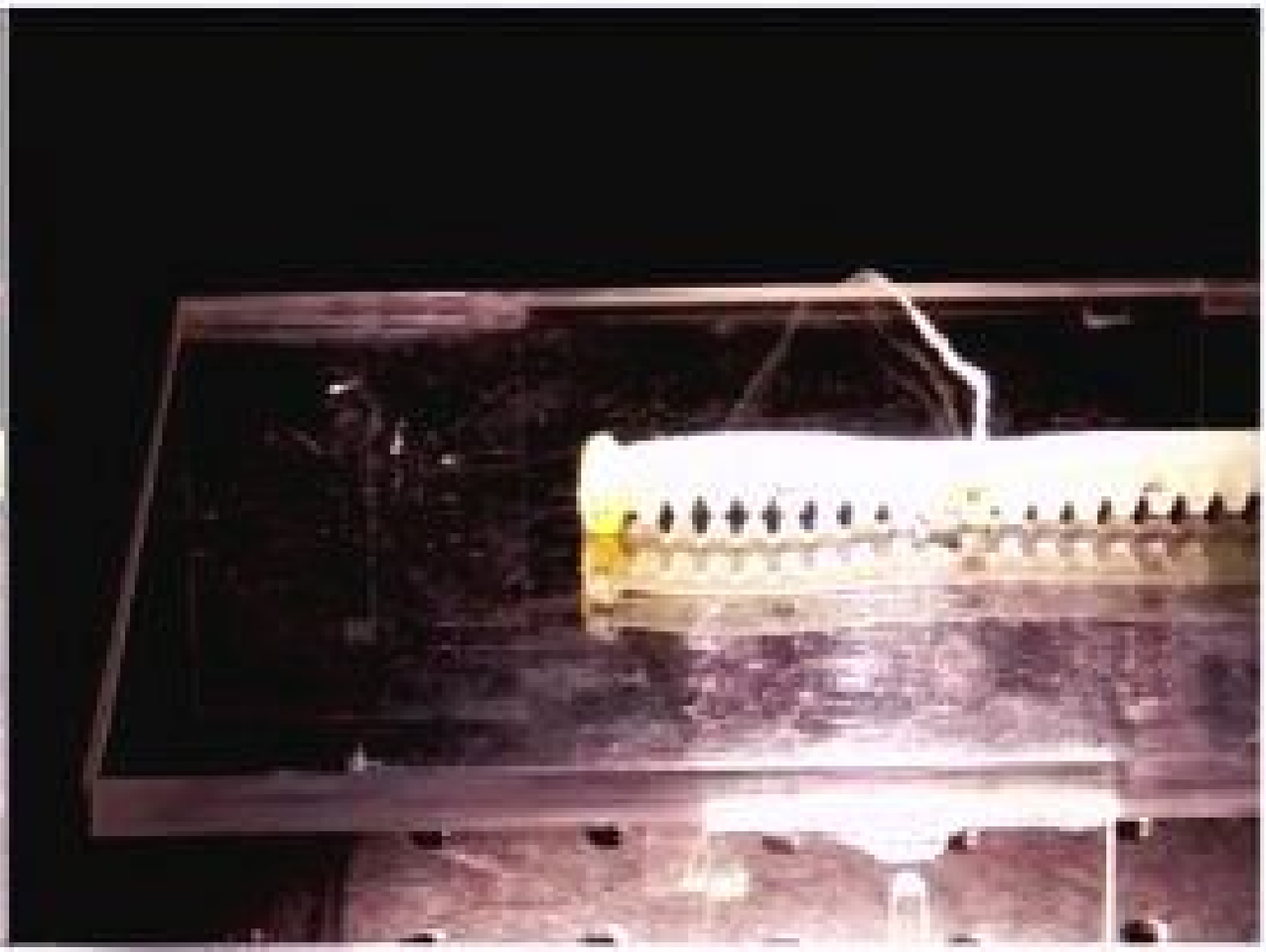


Inching and rolling: GoQBot (Barry Trimmer's caterpillar robots)

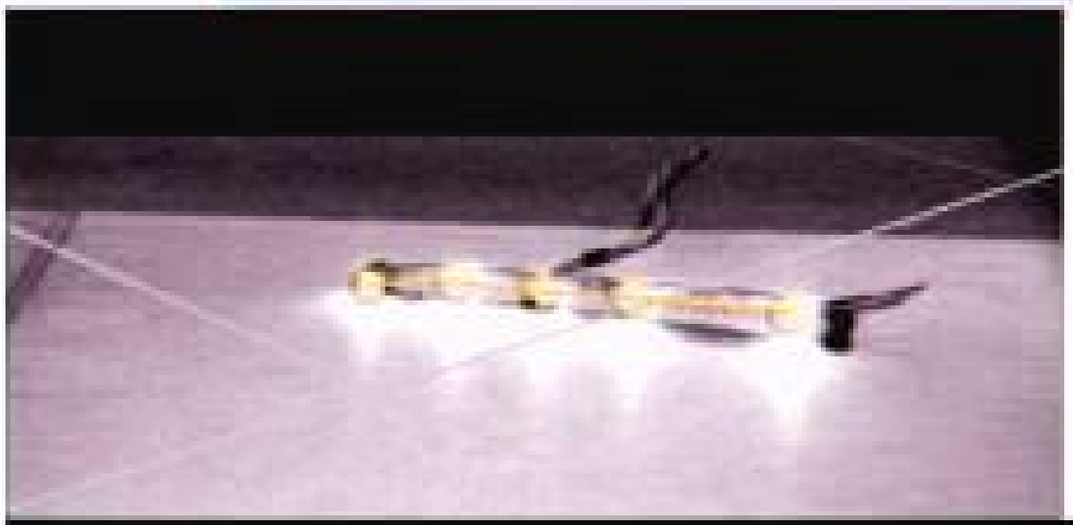


design and construction:
Barry Trimmer, Tuft's University, Boston

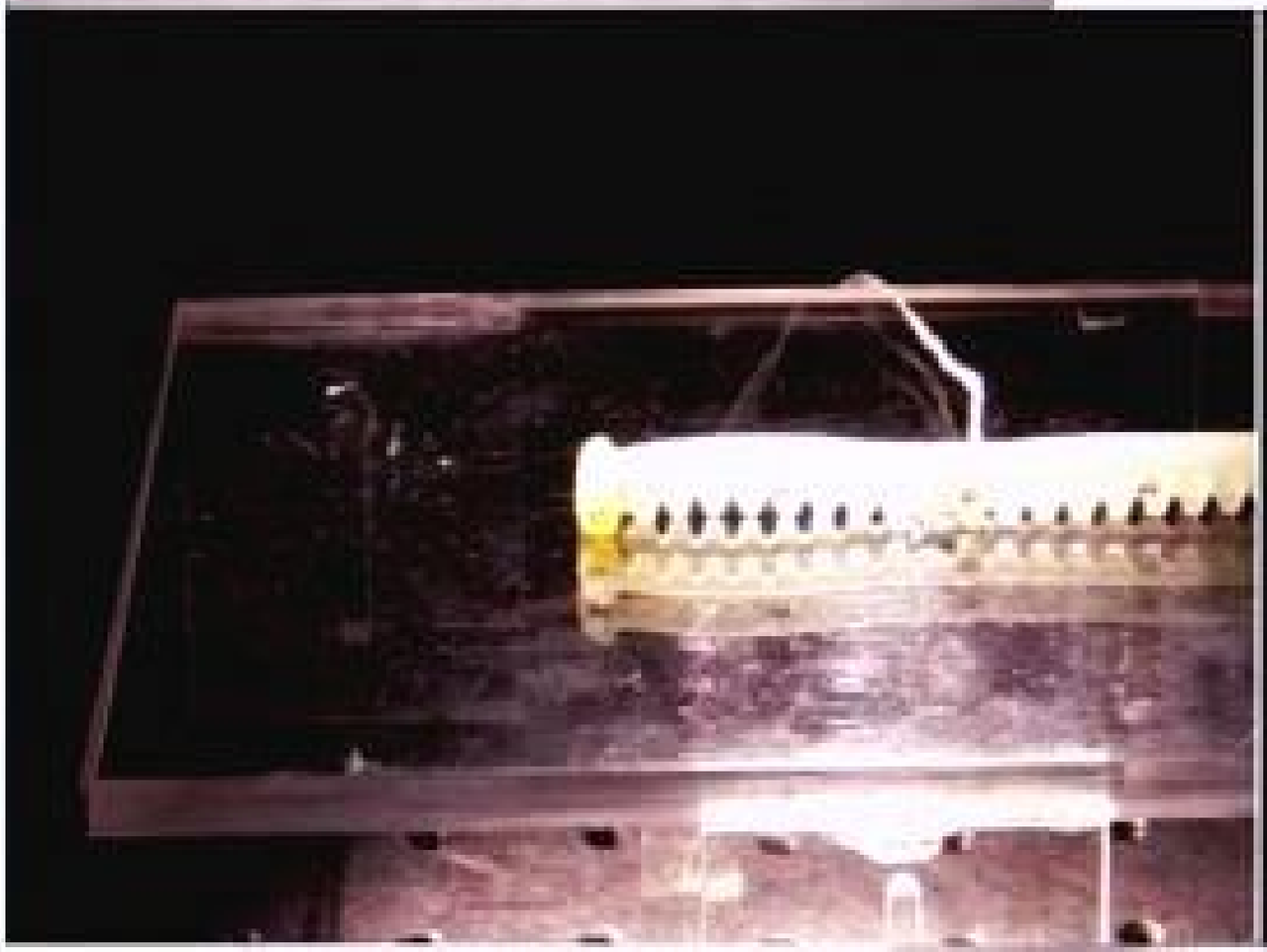


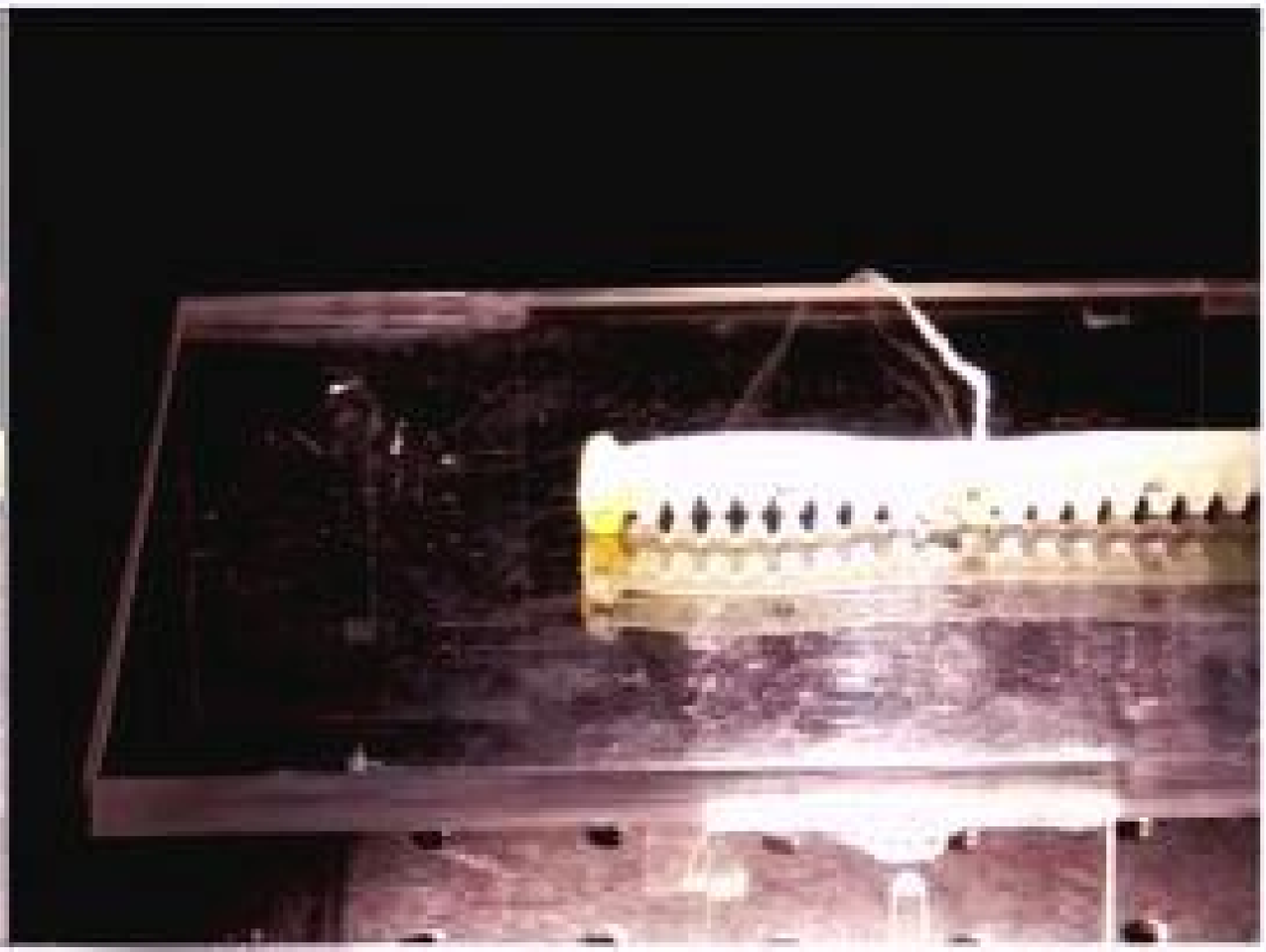


Inching and rolling: GoQBot (Barry Trimmer's caterpillar robots)

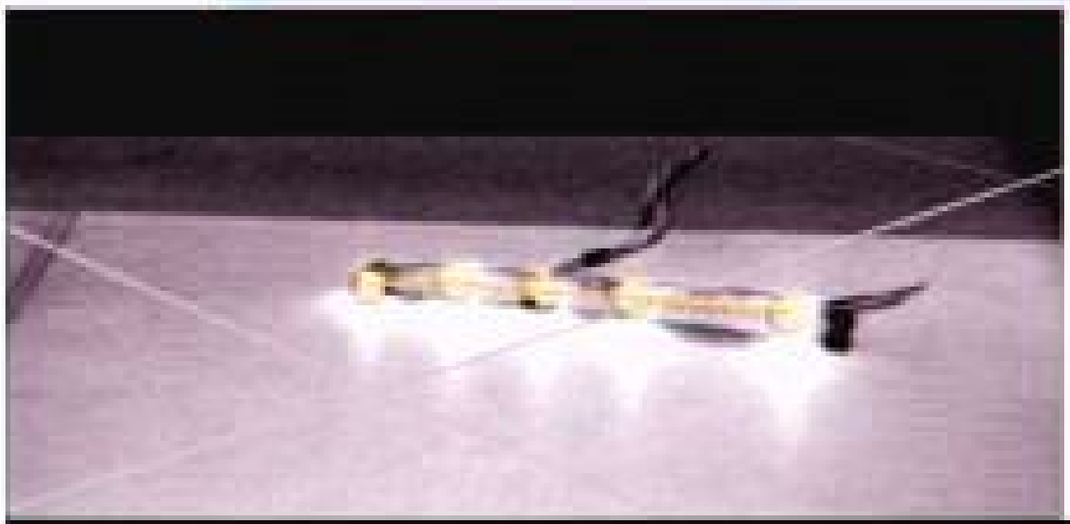


design and construction:
Barry Trimmer, Tuft's University, Boston

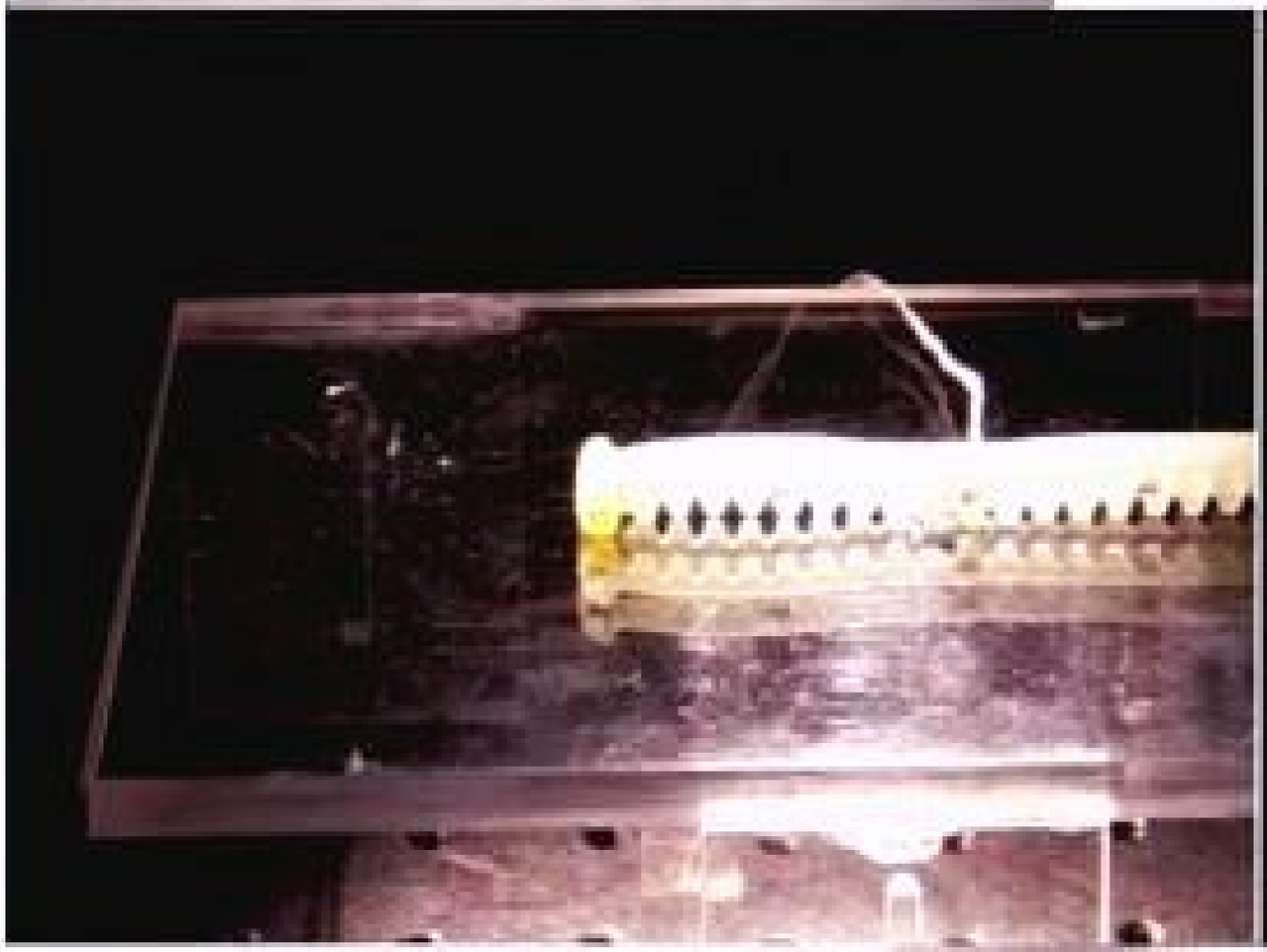




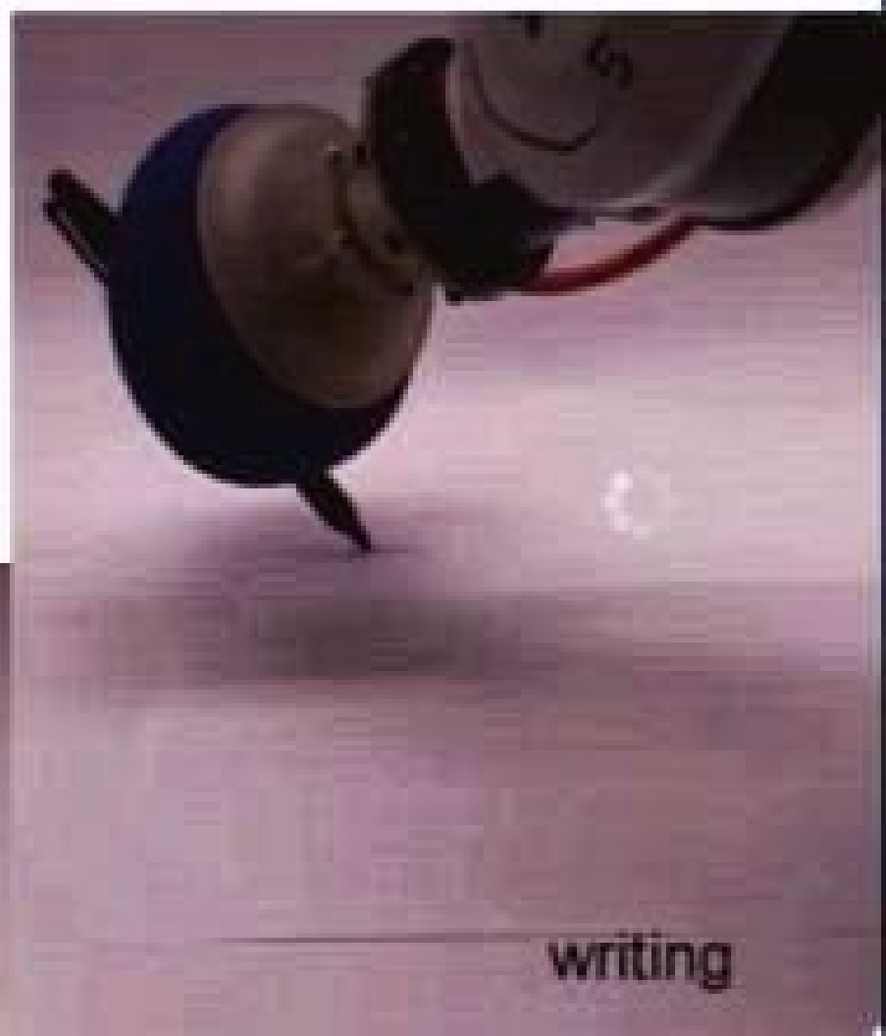
Inching and rolling: GoQBot (Barry Trimmer's caterpillar robots)



design and construction:
Barry Trimmer, Tuft's University, Boston



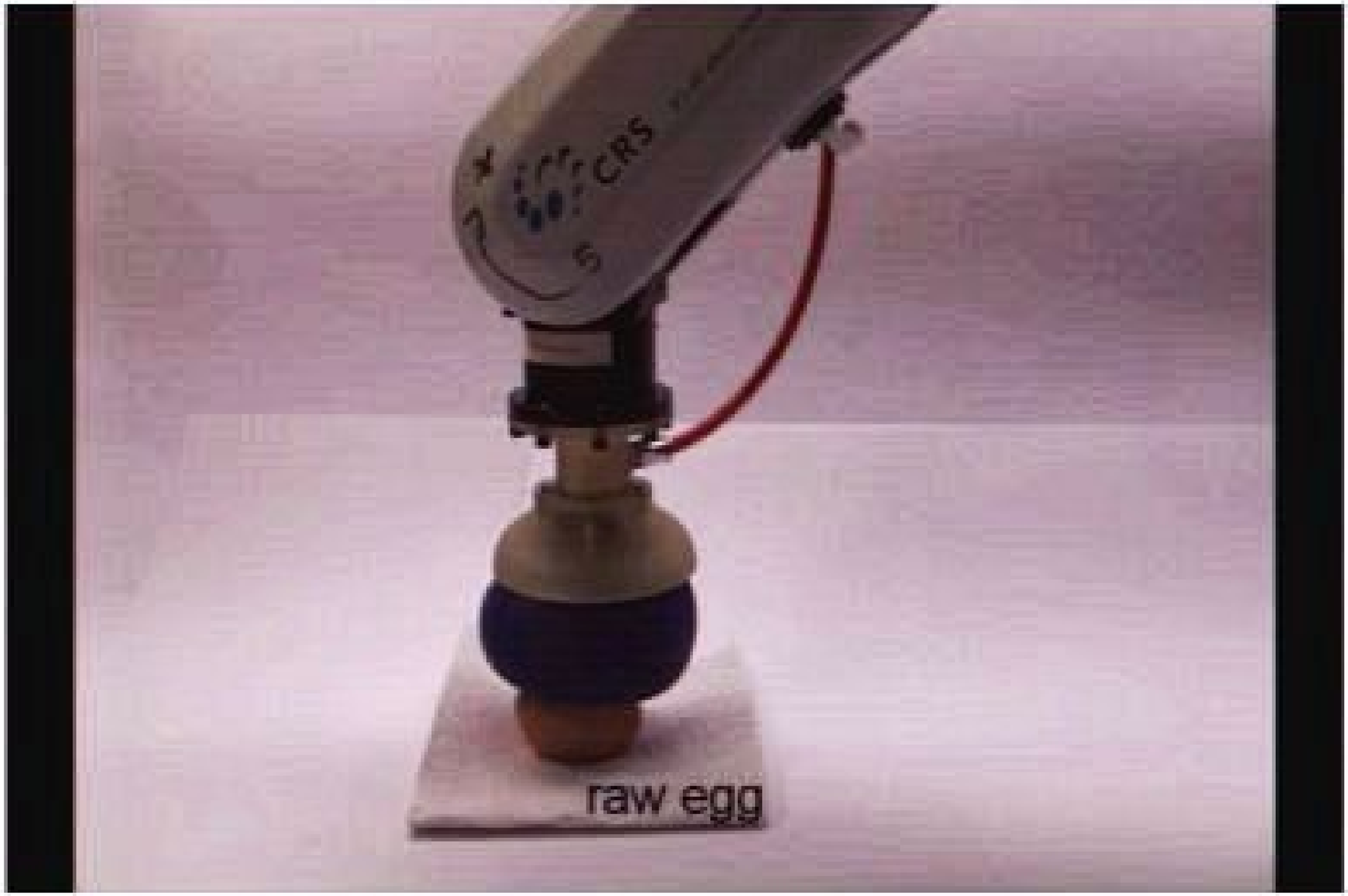
Jaeger/Lipson “coffee balloon gripper”



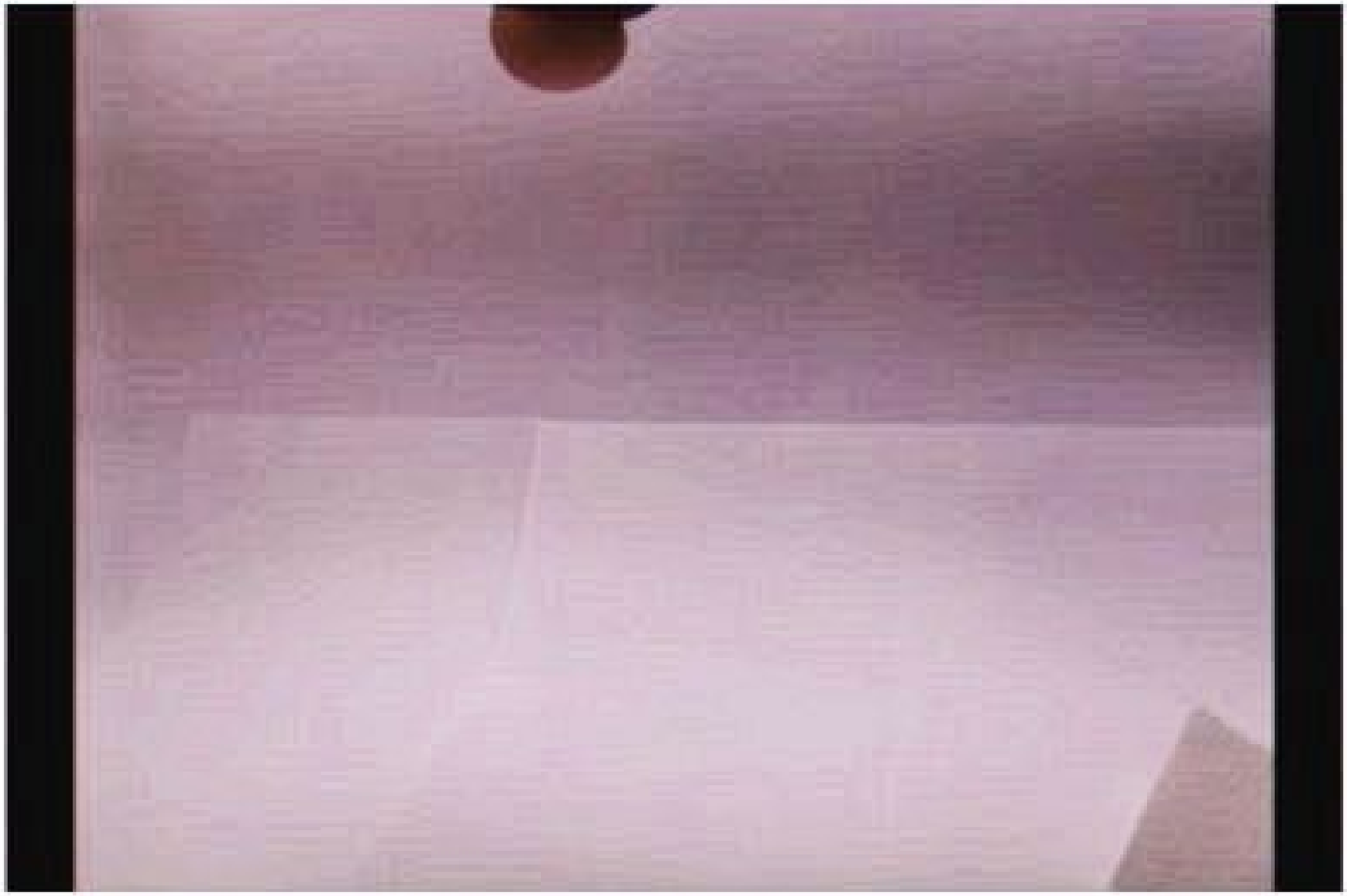
Jaeger/Lipson “coffee balloon gripper”

Jaeger/Lipson “coffee balloon gripper”

Jaeger/Lipson “coffee balloon gripper”



Jaeger/Lipson “coffee balloon gripper”



Orchestration of grasping

morphological computation
exploiting morphology and materials for control

Orchestration of grasping

morphological computation
exploiting morphology and materials for control

Expansion of design space: trading spaces and trade-offs

- morphologies (physical structure, distribution of sensors, actuators)

- many materials; changeable characteristics (e.g. stiffness, length, shape, sensor distribution)

- must understand “trading space”: morphology - computation/control

- trade-offs: morphology/materials - flexibility (but changeable properties)

Morphology and computation: "trading spaces"

increasing dominance of morphology and materials
decreasing dominance of control

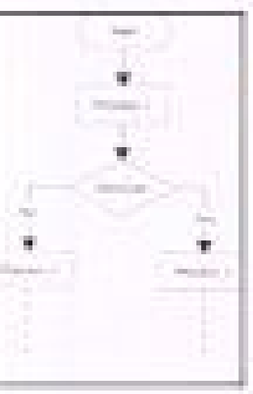
control and behavior less separable
increasing dependence on environment
increased reliance on self-organization

informational computation

morphological computation

control dominant

morphology and materials dominant
"guided self-organization"



pure algorithm

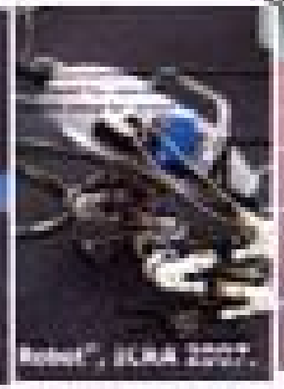
computer (running algorithm)

industrial robot (centralized control

Asimo (and similar robots)

ECCE (compliant, tendon-driven)

Octopus (soft, continuous)



"Robot Frog" (variable compliance)

Cornell Ranger (exploiting morphology)

Jaeger-Lipson coffee-balloon

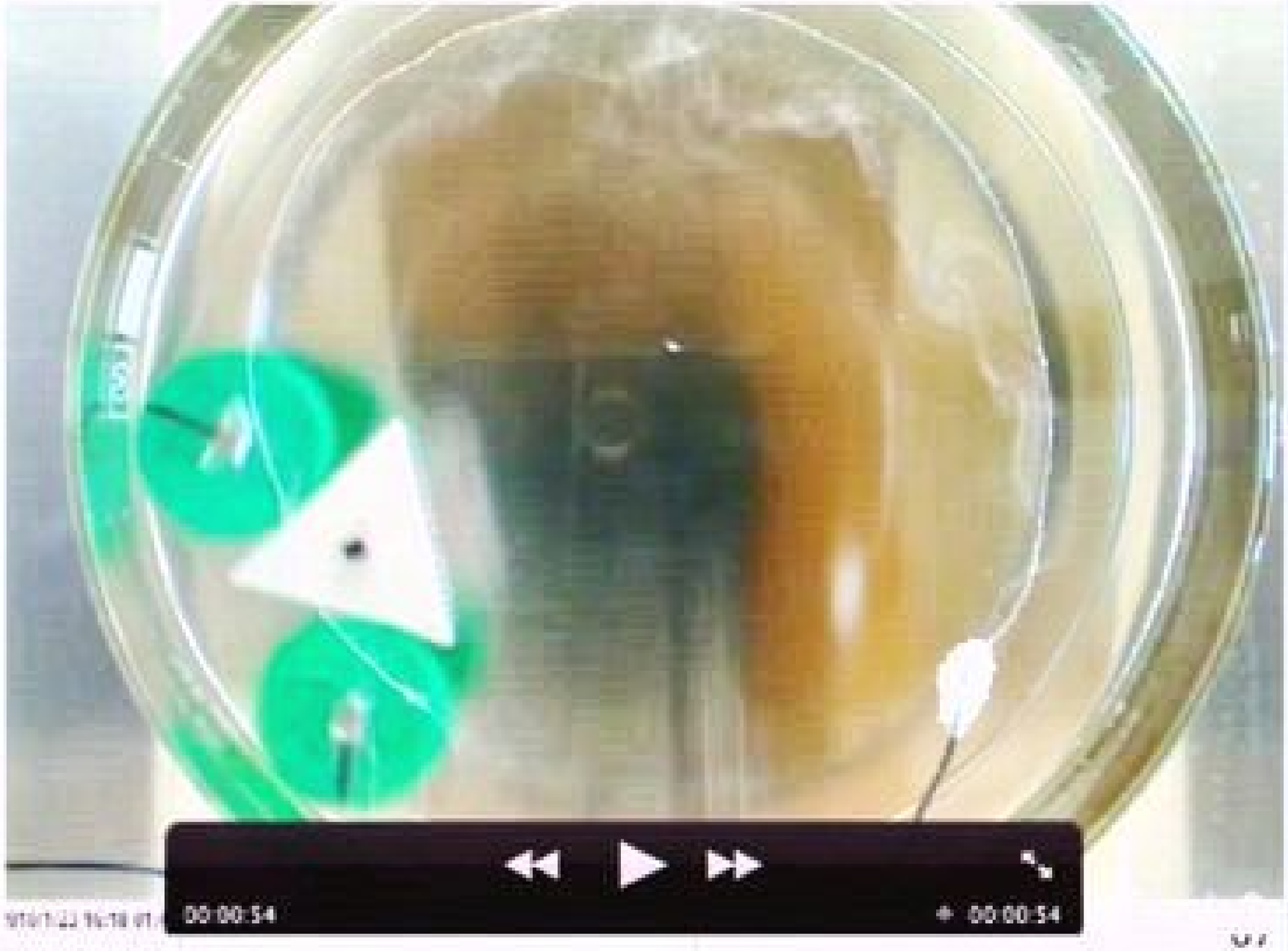
cells molecules "Tribology"

control dominant

morphology and materials dominant

Morphological Computation: self-assembly and emergent functionality

"The self-assembled, emergent bicycle"



Design and construction:
Shuhei Miyashita

University of Zurich[UZH]

Morphology and computation: "trading spaces"

increasing dominance of morphology and materials
decreasing dominance of control

control and behavior less separable
increasing dependence on environment
increased reliance on self-organization

informational computation

morphological computation

control dominant

morphology and materials dominant
"guided self-organization"

pure algorithm

computer (running algorithm)

industrial robot (centralized control

Asimo (and similar robots)

ECCE (compliant, tendon-driven)

Octopus (soft, continuous)

"Robot Frog" (variable compliance)

Cornell Ranger (exploiting morphology)

Jaeger-Lipson coffee-balloon

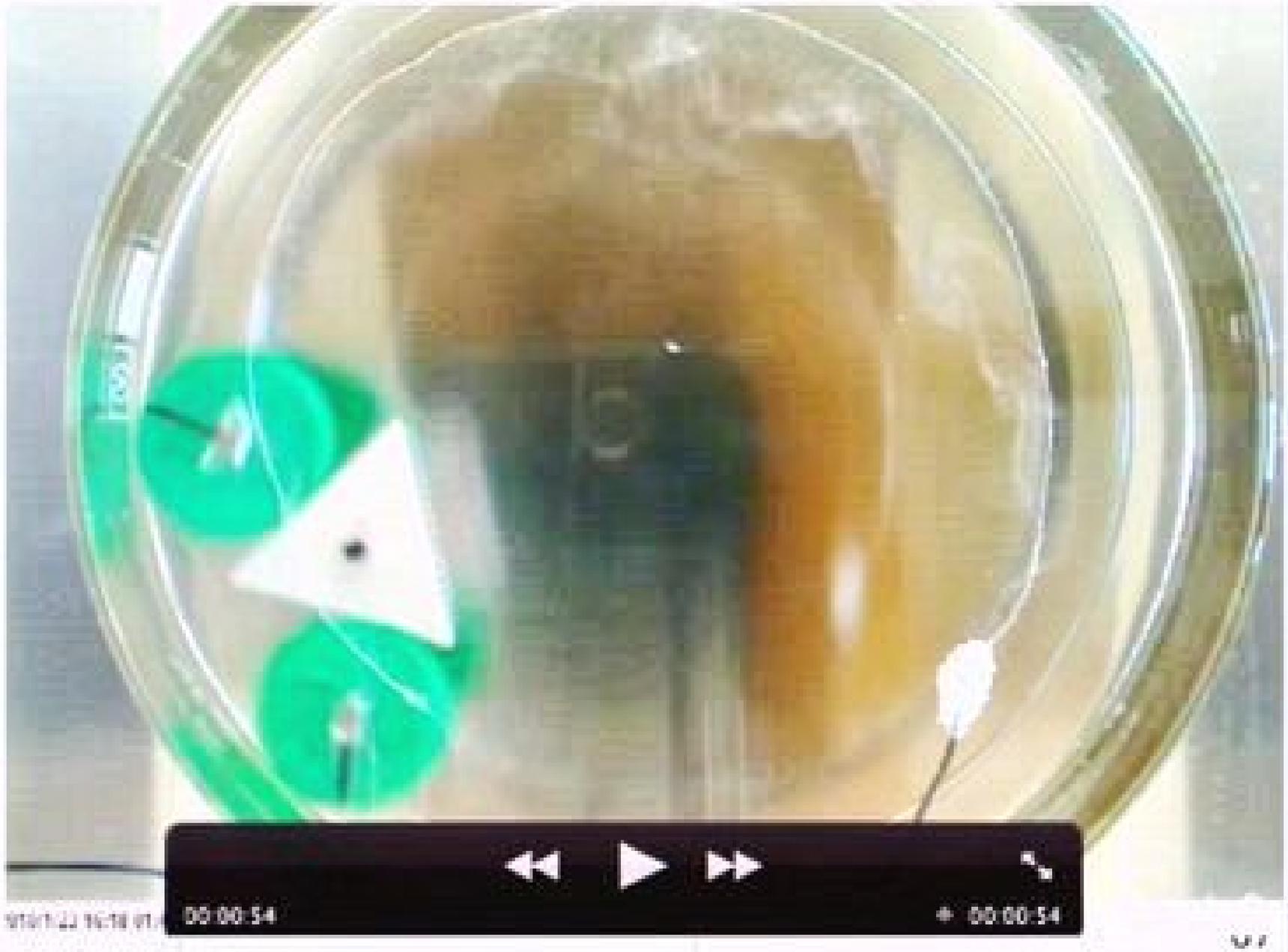
cells molecules "Tribology"

control dominant

morphology and materials dominant

Morphological Computation: self-assembly and emergent functionality

"The self-assembled, emergent bicycle"



Design and construction:
Shuhei Miyashita

University of Zurich[UZH]

Morphological Computation: self-assembly and emergent functionality

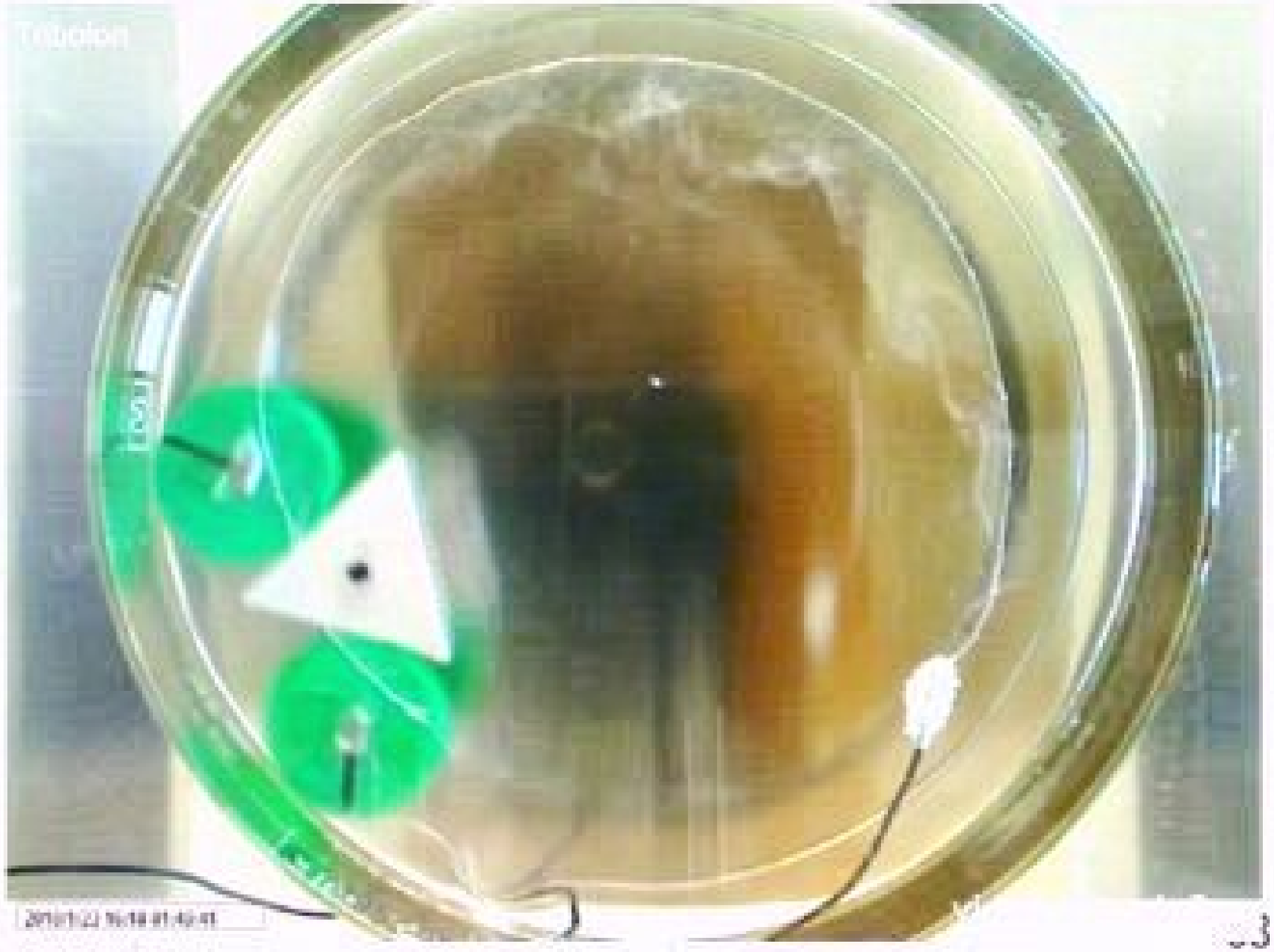
"The self-assembled, emergent bicylce"

Design and construction:
Shuhei Miyashita (previously AI Lab, now MIT)

University of Zurich[UZH]

Morphological Computation: self-assembly and emergent functionality

"The self-assembled, emergent bicylce"



Design and construction:
Shuhei Miyashita (previously AI Lab, now MIT)

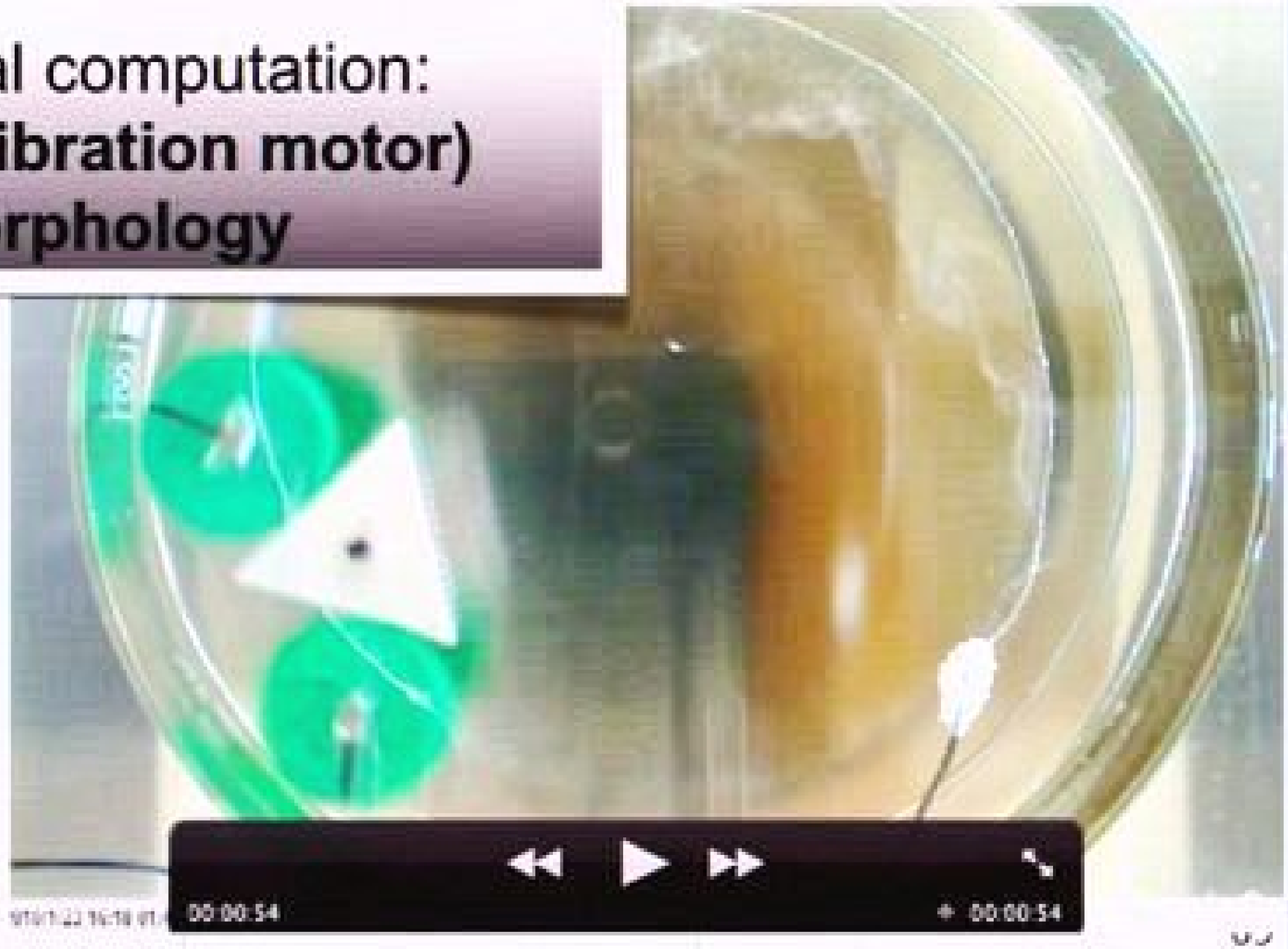
University of Zurich[UZH]

Morphological Computation: self-assembly and emergent functionality

"The self-assembled, emergent bicylce"

morphological computation:
no control (vibration motor)
only morphology

Design and construction:
Shuhei Miyashita



University of Zurich[UZH]

Morphology and computation: "trading spaces"

increasing dominance of morphology and materials
decreasing dominance of control

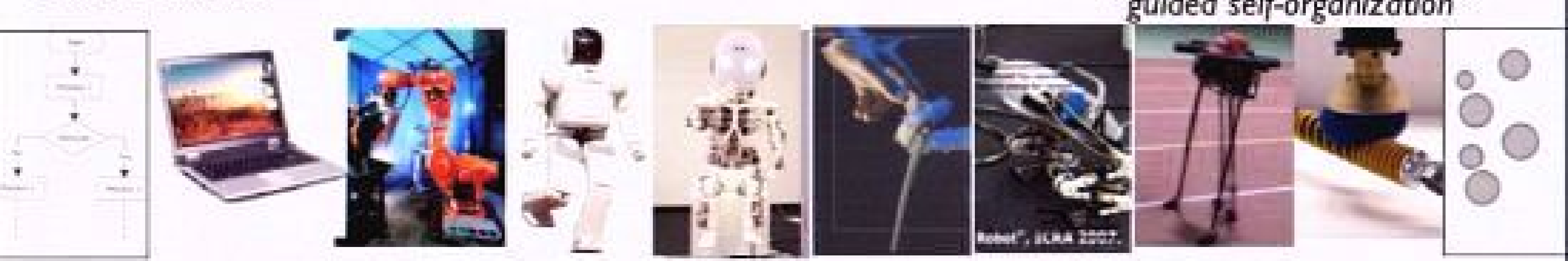
control and behavior less separable
increasing dependence on environment
increased reliance on self-organization

informational computation

morphological computation

control dominant

morphology and materials dominant
"guided self-organization"



pure algorithm

computer (running algorithm)

industrial robot (centralized control

Asimo (and similar robots)

ECCE (compliant, tendon-driven)

Octopus (soft, continuous)

"Robot Frog" (variable compliance)

Cornell Ranger (exploiting morphology)

Jaeger-Lipson coffee-balloon

cells molecules "Tribology"

control dominant

morphology and materials dominant

back to the “four messages”

Message 4: Physical dynamics and information structure

Induction of patterns of sensory stimulation through physical interaction with environment

—> raw material for information processing of brain (control)

—> induction of correlations (information structure)

Essence

- **self-structuring of sensory data through — physical — interaction with world**
- **physical process, not computational**

pre-requisite for learning

—> predictions / expectations

Inspiration:
John Dewey, 1896 (!)
Merleau-Ponty, 1963
Bajcsy, 1963; Aloimonos, 1990; Ballard, 1991
Sporns, Edelman, and co-workers
Thelen and Smith (developmental studies)

Contents

- introduction and background
- the four messages of embodiment
- the "power of materials"
- **summary and conclusions**
- **the "Roboy" project**

The four messages of embodiment

Message 1: Physical embedding
Understanding brain not enough; morphology materials; embedding

Message 2: Real/Artificial worlds
Fundamental differences industrial and real-world environments

Message 3: Task distribution
Cooperation - brain, body, environment

Message 4: Physical dynamics and information structure
Induction of information structure; dependence on morphology and control

“Soft robotics”

- central role of materials!
- no clear separation between controller and to-be-controlled
- new notion of control (morphological computation; “orchestration”)
- understanding the “design space”

Contents

- introduction and background
- the four messages of embodiment
- the "power of materials"
- summary and conclusions

- **the "Roboy" project**

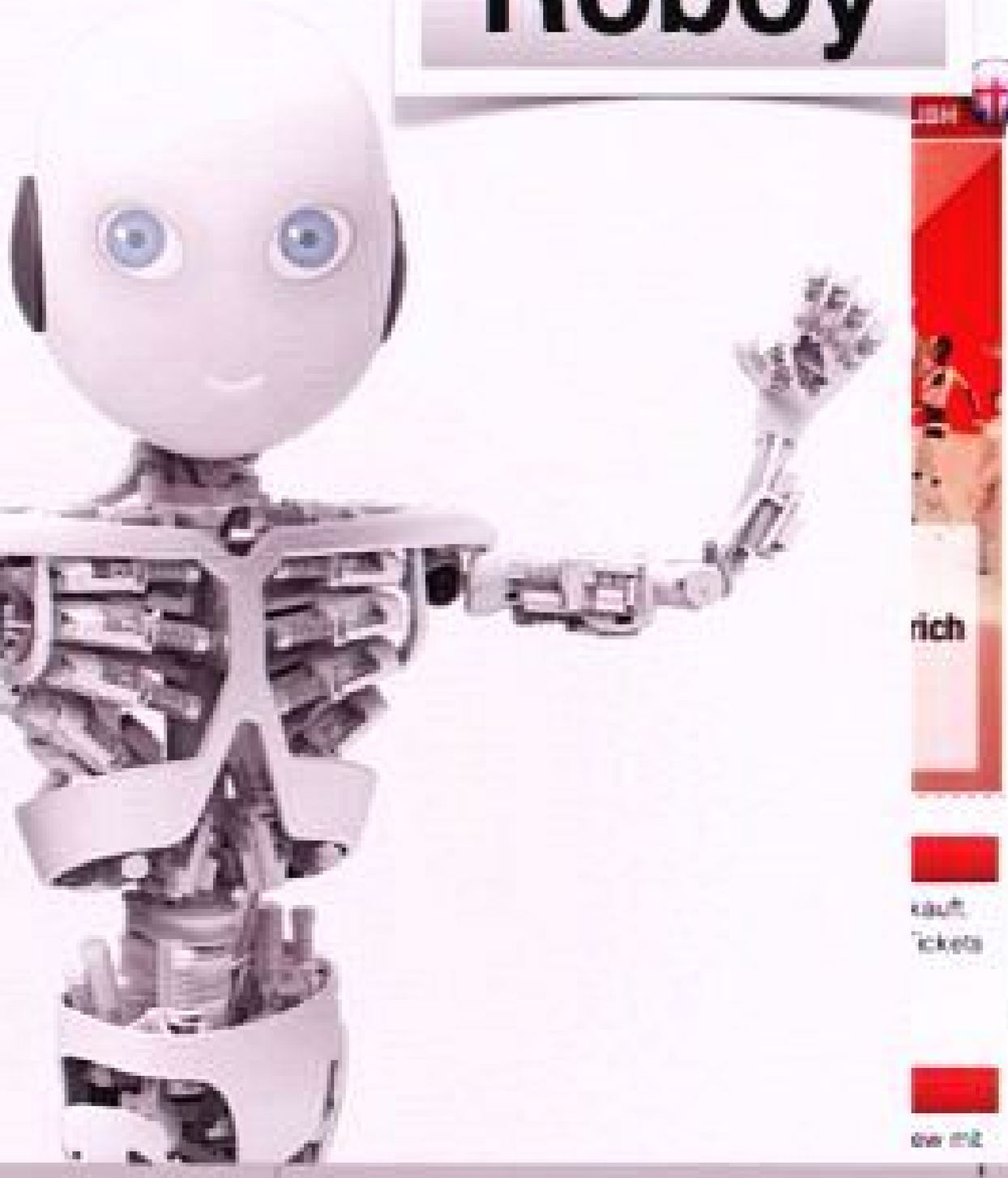
Compliance, “softness”: the next steps

the “Roboy” project

The Zurich AI Lab 25th Anniversary 1987 - 2013

a special “birthday present”?

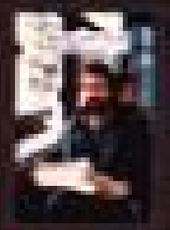
Idea:
June 2012 finish by March 2013



Idea: Pascal Kaufmann

ai lab

Artificial Intelligence Laboratory Zurich



FOUNDATION OF AI LAB, ZURICH

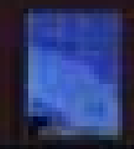
CONNECTIONISM IN PERSPECTIVE, ZURICH

SABBATICAL AT VUB, BRUSSELS

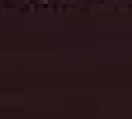
ABBIE DE CORNEDOW WORKSHOP ON "THE ARTIFICIAL LIFE ROUTE TO ARTIFICIAL INTELLIGENCE"

PRACTICE AND FUTURE OF AUTONOMOUS AGENTS

THE "2001" AT THE MIT



1957 1990 1995



The Zurich AI Lab 25th Anniversary 1987 - 2013

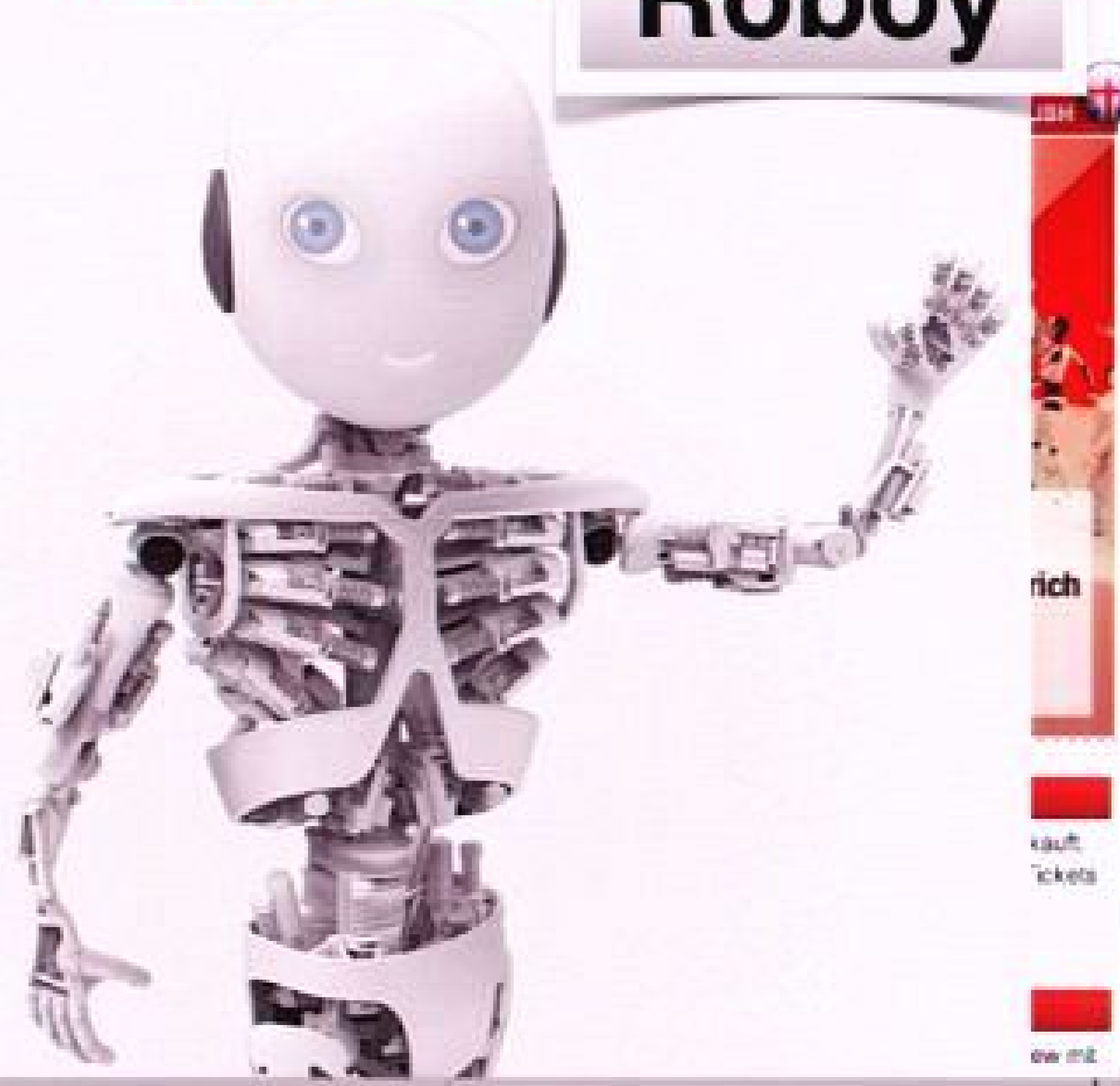
a special “birthday present”?

Idea:
June 2012 finish by March 2013

Idea: Pascal Kaufmann

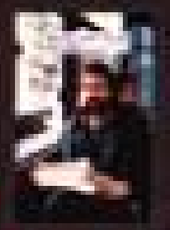
ROBOTS ON TOU

Roboy



ai lab

Artificial Intelligence Laboratory Zurich



FOUNDATION OF AI LAB, ZURICH

CONNECTIONISM IN PERSPECTIVE, ZURICH

SABBATICAL AT VUB, BRUSSELS

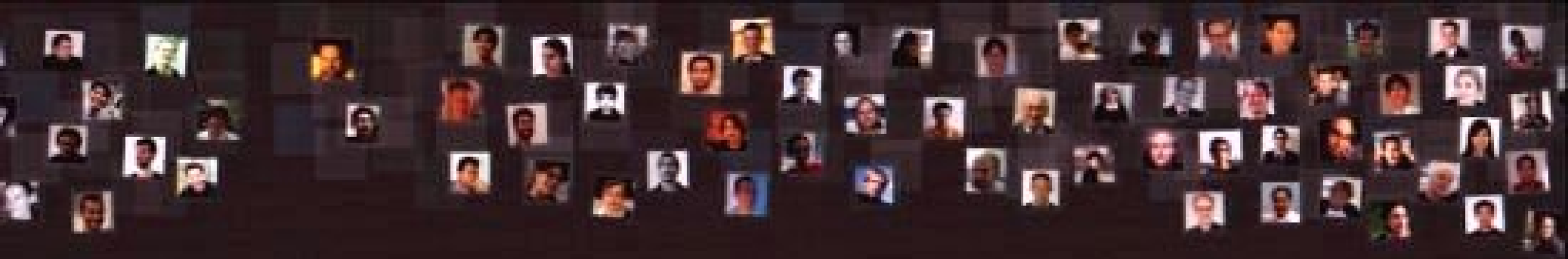
ABBEE DE CORNEDOIM WORKSHOP ON "THE ARTIFICIAL LIFE ROUTE TO ARTIFICIAL INTELLIGENCE"

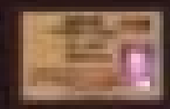
PRACTICE AND FUTURE OF AUTONOMOUS AGENTS

THE "ZOO" AT THE MIT AI

EXPERT SYSTEMS | STARTING ROBOTICS | EVOLUTIONARY COMPUTATION | BIOLOGICALLY INSPIRED ROBOTICS | DESIGN PRINCIPLES

1987 88 89 1990 91 92 93 94 1995 96 97 98





…ICE AND FUTURE OF
…NOMOUS AGENTS

THE "ZOO" AT THE MIT AI LAB

SAB IN ZURICH

IGUANA WORKSHOP LANZAROTE

INTERNATIONAL CONFERENCE ON "MORPHO-FUNCTIONAL MACHINES"

EMBODIED ARTIFICIAL INTELLIGENCE, DAGSTUHL CASTLE, INTERNATIONAL SEMINAR

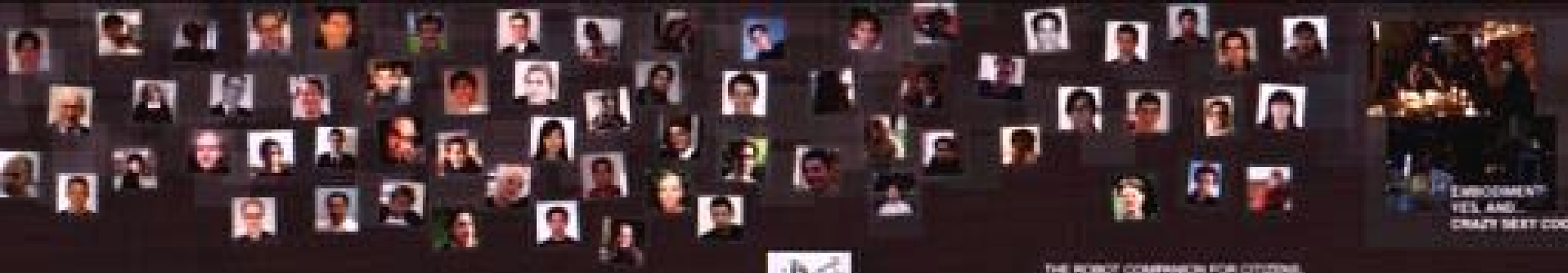
THE "TOKYO LECTURES" 2003-2004

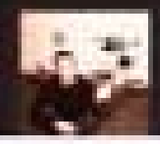
LAB MOVES TO ANDREASSTRASSE

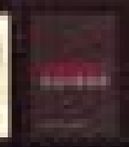
WORLD SUMMIT OF AI ON MONTE VERITA

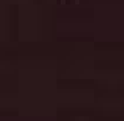
BOOK LAUNCH OF "H…
SHAPES THE WAY WE…

THE 25TH ANNIVERS…
AI LAB



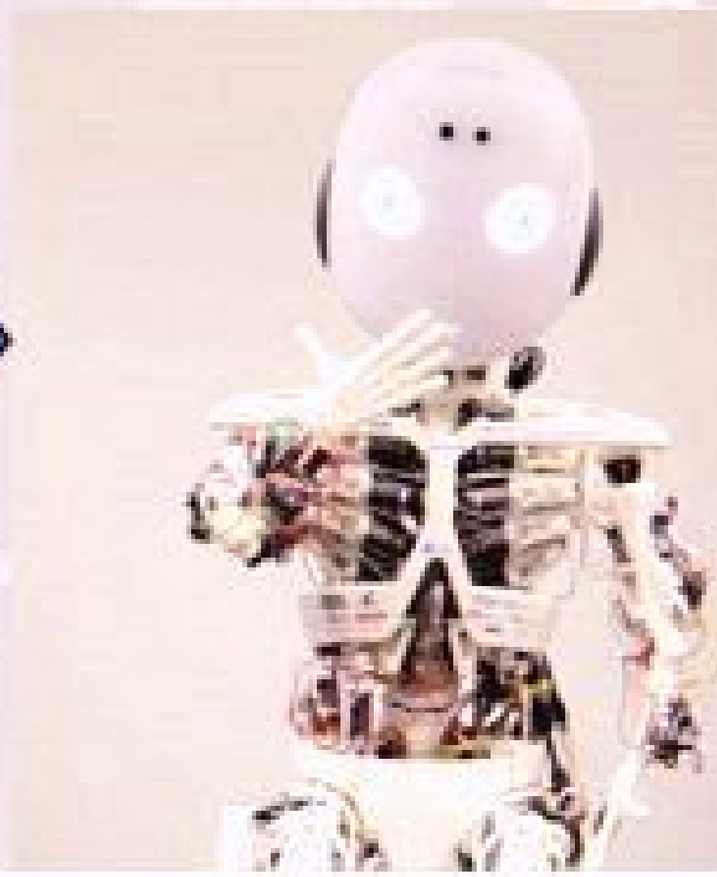






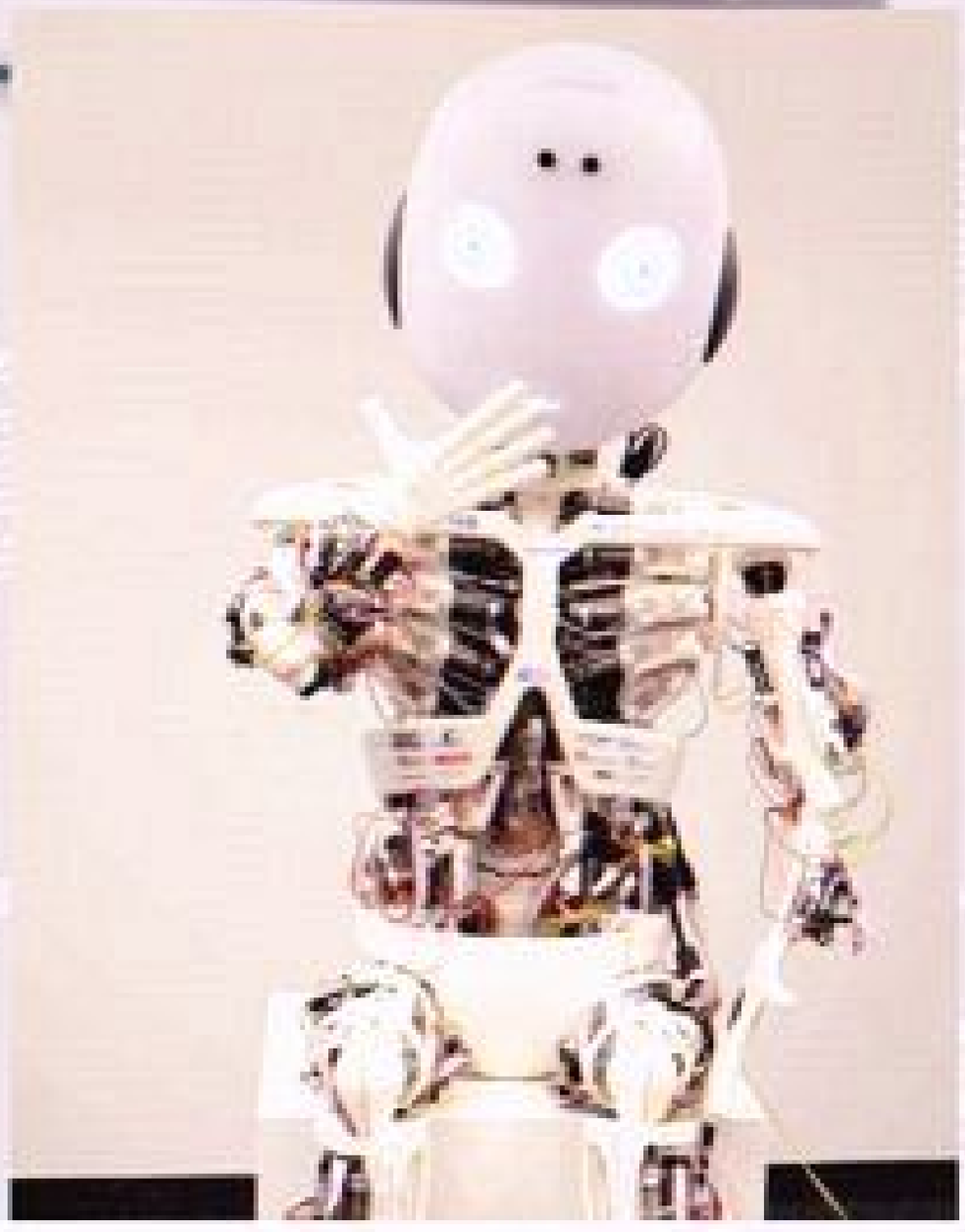
The “Roboy” project
2012 - 2013

“Roboy” — the bio-inspired tendon-driven humanoid robot



Slogan: “Understanding by building”

“Roboy” — the bio-inspired tendon-driven humanoid robot



Slogan: “Understanding by building”

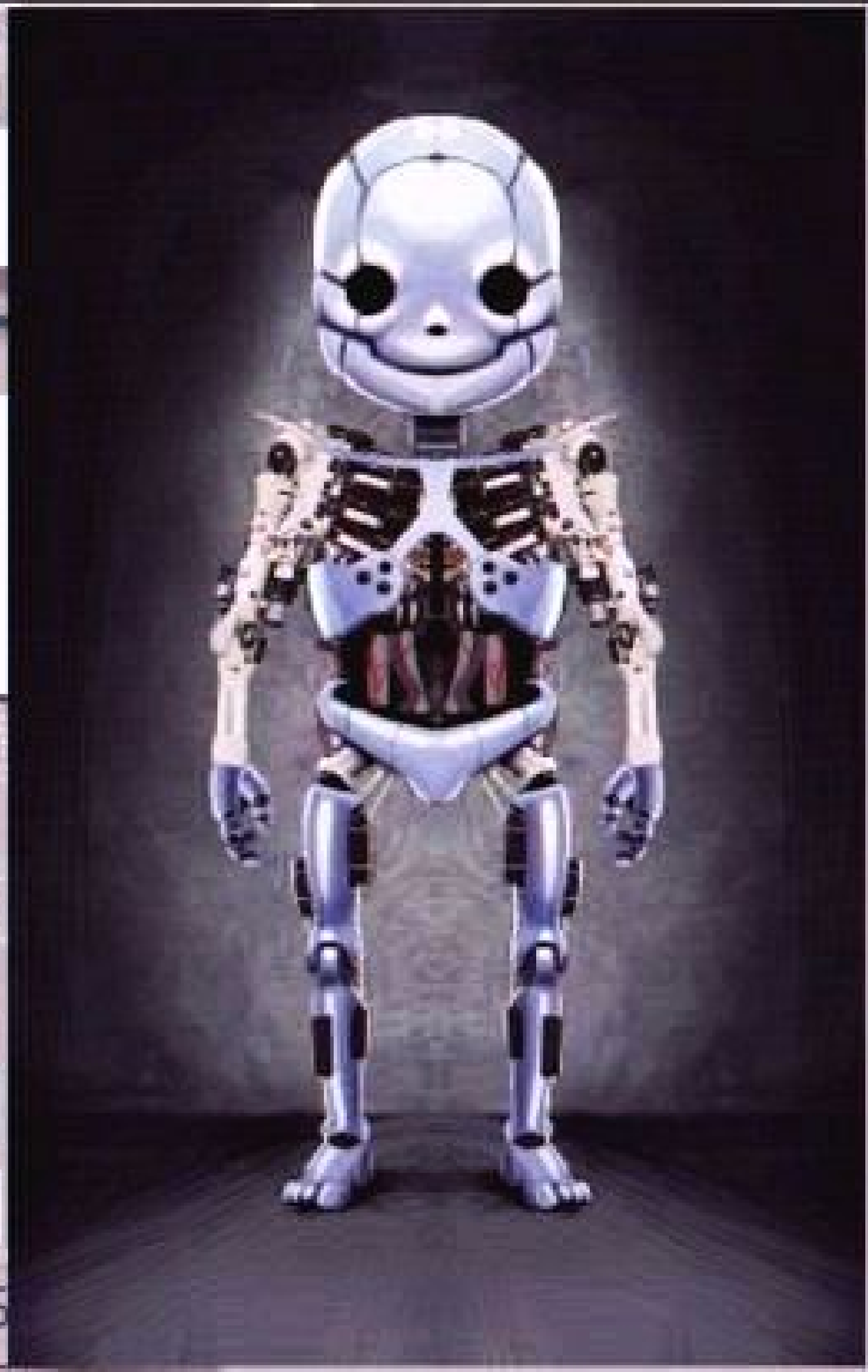
Roboy's predecessor: ECCE (EU-project)

Project goals

- ambassador of new generation of robots
- sharing living space with humans
- evoke positive emotions
- kid-like appearance - cute
- research platform, not (yet) product
- rapid development: 9 months
- open source: creating a community

First design

CUTE??!?

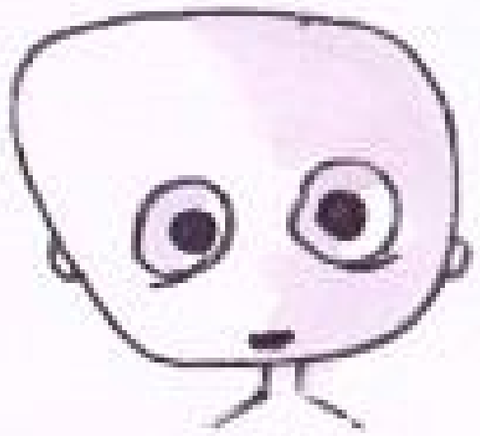



sedax

1

2

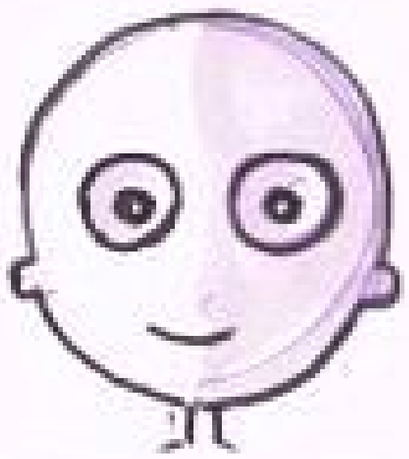
3



4

5

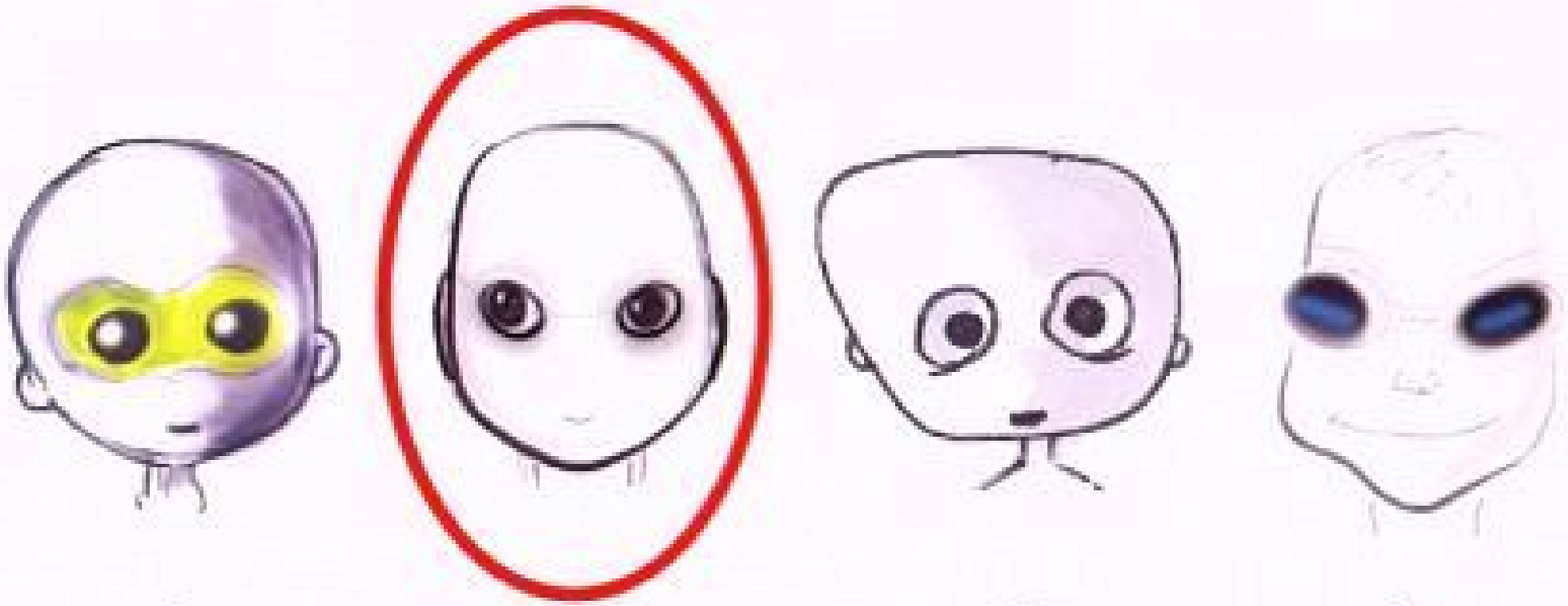
6



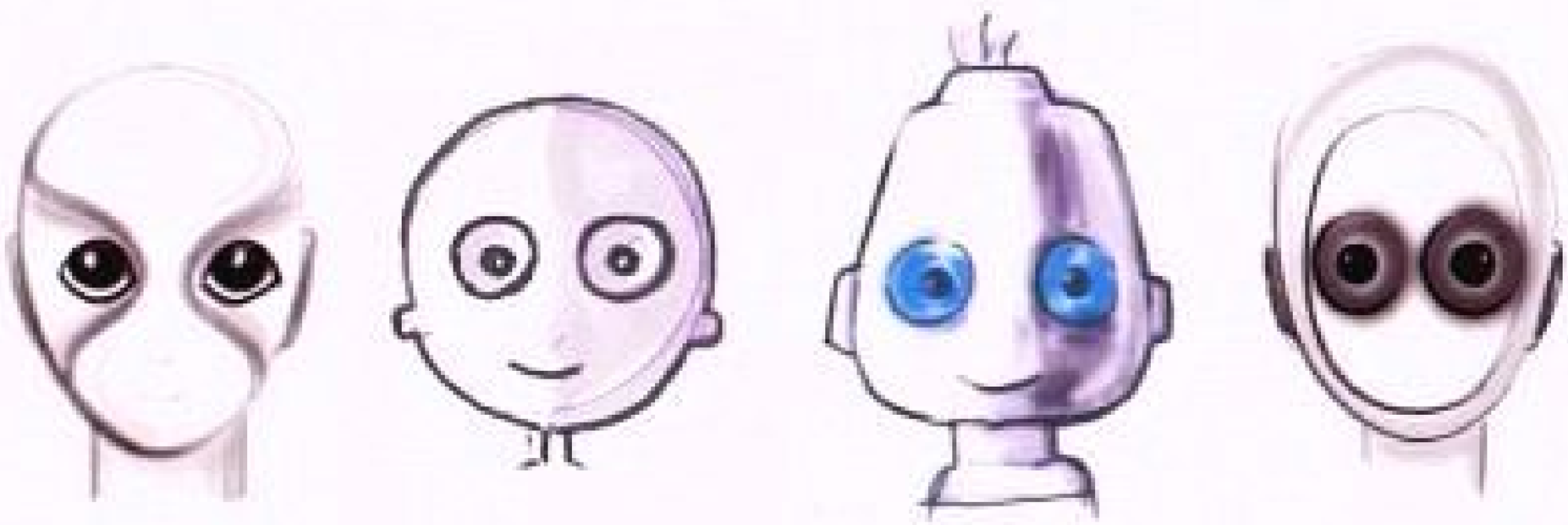
7

8

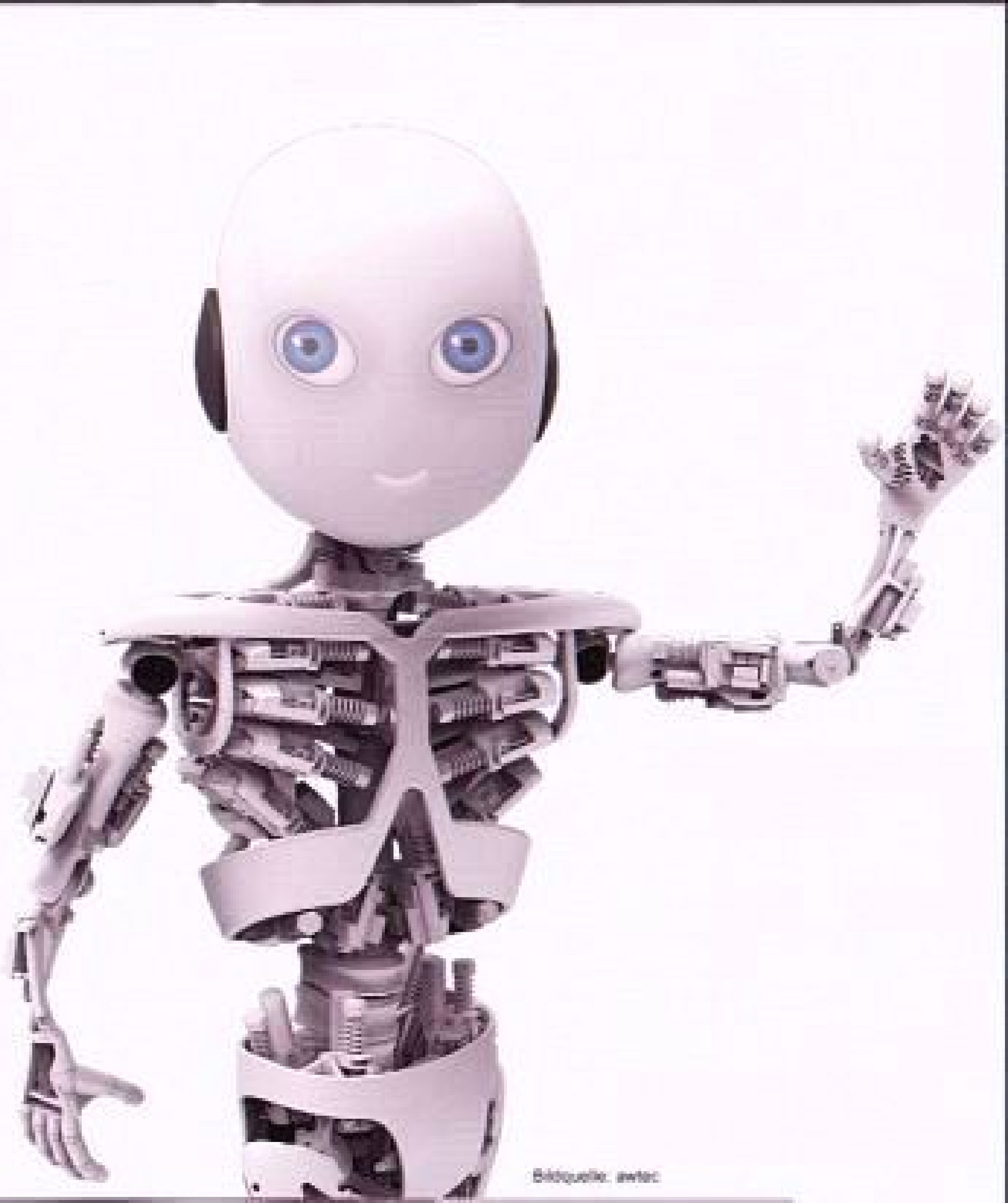
1 2 3 4



5 6 7 8



Roboy's new look



University of Zurich

Teaser video for crowdfunding
November 2012

video: Yves Terrier, Starmind

Teaser video for crowdfunding
November 2012

video: Yves Terrier, Starmind

Various Youtube videos
December 2012

http://www.youtube.com/watch?v=0LJDGsUn_cs&feature=youtu.be

Various Youtube videos
December 2012

http://www.youtube.com/watch?v=0LJDCaSUnGs&feature=youtu.be

Various Youtube videos
December 2012

http://www.youtube.com/watch?v=0LJDCaUnrcs&feature=youtu.be

Various Youtube videos
December 2012

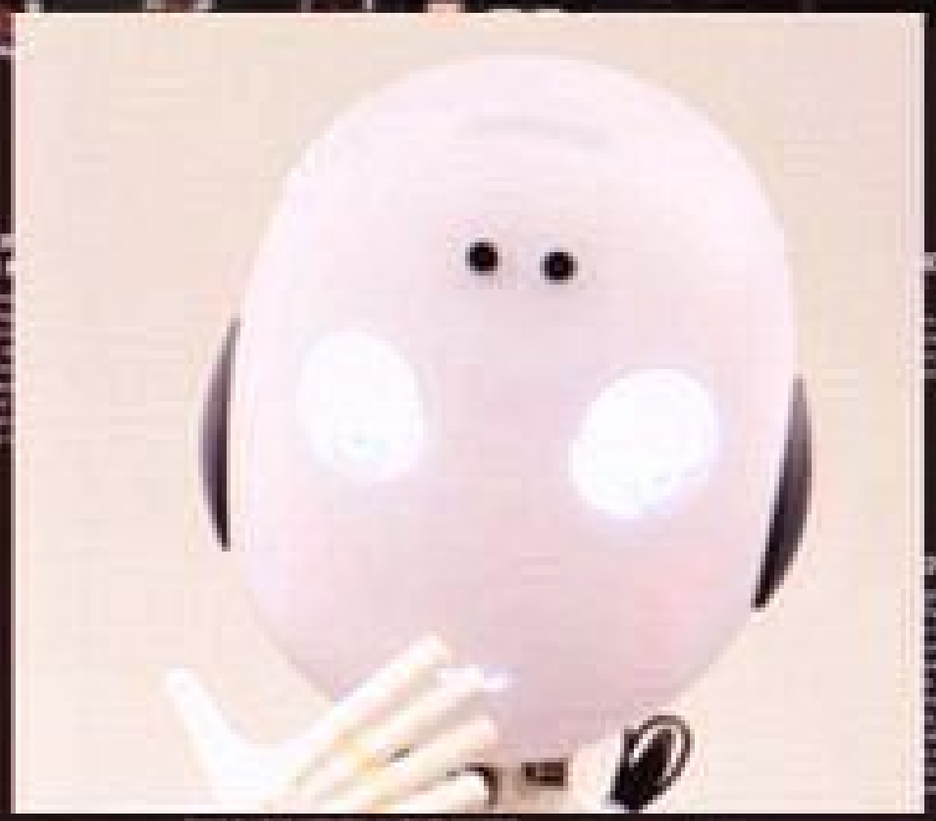
http://www.youtube.com/watch?v=0LJDQ5sUn-s&feature=youtu.be

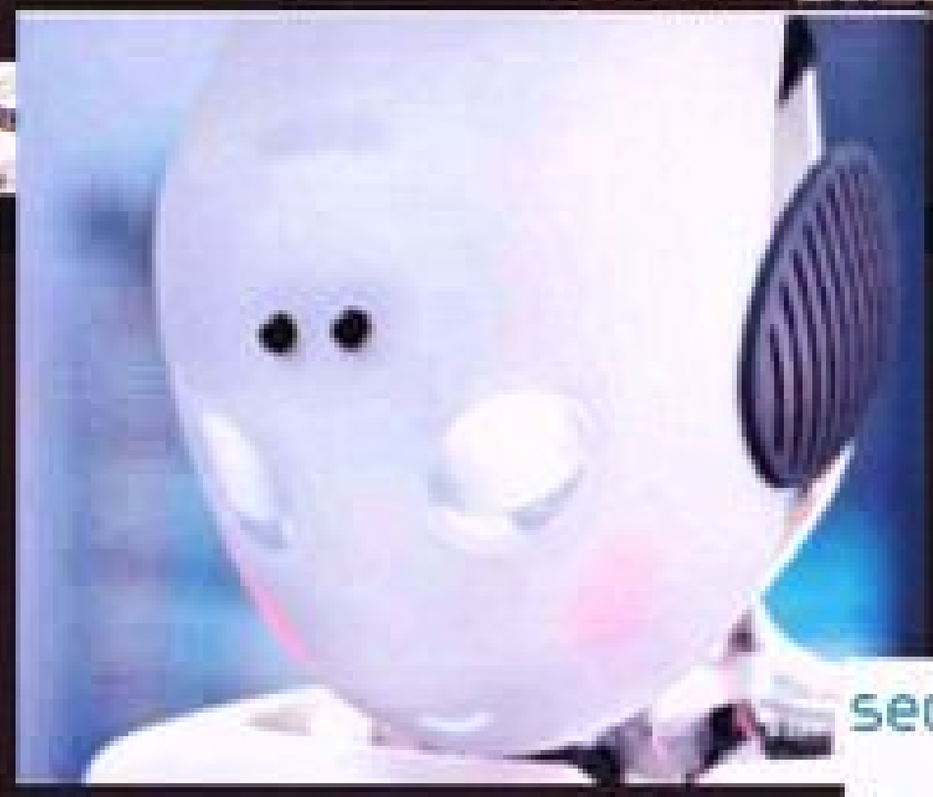
Various Youtube videos
December 2012

http://www.youtube.com/watch?v=0LJDGEsUn-s&feature=youtu.be

Development

head
facial expression





head, facial expression by:
Sedax, Uster

sedax

ROBOTS ON TOUR

World Congress and Exhibition of Robots, Humanoids, Cyborgs and more

***** Ausverkauft *****

25 Jahre AI Lab Zürich: Roboter aus aller Welt für Jung und Alt

AUSVERKAUFT

Robots on Tour ist ausverkauft. Leider gibt es auch keine Tickets mehr an der Tageskasse.

20 minuten

22 Wissen

Invasion in Zürich – die Androiden kommen

20 Sekunden

Profis diskutieren

Roboter für alle

Verlosung

Oberflächen

Der Mensch dient als Vorbild

«Roboter als Teil der Gesellschaft»

Roboy - ganz natürlich

Gehirn

Steuern mit Gedankenkraft

Helfende Hände

Dem Menschen stets zu Diensten

Emotionen

Maschinen drücken Gefühle aus

Der Gast

Humanoide Zukunft?

Produced by

Wissen 23

University of Zurich

25 Jahre AI Lab Zürich: Roboter aus aller Welt für Jung und Alt

ROBOTS ON TOUR

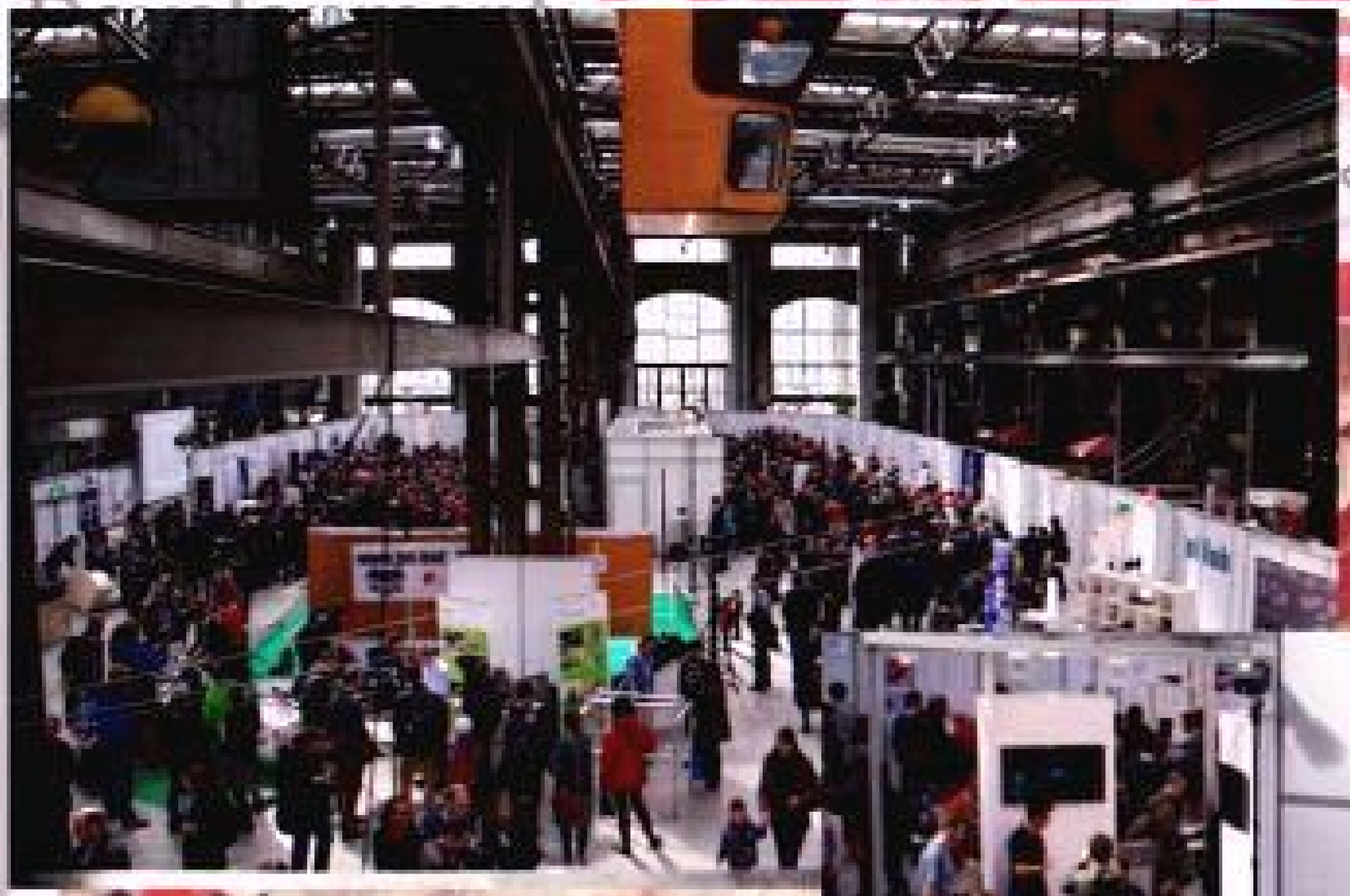
Pictures: Jaan Spitz

Roboter aus aller Welt für Jung und Alt

ROBOTS

13

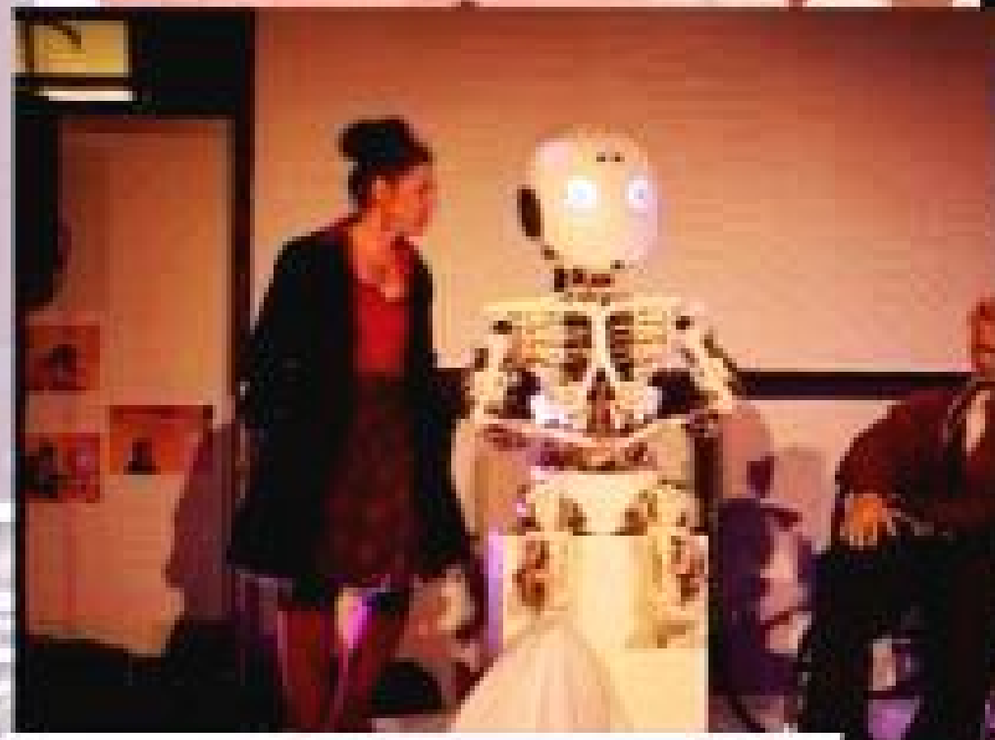
orgs and more



*** Ausverkauft ***

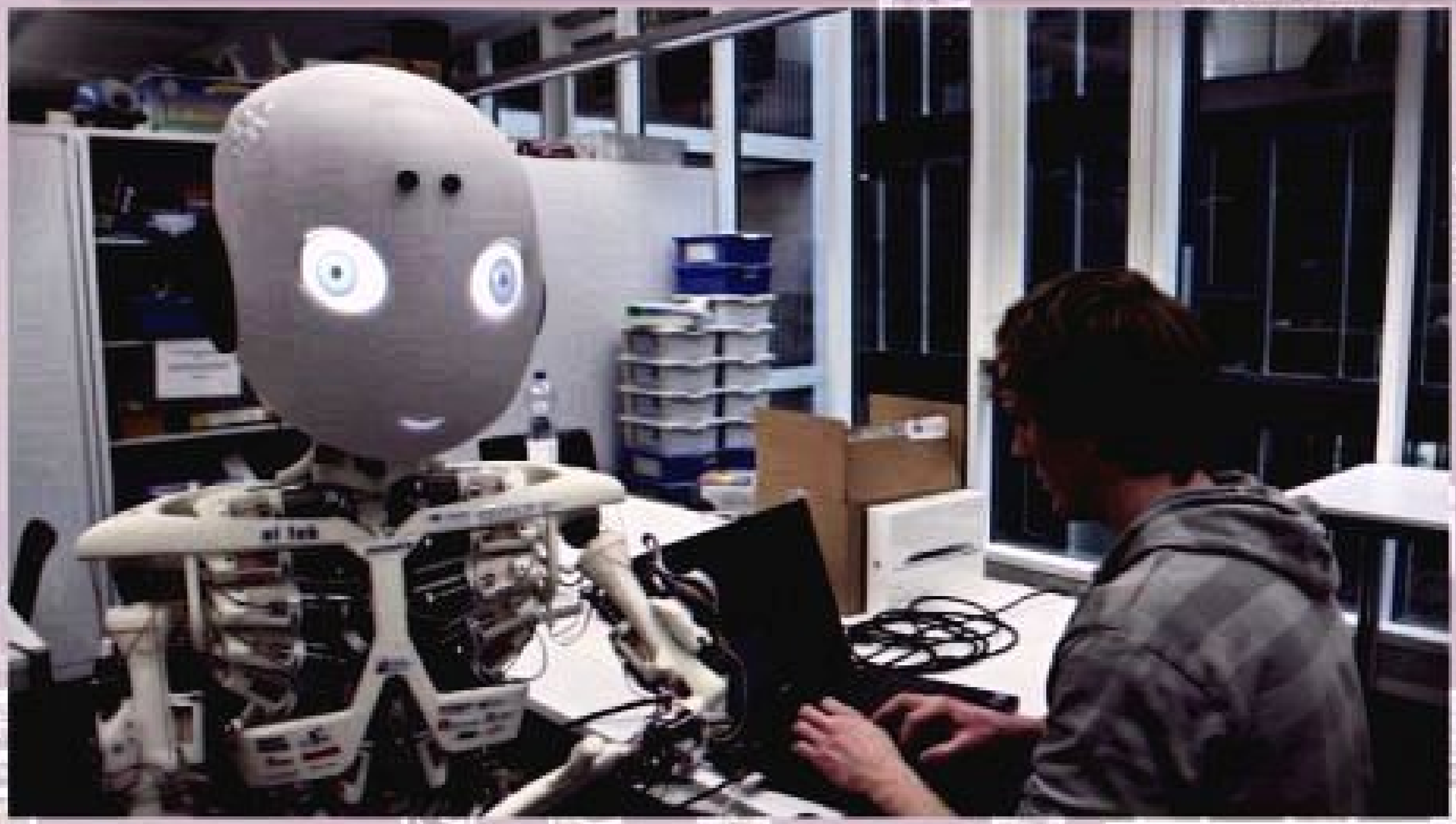
Pictures: Jaan Spitz

r Jung



Pictures: Jaan Spitz

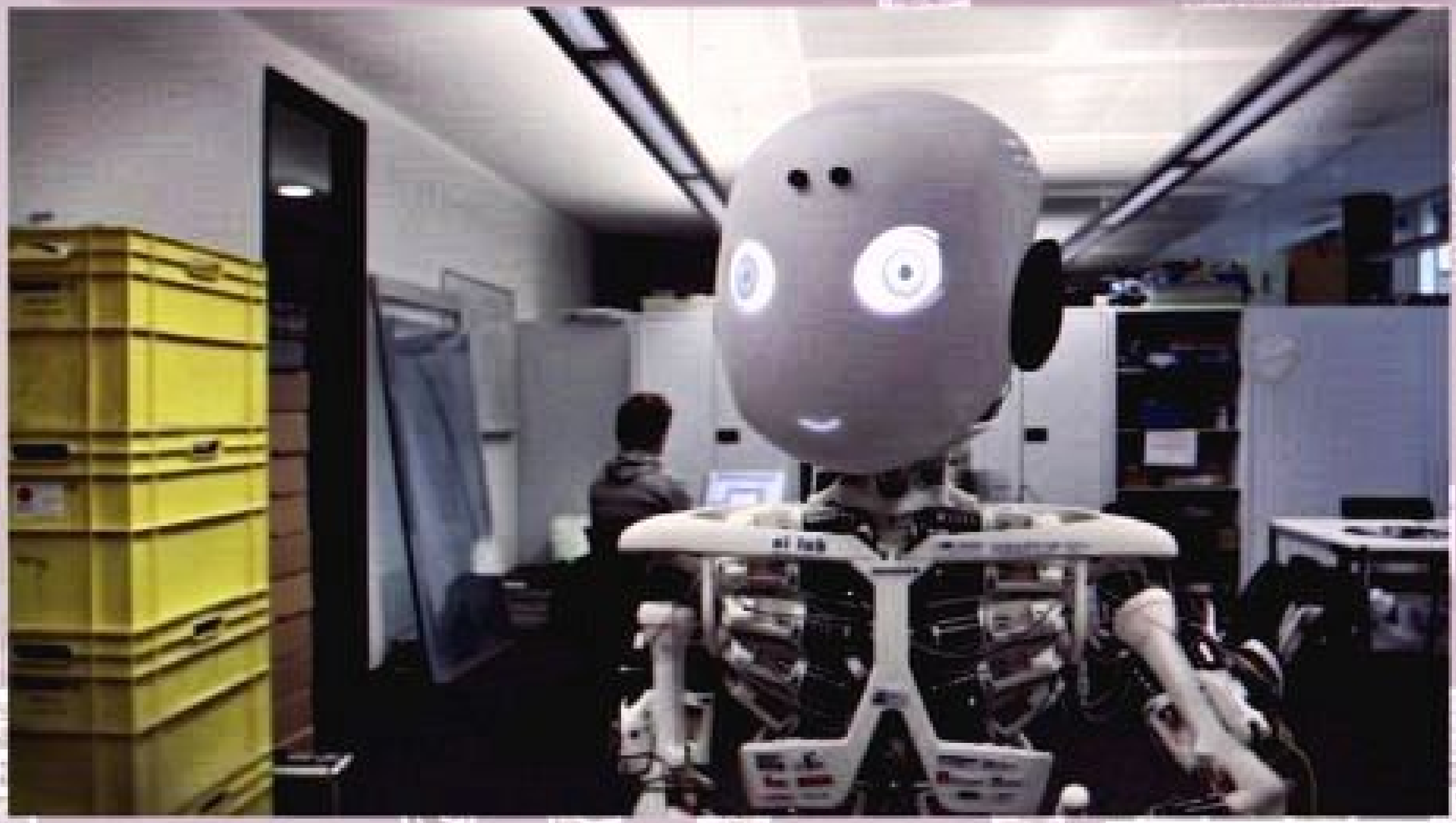
Various Youtube videos
March 2013



video: ZHdK, Zürcher Hochschule der Künste, March 2013

http://www.youtube.com/watch?feature=player_detailpage&v=U6g0iWu

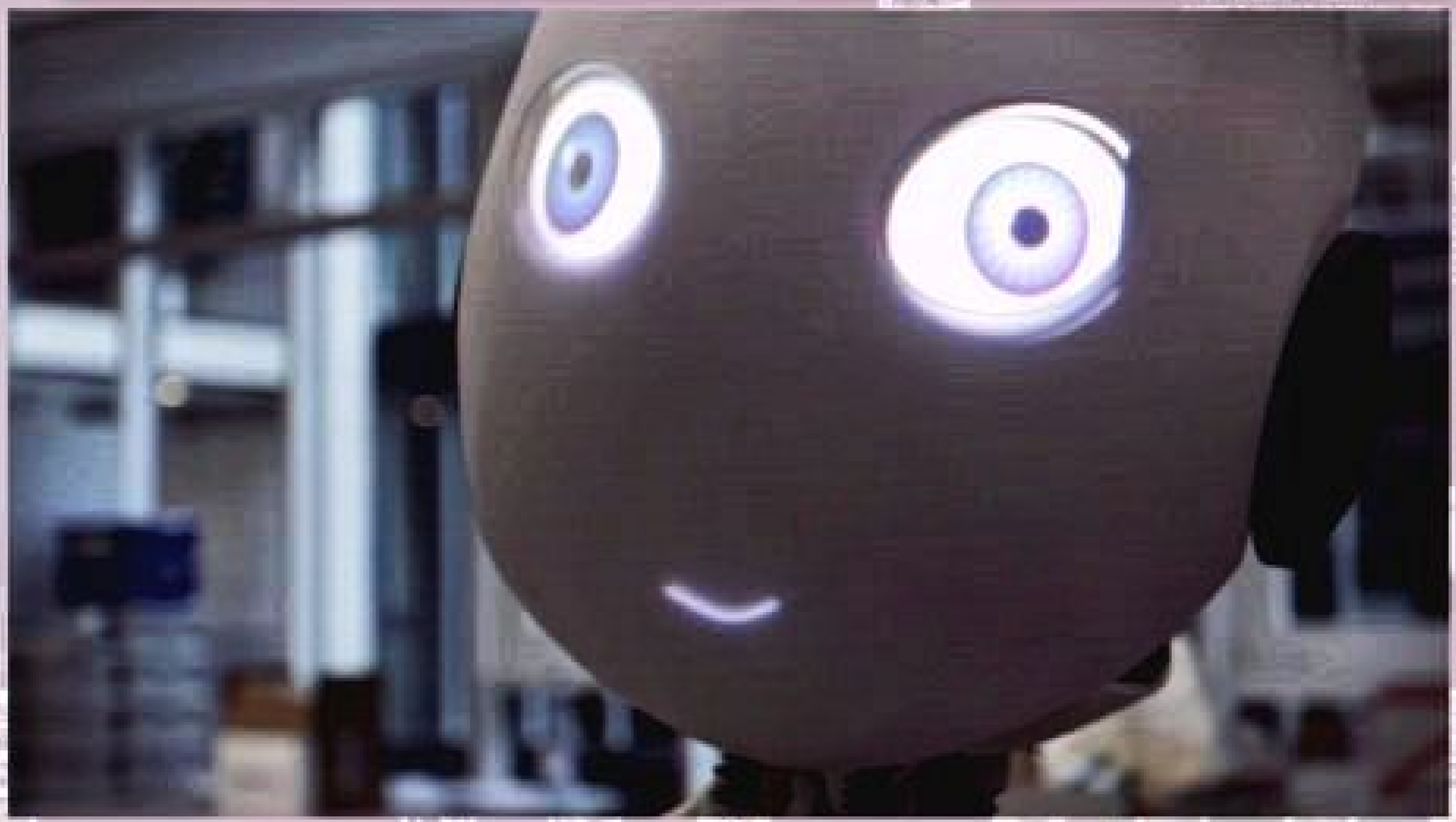
Various Youtube videos
March 2013



video: ZHdK, Zürcher Hochschule der Künste, March 2013

http://www.youtube.com/watch?feature=player_detailpage&v=U6g0iWu

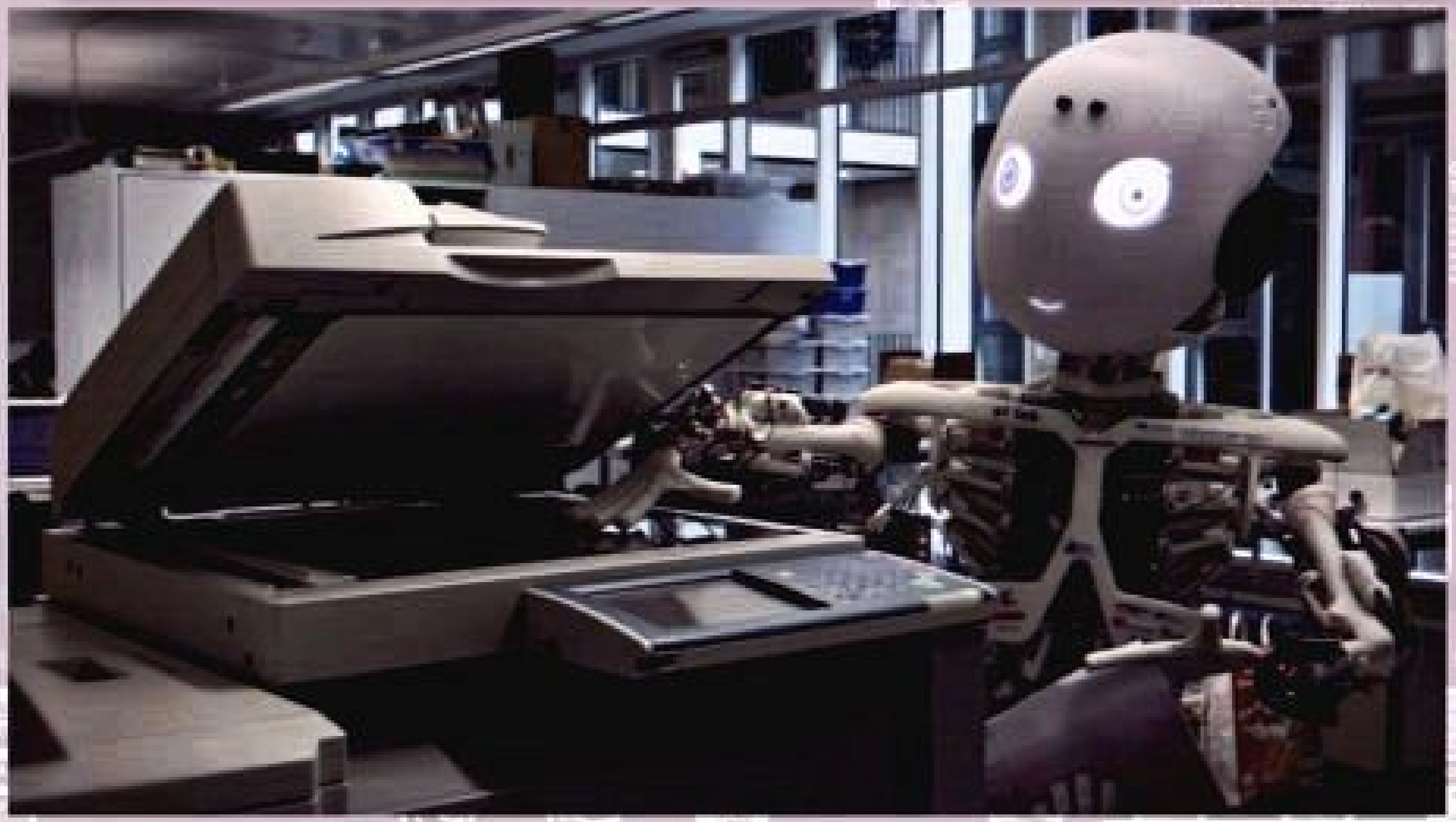
Various Youtube videos
March 2013



video: ZHdK, Zürcher Hochschule der Künste, March 2013

http://www.youtube.com/watch?feature=player_detailpage&v=U6g0iWu

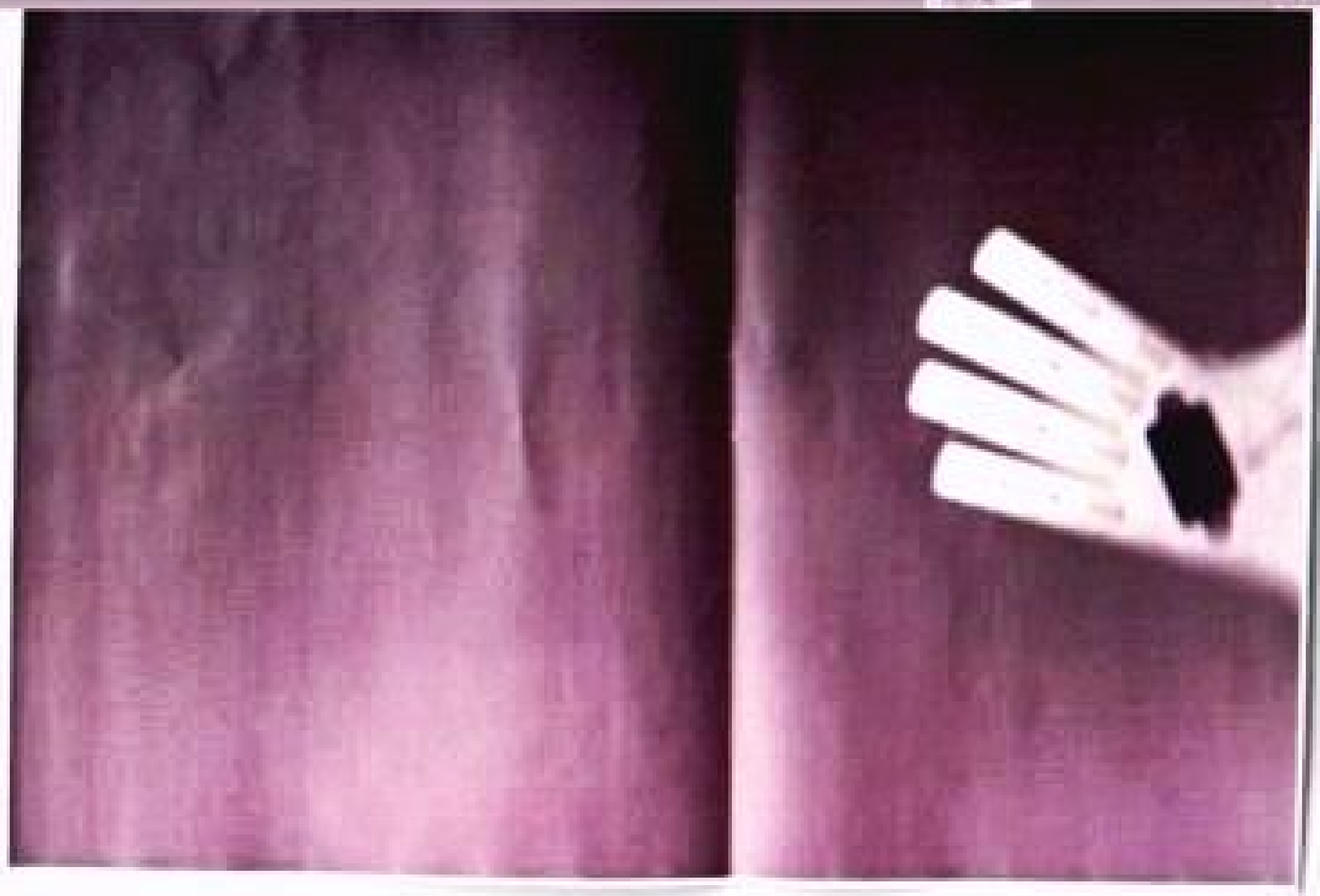
Various Youtube videos
March 2013



video: ZHdK, Zürcher Hochschule der Künste, March 2013

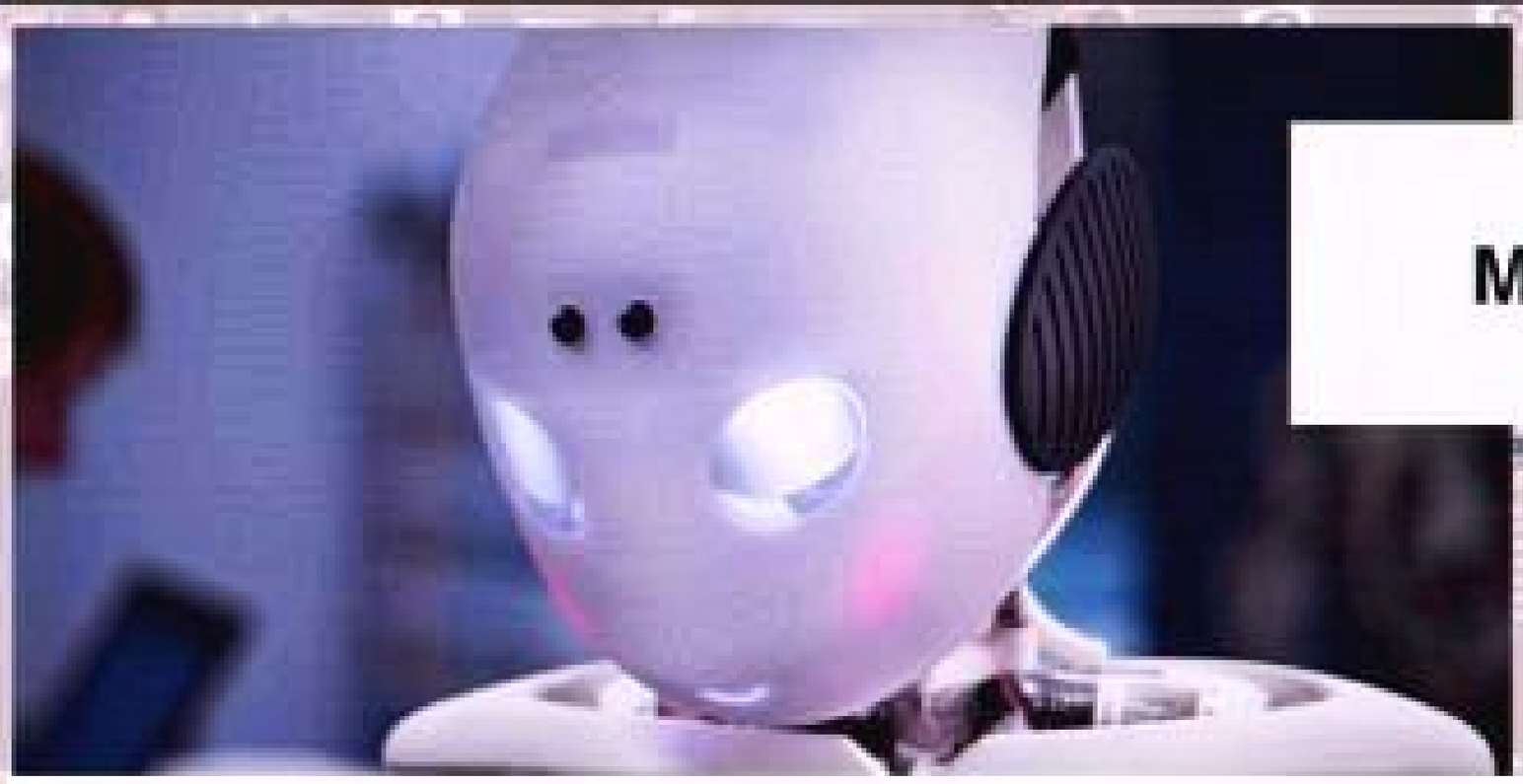
http://www.youtube.com/watch?feature=player_detailpage&v=U6g0iWu

Various Youtube videos
March 2013



video: ZHdK, Zürcher Hochschule der Künste, March 2013

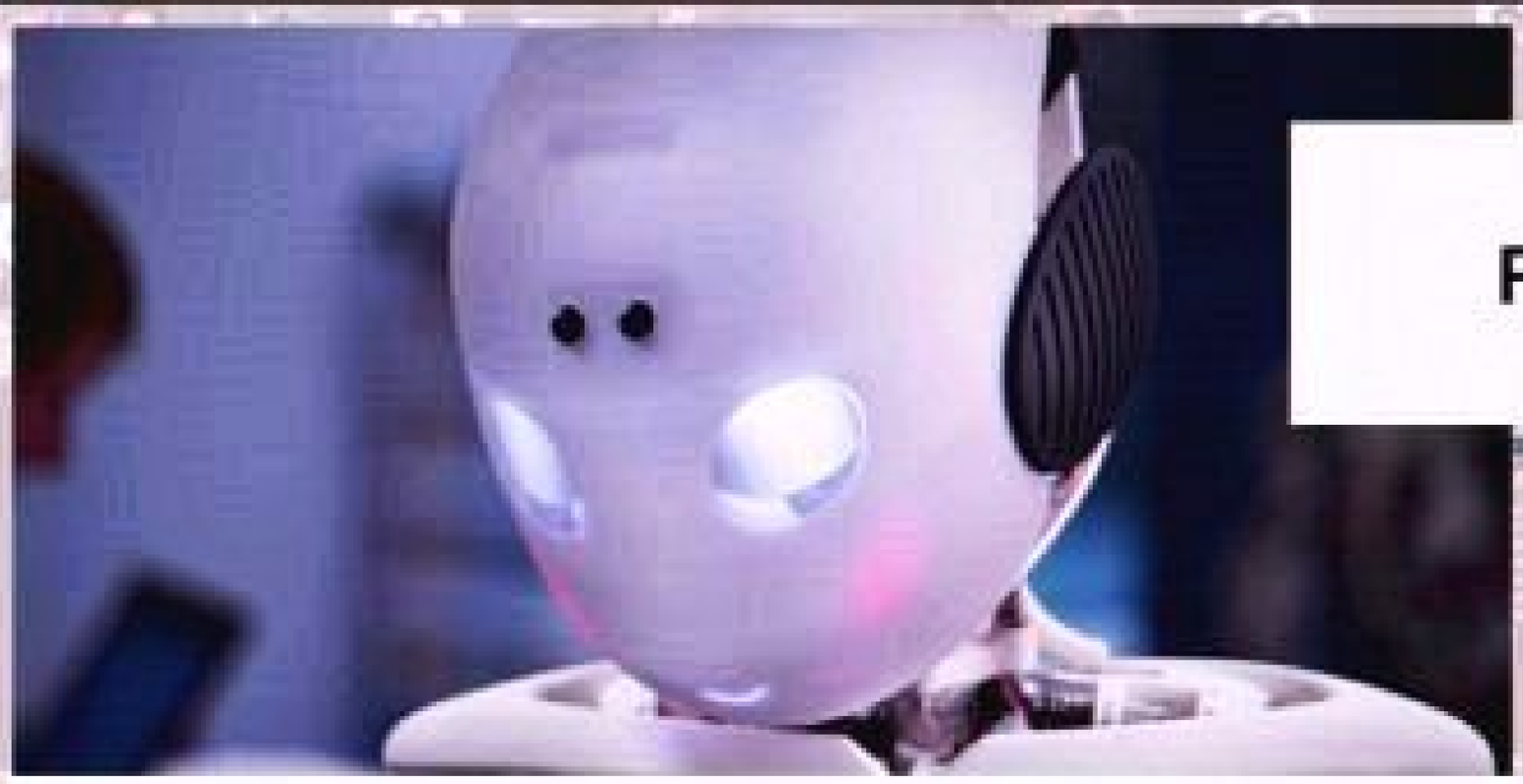
http://www.youtube.com/watch?feature=player_detailpage&v=U6g0iWu



Media Coverage

BBC, Financial Times, Discovery Channel, Wired, Huffington Post, CNET, Science World Report Reuters, Keystone, National Geographic, ZDF, Bild, Welt, Süddeutsche Zeitung, Berliner Zeitung, 3SAT, Daily Mail, SRF Tagesschau, NZZ, Tages Anzeiger, 20Minuten, ...

Switzerland, Germany, France, Spain, England, Sweden, Italy, Turky, Irland, Greece, Japan, China, Indien, USA, Canada, Chile, Argentina, Vietnam, Israel, Egypt, Mexico, Korea, Russia, ...



Roboy on Tour

Itinerary:
ICRA (Karlsruhe), Swiss Innovation Fair (Zurich), Munich (TU), Beijing and Shanghai (China), Tokyo (Japan), London (UK) ...

Summary, conclusions

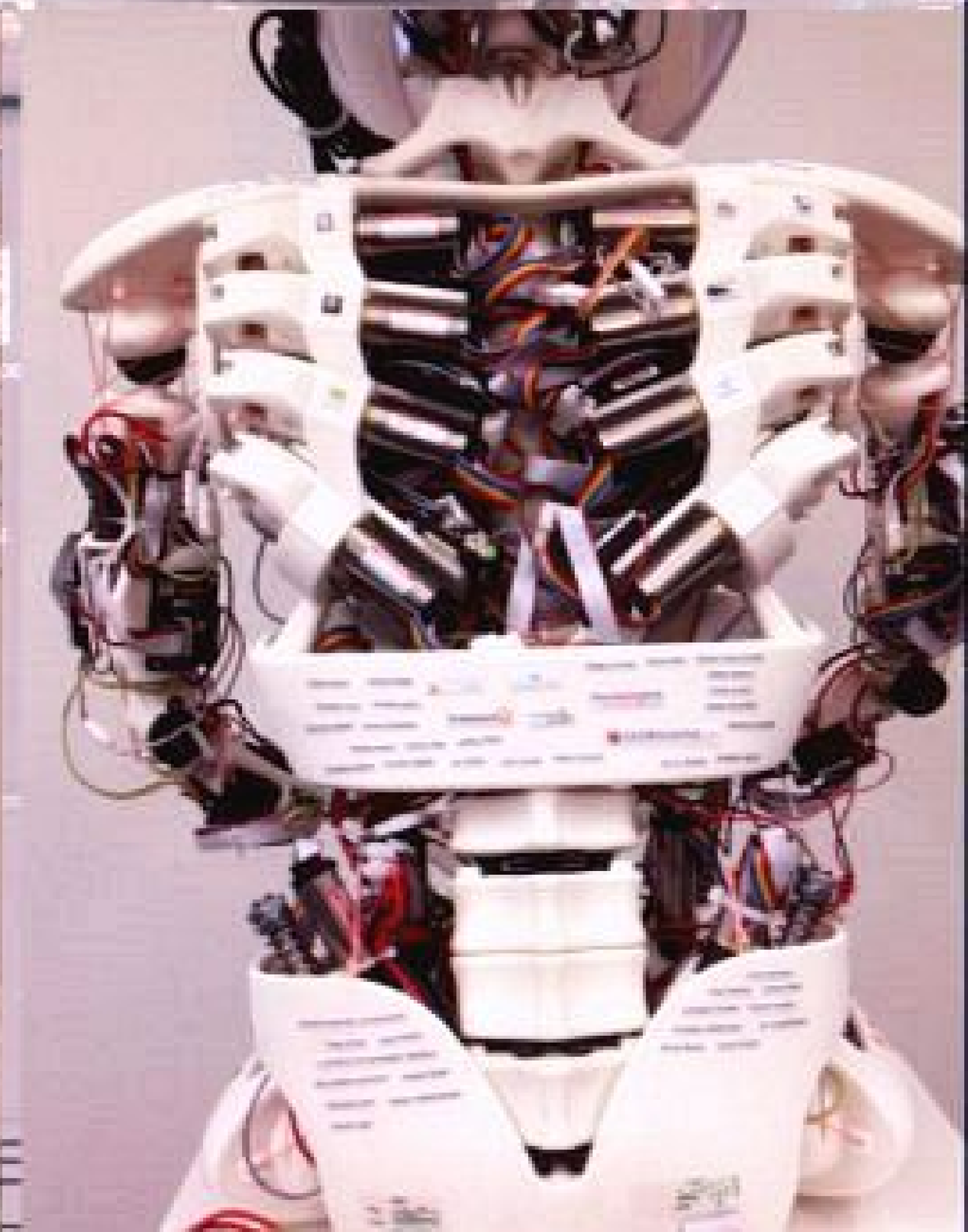
- wonderful experience >
- funding: crucial
- careful: crowdfunding not easy
- media attention: reason?
- tipping points
- discrepancy with funding

Summary, conclusions

- wonderful experience

- 40 people
- 15 companies
- 7 universities (UZH, ETH-Z, TUM, U-Tokyo, Simtec-Singapore, ZHaW, ZHdK-Zurich)
- 50 sponsoring companies

Sponsors - Logos on Roboy



Summary, conclusions

- wonderful experience >
- funding: crucial
- careful: crowdfunding not easy
- media attention: reason?
- tipping points
- discrepancy with funding


CHOUCROUTE
SANDWICHS
Ouvert Jour
Cheers!
Holding a hard object!

Your ideas - warmly welcomed!

Cheers!

Holding a hard object!

Like to know more?

Like to know more?

Read THE book!

University of Zurich

robotics

ai lab

Like to know more?

WHAT book?!???

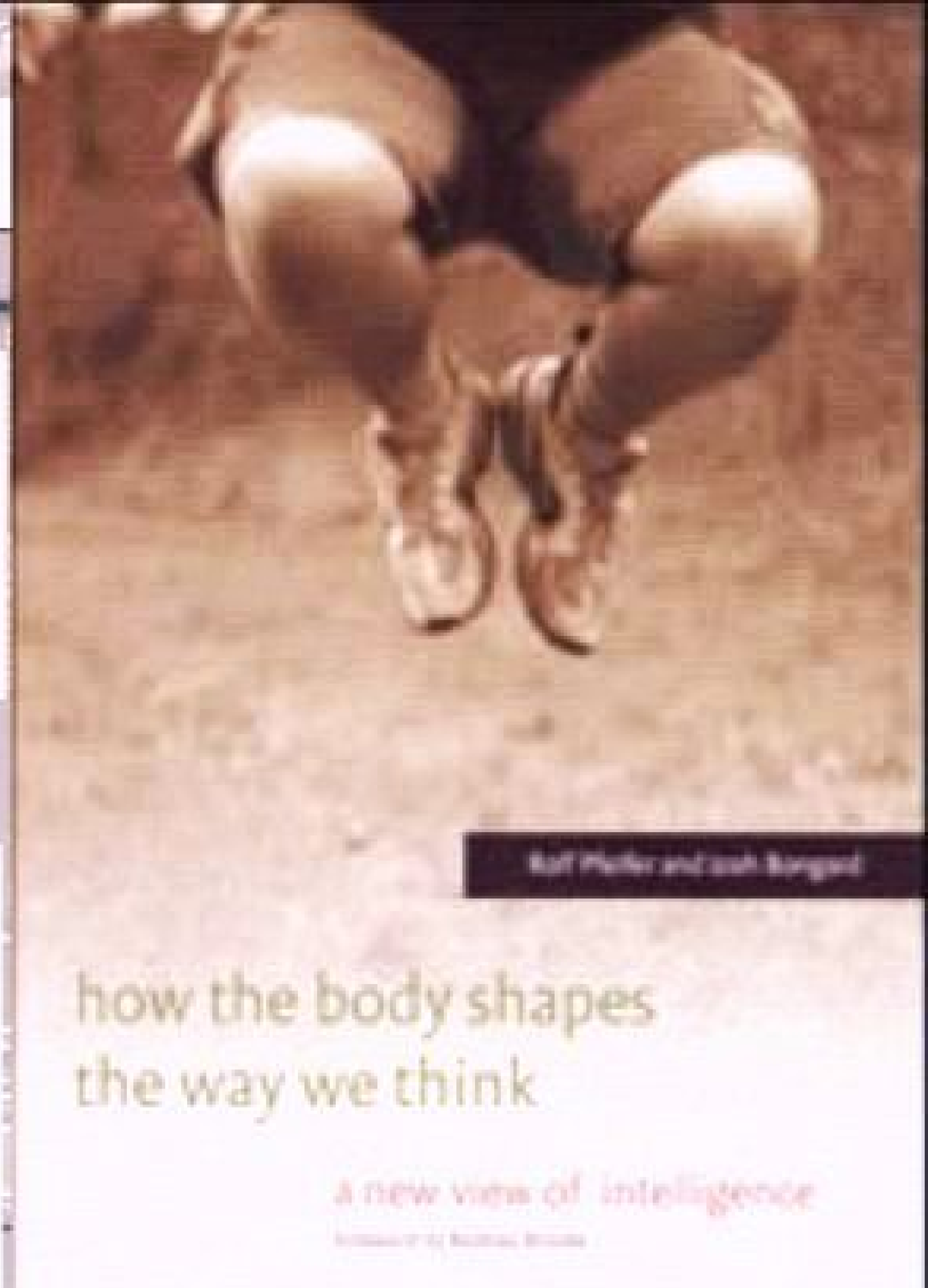
Read:

Rolf Pfeifer and Josh Bongard

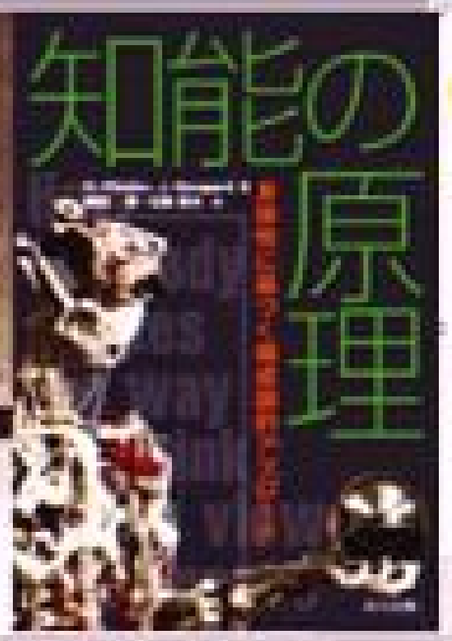
How the body shapes the way we think — a new view of intelligence

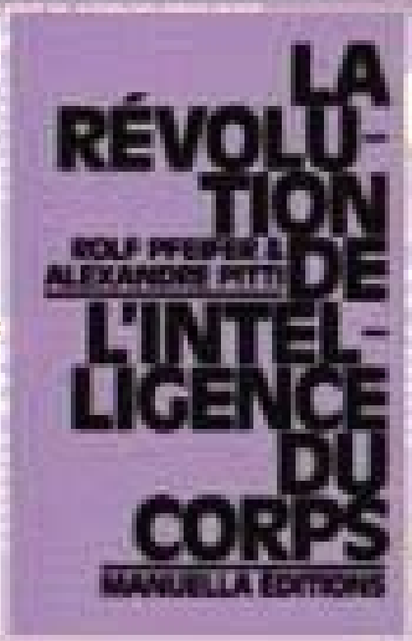
MIT Press, 2007

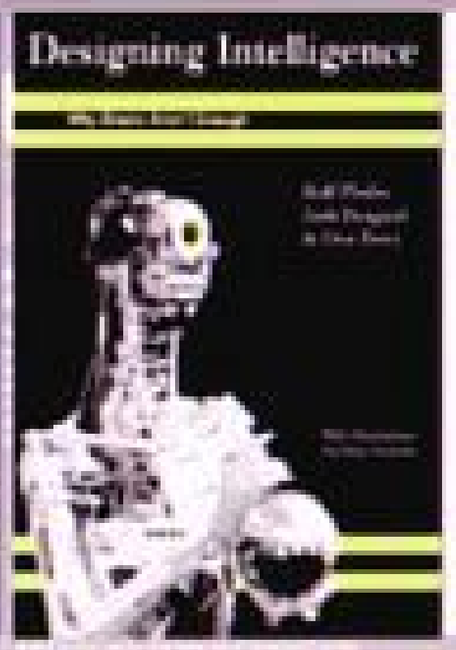
Illustrations by Shun Iwasawa



Read:







English Japanese Chinese French English Arabic

Better robots — better life

Thank you for your attention!