Robotics: Science and Systems

Overview of Robotics

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Outline

- ❑ Definition: what are robots?
- ❑ Elements of robotics
  - ❑ Mechanism & mechanical design
  - ❑ Actuation
  - ❑ Sensing
  - ❑ Motion capabilities: manipulation, locomotion & localization
  - ❑ Artificial Intelligence (AI)
  - ❑ Level of robot intelligence
- ❑ Areas of robotics
  - ❑ Industrial/civil applications
  - ❑ Educational purposes
  - ❑ Research directions
- ❑ Robot control
- ❑ Summary of key RSS elements
- ❑ Robotics in real-world application: a field test

Key elements of RSS

Basic robotics knowledge (property of the system):

1. Robot Kinematics & Dynamics

Process of information:

2. System Identification & State Estimation
3. Kalman Filter

Mobile robots:

4. Localization and Mapping
5. Path & Motion Planning

Key elements of RSS

Planning of articulated robots:

1. Trajectory Planning and Motion Planning

Control:

2. Digital System & Control
3. Design of Advanced Controllers
4. Optimization
5. Model Predictive Control

Machine learning:

6. Machine Learning for Robot Control

What are robots?

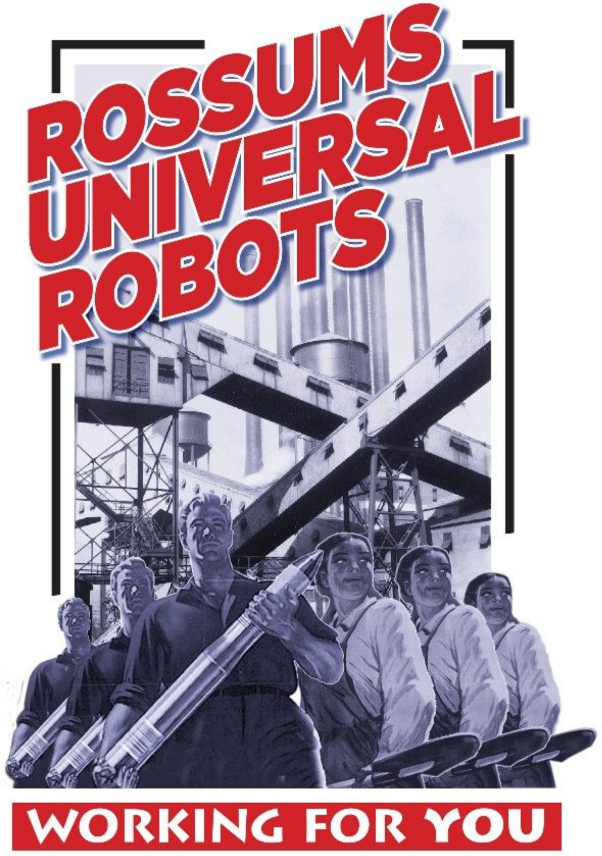
Robotics

An interdisciplinary area of science & engineering that covers:
mechanical engineering, electrical engineering, computer science, and AI.

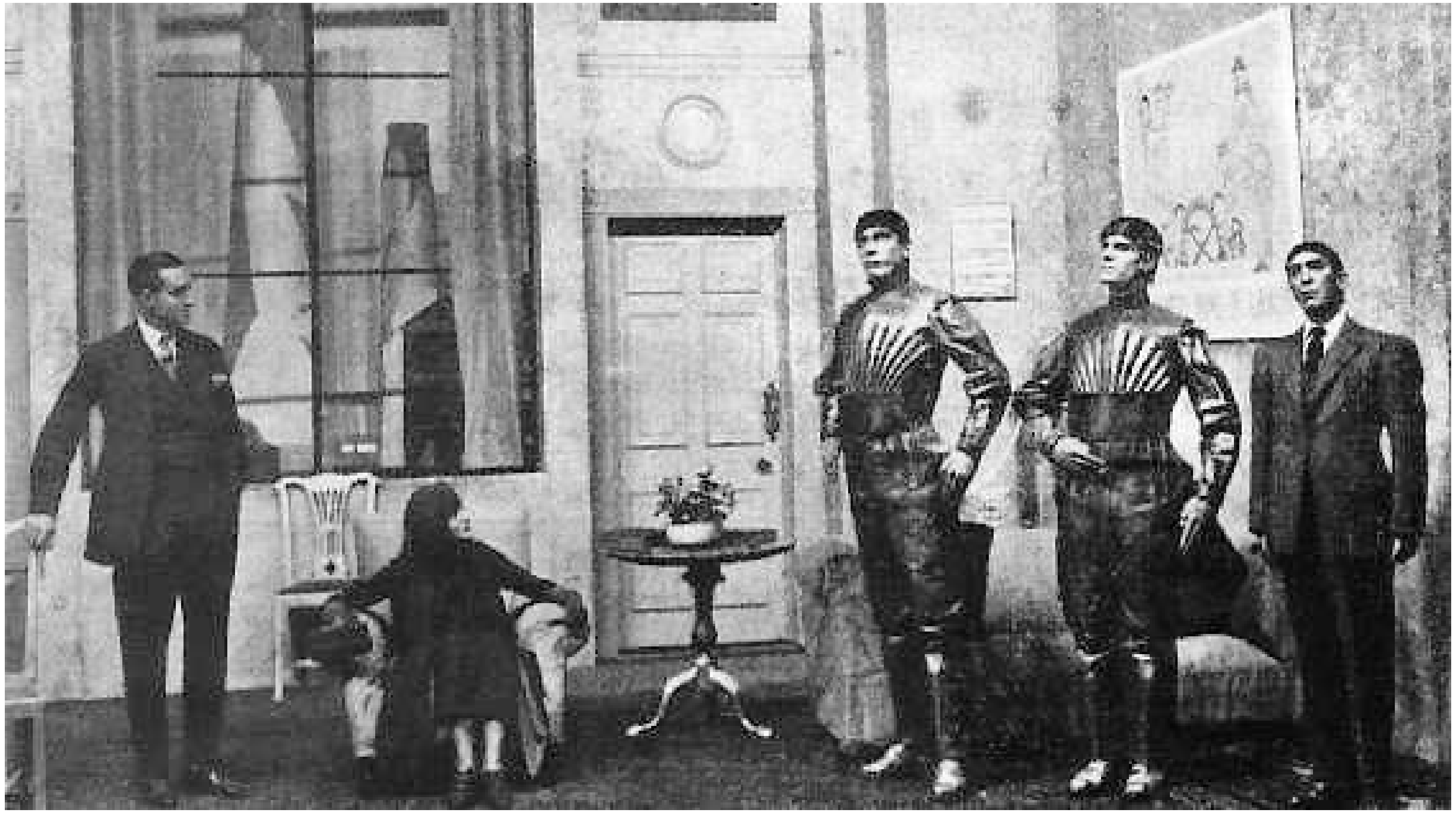
The word “robot” was introduced to the public by Czech writer Karel Čapek in his play R.U.R. (Rossum's Universal Robots) in 1920. In Czech, the same as other Slavic languages, “robota” means “labour” or “work”.

Original purpose of robots, *automatic/autonomous labour* that frees humans from tedious jobs.

Rossum's Universal Robots



© Edward Alderton Theatre, image by Kevin Coward



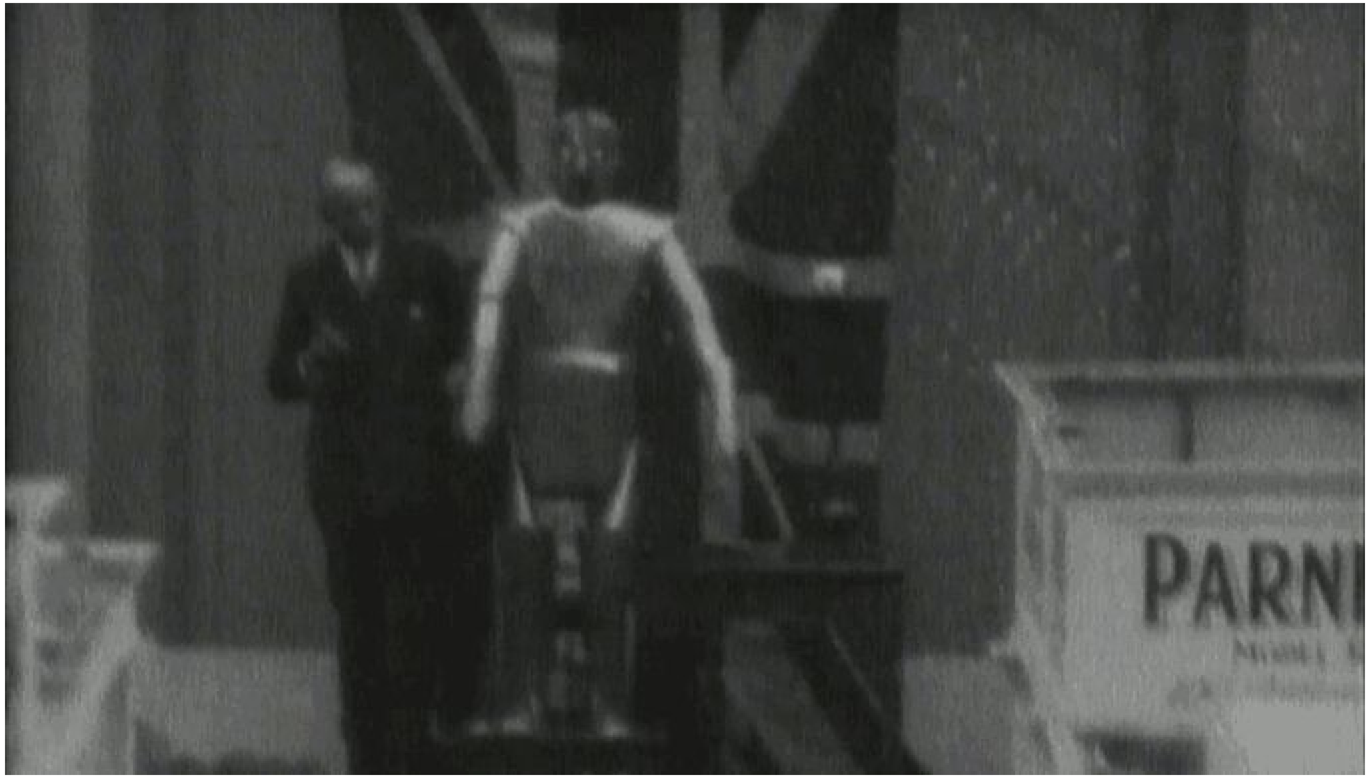
© R.U.R. - Wikipedia

Robotics

Robotics is the science & technology that deals with a variety of elements related with developing such machines or mechatronic devices, eg design & fabrication of the hardware, sensing & controls, and the applications.

Eric: UK's first robot

UK’s first robot, and most interestingly, it is a humanoid robot.



Built in 1928 by Captain Richards & A.H. Reffell

See more at: http://www.sciencemuseum.org.uk/visitmuseum/plan_your_visit/exhibitions/eric

Robots: machines that automate some behavior

The first industrial robot: Unimate

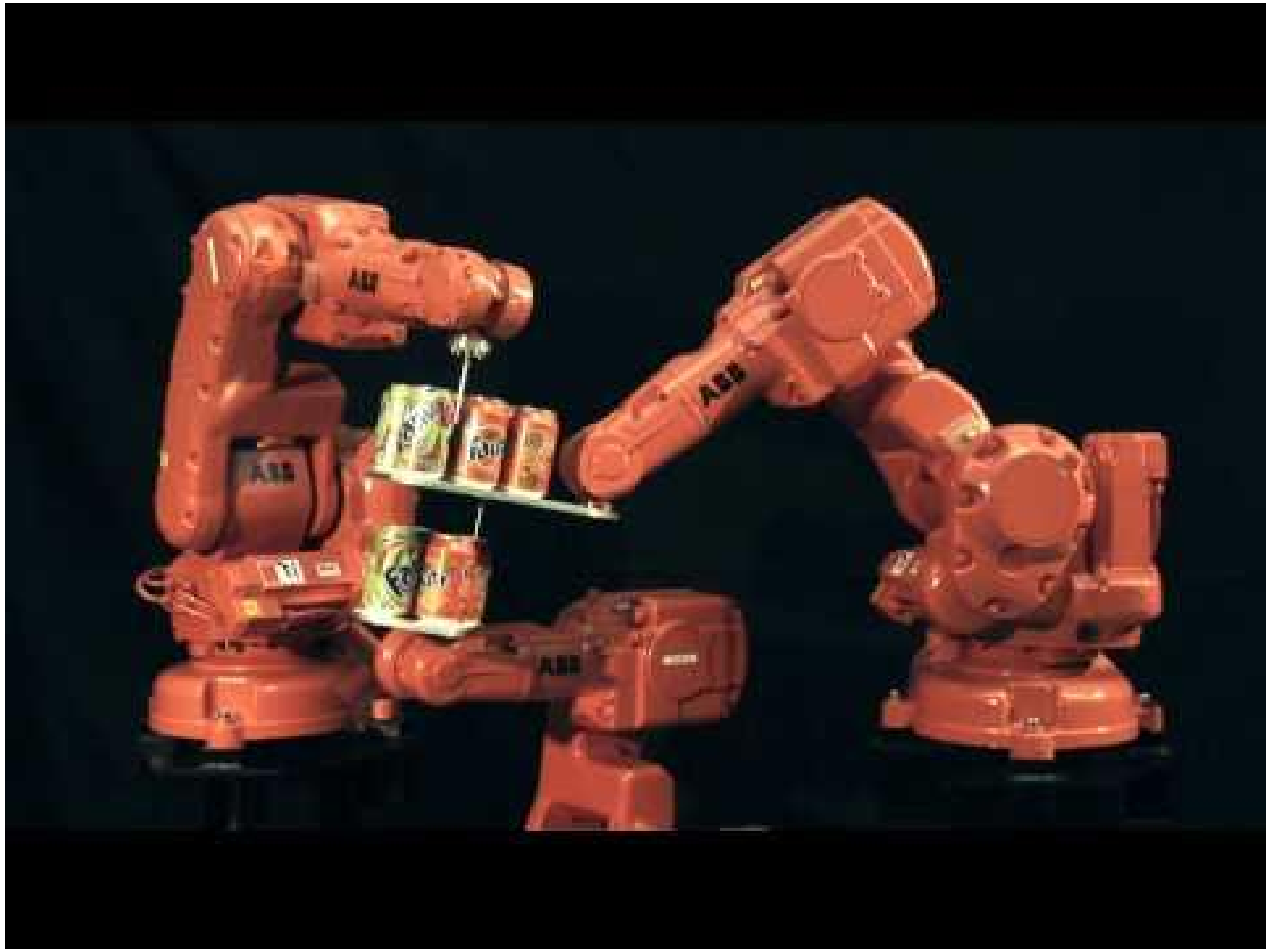
George Charles Devol developed the prototype of Unimate in 1950s, the first material handling robot employed in industrial production work.

The first Unimate robot was sold to General Motors in 1961.

Unimate Robot, © the history channel

Robots: machines that automate some behavior

High-speed motion control



© ABB Robotics

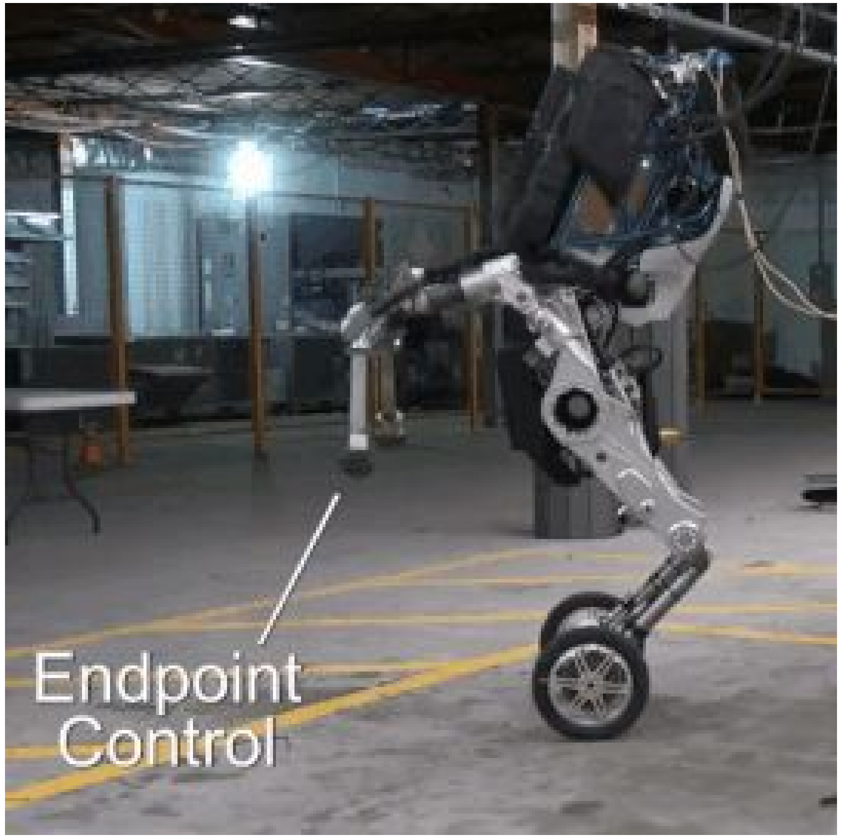
Robot Kinematics & Dynamics
System Identification
Kalman Filter
Digital System & control
Design of Advanced Controllers
Trajectory Planning and Motion Planning

Robots: machines that automate some behavior

Sorting parcels in warehouse application

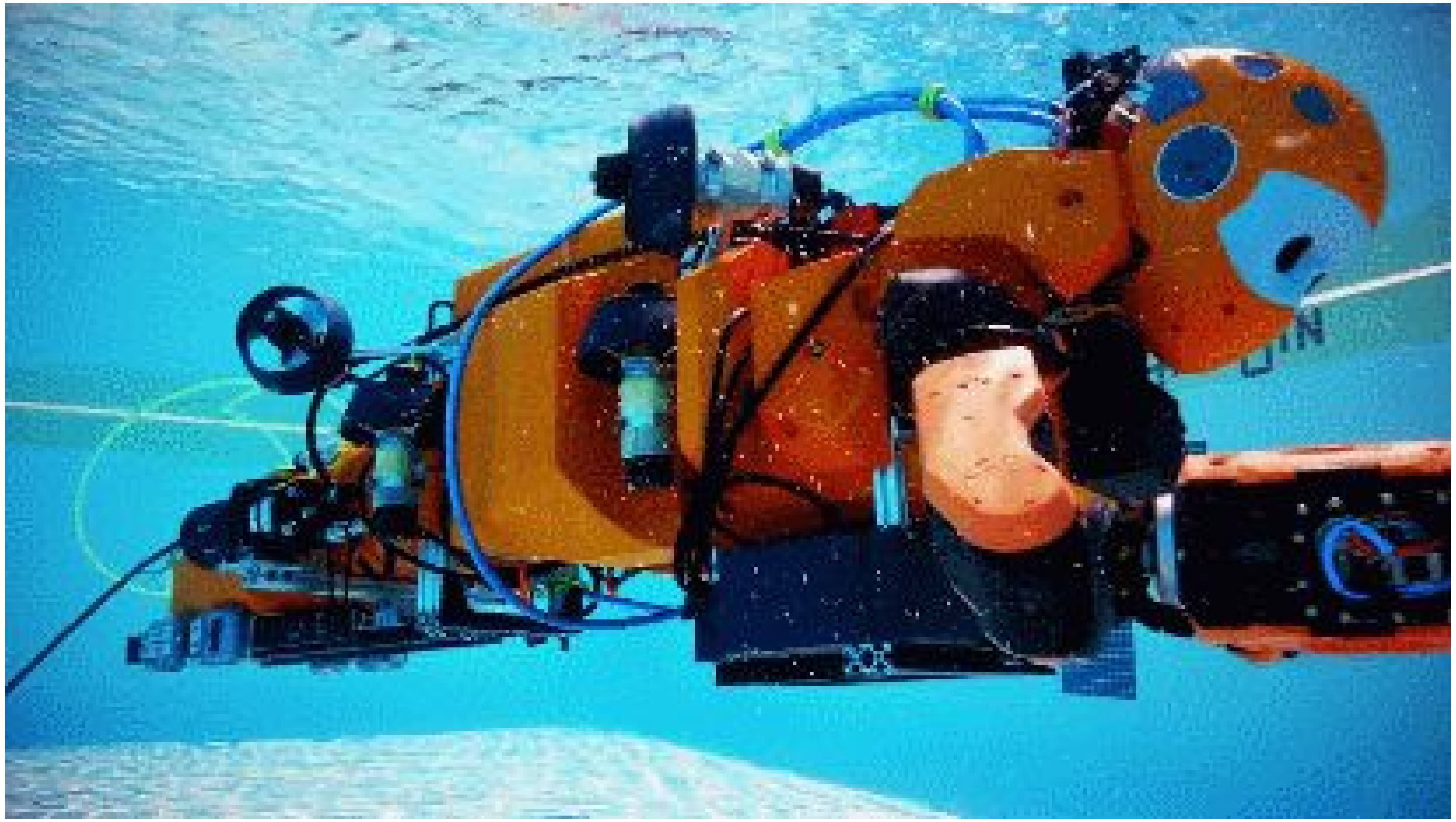
Digital System & control
Localization and Mapping
Path & Motion Planning

Robots: machines that automate some behavior



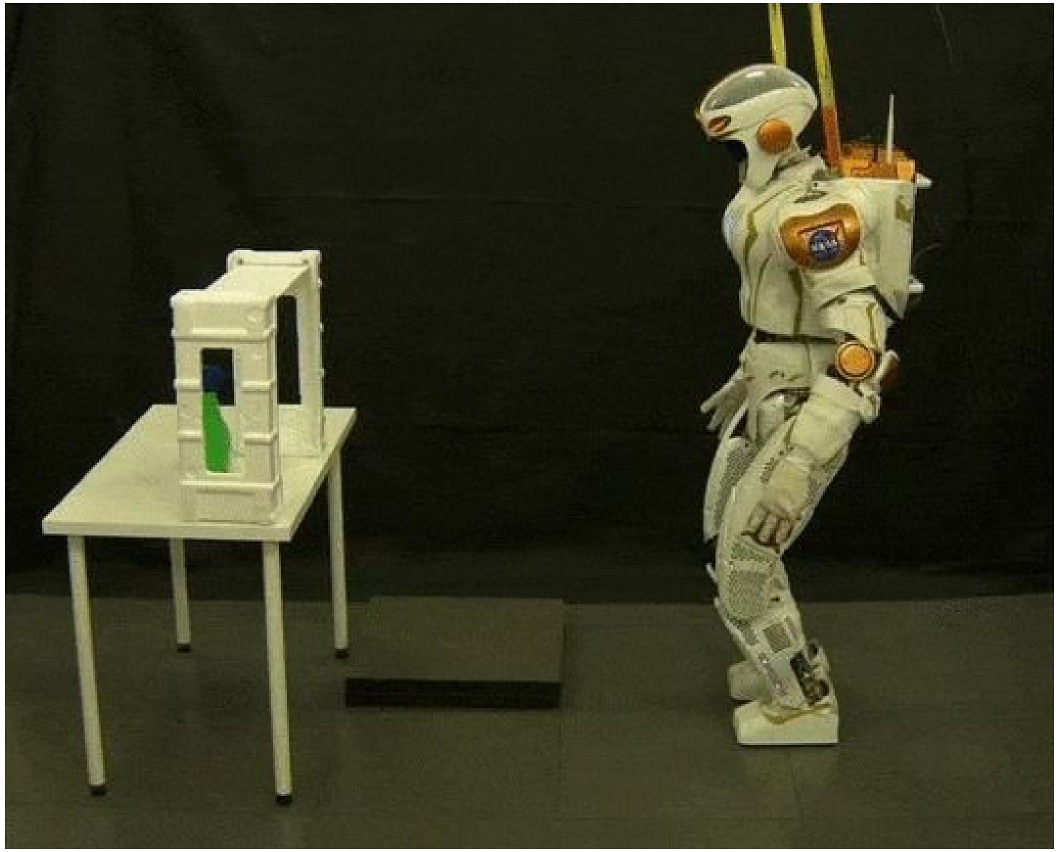
Spot-mini and Handle robots from Boston Dynamics

Robots: machines that automate some behavior



Ocean one, © Stanford University

Robots: machines that automate some behavior



Valkyrie Robot, © University of Edinburgh

Related RSS elements:
Robot Kinematics & Dynamics
System Identification & State Estimation
Kalman Filter
Digital System & control
Design of Advanced Controllers
Optimization
Model Predictive Control
Trajectory Planning and Motion Planning

Mechanism & mechanical design

Design of humanoid robots

Honda Asimo robots

Design of humanoid robots

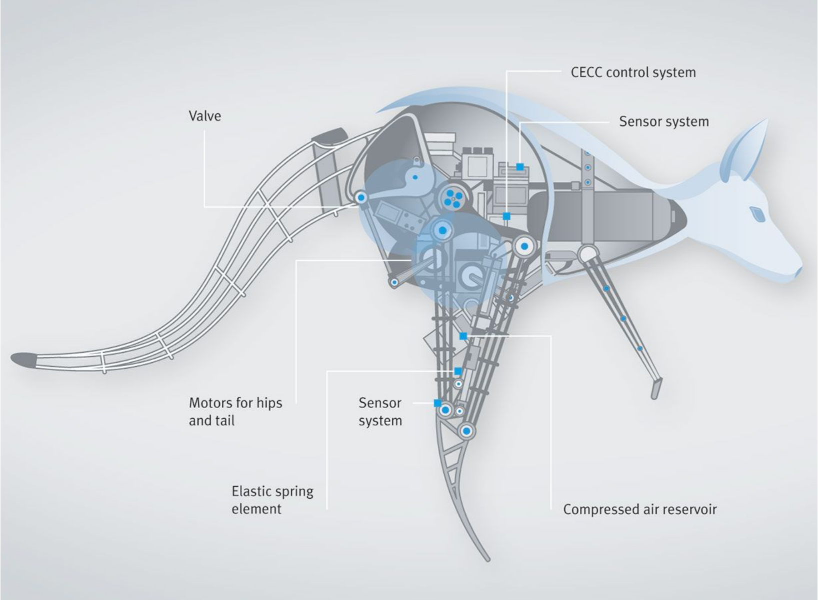
HRP robots

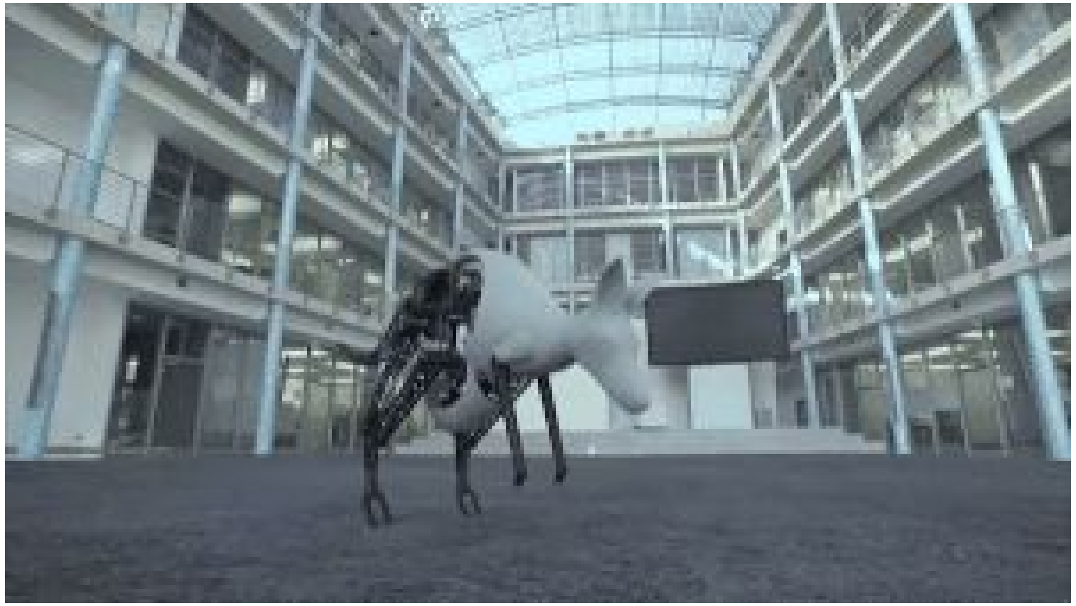
Robots are getting lighter and stronger

Biomimetic robot

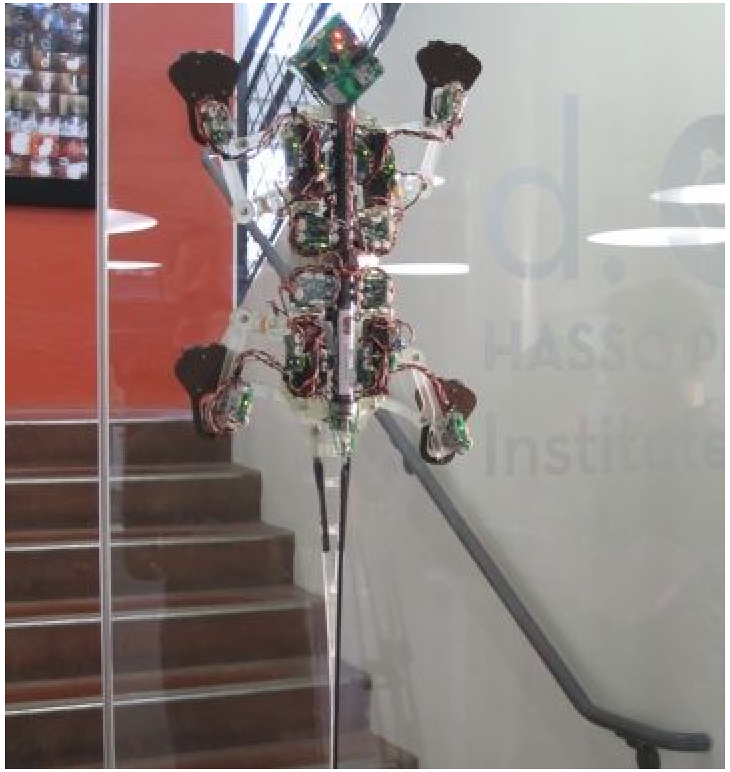
©Festo robot

Biomimetic robot





Biomimetic robot



Biomimetics and Dexterous Manipulation Lab, Stanford

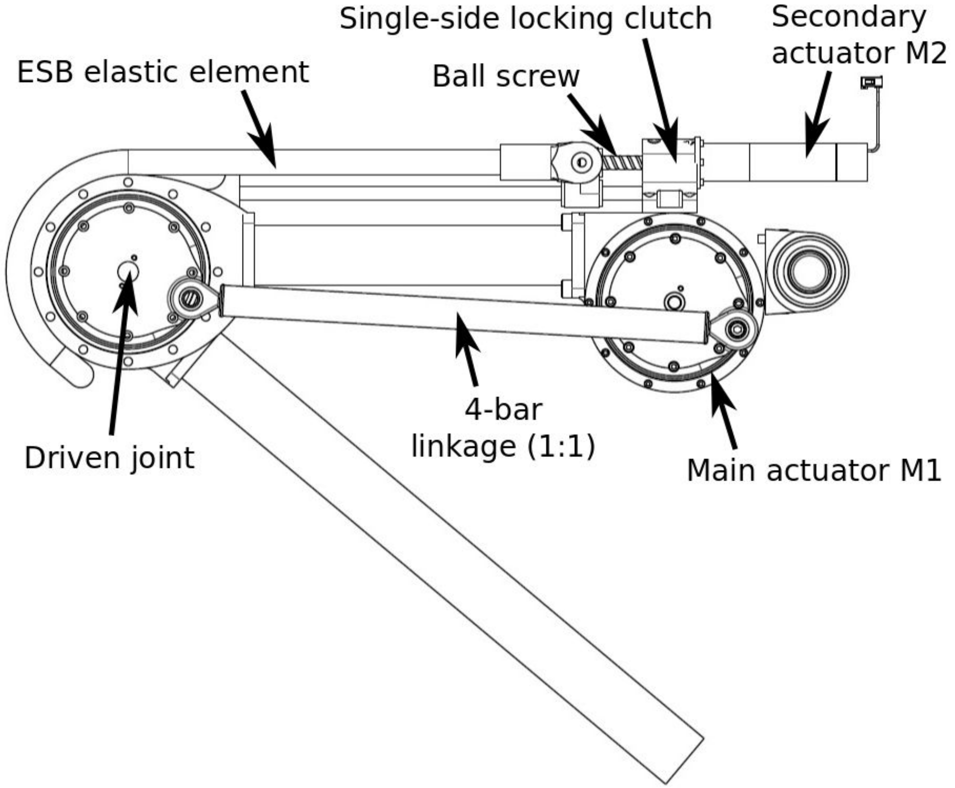
Smart mechanism

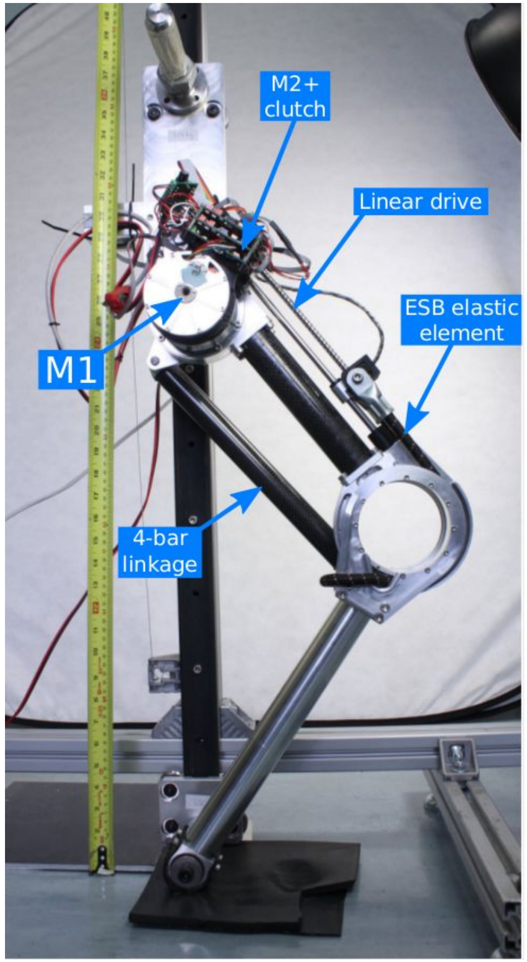
Metamorphic robots kings, see video

From Prof. Jian S. Dai, King's College London: http://nms.kcl.ac.uk/jian.dai/research.html

Design of energy-efficient robotic legs

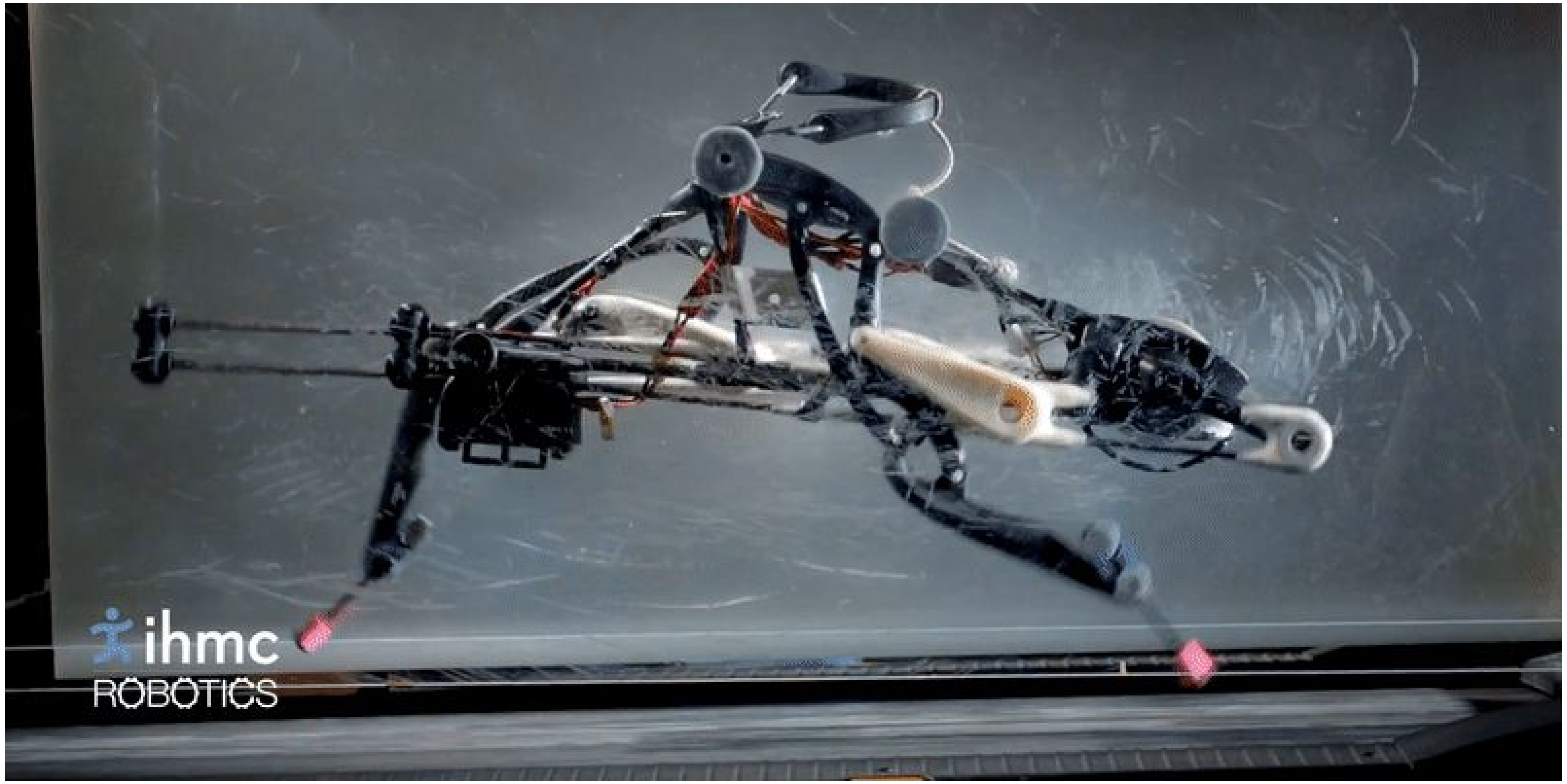
Smart design of using soft elements for strong energy.





W. Roozing, Z. Li, G. A. Medrano-Cerda, D. G. Caldwell and N. G. Tsagarakis, "Development and Control of a Compliant Asymmetric Antagonistic Actuator for Energy Efficient Mobility," in IEEE/ASME Transactions on Mechatronics, vol. 21, no. 2, pp. 1080-1091, April 2016.

Smart mechanism: ostrich runner



Related field/knowledge: Newtonian & Solid Mechanics, Rigid body dynamics (momentum, force acting on rigid body, kinetic & potential energy).
Book: Featherstone, Roy. Rigid body dynamics algorithms. Springer, 2014.
Articles: IEEE/ASME Transactions on Mechatronics.

Related RSS elements

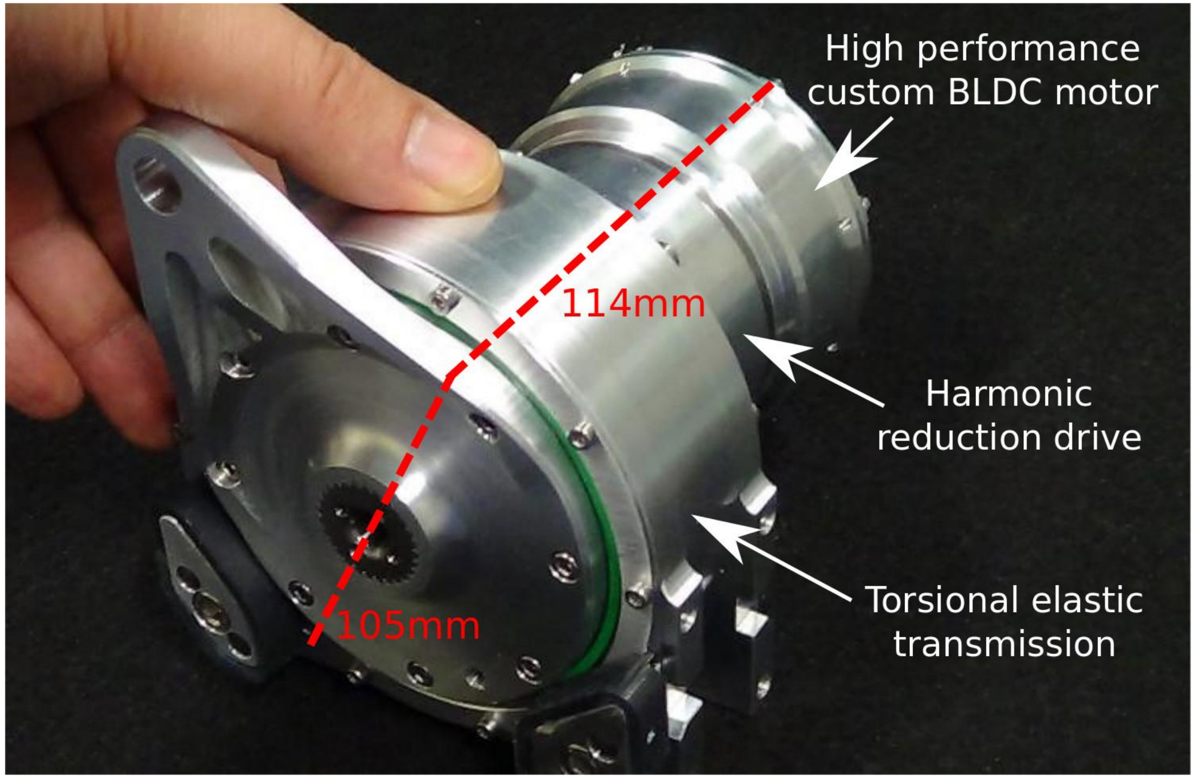
The mechanical design of these systems are not the scope of RSS, however, controlling them involves:

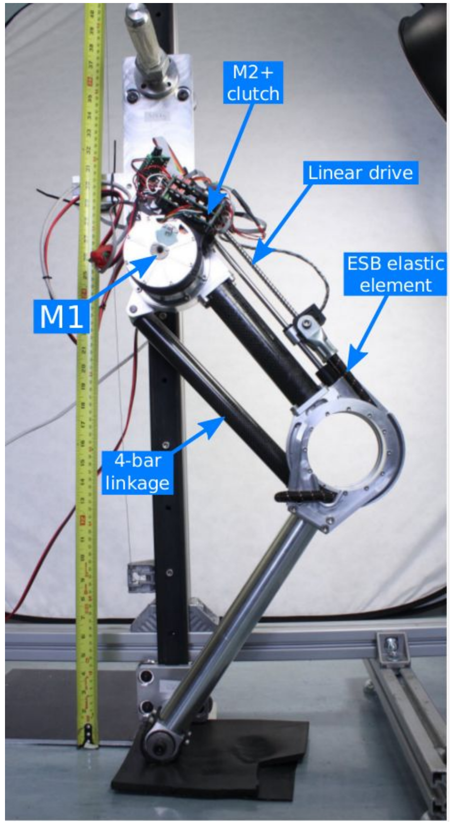
- Robot Kinematics & Dynamics
- Kalman Filter
- Digital System & control
- Design of Advanced Controllers
- Optimization
- Trajectory Planning and Motion Planning

Actuation

High-power actuators

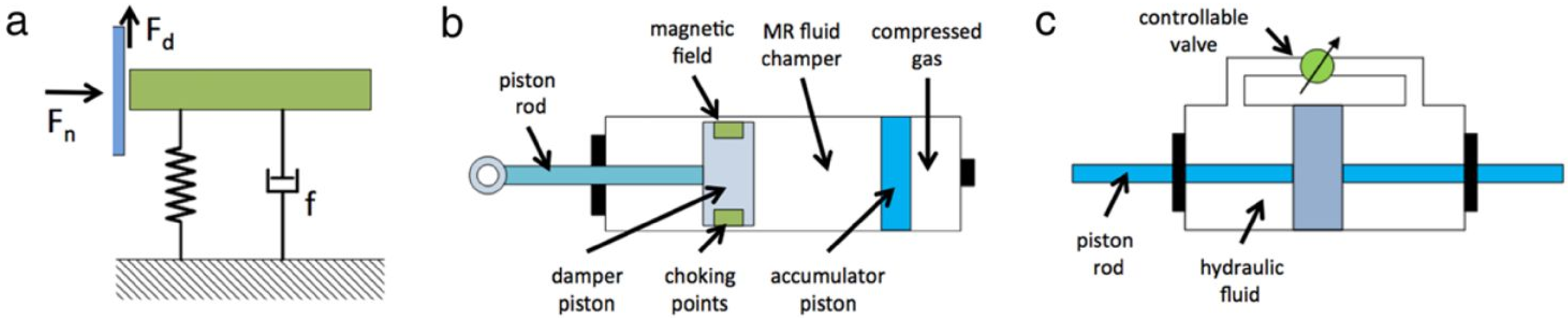
Actuator of the previous example: torque control, high power





Soft actuators

Variable impedance by active control



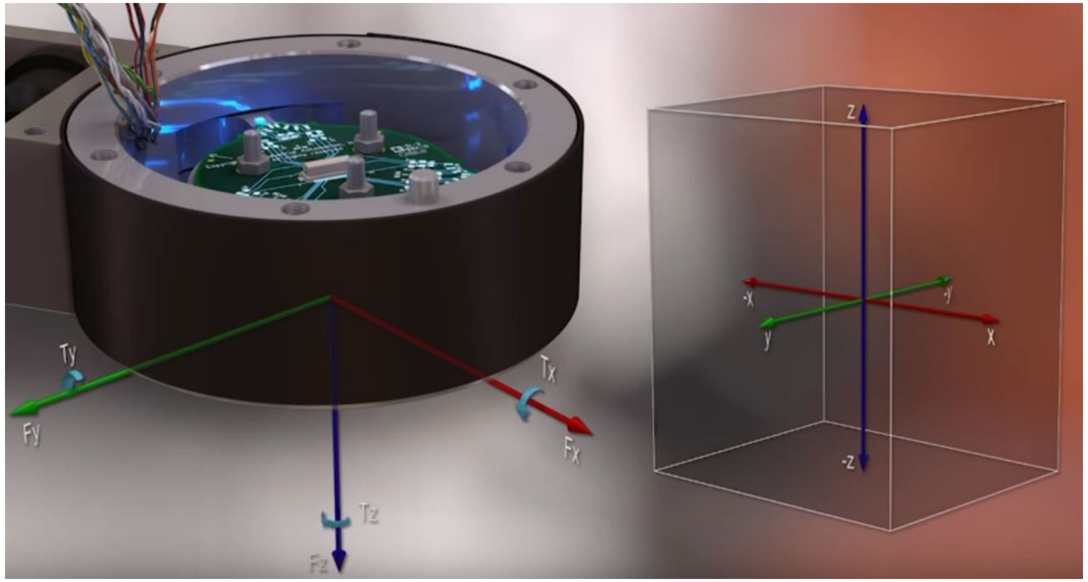
Different variable damping actuator principles: (a) friction, (b) MR, (c) variable orifice fluid damper.

Vanderborght, Bram, et al. "Variable impedance actuators: A review." *Robotics and autonomous systems* 61.12 (2013): 1601-1614.

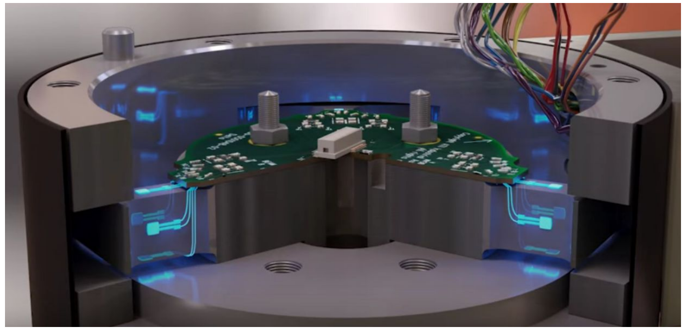
Sensing

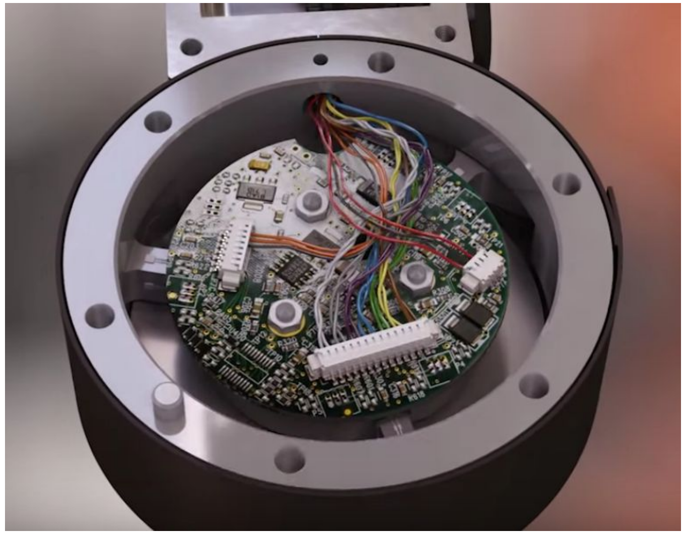
Torque sensors

Force/torque sensing



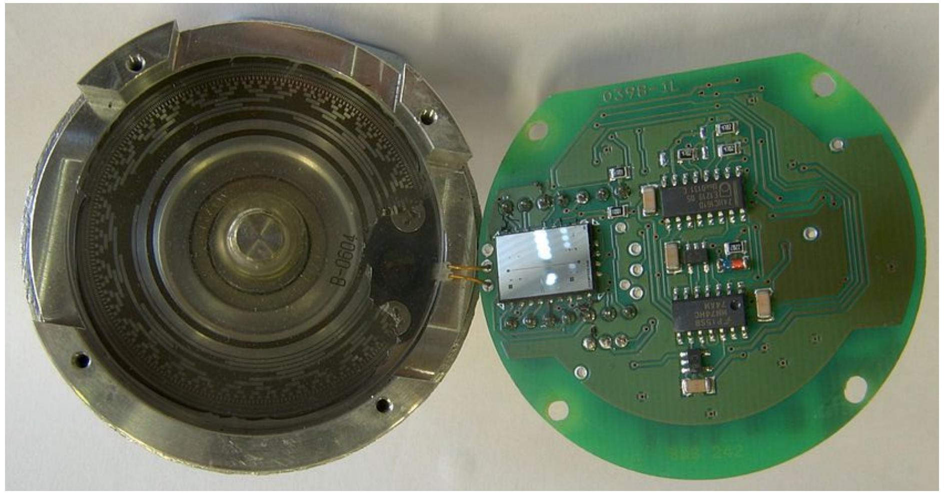
6-axis FT sensor typically mounted on the end-effector

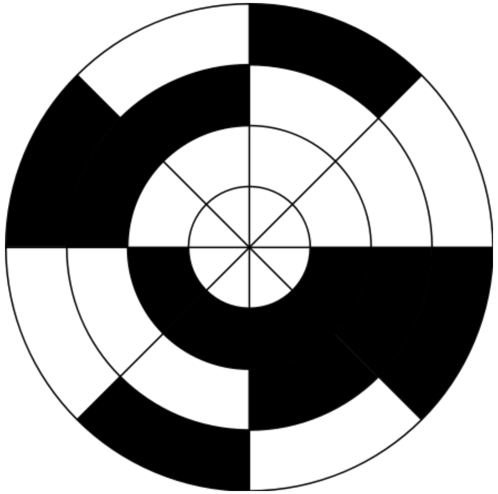




Position sensors

Absolution position sensors





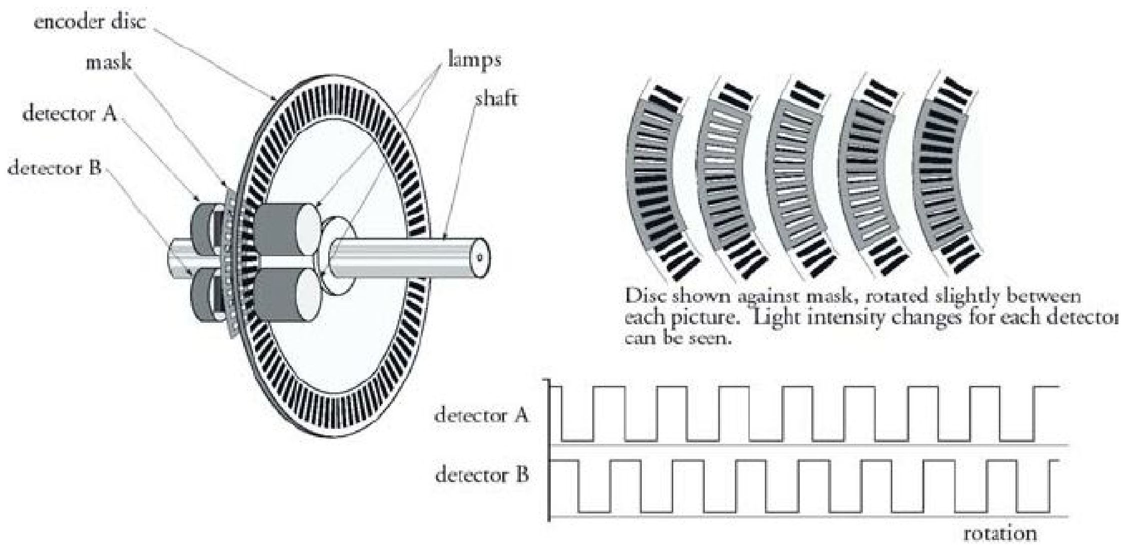
Mechanical absolute encoders

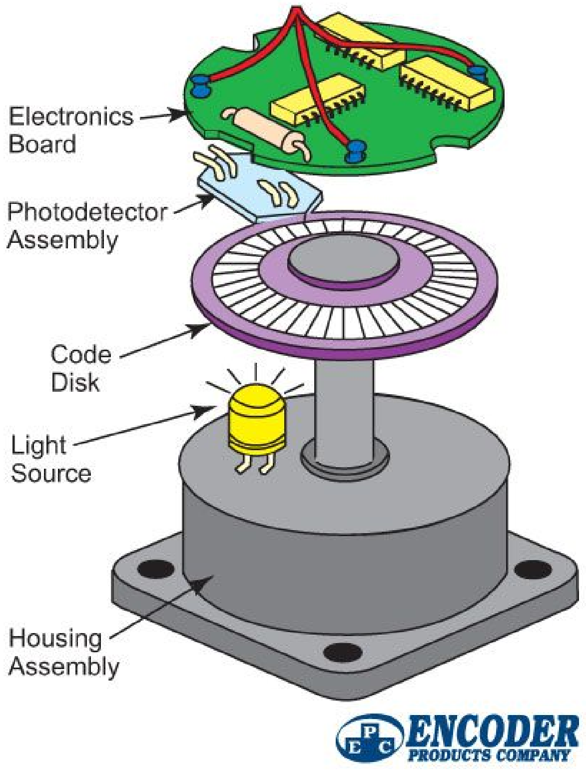
Optical absolute encoders (13 tracks)

Schematics of optical absolute encoders (3 tracks)

Position sensors

Relative position sensors, usually have higher resolutions.

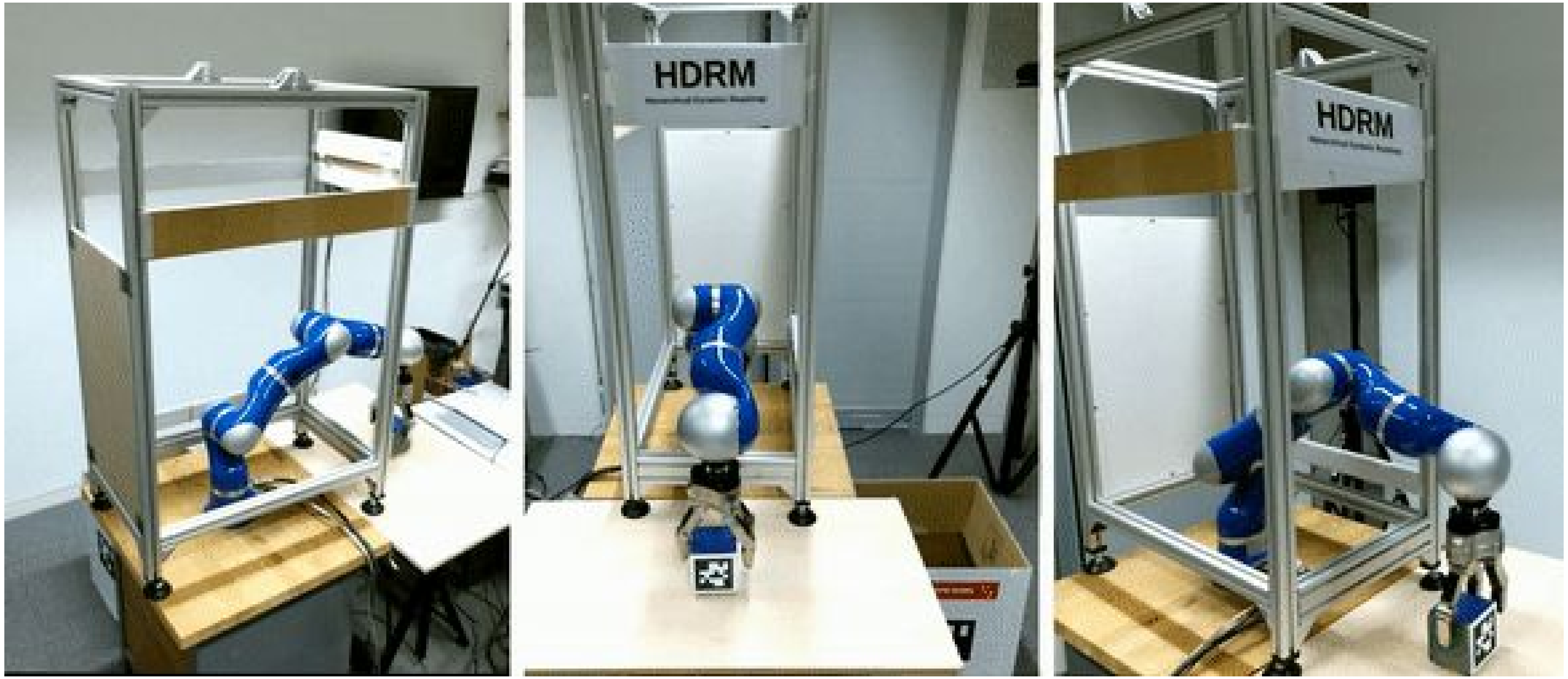




Motion capabilities: manipulation, locomotion & localization

Motion capabilities: manipulation

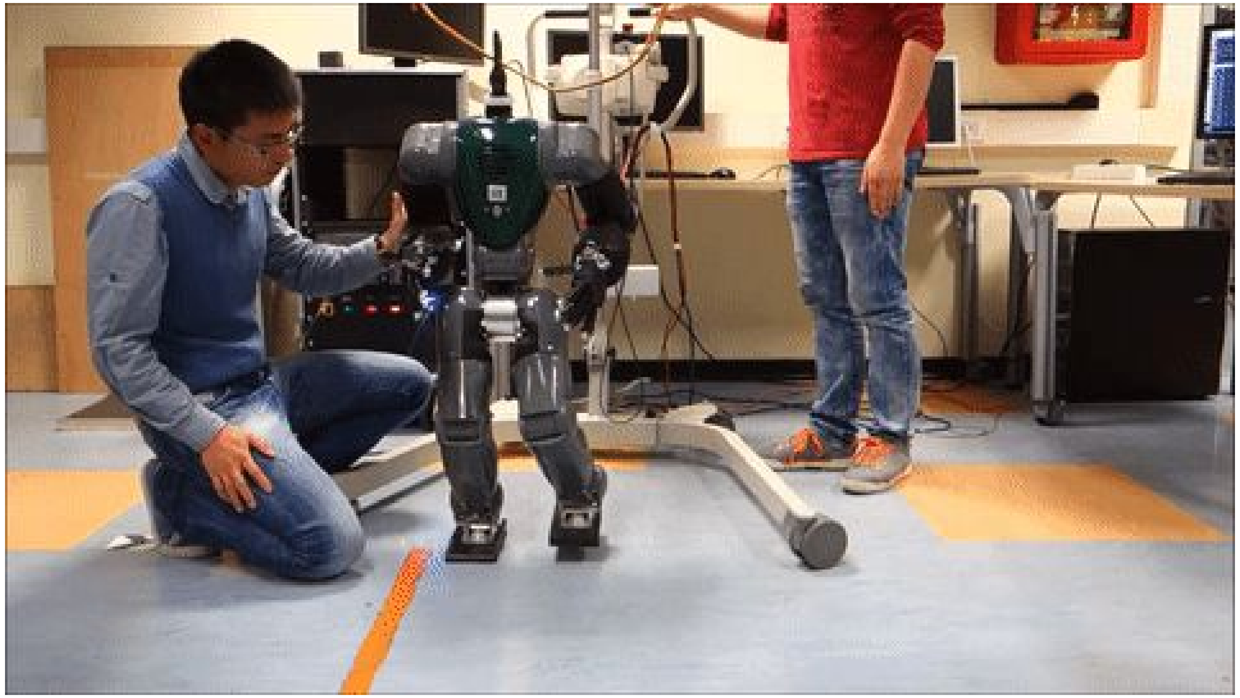
Retrieving an object in a clustered environment.



Yiming Yang et al., “HDRM: A Resolution Complete Dynamic Roadmap for Real-Time Motion Planning in Complex Environments”, 2017

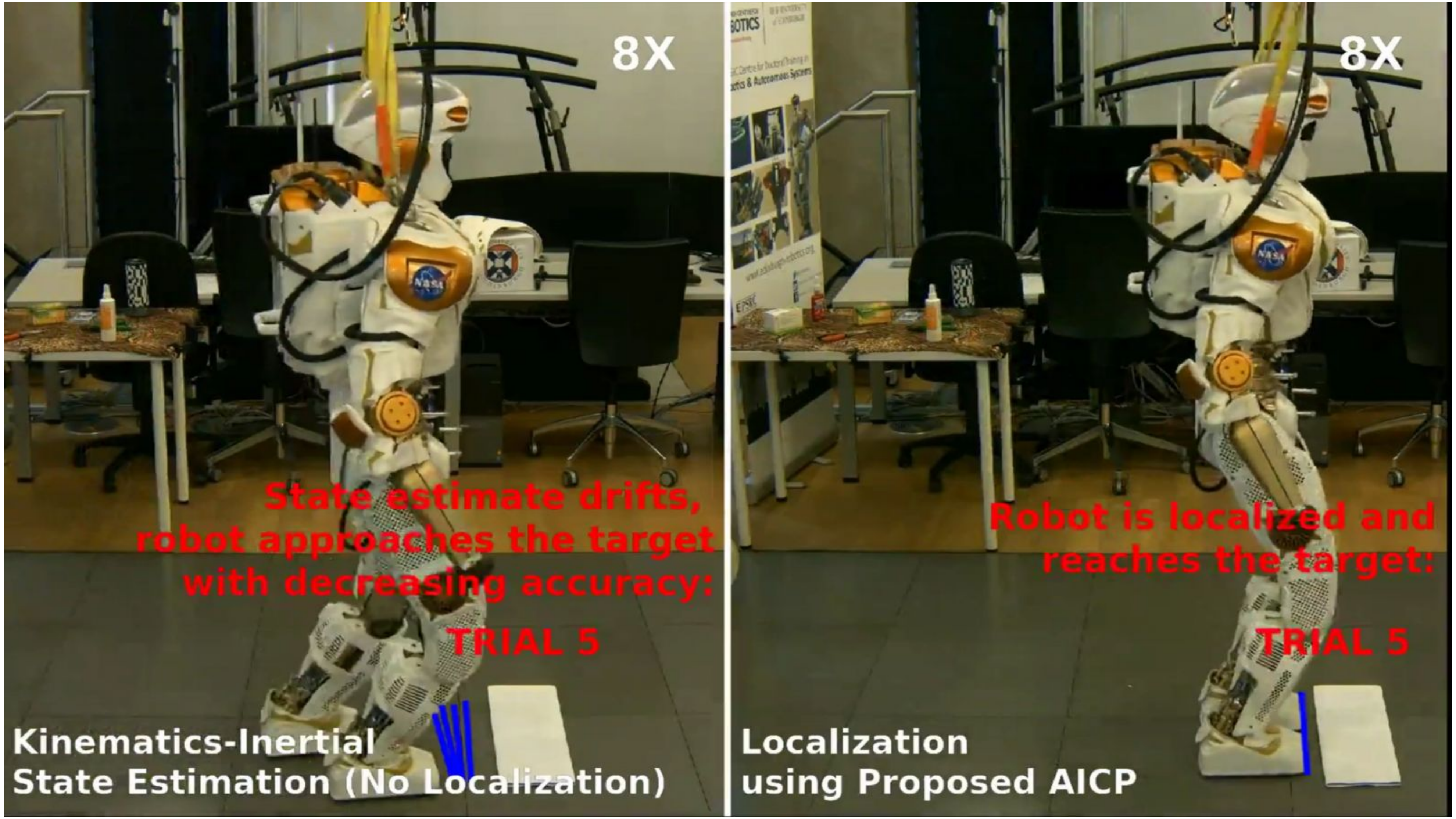
Motion capabilities: manipulation

Bipedal walking in presence of external pushes



Related field/knowledge: Kinematics, Collision-avoidance motion planning, Rigid body dynamics.
Book: Featherstone, Roy. Rigid body dynamics algorithms. Springer, 2014.
Articles: IEEE Transactions on Robotics; IEEE International Conference on Robotics and Automation (ICRA), etc.

Motion capabilities: localization



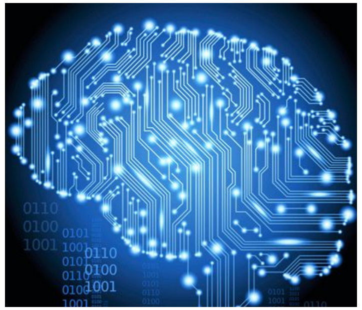
Related RSS elements in these systems

- Robot Kinematics & Dynamics
- Localization and Mapping
- Path & Motion Planning
- Kalman Filter
- Digital System & control
- Design of Advanced Controllers
- Optimization
- Model Predictive Control
- Trajectory Planning and Motion Planning

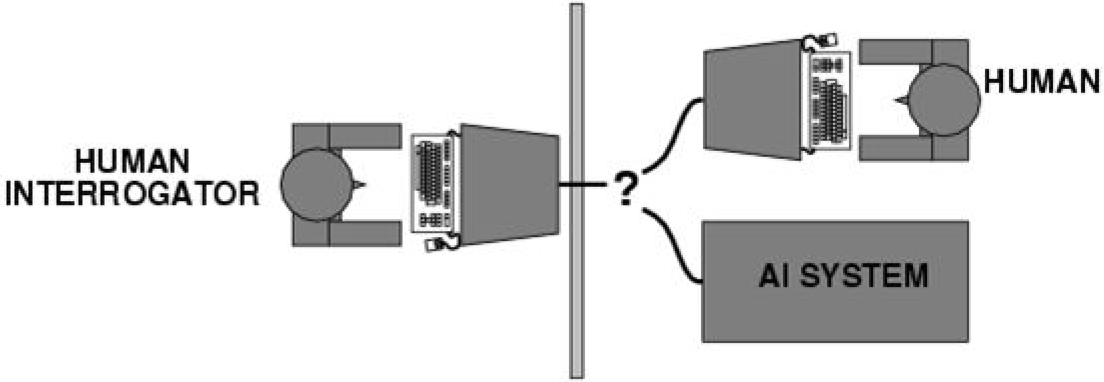
Artificial Intelligence (AI)

Ideas of AI

In the 1940s and 50s, a lot of discussion was held by scientists from different fields on the possibility of creating an artificial brain.



Can machines think? In 1950, Alan Turing proposed Turing Test: a human judge engages in a natural language conversation with a human and a machine designed to generate performance indistinguishable from that of a human being.



Turing Test

A natural language conversation, is that a human or a machine?

Hi, what is the news about Harvey?

Alana_live

[eliza-e557b16-2017-08-12-1858] Sorry I don't have access to that document.

I mean the hurricane.

Alana_live

[eliza-e557b16-2017-08-12-1858] So, what is your guilty pleasure?

Ok. What is the news about Harvey hurricane?

Alana_live

[persona-e557b16-2017-08-12-1858] Thank you! I am still learning. What do you want to talk about next? I can tell you an interesting fact or chat about politics, news, or movies..

news on Harvey hurricane

Alana_live

[eliza-e557b16-2017-08-12-1858] So what is the last concert you went to?

news on Harvey

Alana_live

[eliza-e557b16-2017-08-12-1858] Anyway, what are your plans for the rest of the day?

news on Harvey

Alana_live

[news_api-f5f1472-2017-08-11-1640] I heard on the radio that The Specter of Climate Change Hangs Over Hurricane Harvey. Was Hurricane Harvey the result of climate change? Do you want to know more?

The *Dartmouth workshop*

In 1956, a summer workshop for artificial intelligence, named the *Dartmouth Summer Research Project on Artificial Intelligence* open a new field of AI.

In John McCarthy's proposal, he stated that the conference was

"to proceed on the basis of the conjecture that every aspect of learning or any other feature of intelligence can in principle be so precisely described that a machine can be made to simulate it."

Archive of Dartmouth workshop: http://raysolomonoff.com/dartmouth/

The *Dartmouth workshop*

The Proposal states:

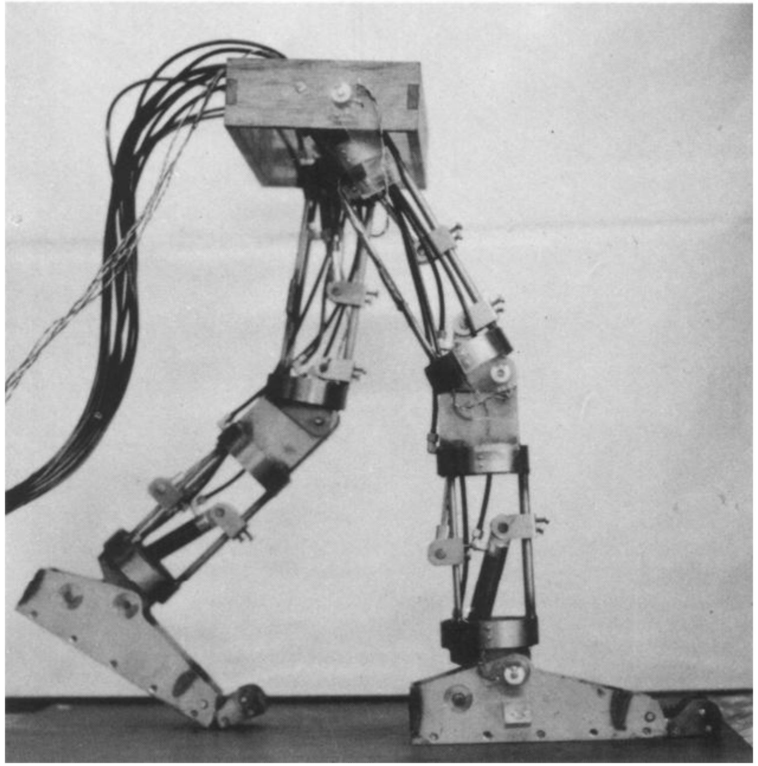
“We propose that a 2 month, 10 man study of artificial intelligence be carried out during the summer of 1956 at Dartmouth College in Hanover, New Hampshire. The study is to proceed …... We think that a significant advance can be made in one or more of these problems if a carefully selected group of scientists work on it together for a summer.”

1956, birth of the field of artificial intelligence (AI) research.

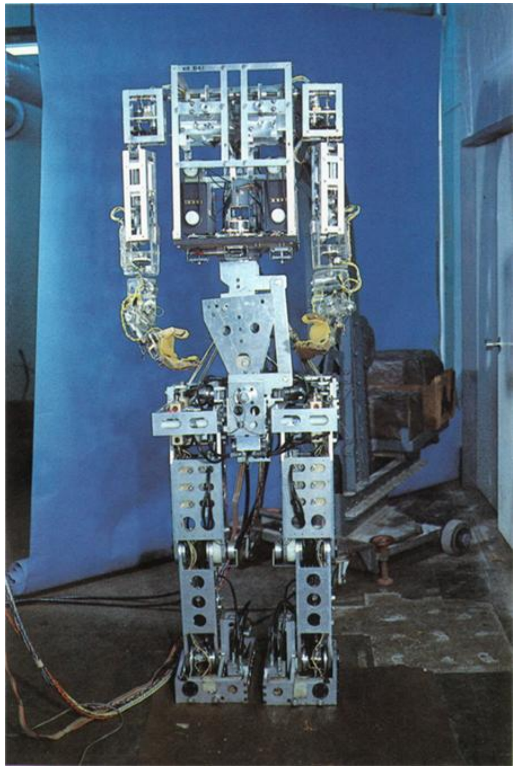
Original proposal: https://www.cs.swarthmore.edu/~meeden/cs63/f11/AIproposal.pdf

Golden age of AI 1956–1974

Development of humanoid robot occurred in this golden age. Waseda University, Japan, initiated the WABOT project in 1967, and in 1972 completed the WABOT-1, the world's first full-scale intelligent humanoid robot.



WL-3-1969

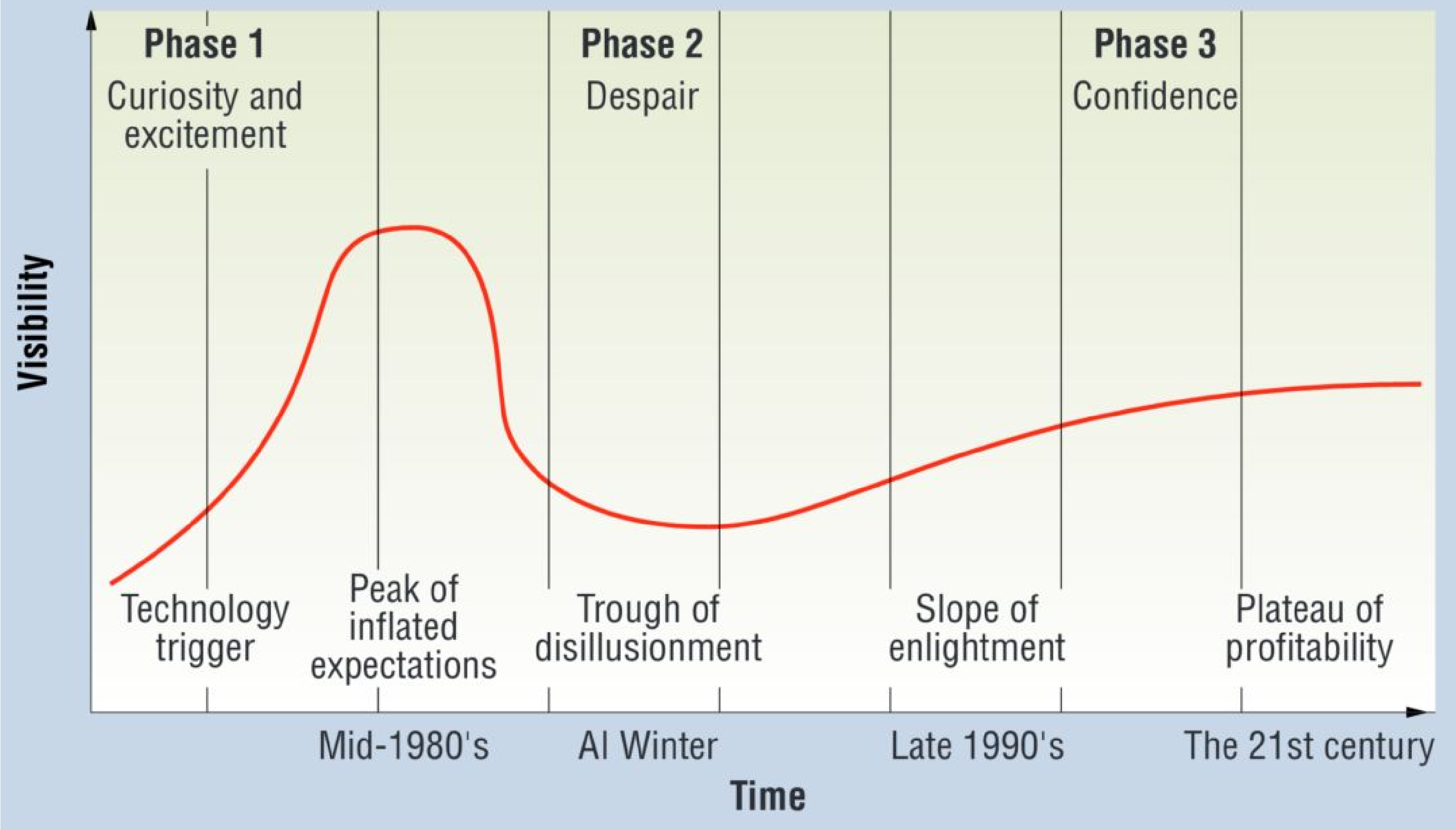


WABOT-1, 1973

WABIAN-2R, 2008

AI winter

AI, cannot be exempted from the hype cycle for new technology.

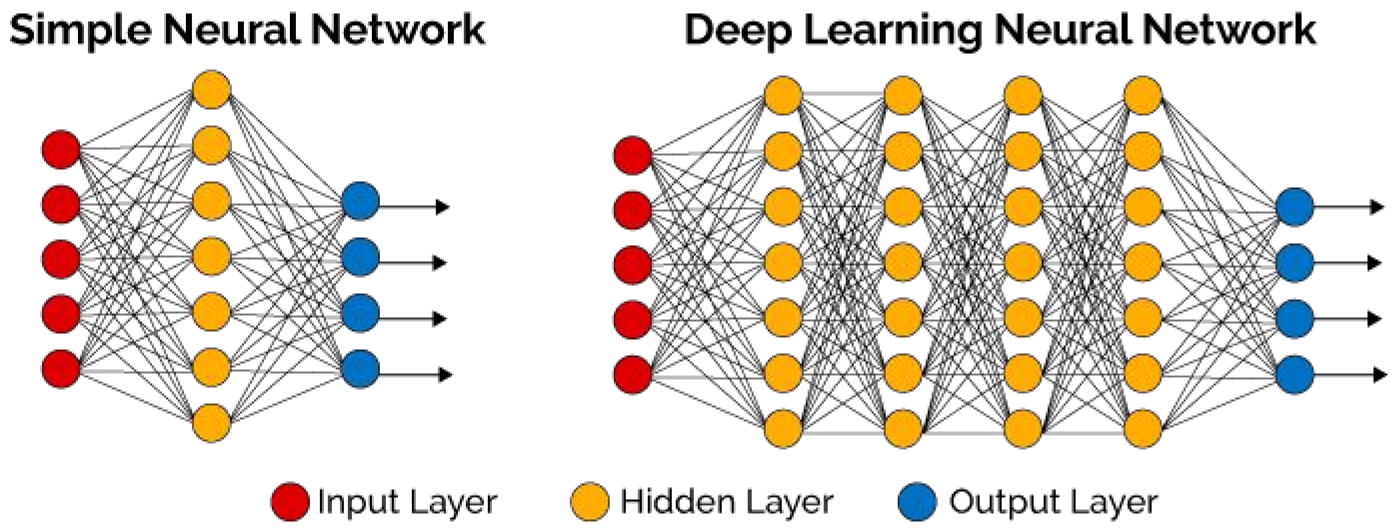


Menzies, Tim. "21st-century ai: Proud, not smug." IEEE Intelligent Systems 18.3 (2003): 18-24.

New era of deep learning, 2012

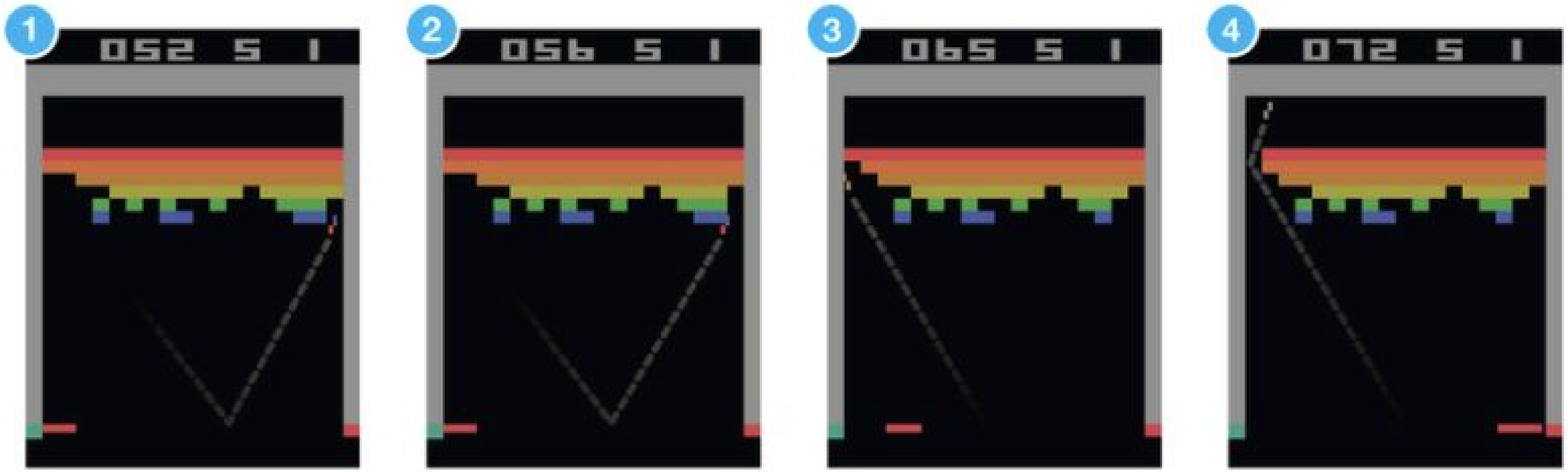
In 2012, Deep Convolutional Neural Networks won the large-scale ImageNet competition by a significant margin over shallow machine learning methods.

Deep learning: more hidden layers, which enable composition of features from lower layers, potentially modeling complex data with fewer units than a similarly performing shallow network.



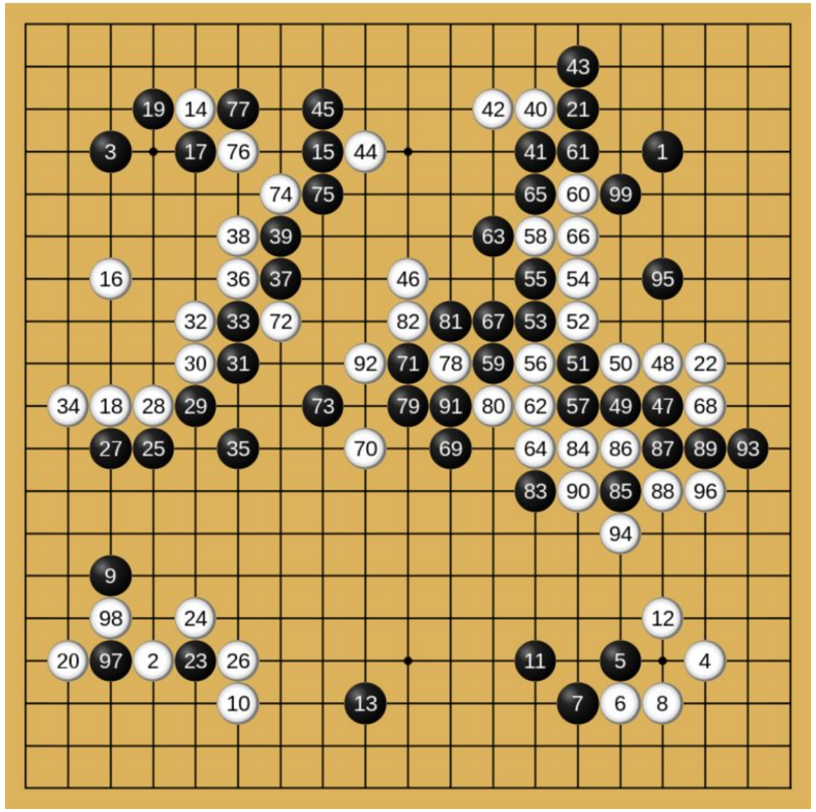
New era of deep learning, 2014

2014, DeepMind developed Deep Q-learning capable of learning how to play Atari video games using only pixels as data input. [video]



Alpha-Go vs Lee Sedol, 2016

AlphaGo is a narrow AI specialized in playing the board game Go.



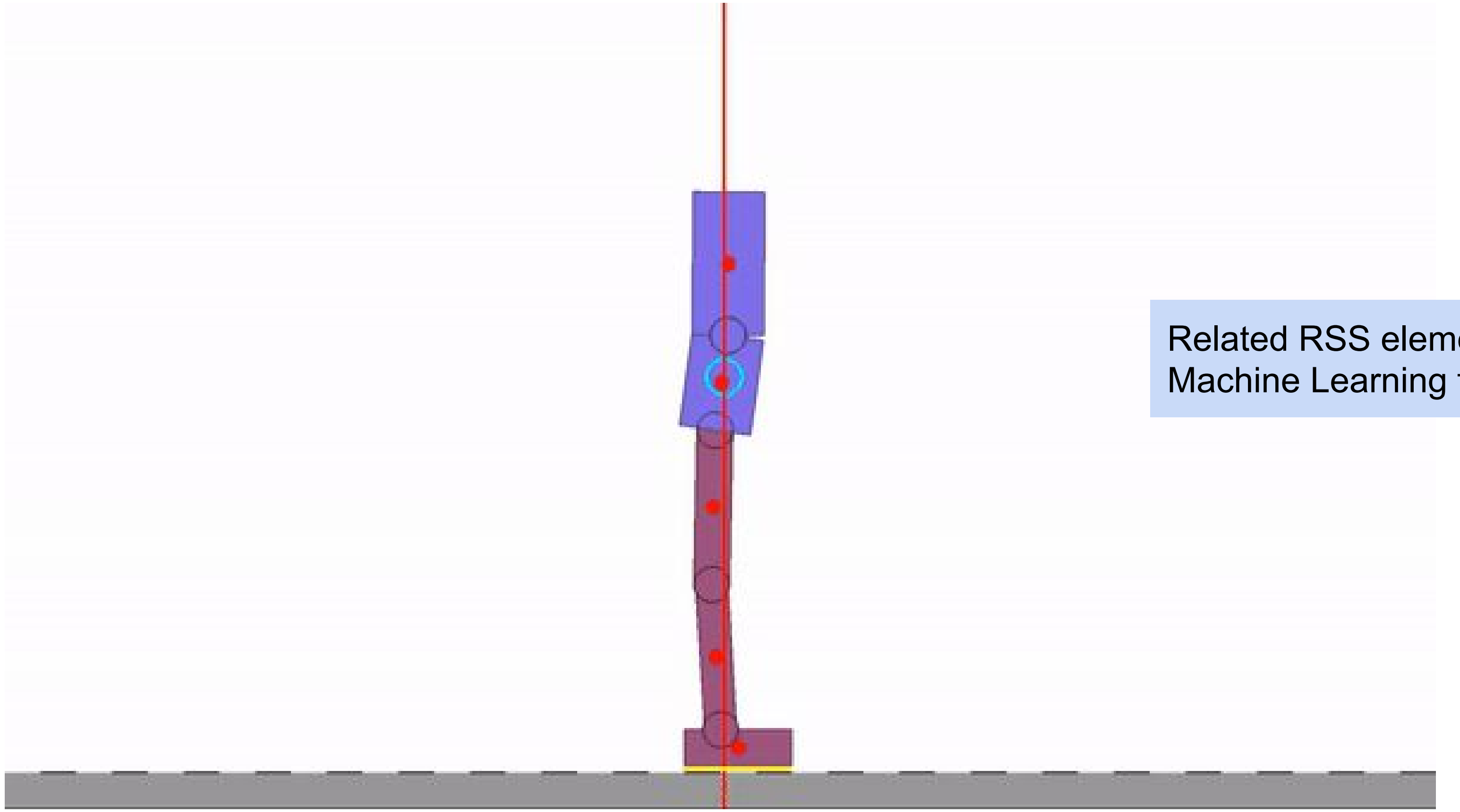
Alpha-Go vs Lee Sedol, 2016

What AI and robotics still cannot do? Can you see it?

Reliable control of physical interaction is hard in a real world.

Machine learning for solving robotics problems

Balance control of humanoid robot

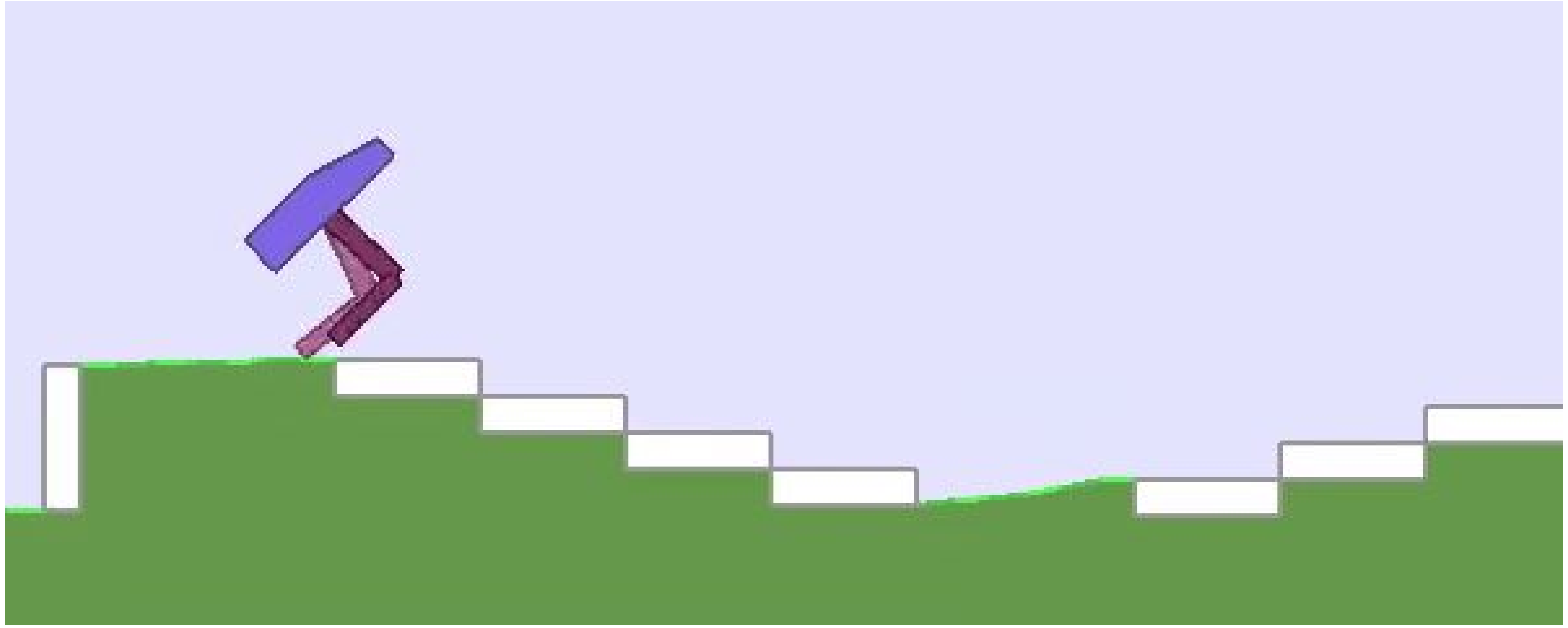


Related RSS elements:
Machine Learning for Robot Control

Credits: Chuanyu Yang, PhD student, University of Edinburgh

Machine learning for solving robotics problems

Solving Bipedal-Walker challenge in OpenAI gym.



Related RSS elements:
Machine Learning for Robot Control

Credits: Doo Re Song Msc thesis,School of Informatics; Chuanyu Yang, PhD student, University of Edinburgh

Level of robot intelligence

Robot intelligence

Level 5	Human intelligence level
Level 4	Task-level programming
Level 3	Structured programming
Level 2	Motion primitive programming
Level 1	Point to point programming

Areas of robotics

Diversity of categorization

By applications/services: welding, warehouse, cleaning, robots

By particular (actuation) technology: hydraulic, pneumatic robots

By the environment of the applications: aerial, aquatic, ground, space, underwater robots

By morphologies: robot arms, humanoid, insect (bio-inspired) robots

By features of functionality: wheeled, legged robots

…………

There are usually multiple ways of defining the type of robots.

Robots in industry

YASKAWA: motoman.com

FANUC: fanuc.eu/uk/en/robots

Kawasaki Robotics: robotics.kawasaki.com

ABB: new.abb.com/products/robotics

KUKA: kuka.com

Schunk: schunk.com/be_en/homepage

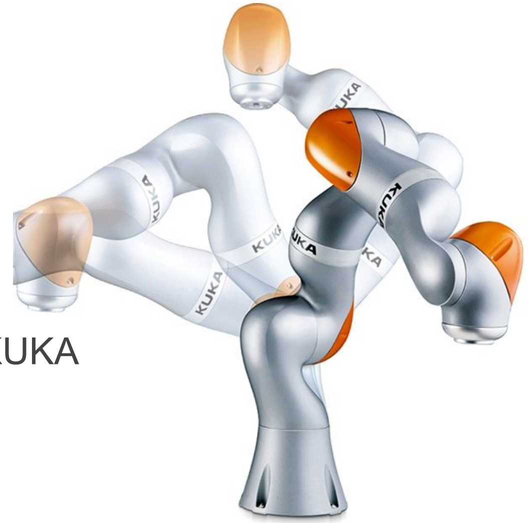
Universal Robots: universal-robots.com

Industrial robots

YASKAWA

Fanuc

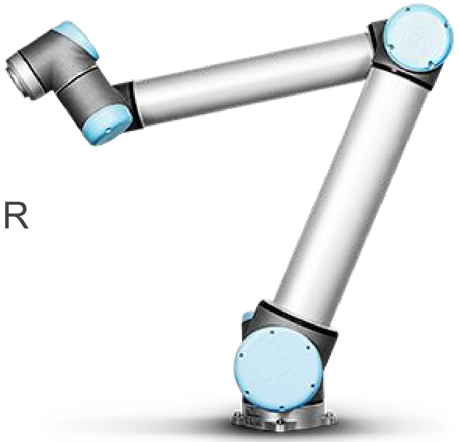
KUKA



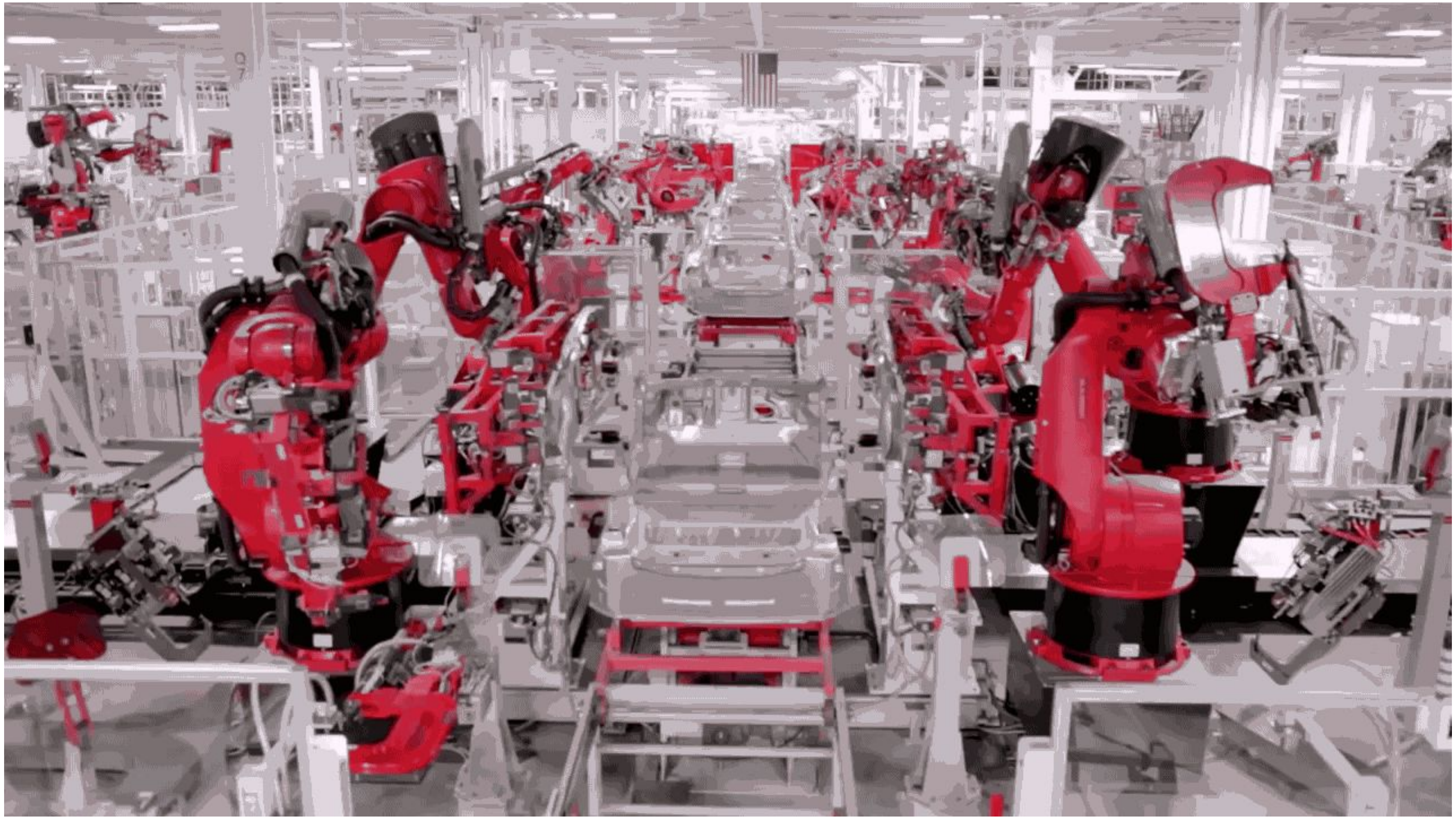
ABB

Schunk

UR



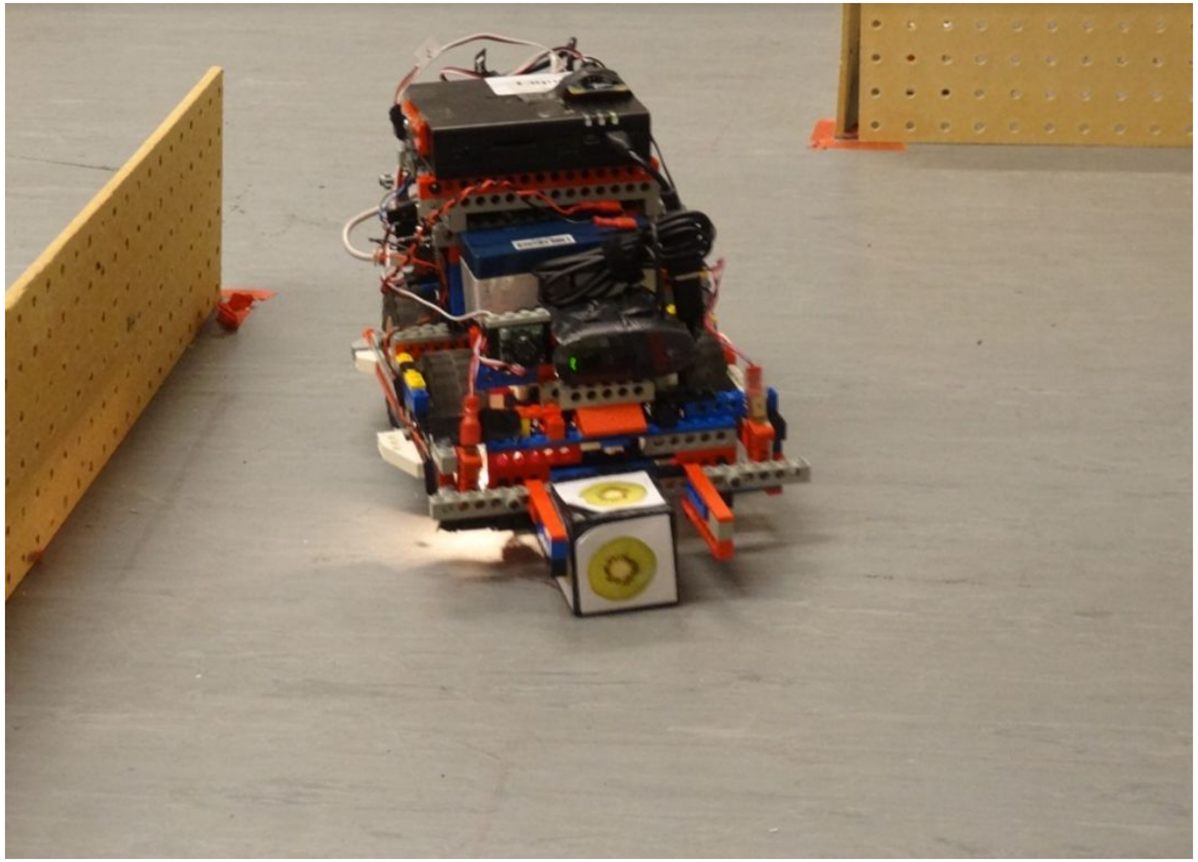
Car assembly in Tesla



Picture source: pinterest.com

Robots in education

RSS practical: student-built lego robot that navigates.



Robots in research

Valkyrie Robot, @ Edinburgh Centre for Robotics, University of Edinburgh

Robot Control

Robotics research

Historically, robotics strongly involves the realization of physical motions, and most robots are essentially motion systems (“robota” → labour).

Therefore, the majority of robotics research focuses on:

1. Sensors
2. Actuators
3. **<u>Control</u>**

Particularly, as sensing and actuation problems are being solved gradually, more effort is made towards control, or more precisely speaking, **autonomy**.

Automation → Autonomy → Intelligence

Concept of control

What is control?

1. Apply action or influence to achieve an expected outcome.
2. It needs to apply actions, an actuation or an agent.
3. It needs sensor feedback, a probe, if a feedback control system.

Generally, control (feedback control) is about reasoning about how to apply actions given the feedback information in order to achieve a goal.

Control systems

The 5 levels of robot intelligence are about how to **control** a robotic system.

Three levels of **control**:

1. **Servo/tracking control (SISO, MIMO)**
2. **Optimization, optimal control**
3. **Machine learning**

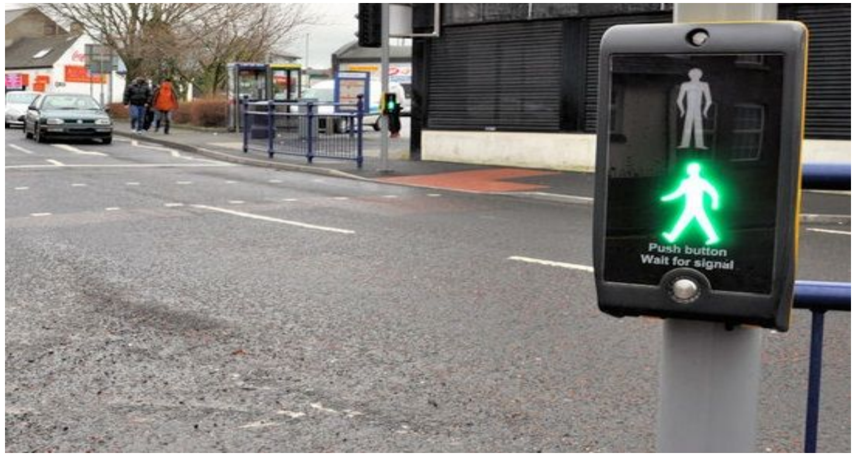
The first two are model-based approaches, where knowledge of mechanics and physics is required. Knowledge is given a priori, computationally cheap.

Machine learning is a model-free approach, it ‘learns’ the model through data in a statistical manner. Model is built by big data, computationally expensive.

Open-loop control

Examples:

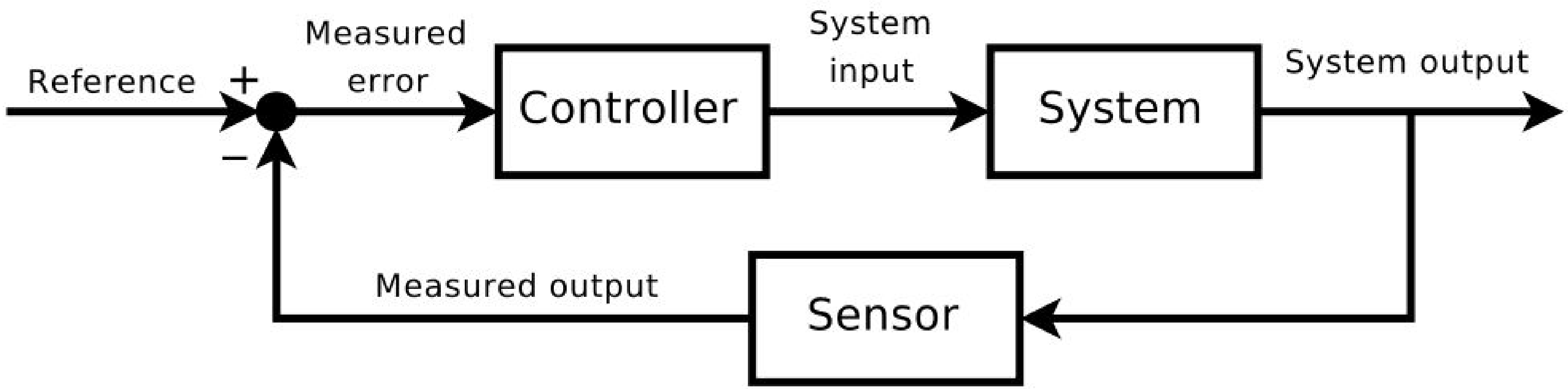
1. Traffic light system, only the request is the input, the rest is pre-programmed regardless of the situation;
2. Fountain;
3. Or your washing machine;
4. ⋮



Closed-loop control

Closed-loop (feedback) control: monitors feedback, uses the deviation signal to control the action so as to reduce the deviation to zero.

Note: closed-loop (feedback) control, closed-loop and feedback are mutually exchangeable words.



Closed-loop control

Closed-loop (feedback) control uses negative feedback.

A centrifugal governor is a good example of a mechanical controller.

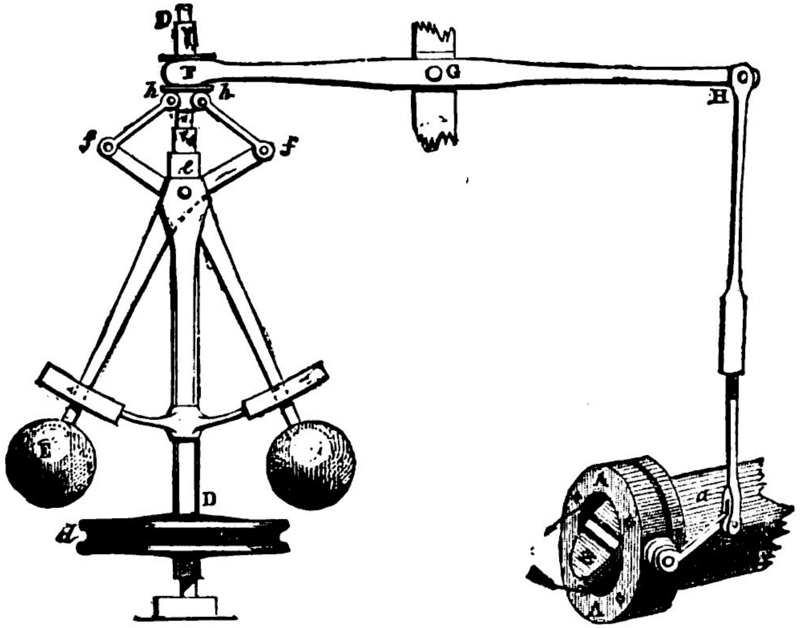


FIG. 4.—*Governor and Throttle-Valve.*

Invented in 1788 by James Watt to control the steam engine.

Robot control

Three levels of **control**:

1. **Servo/tracking control**
2. **Optimization, optimal control**
3. **Machine learning**

Typically featured by stable, robust, and dynamic motions

Typically featured by a diversity of intelligent behaviors

Human intelligence level

Task-level programming

Structured programming

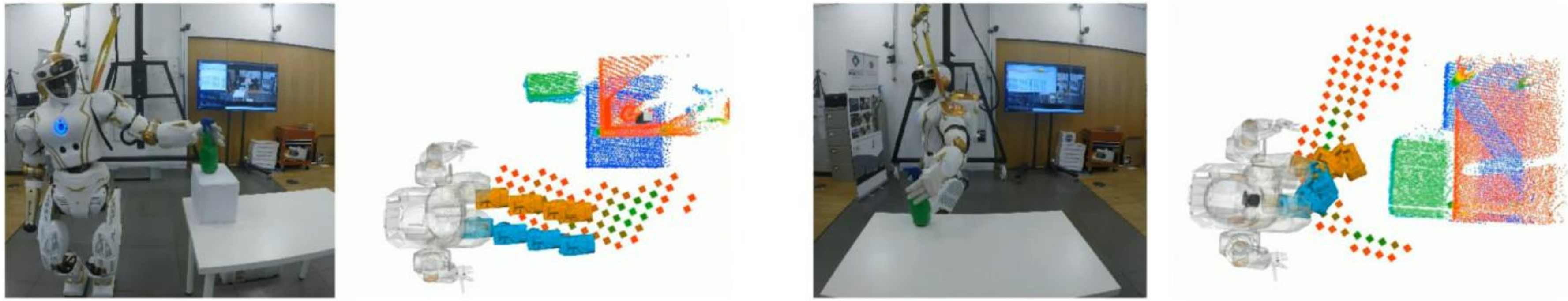
Motion primitive programming

Point to point programming

In many cases, as shown before, robot control attempts to *exploit* kinematics and dynamics of the system.

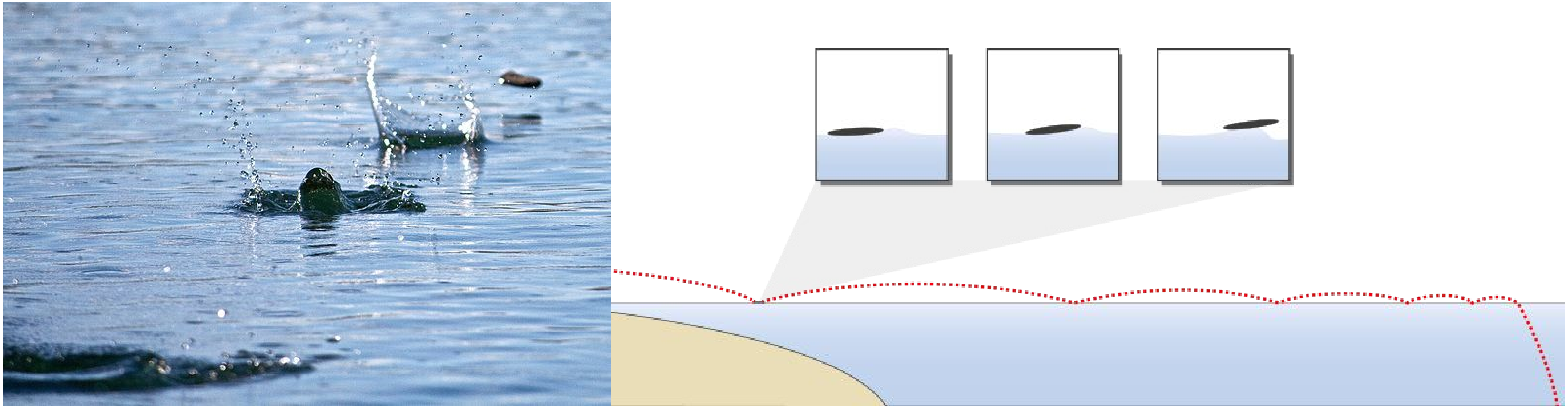
Why kinematics matter?

Explore all configurations, maximize or validate reachability.



Why dynamics matter?

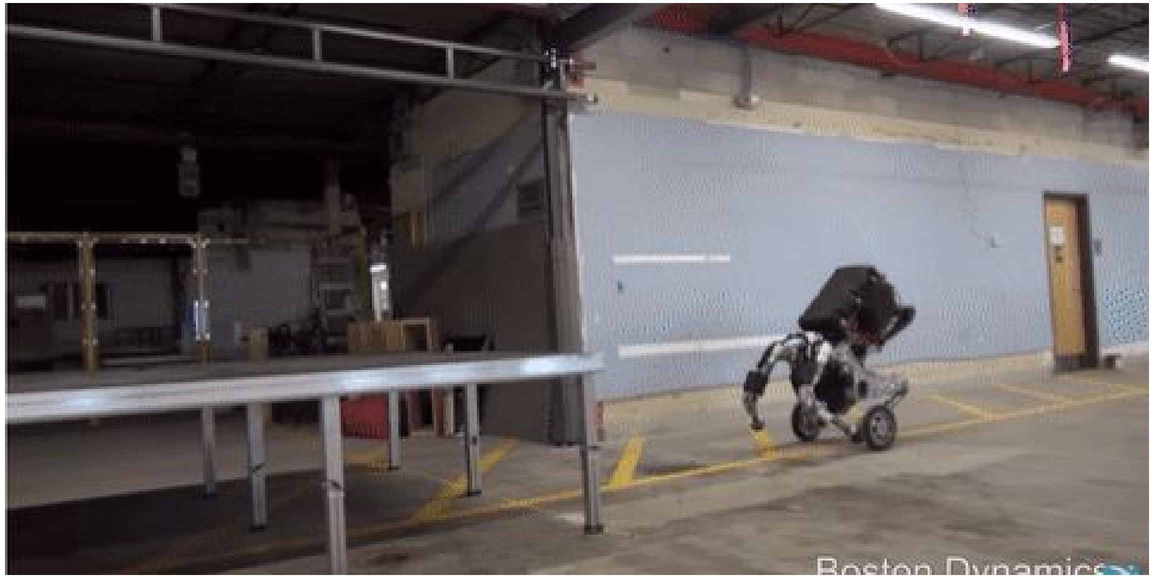
Can an object (ρ >0) stay above the water?

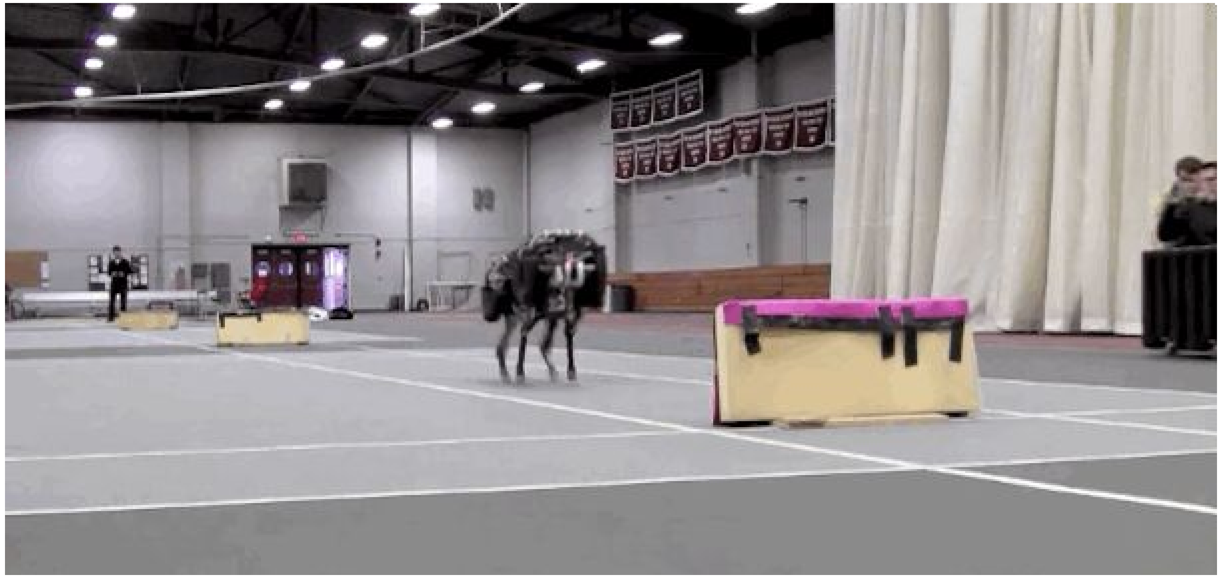


Stone skipping

Why dynamics matter?

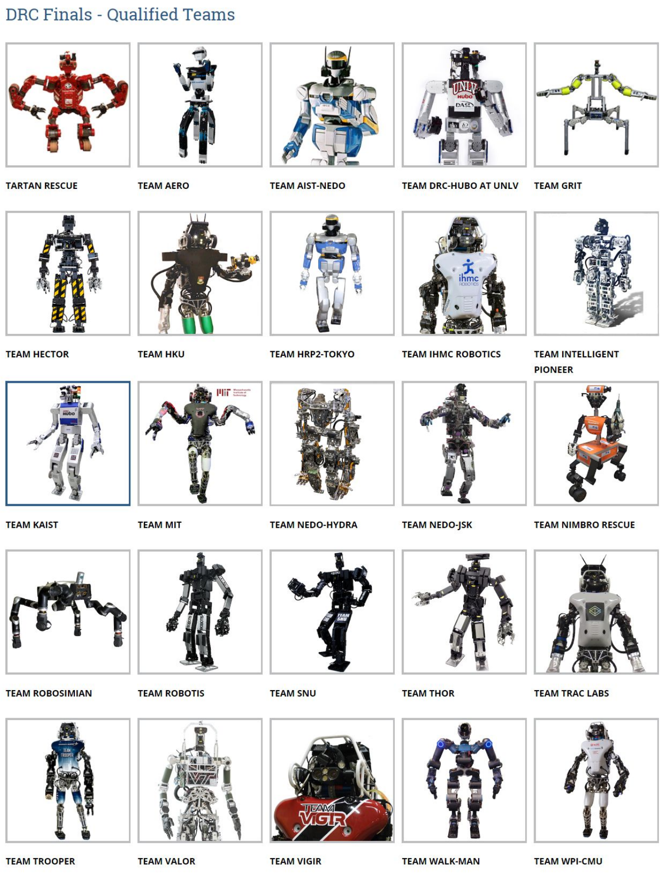
Tasks and performance that can only be achieved by dynamic motions

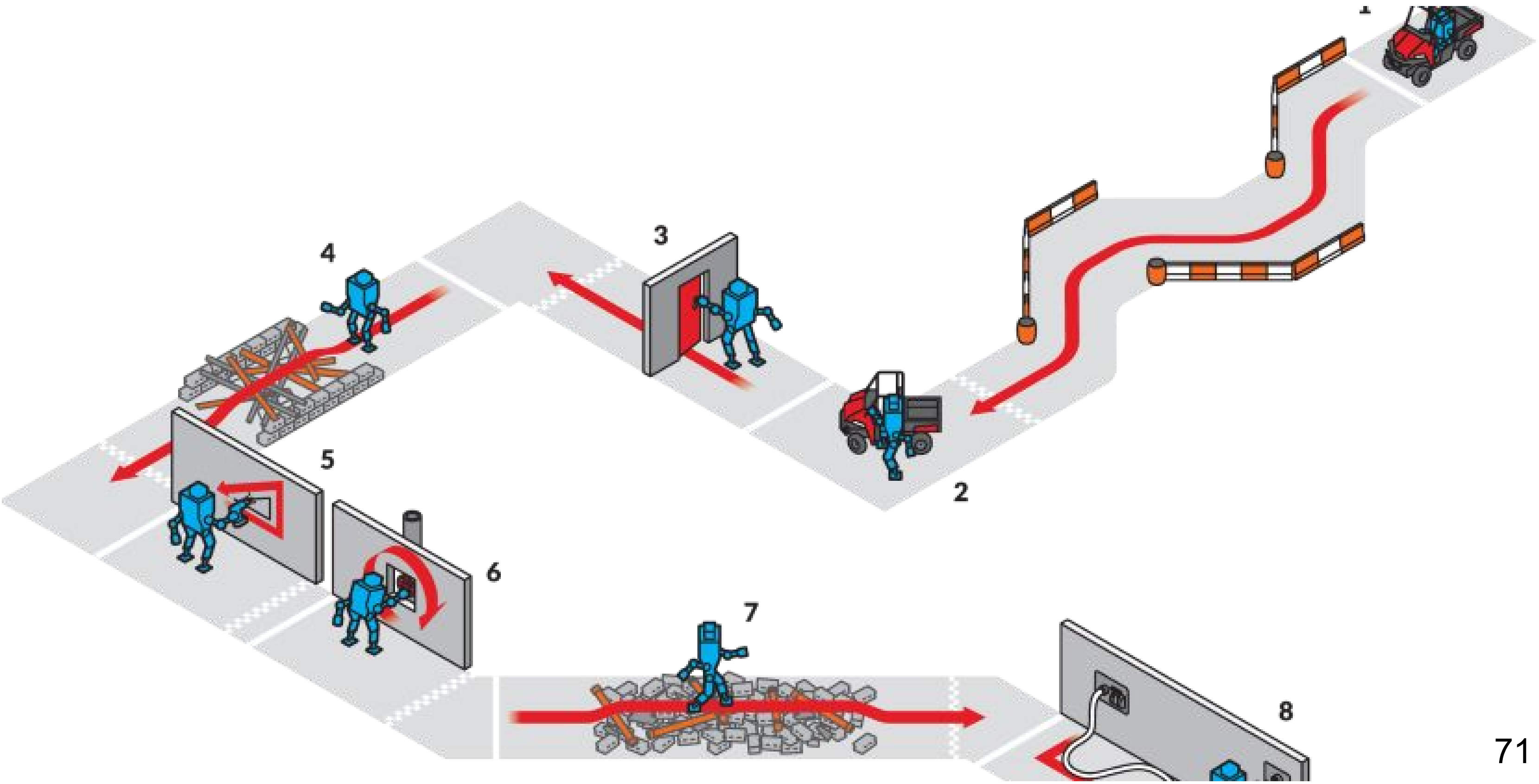




Why behaviors matter?

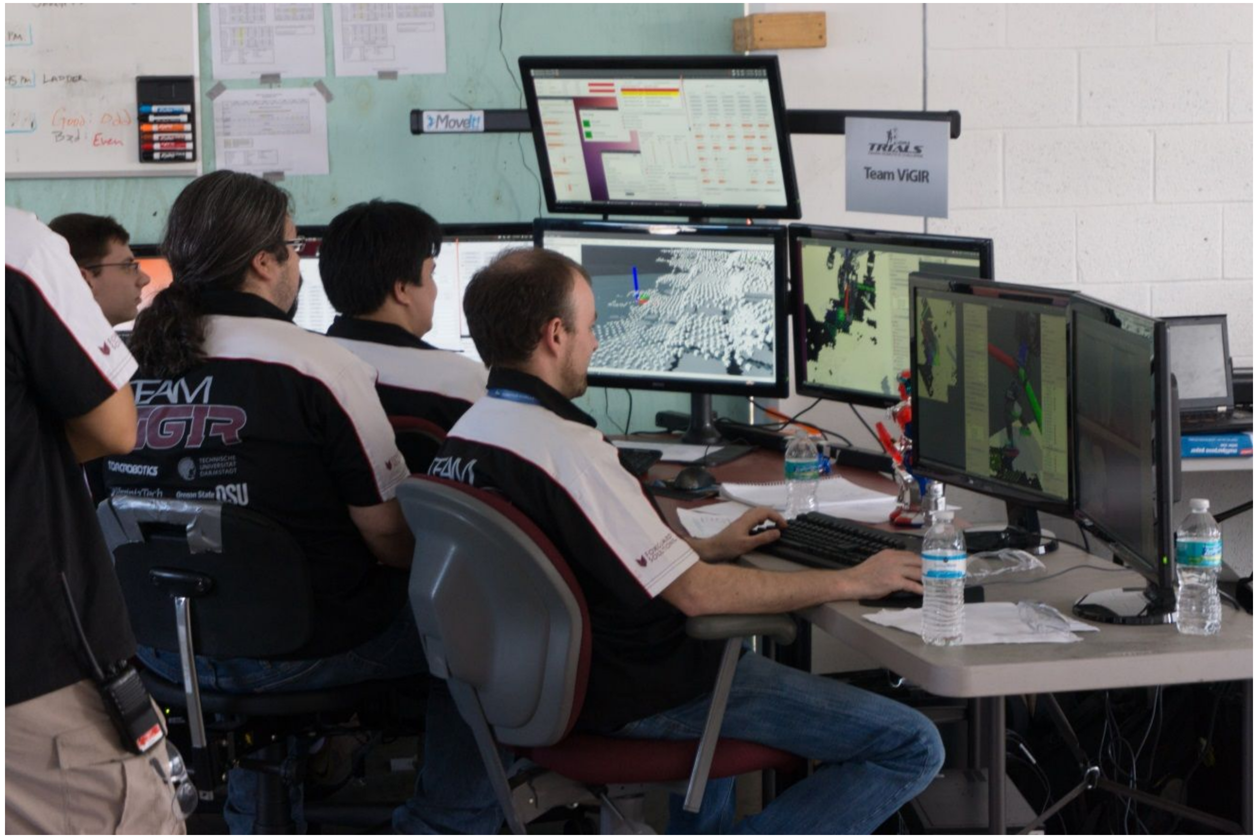
Most robotic applications are particularly programmed for solving specific problems. However, what if we want more universal or versatile machines?





Why behaviors matter?

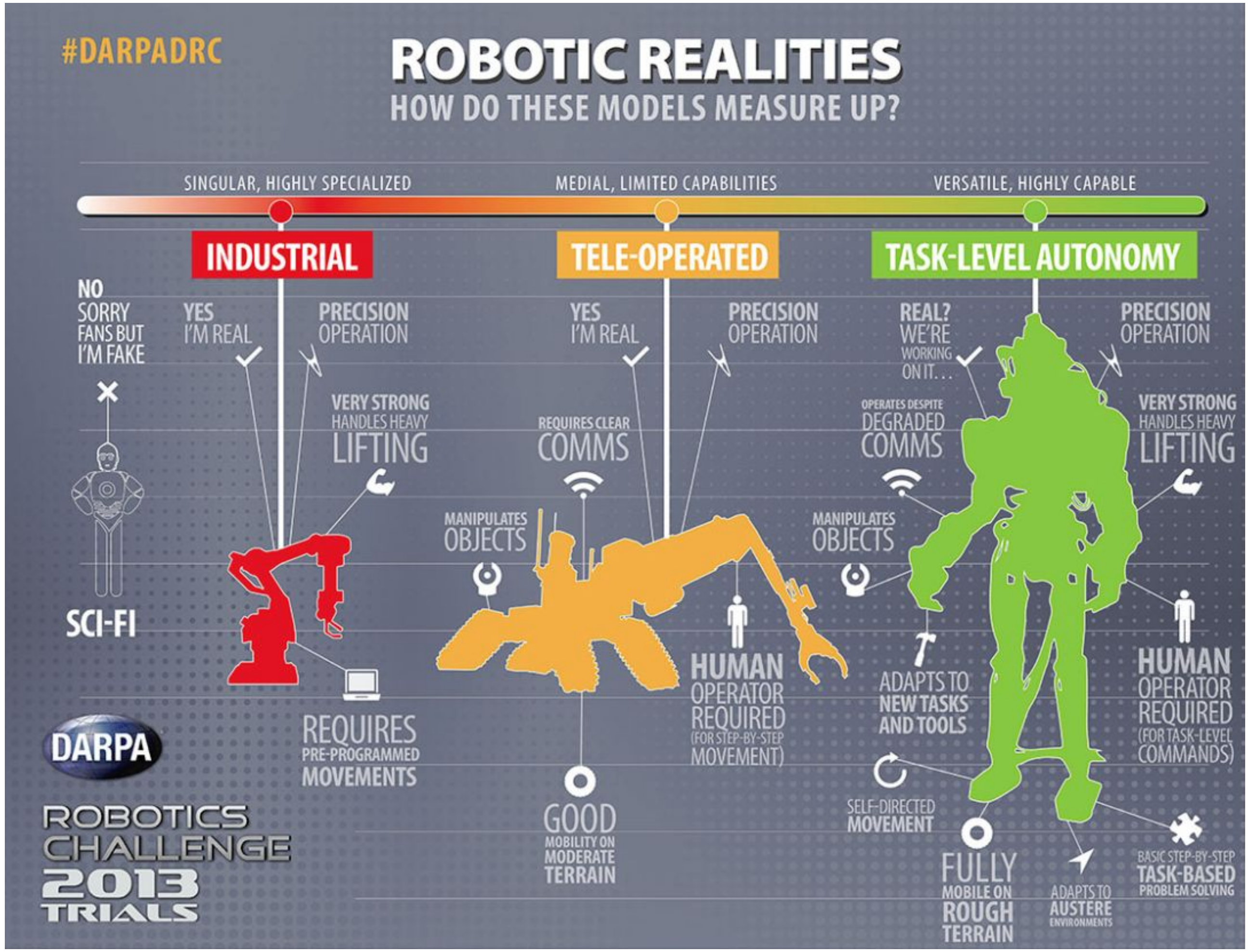
Human intervention supervision.



Why behaviors matter?

Human intervention supervision.

Roadmap for robotics



Summary of key RSS elements

Robot Kinematics & Dynamics	J. J. Craig, Introduction to Robotics: Mechanics and Control
State Estimation & Kalman Filter	Peter Corke, Robotics, Vision and Control, Springer-Verlag.
Localization and Mapping Path & Motion Planning (mobile)	H. Choset, K.M. Lynch, S. Hutchinson, G. Kantor, Principles of Robot Motion: Theory, Algorithms, and Implementations. S. Thrun, W. Burgard and D. Fox, Probabilistic Robotics. Peter Corke, Robotics, Vision and Control, Springer-Verlag.

Summary of key RSS elements

Trajectory Planning and Motion Planning (articulated) Digital System & Control Design of Advanced Controllers	Siciliano, B., et al., Robotics: Modelling, Planning and Control. Peter Corke, Robotics, Vision and Control, Springer-Verlag. Franklin, Gene F., et al., Feedback control of dynamic systems.
Optimization	Yoshihiko Nakamura, Advanced Robotics: Redundancy and Optimization.
Model Predictive Control	J.M. Maciejowski, Predictive control : with constraints.
Machine Learning for Robot Control	Ian Goodfellow, et al., Deep Learning.

Robotics, making a better world

Field test of robots in a post-earthquake scenario, video.