

Robotics

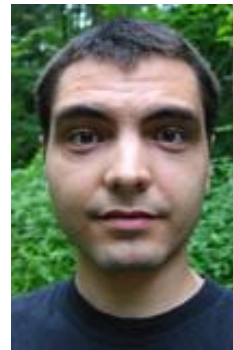
Emo Todorov

Applied Mathematics
Computer Science and Engineering

TAs:



Vikash Kumar



Igor Mordatch

Administrative

No textbook.

Lecture slides and readings will be posted online:

<http://homes.cs.washington.edu/~todorov/courses/cseP590>

No fixed office hours.

Grading will be based on three homeworks.

Catalyst forum (preferred): ???

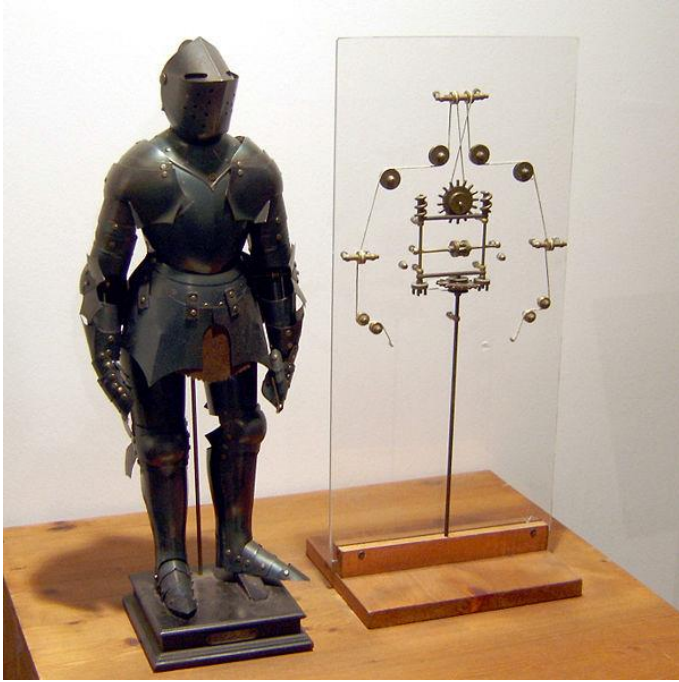
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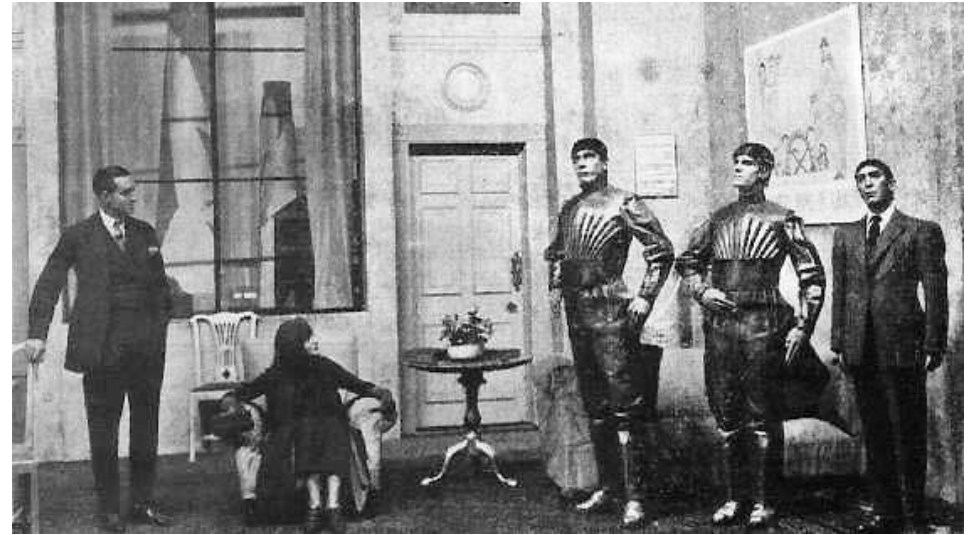
vikash@cs.washington.edu

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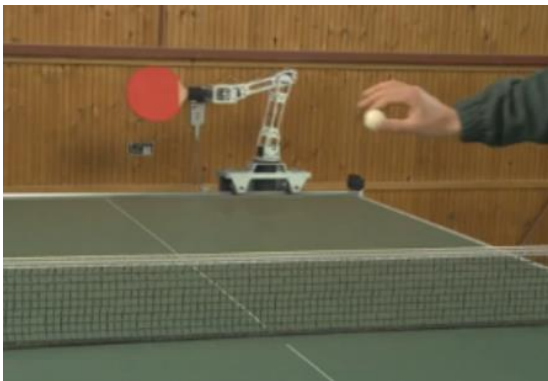
Ideas about robots



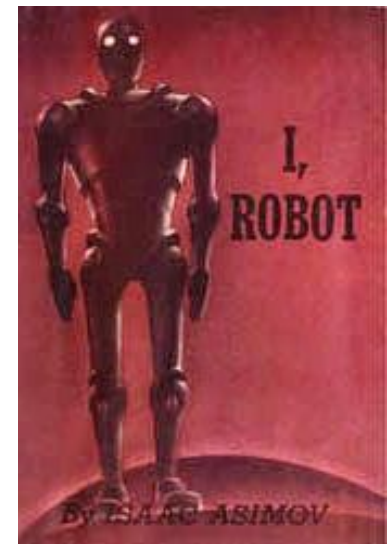
Leonardo da Vinci, 1495



Karel Čapek, 1921



Ulf Hoffmann, 2014



Isaac Asimov, 1950

What can be done today

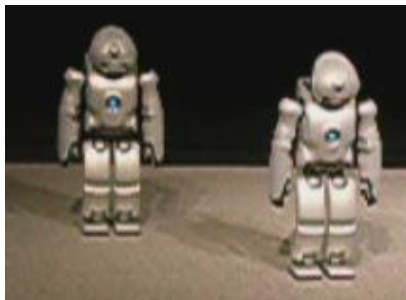
Industrial robots



Dynamic walking robots



Entertainment robots



Flying robots



Applications of robotics: Pictorial survey

The rest of the slides in this lecture are from:

Prof. Alessandro De Luca

DIPARTIMENTO DI INGEGNERIA INFORMATICA
AUTOMATICA E GESTIONALE ANTONIO RUBERTI



SAPIENZA
UNIVERSITÀ DI ROMA



Robots !!



Comau H4
(1995)



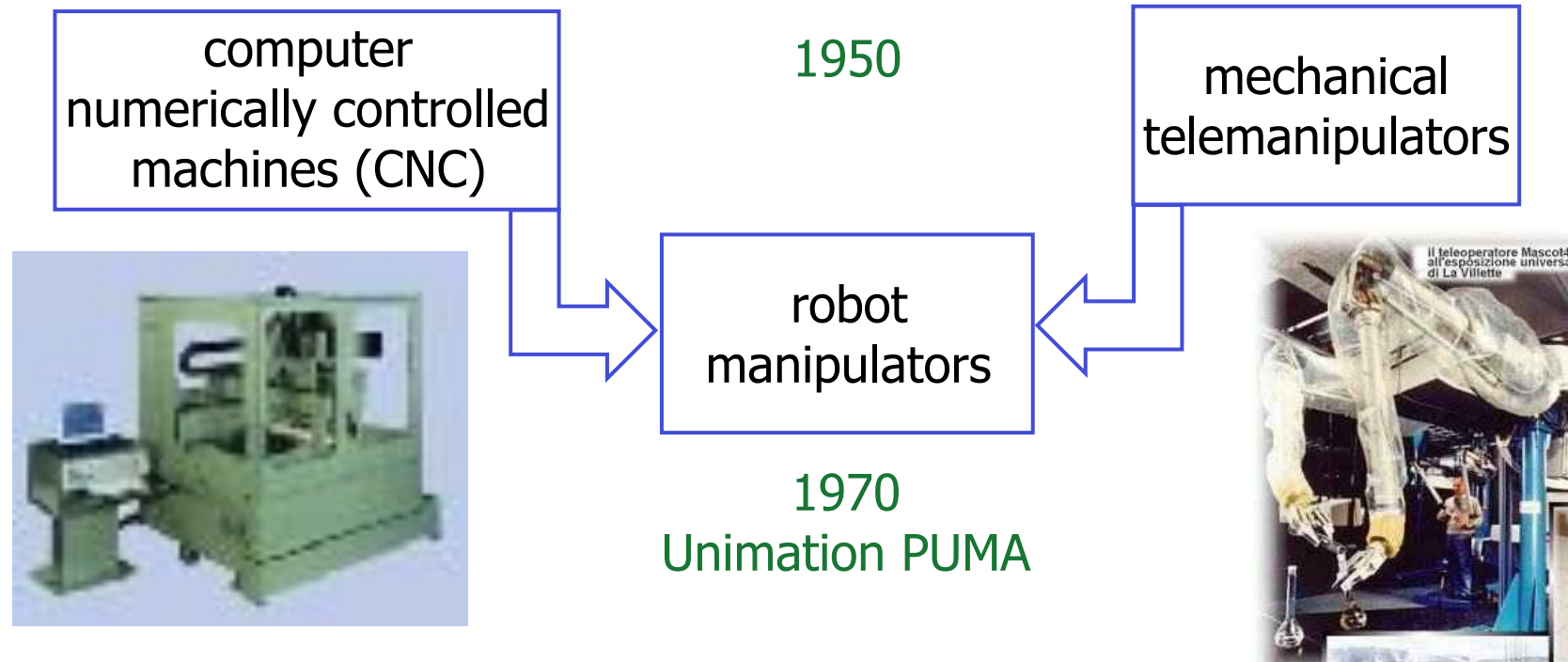
Waseda WAM-8
(1984)



Spirit Rover
(2002)



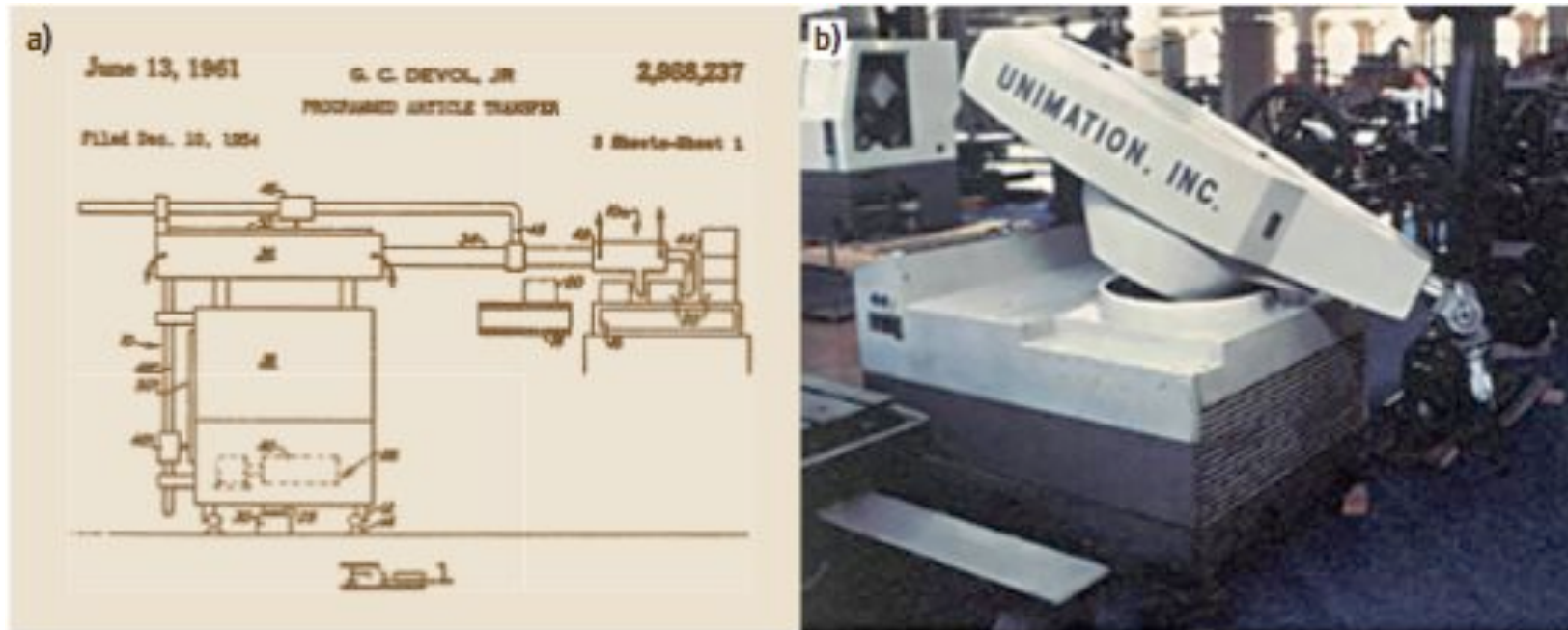
Evolution toward industrial robots



- with respect to the ancestors
 - **flexibility** of use
 - **adaptability** to a priori unknown conditions
 - **accuracy** in positioning
 - **repeatability** of operation



The first industrial robot



US Patent

General Motor plant, 1961

G. Devol and J. Engelberger (Unimation)



Robot manipulators

ASEA IRB-6
(1973)
first robot
all-electric-drives



Hirata AR-300
(1978)
first SCARA
robot



Cincinnati
Milacron T3
(1974)
first micro-
computer
controlled
robot

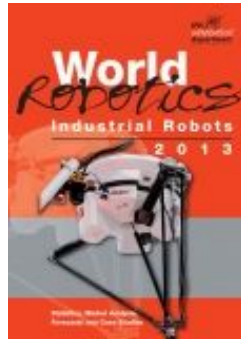


Unimation
PUMA 560
(1979)
6R with
human-like
dexterity

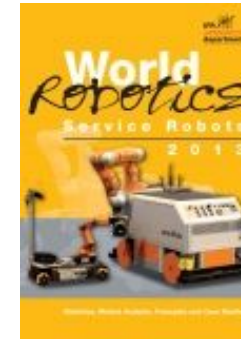




World Robotics 2013



executive summary for 2013
(yearly statistics by IFR)



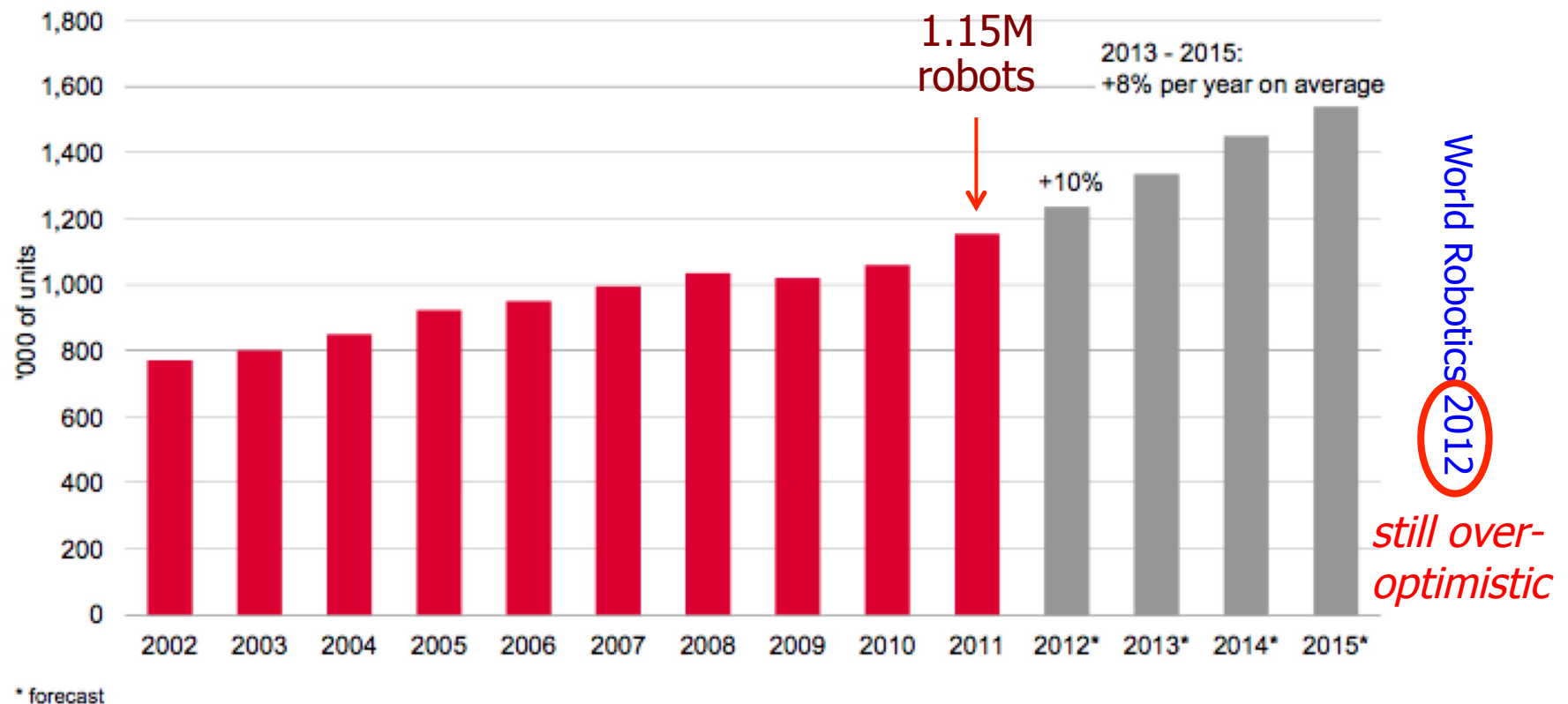
- robotics market value: **\$8.7 billion**; + software, peripherals, systems: **\$26 billion**
- year 2012 was second highest in sales (but **-4%** w.r.t. the record year 2011)
- **industrial** robot sales in 2012: 159K units (large variations in different areas)
 - Americas: +7% (28K); USA: +9% (22K units)
 - Asia/Australia: -5% (86K); Japan \approx (28.7K), China \approx /+ (23K), Korea -24% (19.4K)
 - Europe: -6% (41K); Germany -10% (17.5K), Italy -14% (4.4K)
 - increase in automotive, reduction in electronics (strong) and machinery
- **forecast** on operational stock of industrial robots: **1.5M** units in 2015
- **service** robot sales in 2012: **+2%** (16K units) for professional use and **+15%** (**3M** units) for personal/domestic use, out of which 1.1M units for entertainment
 - professional use: defense (6.2K units, most UAV, 40% share), field robots (5.3K, 33%), medical/robot surgery (1300 units, but **44% in value**)



Diffusion

Industrial robots in operation worldwide

**Worldwide estimated operational stock of industrial robots
2002 - 2015***

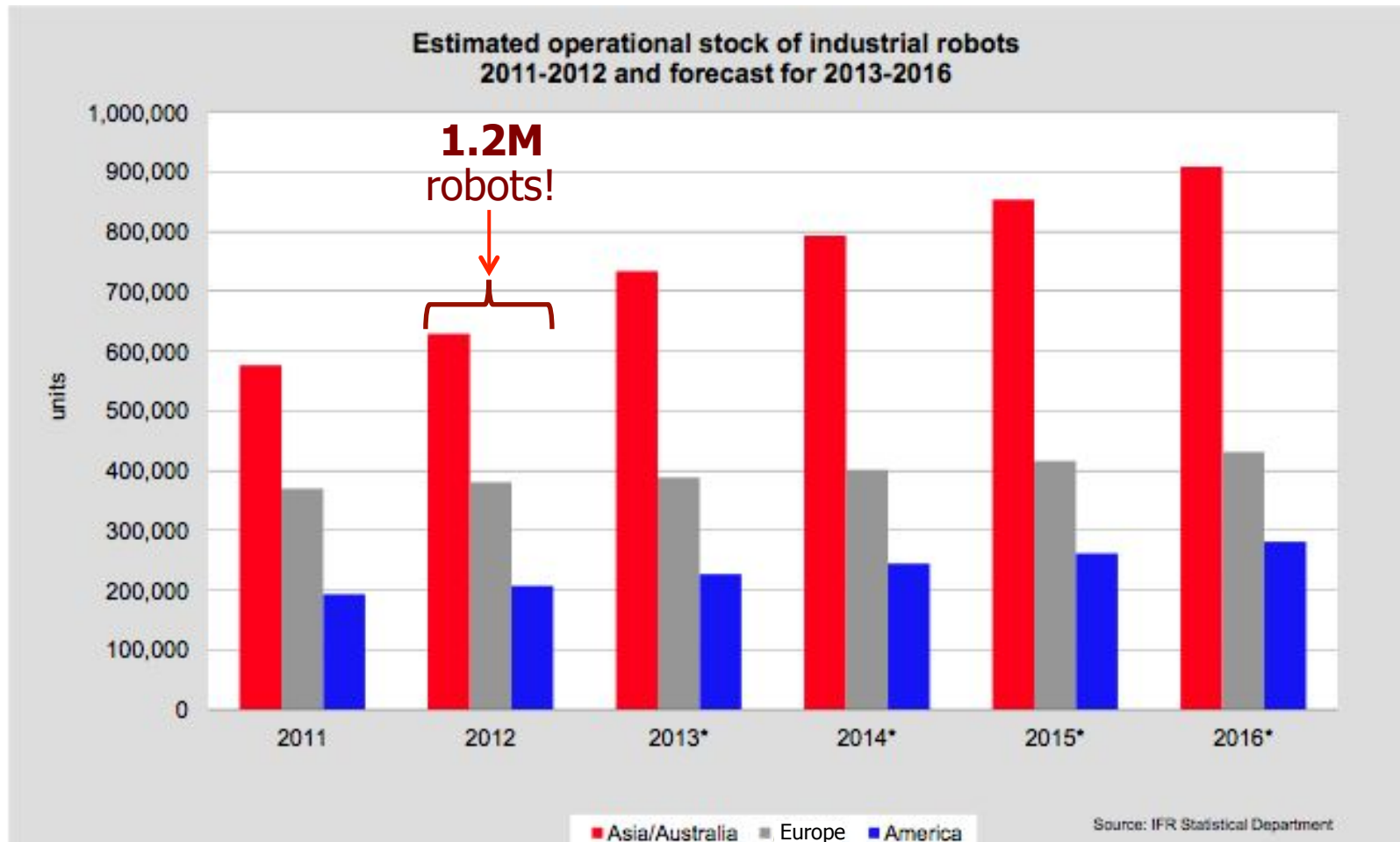


(as reference: industrial robots in stock in 1983 = 66K)
length of robot service life is estimated in 12-15 years



Diffusion

Industrial robots in operation by world regions

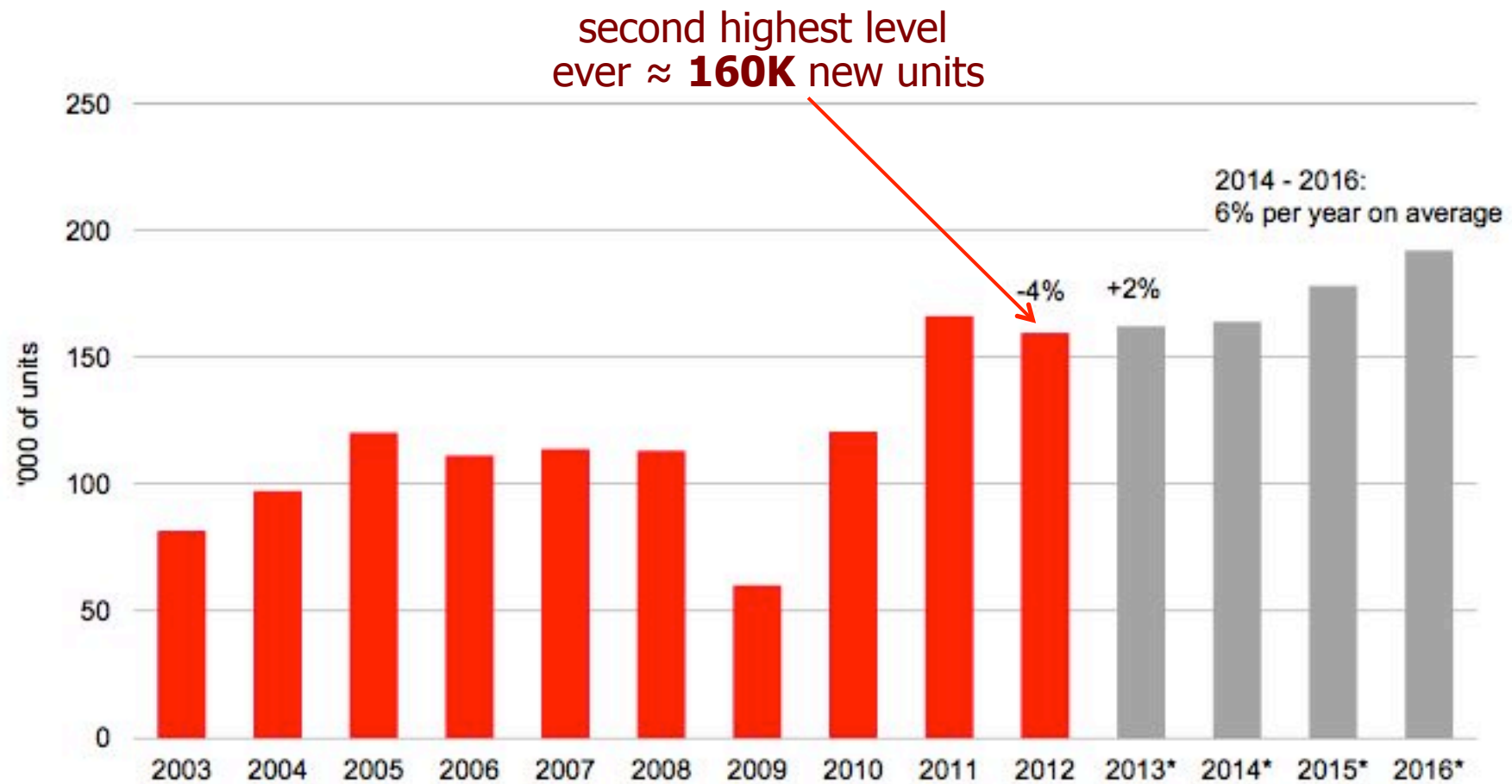


World Robotics 2013



Annual supply

New industrial robots worldwide



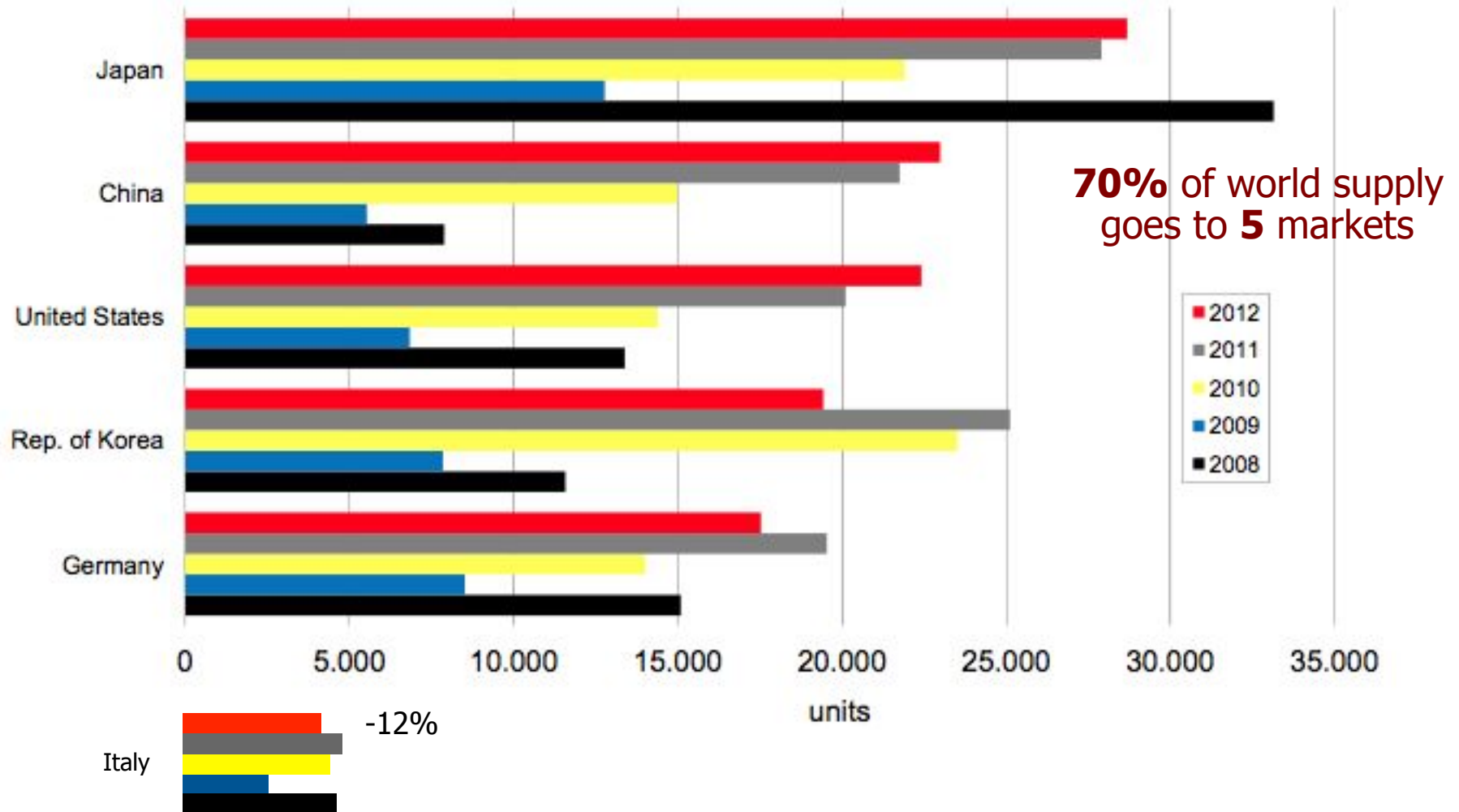
* forecast

World Robotics 2013



Annual supply

Largest markets of new industrial robots



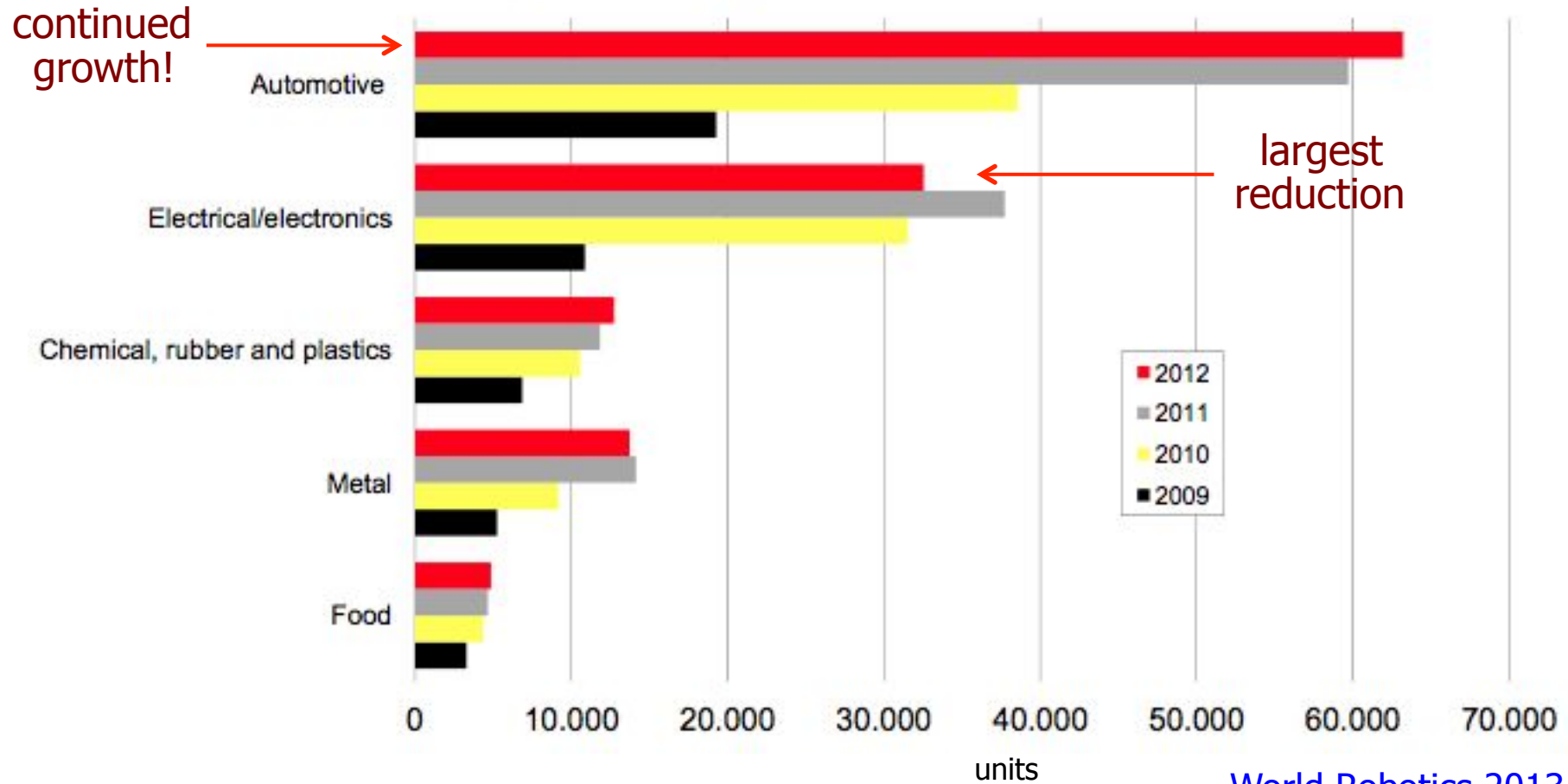
elaborated from World Robotics 2013

Annual supply

New robots by industrial sectors



Estimated worldwide annual supply of industrial robots at year-end by main industries 2009 - 2012

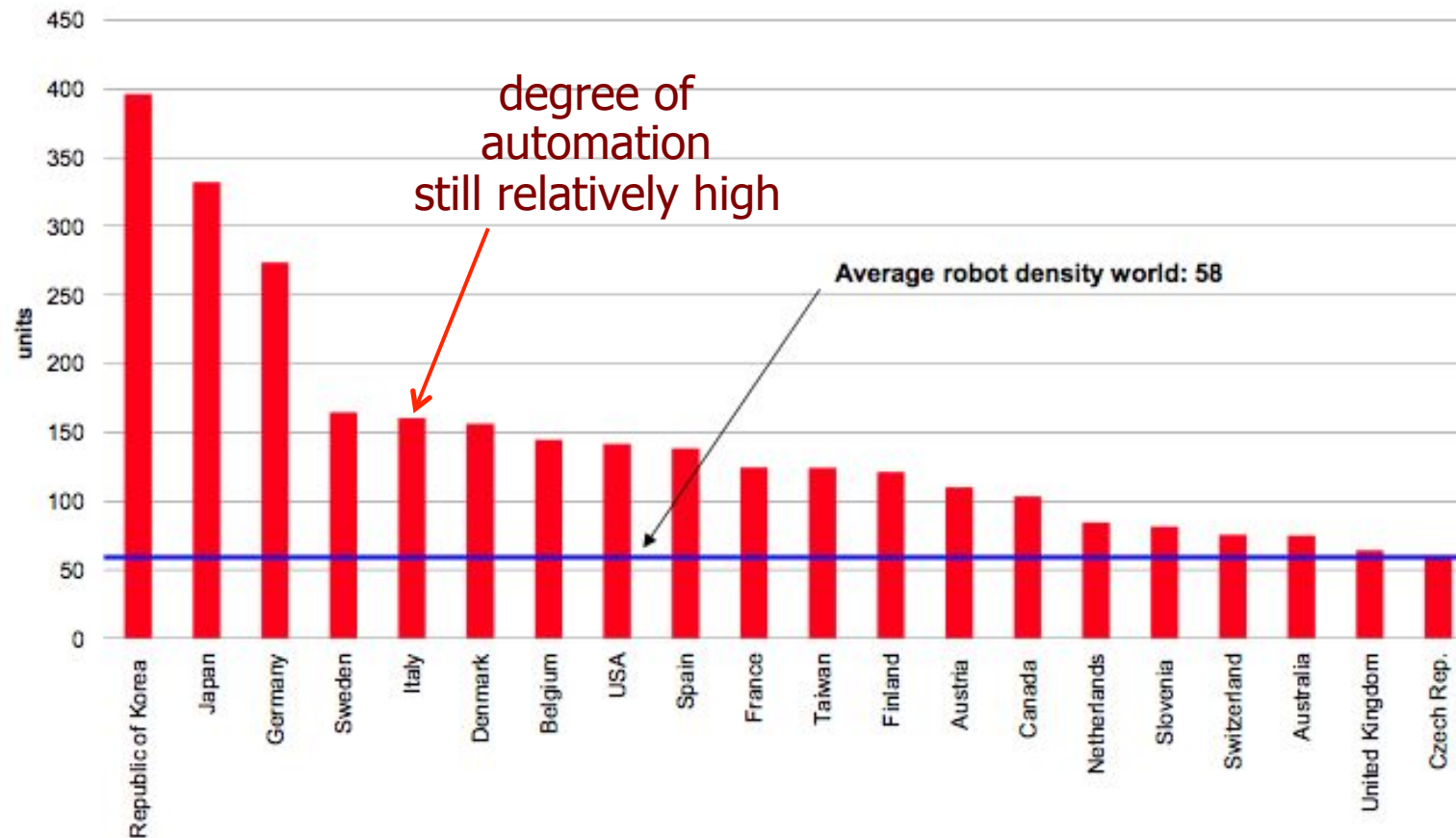


World Robotics 2013



Density of robots - 1

Number of multipurpose industrial robots (all types)
per 10,000 employees in the manufacturing industry (ISIC rev.4: C) 2011



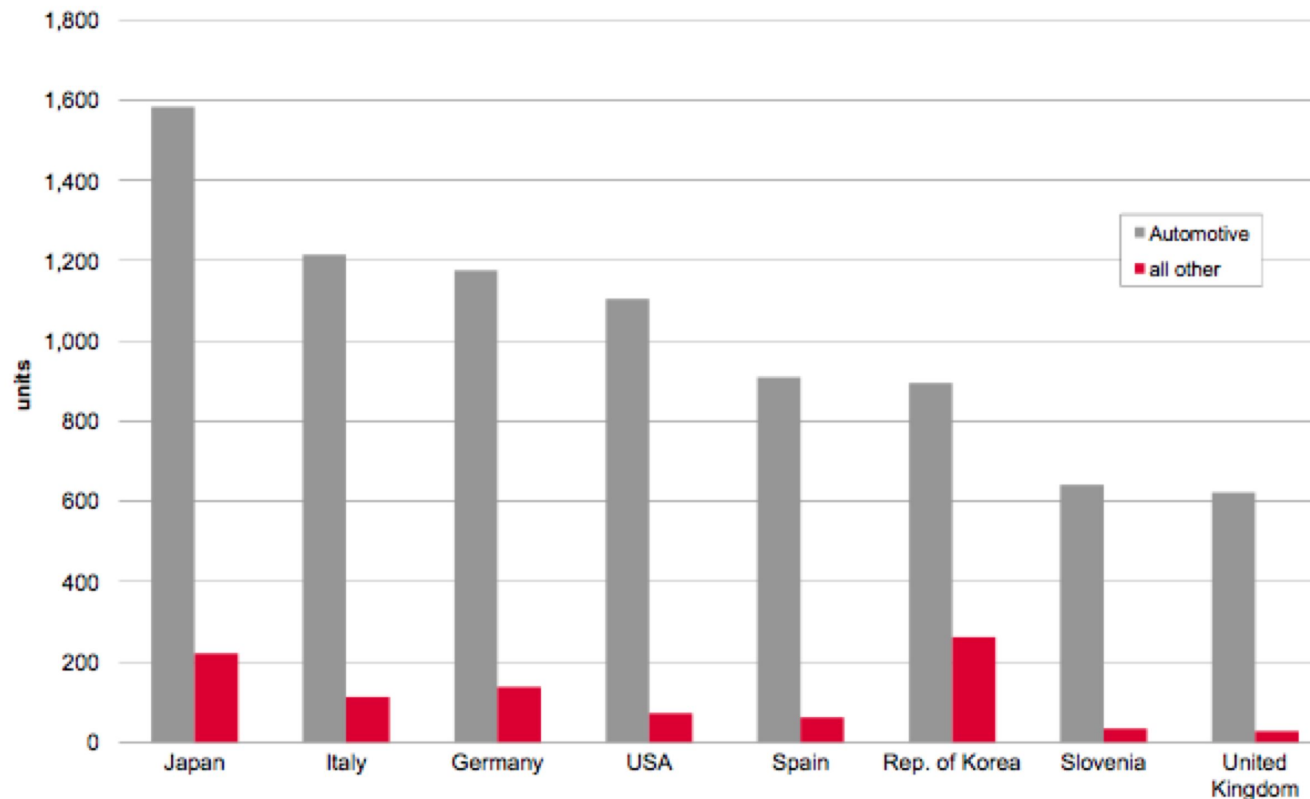
World Robotics 2013

in the **manufacturing** industry in 2011 (revised data)



Density of robots - 2

Number of multipurpose industrial robots (all types)
per 10,000 employees in the automotive and in all other industries 2011

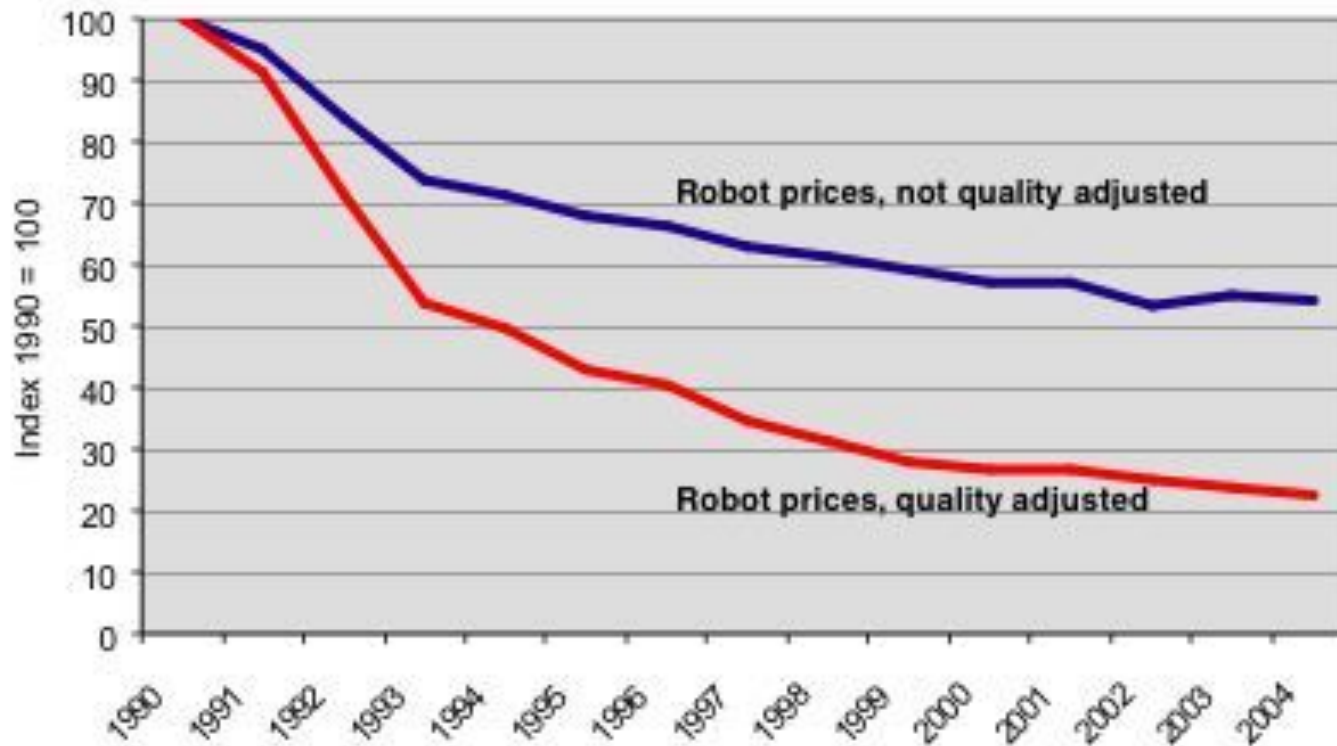


from World Robotics 2012

number of robots per 10000 employees
in the automotive and in **all other** industries in 2011



A long-range trend in robot prices



An articulated industrial robot with six degrees of freedom of medium/large size costs **about 100 KEuro**



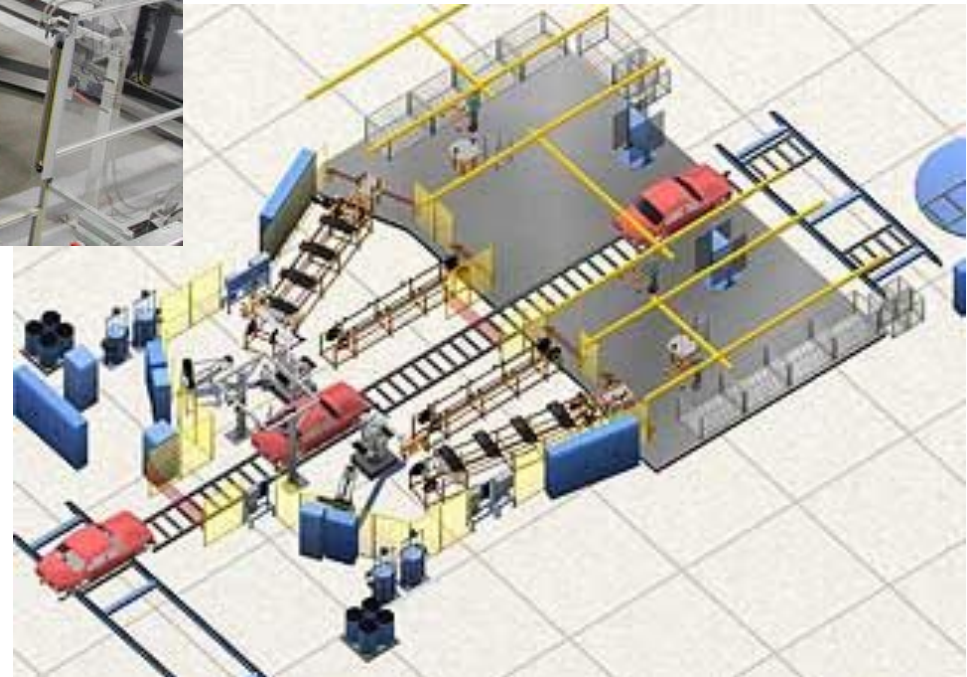
Industrial applications

- manipulation (pick-and-place)
- assembly
- spray painting and coating
- arc welding
- spot welding with pneumatic or servo-controlled gun
- laser cutting and welding
- gluing and sealing
- mechanical finishing operations (deburring, grinding)



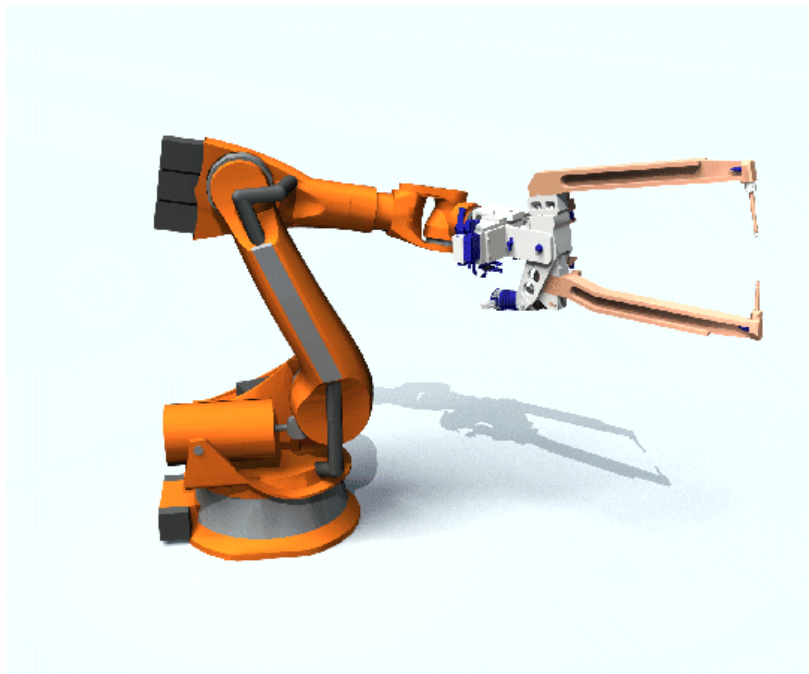


Robotized workcells

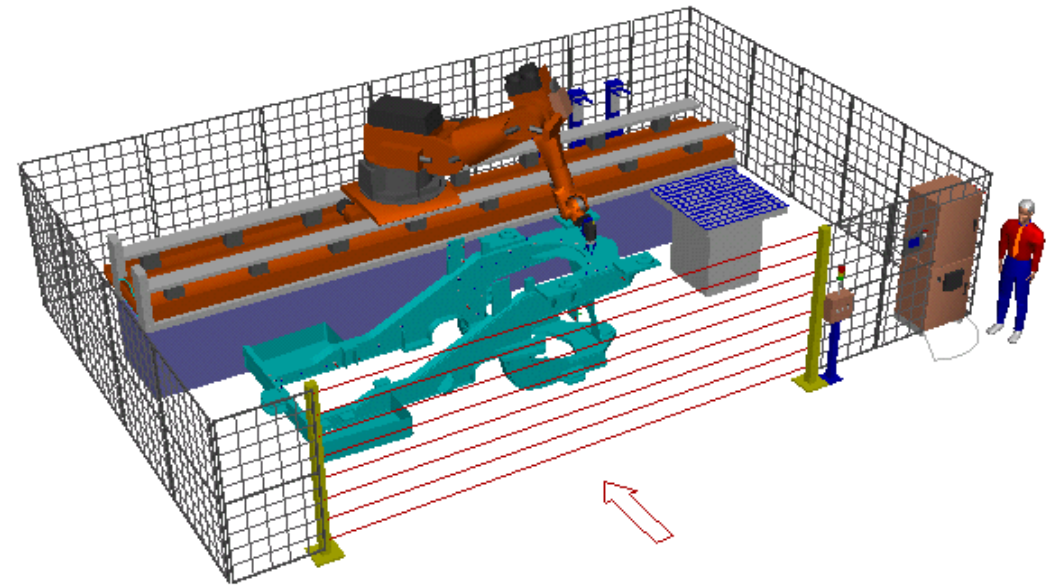




Welding - 1



- spot with servo-controlled gun



- stud welding

Welding - 2

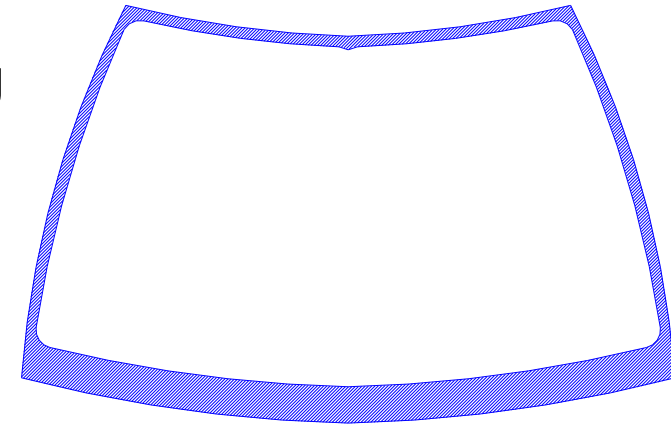
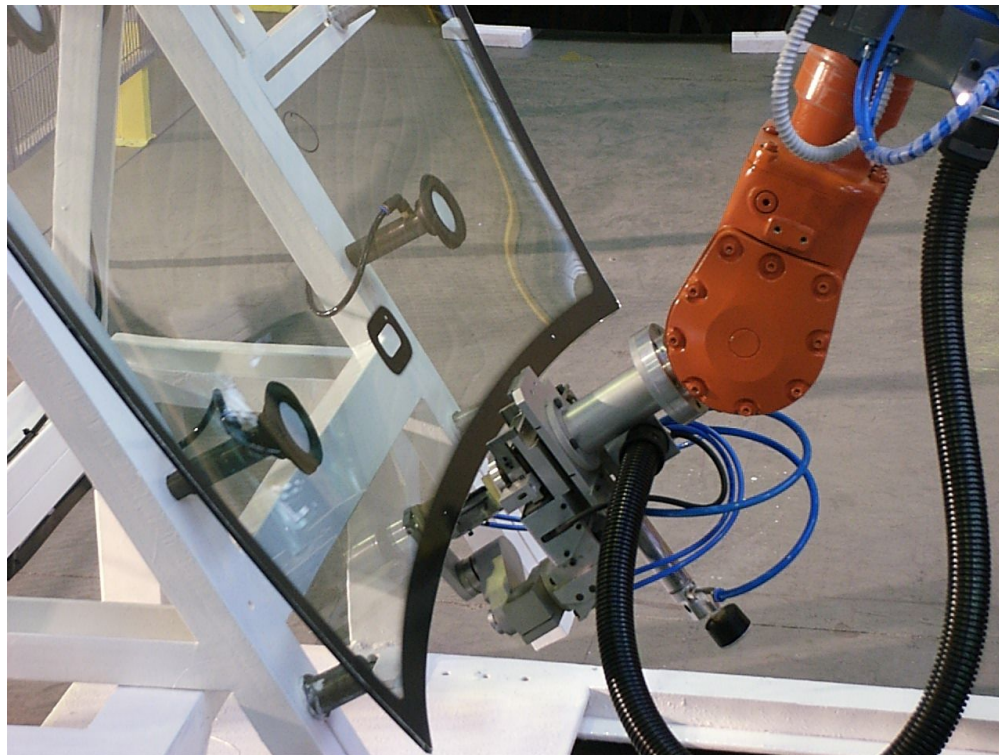


- spot (discrete) or arc (continuous)



Deburring

- car windshields may have large manufacturing tolerances and a sharp contour profile



- the robot follows a given predefined Cartesian path
- the contact force between cutting blade and glass must be feedback controlled
- deburring robot head mounts a force load cell and is pneumatically actuated



Robot manipulator kinematics



Kuka 150_2
(series 2000)
open kinematic chain
(rigid bodies
connected by joints)



Comau
Smart H4
closed kinematic chain



Fanuc
F-200iB
parallel kinematics



Other types of robots - 1



Mitsubishi RP
(repeatability 5 micron,
payload 5 kg)



Mitsubishi RH
(workspace 850 mm,
velocity 5 m/s)



Bosch Turbo

SCARA (Selective Compliant Arm for Robotic Assembly)

- 4 degrees of freedom (= joints): 3 revolute + 1 prismatic (vertical) axes
- compliant in horizontal plane for micro-assembly and pick-and-place



Other types of robots - 2



Comau Mast
gantry robot
(payload up to 560 kg)



ABB Flexpicker
(150 pick-and-place
operations/minute)



Mobile base robots in industry



- **AGV** (Automated Guidance Vehicles) for material and parts transfer on the factory floor: wire- or laser-driven along predefined paths



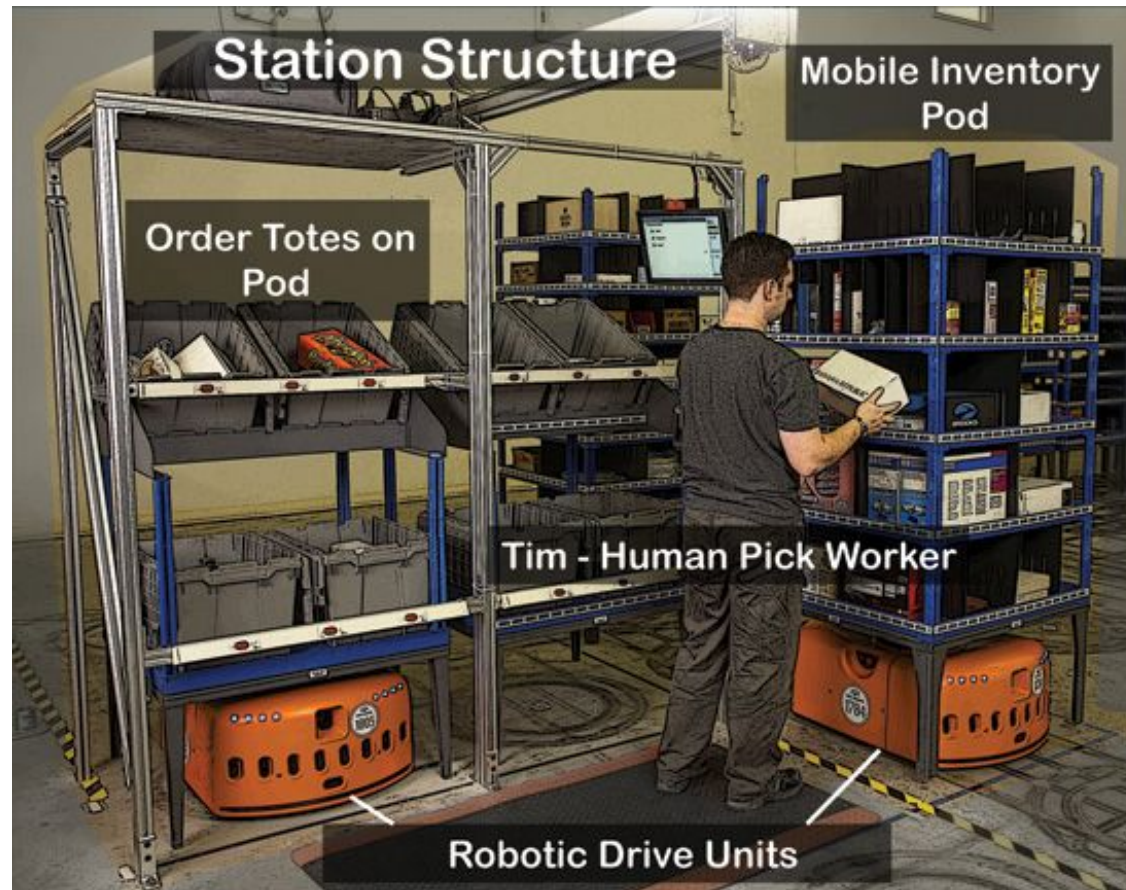
Lifting AGV for warehouses



video by Elettric80



Kiva Systems



company acquired for \$775 million by Amazon (**store automation**)

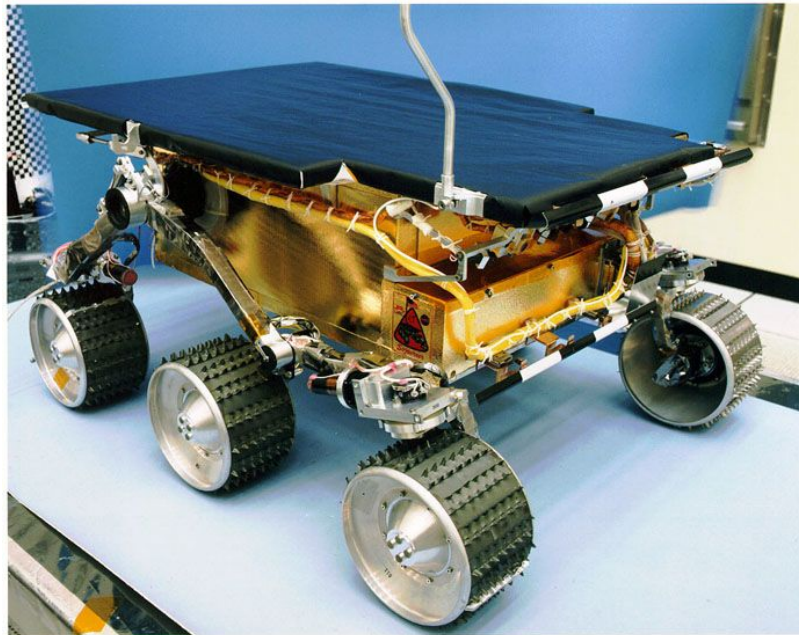
Some application domains



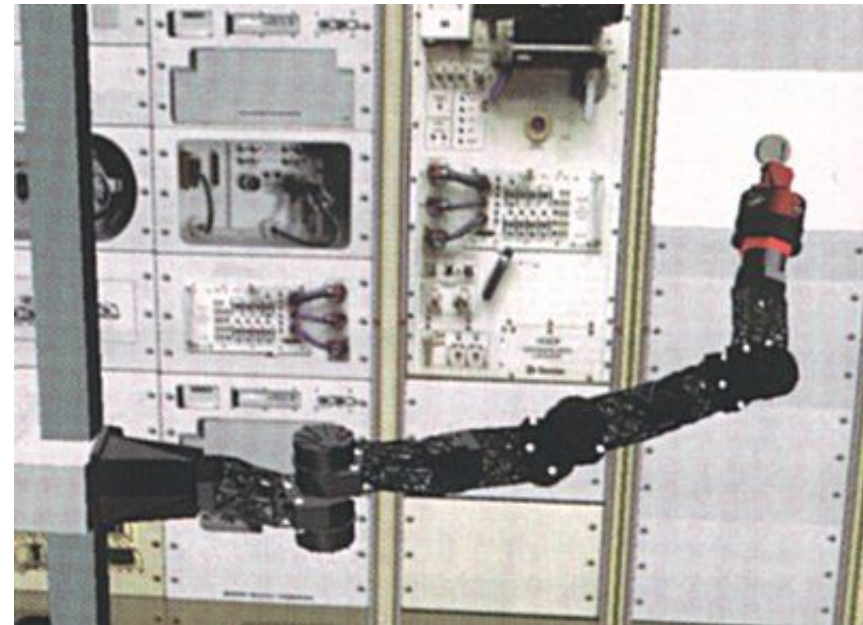
- extreme environments
 - space
 - underwater
- medical robotics
 - assistive
 - rehabilitative
 - surgical
- home cleaning
- agriculture
- lawn mowing
- food industry
- mine exploration
- de-mining
- civil and naval construction
- automatic refueling
- museum guide
- fire fighting
- inspection and surveillance
- emergency rescue
- entertainment
- humanoids

professional & personal service robots

Space robotics



- NASA *Sojourner*, first robot to explore Mars in 1997

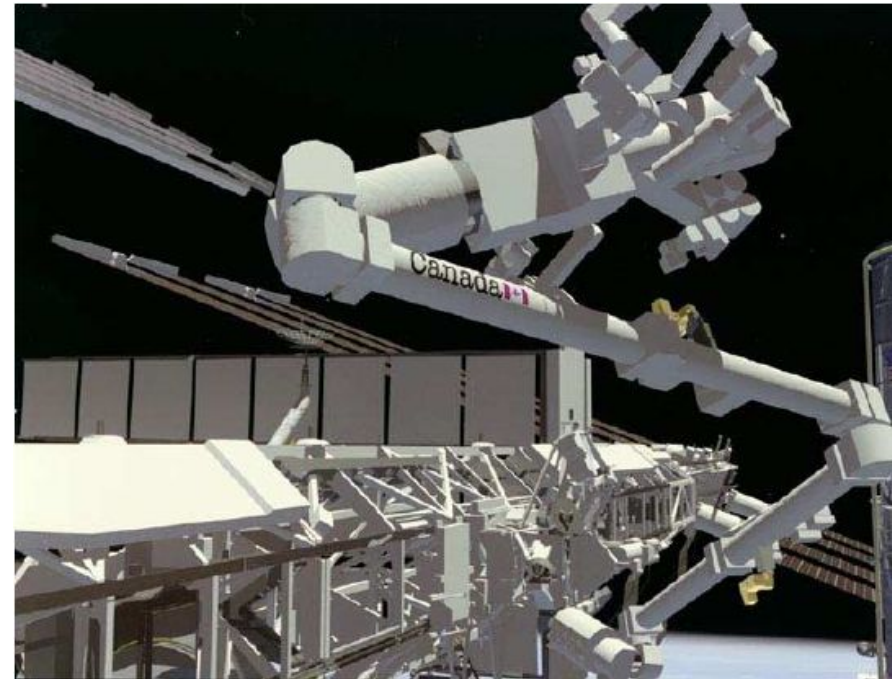


- DLR *Rotex* robot arm in a set of experiments of the Spacelab-D2 mission on the Columbia shuttle in 1993

Space robotics



- robotic arm *SSRMS (Canadarm)* in operation on the Space Shuttle, with outstretch of about 30 meters



- the service manipulator on the ISS is mounted on a supporting rail

Robots on ISS videos



Canadarm2 delivering Destiny Lab
from Space Shuttle Atlantis to ISS
(Feb 2001)

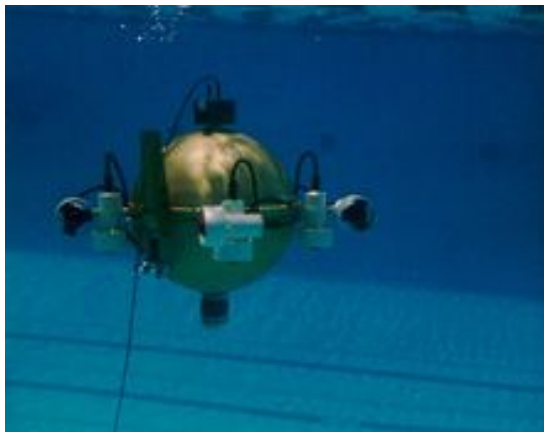


service manipulator and Robonaut
on the ISS (artistic views)

Underwater robotics



- Odyssey-IV (MIT)



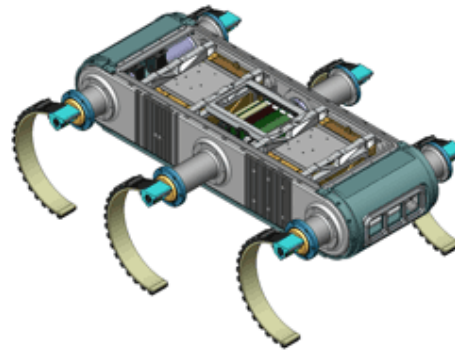
- Odin-III, **omni-directional** (University of Hawaii)

- typically actuated by thrusters (directional forces on the tail)
- cannot translate sideways ("maneuvers" are necessary)



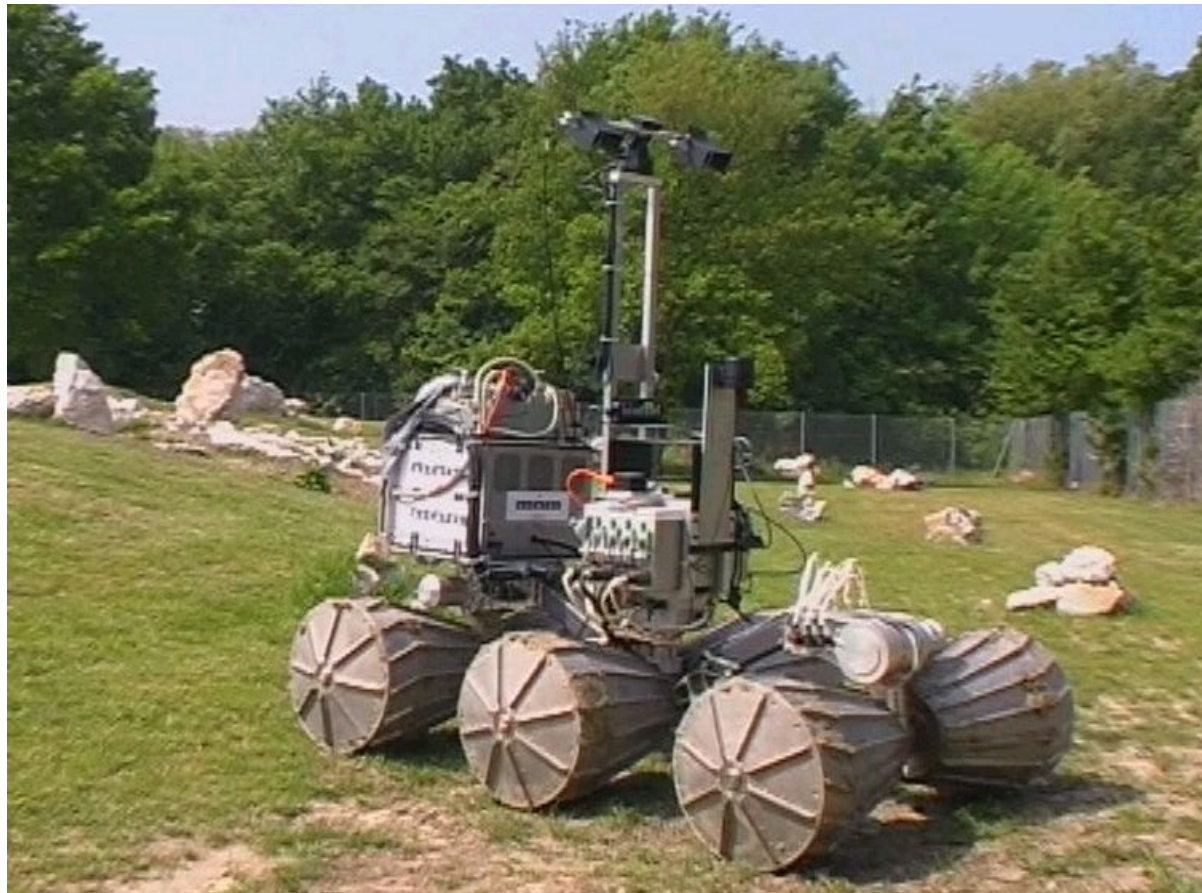
- ROMEO in Antarctica (CNR, Automazione Navale, Genova)

Underwater robotics



- Aqua robot, amphibious robotic vehicle (McGill University)
- size and weight: 50x65x13 cm, 18 kg
- locomotion: through six independently actuated flippers
- maximum depth: 37 m
- sensors: two cameras (front/back), acoustic sensor for localization (sonar), tri-ocular sensor (structured light)
- power source: 48V lithium battery

Outdoor exploration



- the *LAMA* robot at CNRS-LAAS (Toulouse) is a french-russian cooperation

Volcanology



video

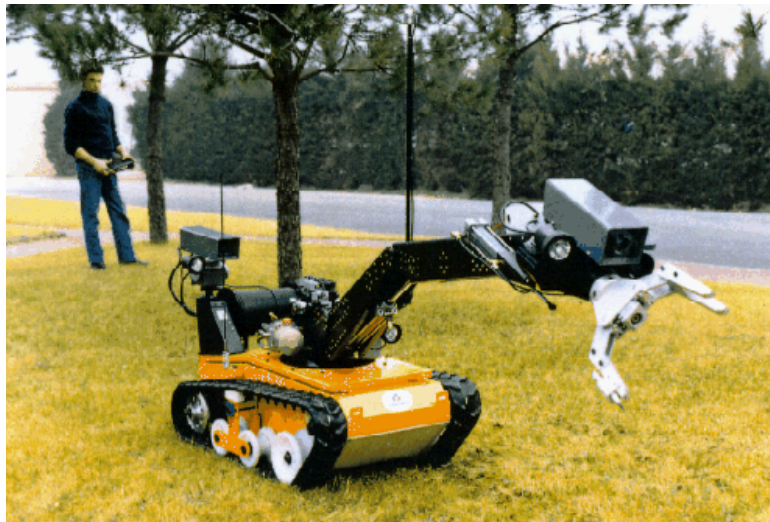


video



RoboVolc vehicles on the surface
of the Etna volcano:
wheeled and tracked robots
(University of Catania, 2003)

De-mining



- teleoperated mobile robot on tracks used by the police for bomb disposal



- PEMEX lightweight anti-personnel mine detector (EPFL, Lausanne)
- weight: 16 kg, max 6 kg for wheel
- two 70 W DC motors (vel 2 m/s)
- oscillating sensorized head

Medical robotics

patient aid

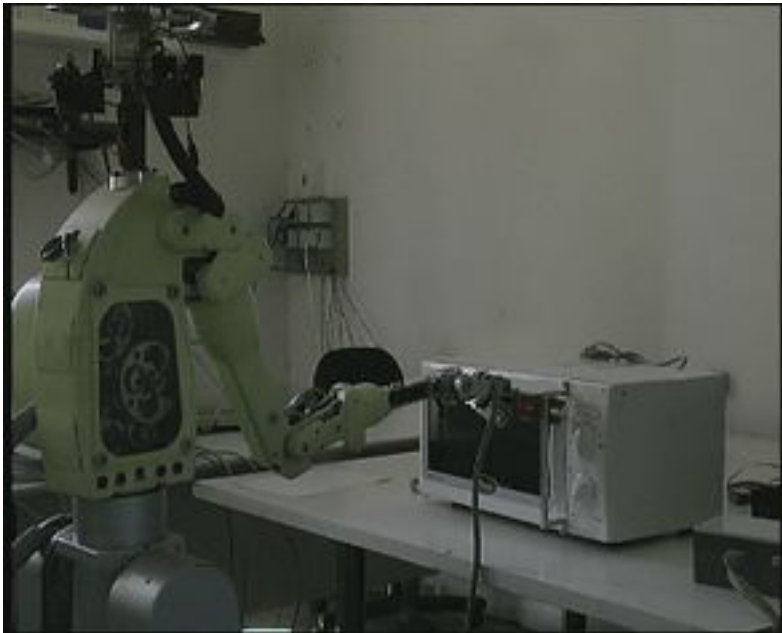


- deambulation support system
PAM-AID (Trinity College, Ireland)



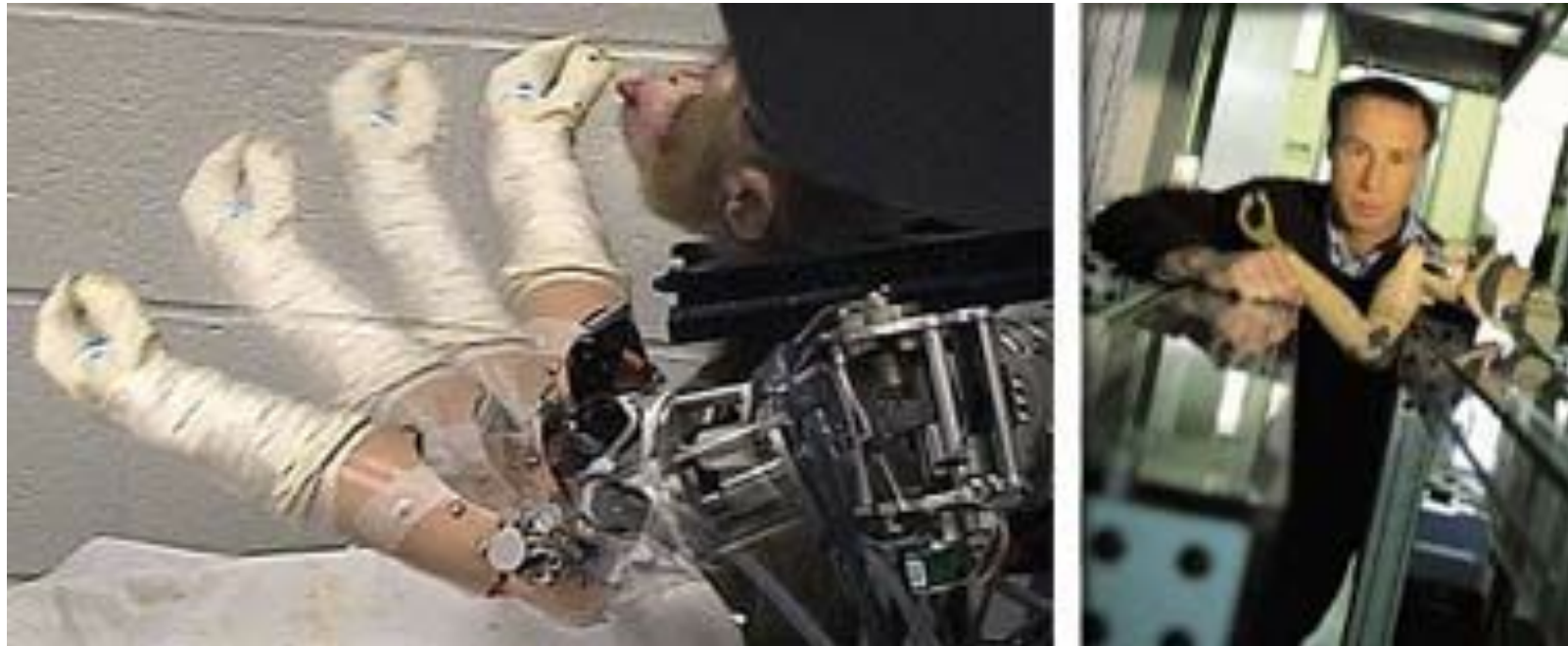
- *MOVAID* project for the aid of disabled people
in home activities (Scuola Sup Sant'Anna, Pisa)

MOVAID project videos



domestic activities using the 7R *Dexter* arm

Medical Robotics rehabilitative



- robotic arm with shoulder and elbow having full mobility and with a gripper hand (Pittsburgh University)
- in tests on monkeys (with immobilized upper limbs), motion commands sent to the arm by the central nervous system (brain) are measured by a set of electrodes and used to command the robotic arm

Medical robotics rehabilitative



- commercialized by Ossur (Iceland)
- a prosthesis sensorized at the knee (angle and force), capable of processing sensor data and of extracting a gait model of the user, so as to adapt its dynamical behavior (knee motion and stiffness)

Medical robotics rehabilitative



- "RUPERT" Robotic Upper Extremity Repetitive Therapy (Arizona State University + Kinetic Muscles, Inc.)
- sustains the human arm with pneumatic muscles (McKibben actuators)
- it can be programmed for the execution of cyclic exercises of rehabilitation

Medical robotics

hospital and nursing



video



- *HELPmate* mobile robot (USA) works in hospitals as auxiliary personnel

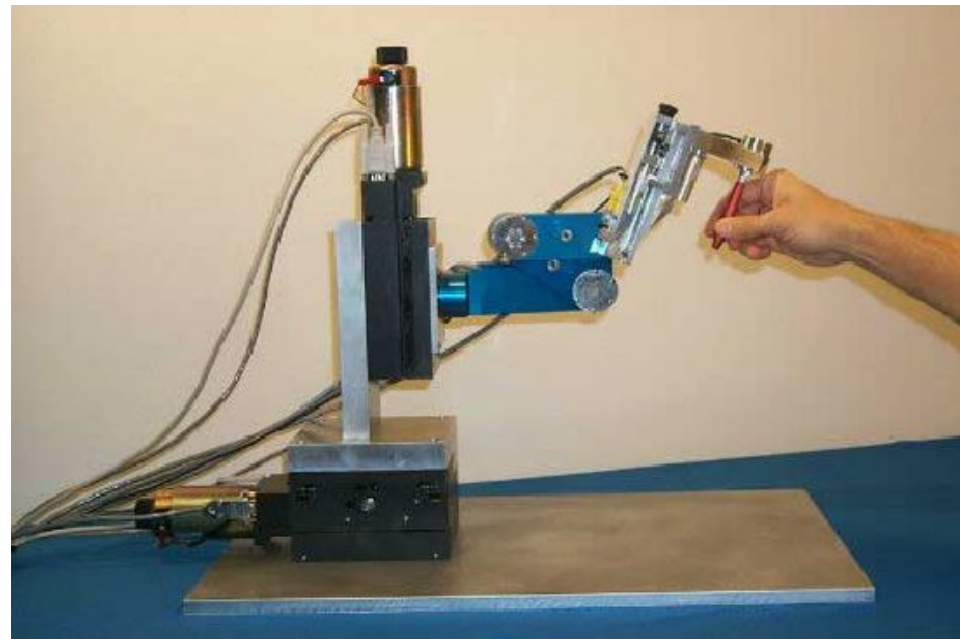


- user interface of the *Care-O-Bot* robot nurse (IPA Fraunhofer, Germany)

Surgical robotics

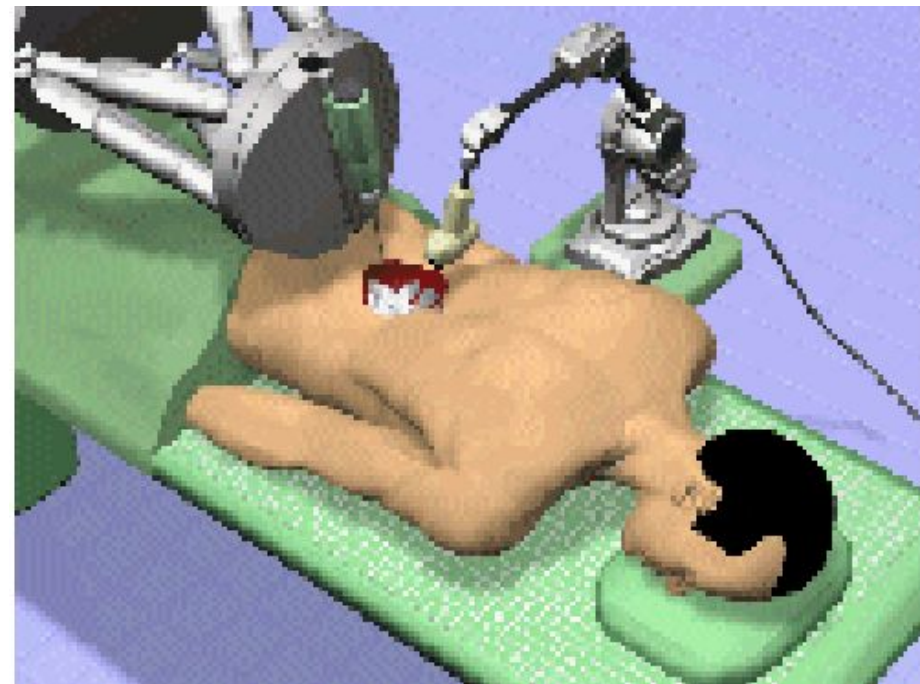
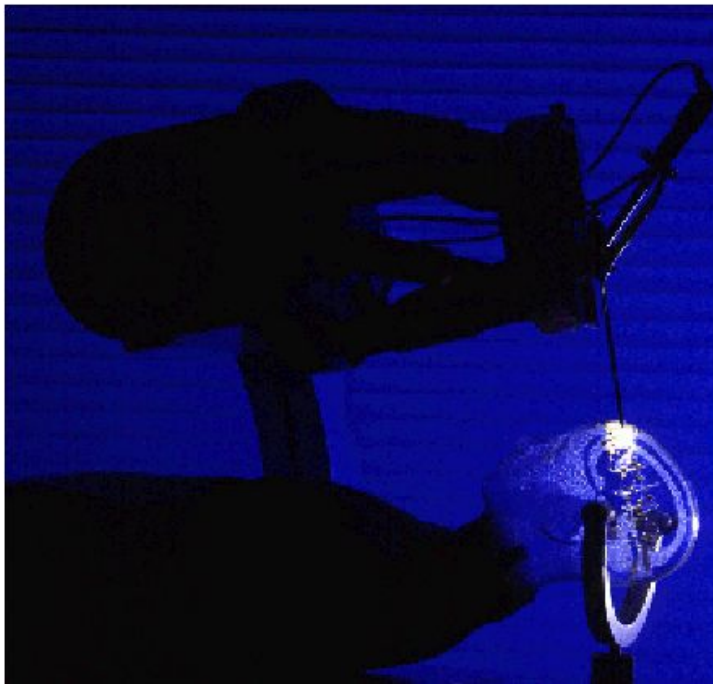


- *Robodoc* by Integrated Surgical Systems (USA) was used first for orthopedic surgery (ankle replacement)



- *Steady-Hand* force-assisted system (Johns Hopkins Univ) improves accuracy and repeatability of surgeons allowing task-driven compliance

Surgical robotics



- emulation of a laser brain surgery operation and graphic rendering of a surgery intervention on the spinal cord patient is first "mapped" off-line by a series of CAT scans; data are then "localized" in the actual operation field (IPA Fraunhofer)

Surgical robotics



overview of the operating room



command station



(haptic) interface

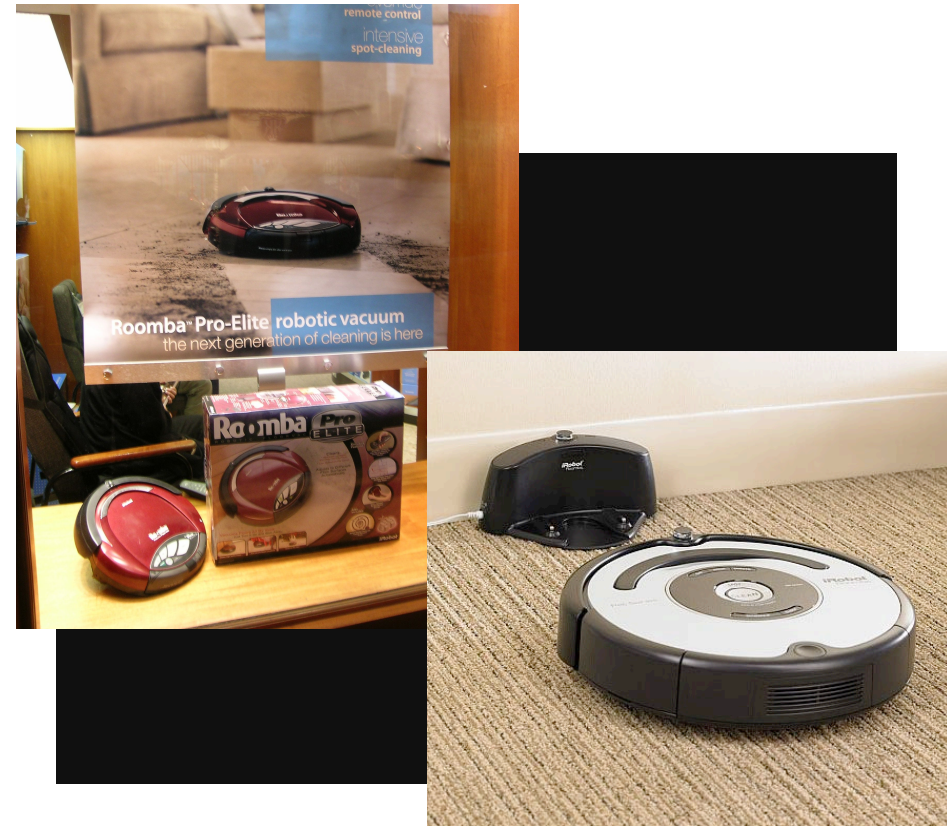
- da Vinci[©] system (Intuitive Surgical Inc.)
[see the course "Medical Robotics"]



Home cleaning



- vacuum cleaner robot
Trilobite by Electrolux (Sweden)



- commercial **video**
iRobot *Roomba 560* (USA)
— now available everywhere!

Cleaning of external surfaces



- *Skywash* cleans civil airplane bodies and is “the largest robot worldwide” (AEG/Dornier/FhG-IPA/Putzmeister)
- a robot prototype for cleaning large glass windows of civil buildings

Lawn mowers



video

- *Automower* autonomous robot by Husqvarna (Sweden) has low power consumption (biocut) and solar recharge

Food industry



video

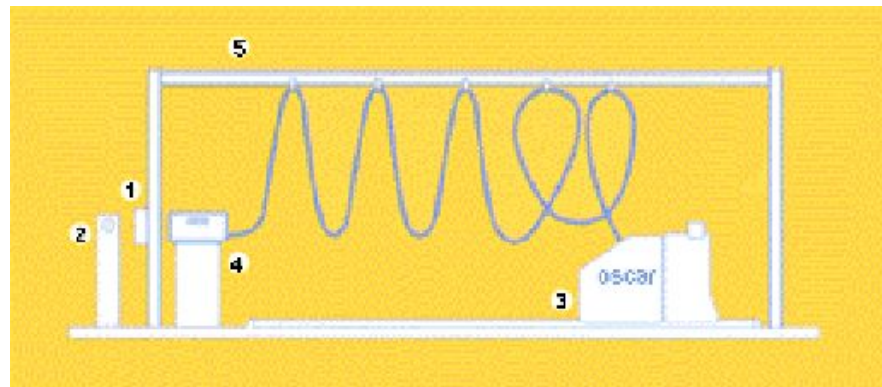


- *Ulixes* robot by IMT (Germany) aligns 10000 sausages per hour



- *AdeptOne* SCARA robot with 4-sausage gripper

Automatic refueling



- OSCAR robot (France) for gasoline refuel of fleets of transportation busses



Automatic refueling



a "kit" is available for all car models:
tank cap, transponder, pipe union

Autofill system in two tank stations of
OK (Mörgby, Sweden) and BP (USA)

Automatic refueling



- cooperation of Reis Robotics, Mercedes, BMW, and IPA Fraunhofer



- *Smart Pump* system (USA)

Inspection and surveillance



- 6-dof *Puma* arm mounted on the *Nomad XR400* (multiple steering wheels, synchro-driven)



- 5-dof *Scorbot* arm mounted on a *ATRV-JR* (fixed wheels, skid-steering vehicle)

two examples of *mobile manipulators*

Mine exploration



- *Groundhog* (Carnegie Mellon)
- 750 kg, double axes, articulated
- movable SICK laser (rangefinder)
- gas and immersion sensors
- SLAM algorithm (Simultaneous Localization And Mapping)

RoboCup and RoboRescue



- RoboCup middle-size league (wheeled mobile robots, here with omni-directional vision)
- *Orpheus* robot won the RoboRescue (exploration and search of victims in a disaster environment)

2003 edition, Padova Fair

DARPA Grand Challenge



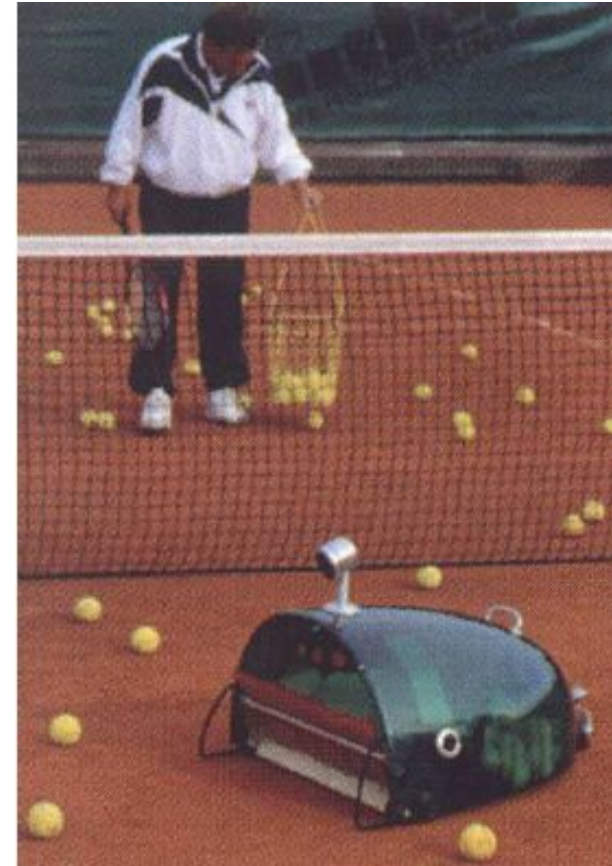
5 SICK lasers for mapping and localization on the 2005 winning VW Touareg "Stanley"



the "Ghostrider" motorcycle testing in Nevada

- competition for fully **autonomous** vehicles on a long mixed-type track

Free time



- bartender robot by Erhardt+Abt (Germany)
- the robotic ball boy (RWI and Carnegie Mellon Univ, USA) that won in 1996 the "Clean up the tennis court!" competition of the AAAI

Museum guidance



- three mobile robots for museum guidance (Museum für Kommunikation, Berlin)

Entertainment



- the *Anaconda* robot (Edge Innovations, USA) weights various tons, has 60 artificial spinal vertebrae, is 12 meters long, and is actuated by hydraulic motors so as to reach a speed of up to 60 km/h

Human motion replication



- the anthropomorphic robot by Sarcos Entertainment Systems (USA) replicates the movements of a human wearing a sensorized exoskeleton

Human-Robot Interaction (HRI)



- **physical** and **cognitive** interaction between a Sarcos robot and a human
intrinsic mechanical compliance in the robot structure
is here more important than accuracy in motion execution

Human-robot cooperation

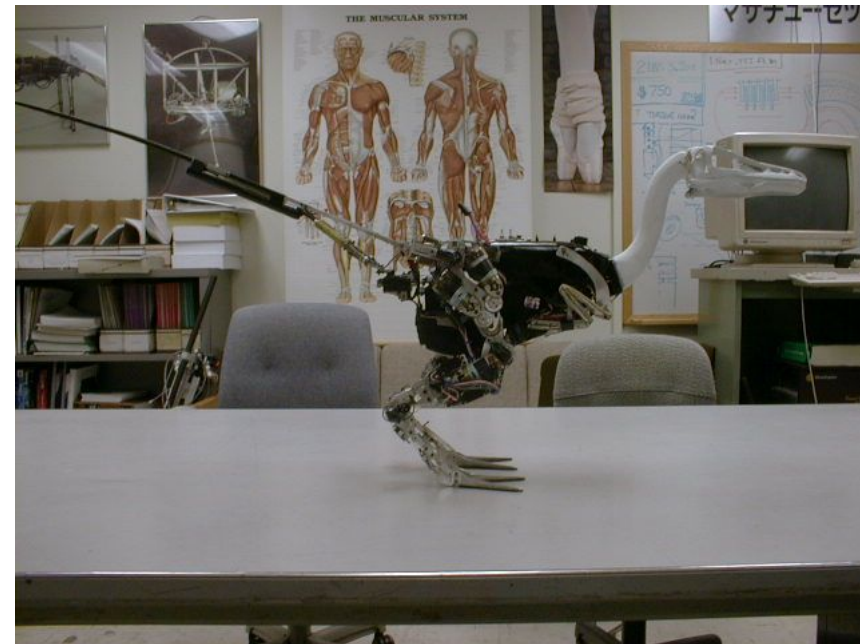


- *Mr. Helper* (Tohoku Univ) cooperates in carrying heavy and/or large loads



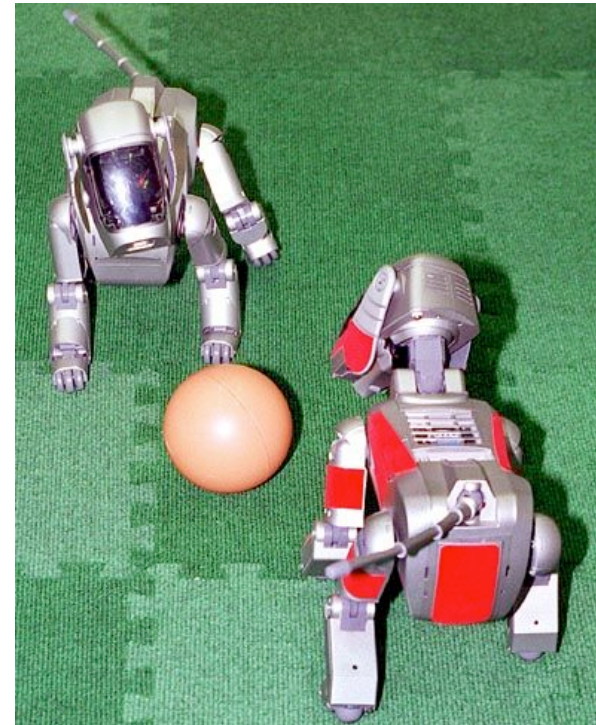
- *CoBot* scooter-like robot for mounting car doors (General Motors)

Biomorphic robots



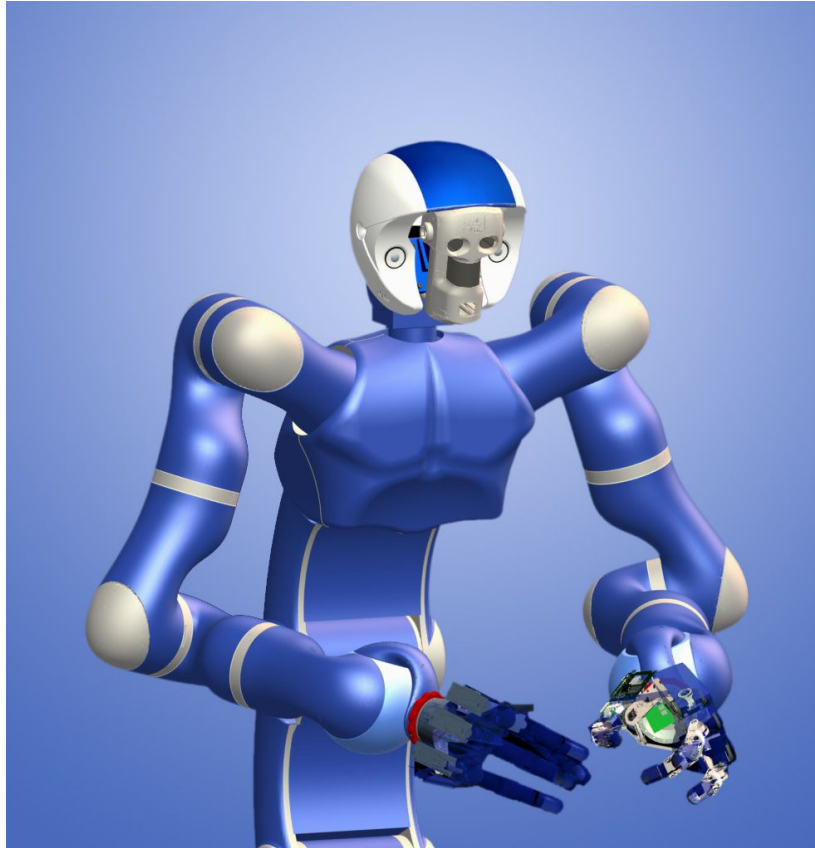
- biomorphic robots by MIT Leg Lab, USA:
Troody dinosaur and *Flamingo* bird

Four-legged locomotion

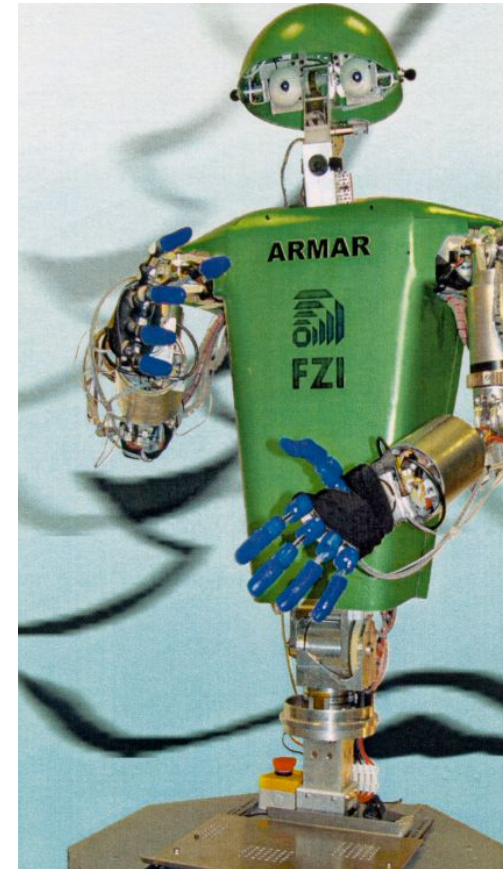


- *AIBO ERS-210* by Sony, playing on the soccer field of RoboCup
 - 16 actuated dofs with encoders, color camera, 3 accelerometers, ultrasound sensors, tactile and micro-switch (feet), battery: everything in 1.6 kg!

Anthropomorphic upper limbs



- *Justin* robot has 7+7+3 degrees of freedom + many dofs in the two hands (DLR, Germany)



- the robot developed in the German national project on humanoids

Humanoid robots

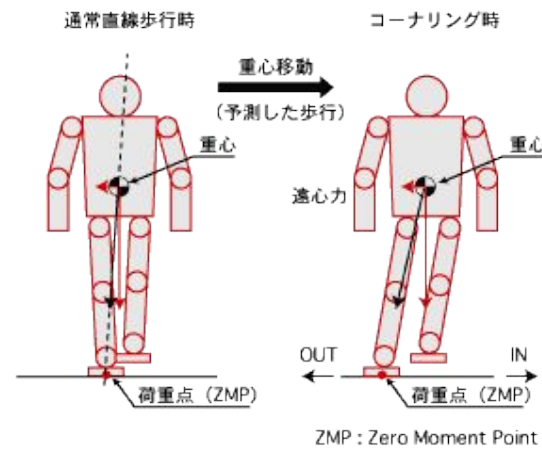


- Metropolis (Fritz Lang, 1927)



- Pino by ZMP (2003)

Humanoid robots



- the *ASIMO* project by Honda started in 1986

ASIMO in action



ASIMO
climbing stairs
(Robodex 2003)



first and
second series
(smaller size)



video



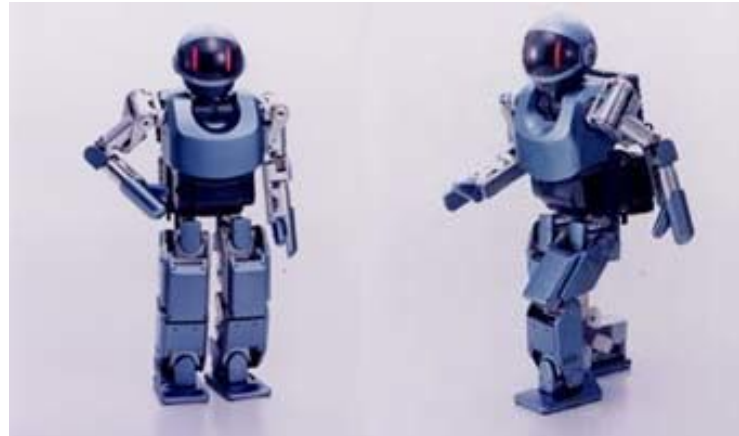
video



Humanoid robots



- *HRP-2*
(58 kg, 150 cm, 30 dofs)
2002 Tokyo Univ



- Sony *SDR-3X*
(about 60 cm)



- humanoid robot
(Q. Huang, PR China)

Sony Q-RIO



group dancing [video](#) (2003)

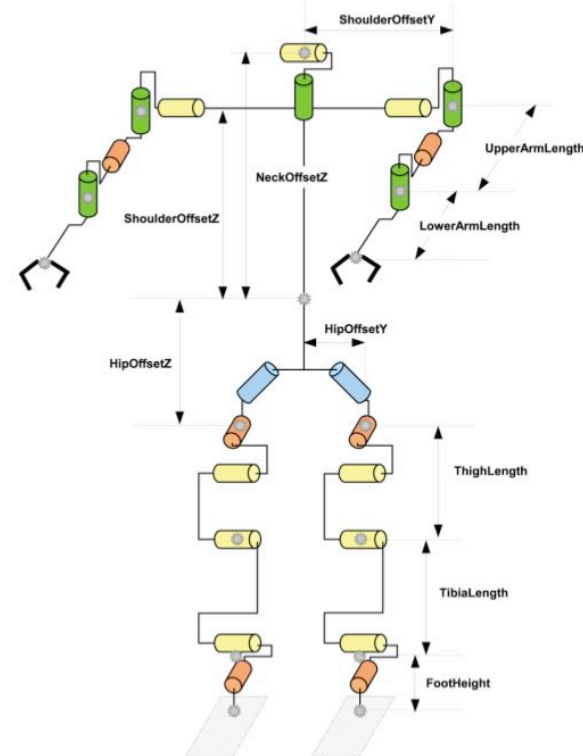
- Sony *Q-RIO*
the first robot able to balance on a surf and stand up from the floor
(dead in 2006...)



Humanoid robots



height = 57 cm
weight = 4.5 kg



kinematic
description

- NAO, Aldebaran Robotics
since 2008, replaces AIBO quadrupeds in RoboCup standard league