Robotics for industry, research & service: a state of the art in 2015

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Involve Challenge 2015

INSA INSTITUT NATIONAL DES SCIENCES APPLIQUÉES LYON

Robotics
State of the art 2015

- Robots
  - Definitions
  - Market
- Manipulators
- Mobile
- Humanoids
- Modular
- Conclusion

What is a robot

- Etymology: Karel Capek, 1921, **Robotnik** = worker
- First industrial robot from Unimation 1959 (Devol & Engelberger)
- A robot is a **mechanical system** under **automatic control** that performs operations such as **handling** and **locomotion** (Source : IFToMM terminology http://www.iftomm.3me.tudelft.nl)
- Summary

Manipulators	Classical topics (1950)
Mobile robots	
Humanoids	Recent topics (1980)
Modular robots	

- Robotics = Mecha + tronics + Automatic control
- Industrial automates and milling machines will not be treated

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What is an industrial robot

- Industrial Robot according to ISO 8373 (www.ifr.org)
- An **automatically controlled**, **reprogrammable**, **multipurpose** **manipulator** programmable in **three or more axes**, which may be either fixed in place or mobile for use in industrial automation applications
- **Reprogrammable**: whose programmed motions or auxiliary functions may be changed without physical alterations (**Physical alterations**: alteration of the mechanical structure or control system except for changes of programming cassettes, ROMs, etc.)
- **Multipurpose**: capable of being adapted to a different application with physical alterations
- **Axis**: direction used to specify the robot motion in a linear or rotary mode

IFR statistics : Robot supply

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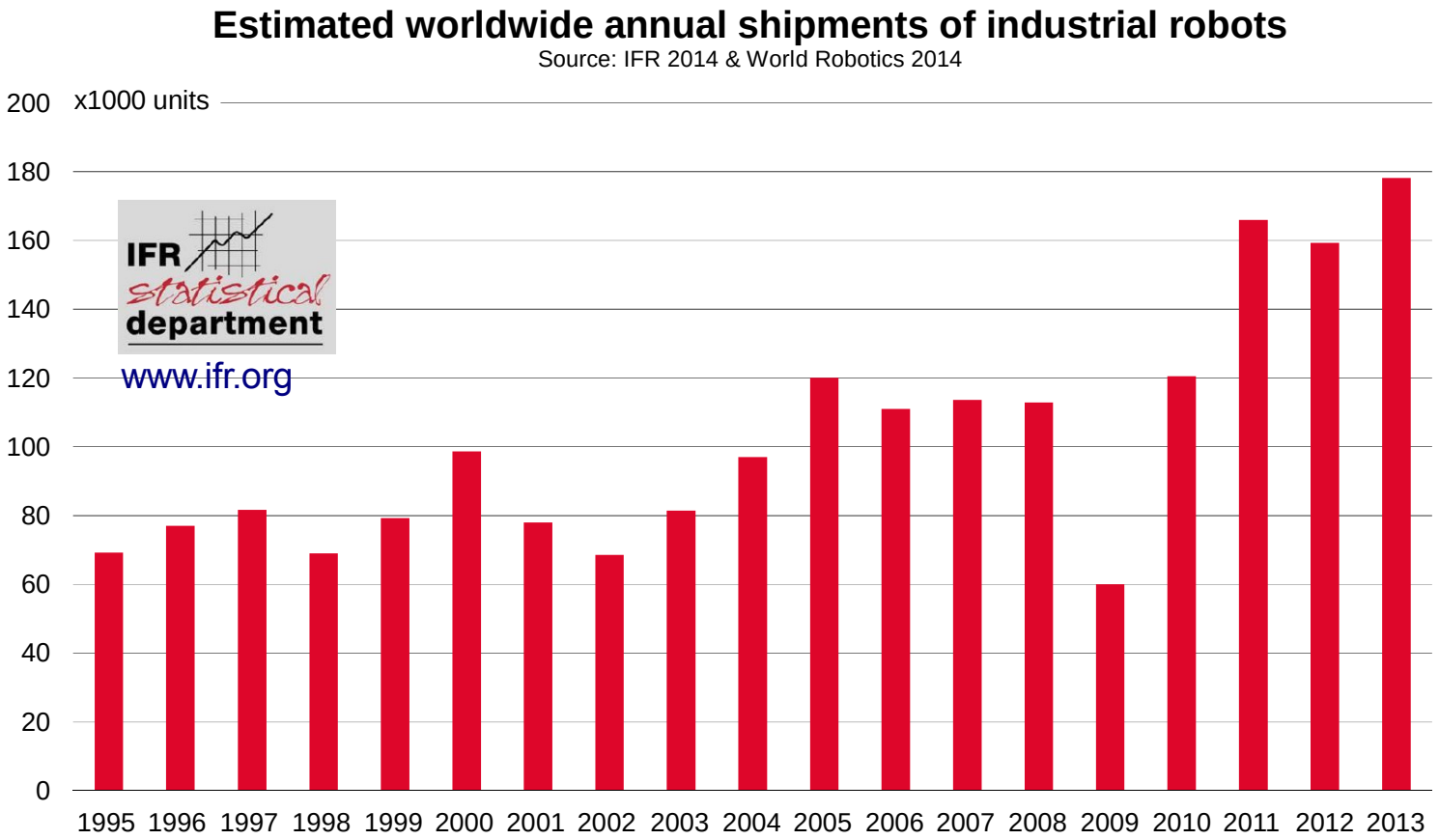

- A market with regular growth
- 178,000 new industrial robots were sold all over the world in 2013 (2012 + 12%)

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IFR statistics : Robot supply per continent

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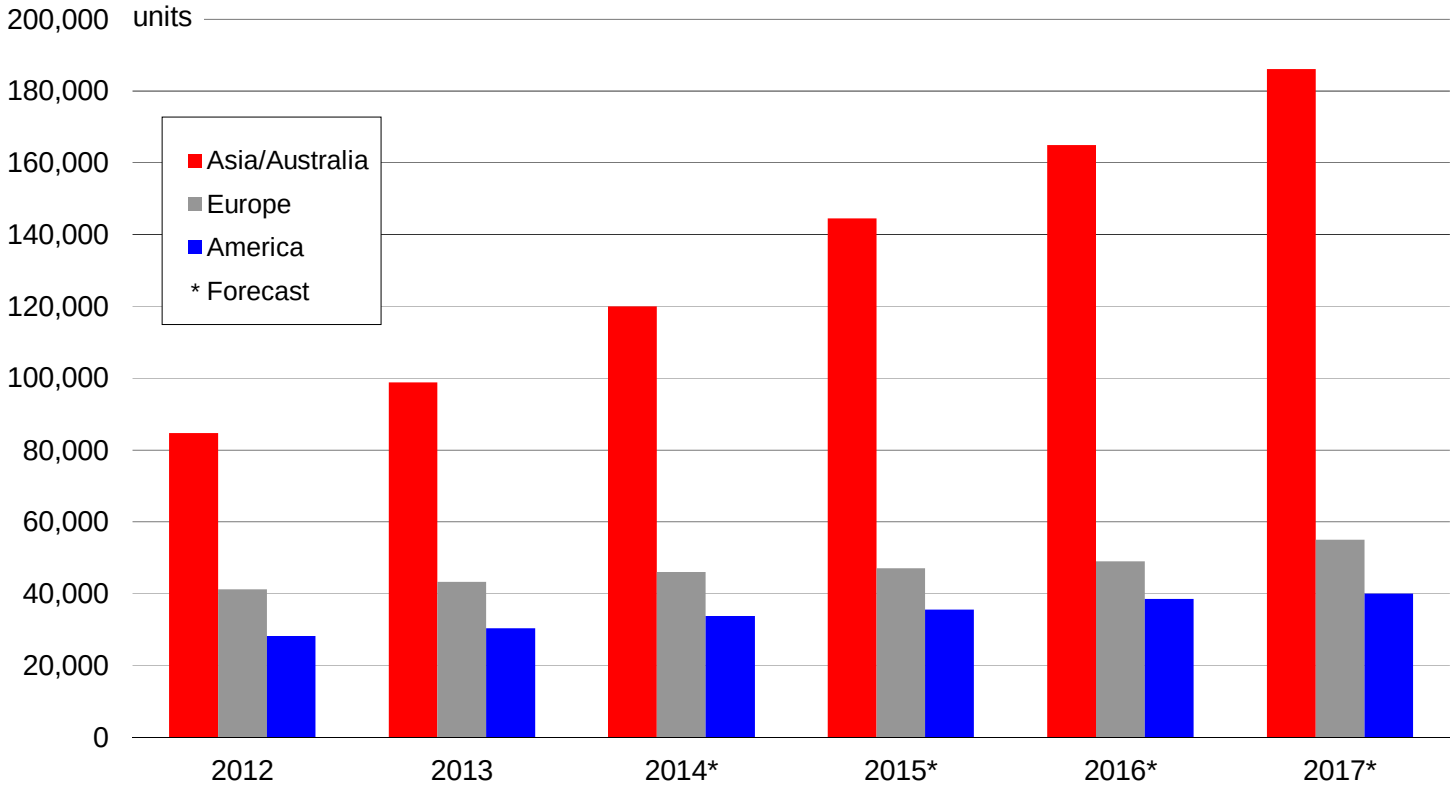
Annual supply of industrial robots 2012-2013 and forecast 2014-2017
Source: World Robotics 2014



- Asia >> Europe > America
- Asia is expected to grow even further 2015 → 2017

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IFR statistics : Robot population per continent

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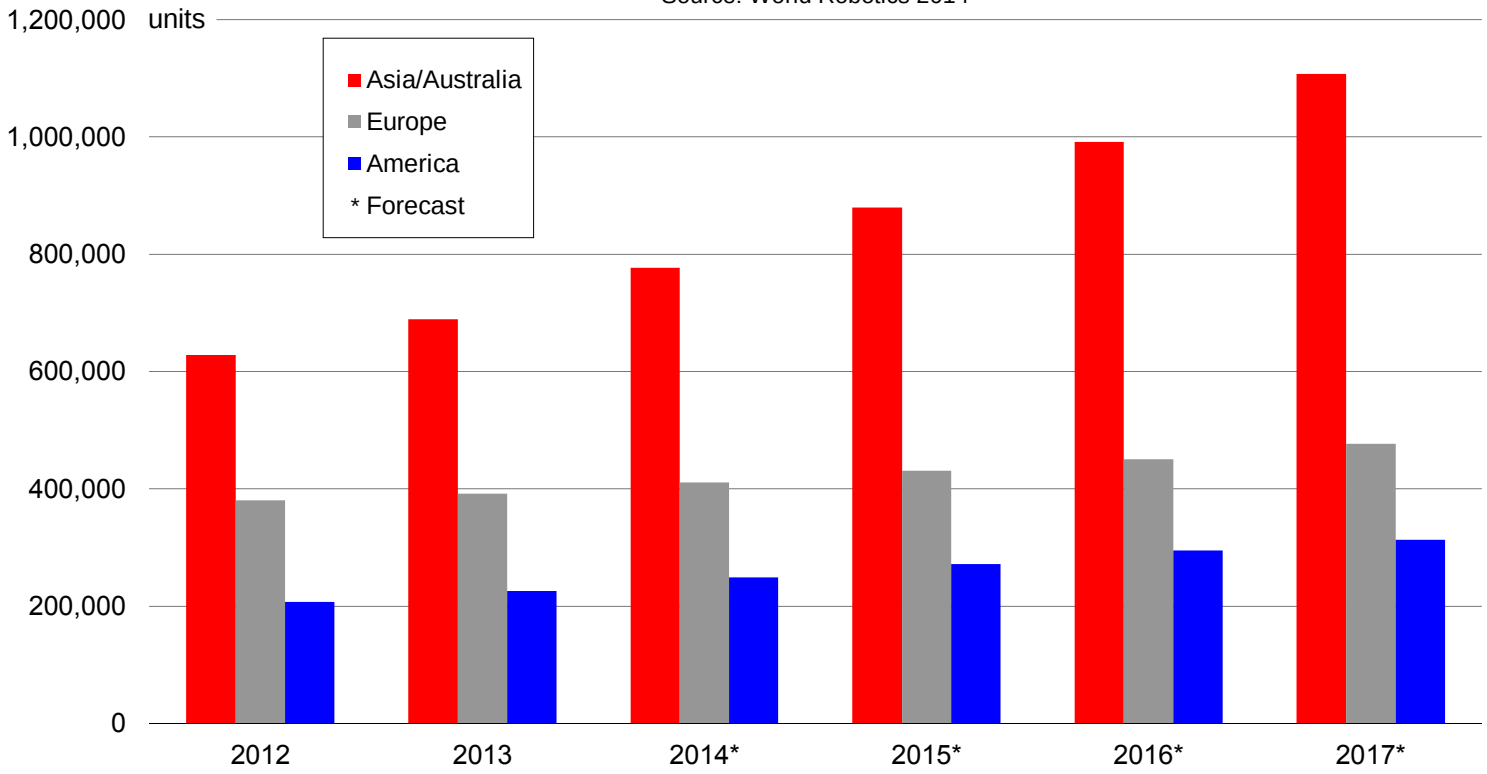
Estimated operational stock of industrial robots 2012-2013 & forecast 2014-2017
Source: World Robotics 2014



- World industrial robot population in 2013 ≈ 1.3 million
- Asia > Europe + America in 2013, and it should increase

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IFR statistics : Robot supply per industry

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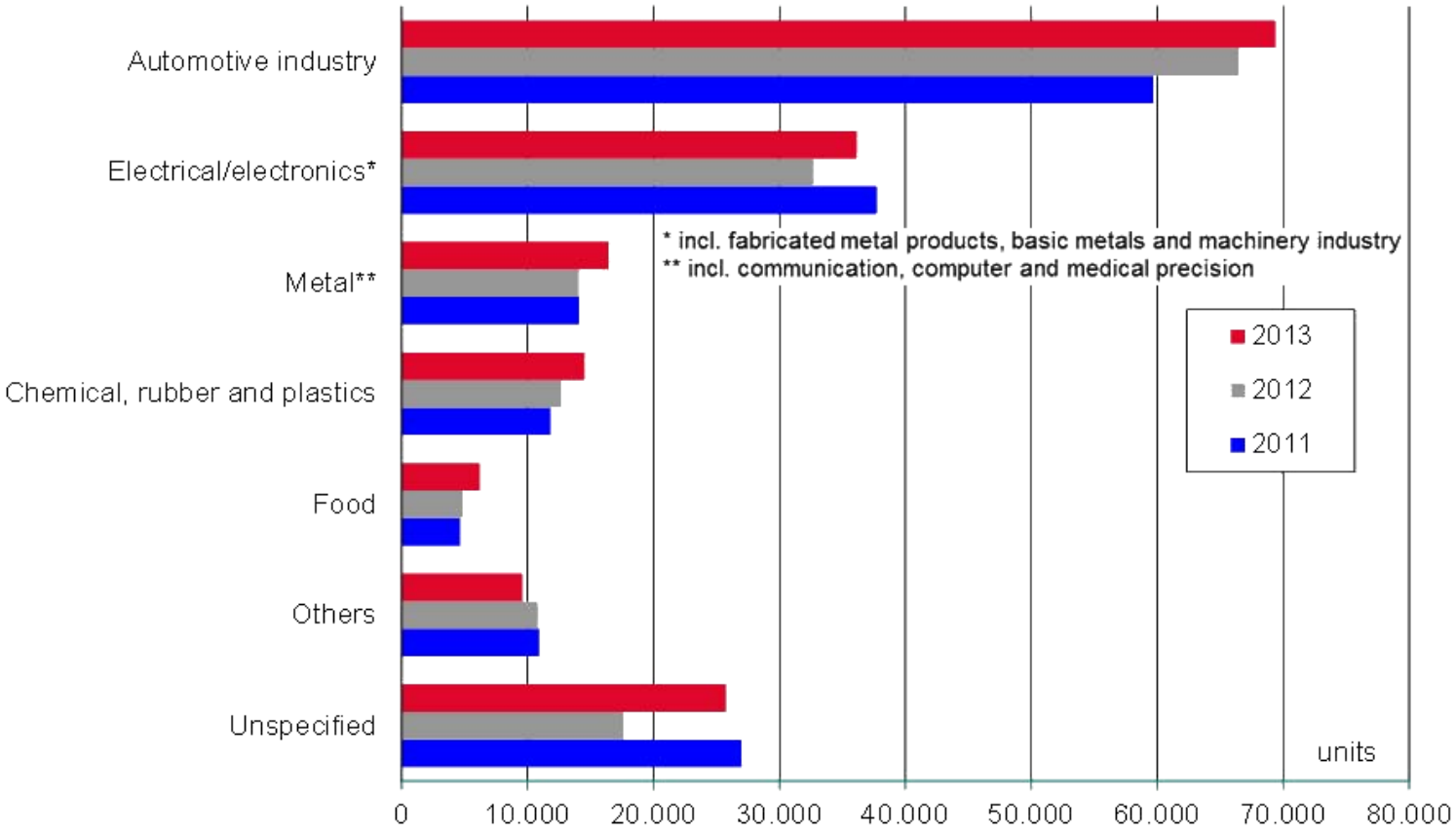
Estimated worldwide annual supply of industrial robots at year-end by industries 2011 - 2013

Source: World Robotics 2014



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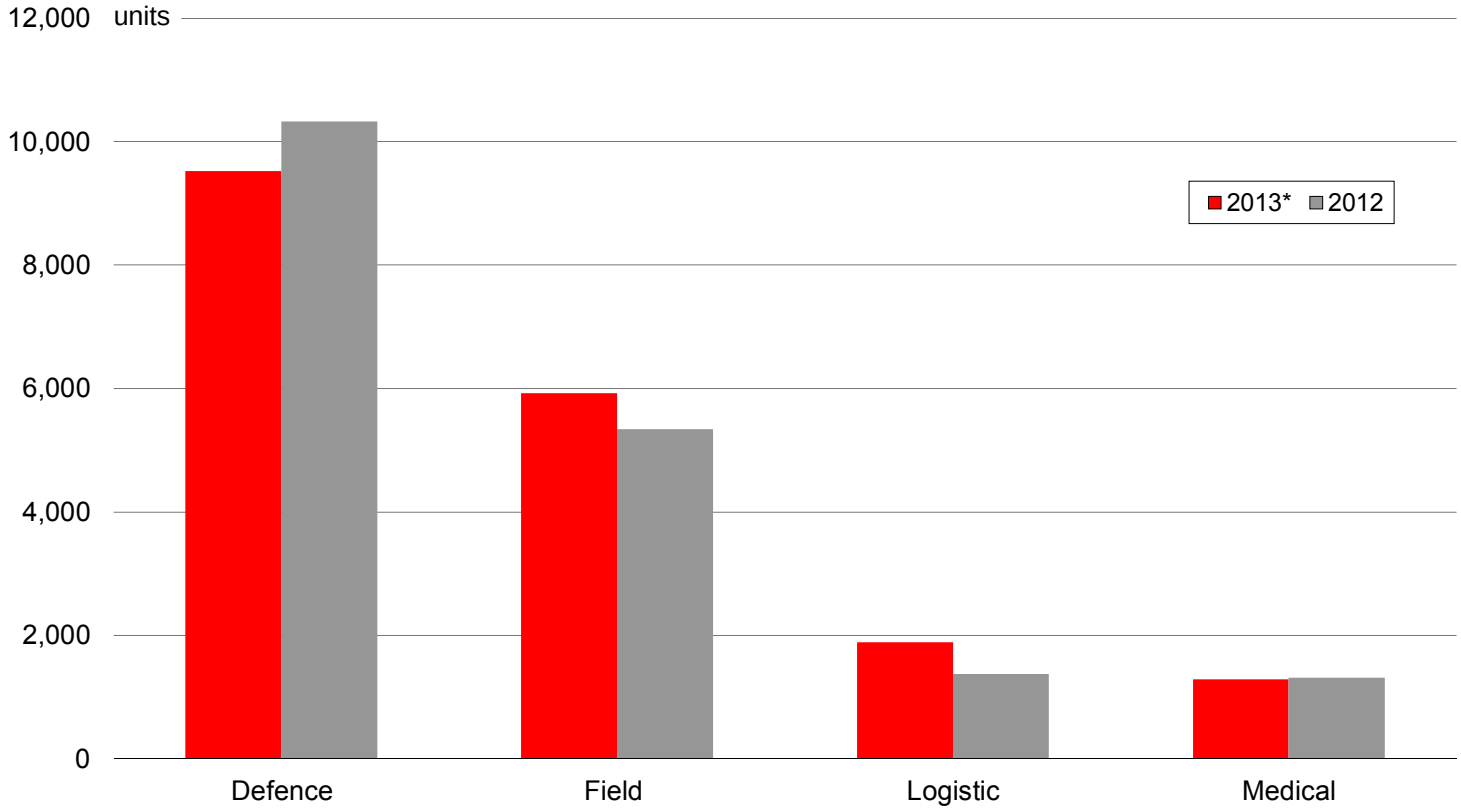
IFR statistics : Service robots

Service robots for professional use
Sold units 2013 and 2012 (main applications)
Source: World Robotics 2014



- A new category of commercial robots: **service robots**
- Defence and field robots prevail

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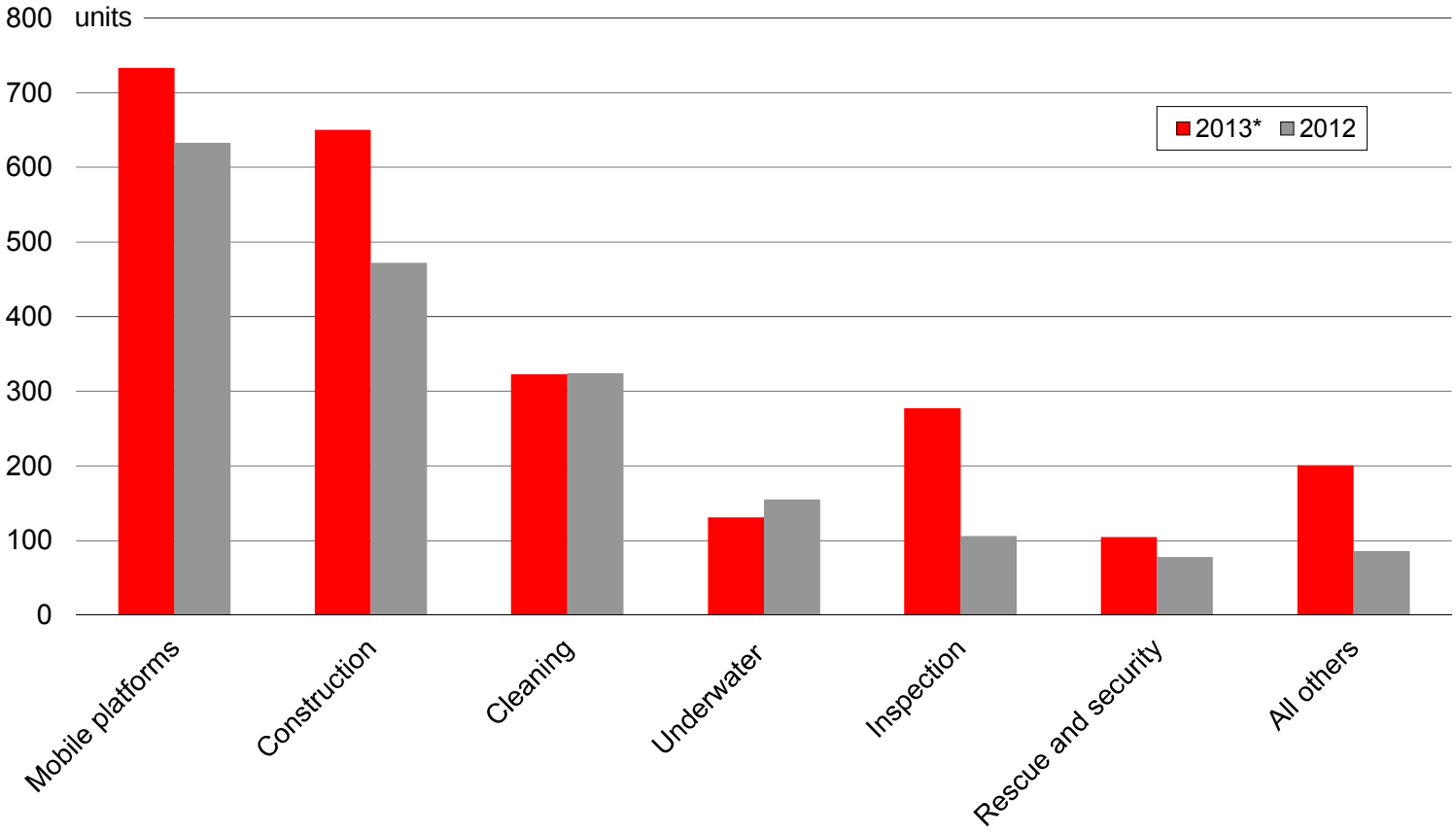
IFR statistics : Service robots

Service robots for professional use
Sold units 2013 and 2012 (main applications, continued)
Source: World Robotics 2014



- Other marginal applications (less than 1000 units reported)
- Wide number of applications with strong potential

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IFR statistics : Robot supply per industry

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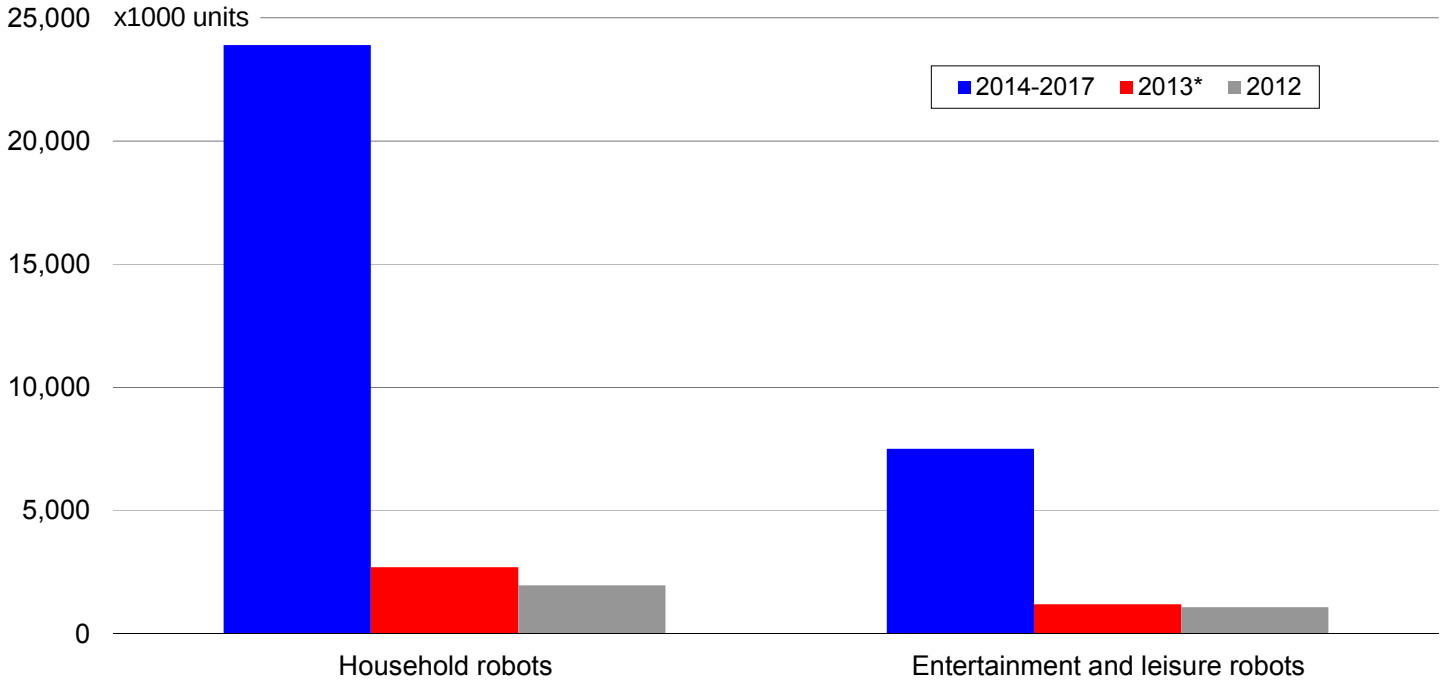
Service robots for personal and domestic use
Units sales: forecast 2014-2017, sold 2013 and 2012
Source: World Robotics 2014



- Household robots > Entertainment in 2012
- An expected explosion of the market

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Industrial manipulators

Robotics
State of the art 2015

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  - • Modelling
  - • Serial
  - • Parallel
  - • Surgery
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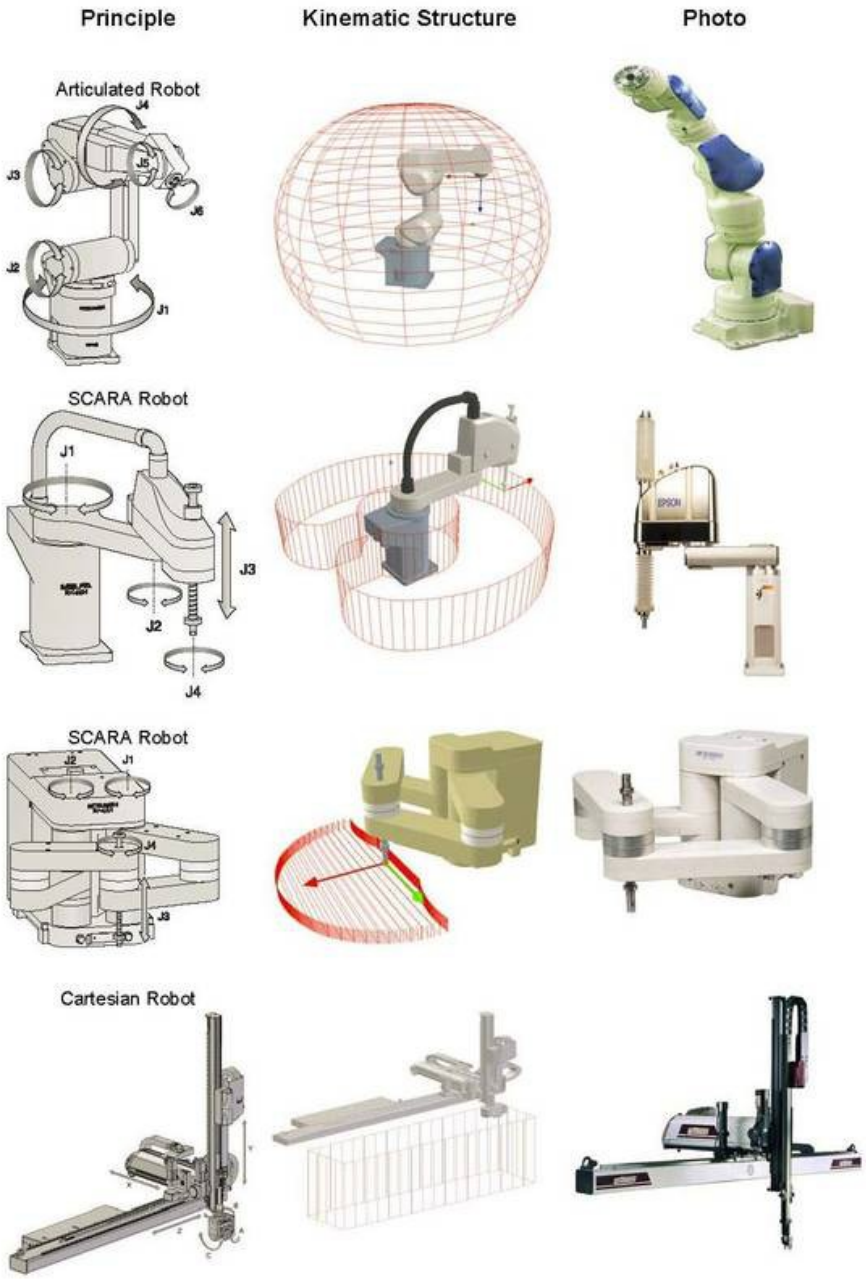
- Industrial overview from International Federation of Robotics

  www.ifr.org

  - ✔ Members from ABB, Adept, Comau, Duerr SYstems, Fanuc, Kuka, Universal Robots, Yaskawa Motoman...
  - ✔ Information letter every 3 months
  - ✔ Industrial statistics: 178,000 new industrial robots were sold all over the world in 2013 (2012 + 12%)



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Industrial robot applications

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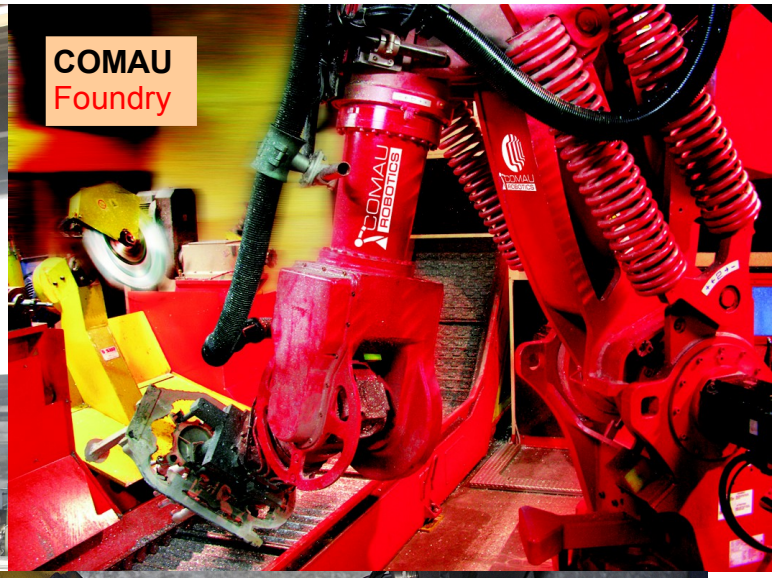
ABB
Die casting



COMAU
Foundry

FANUC
Removing a hot preformed forging from a furnace

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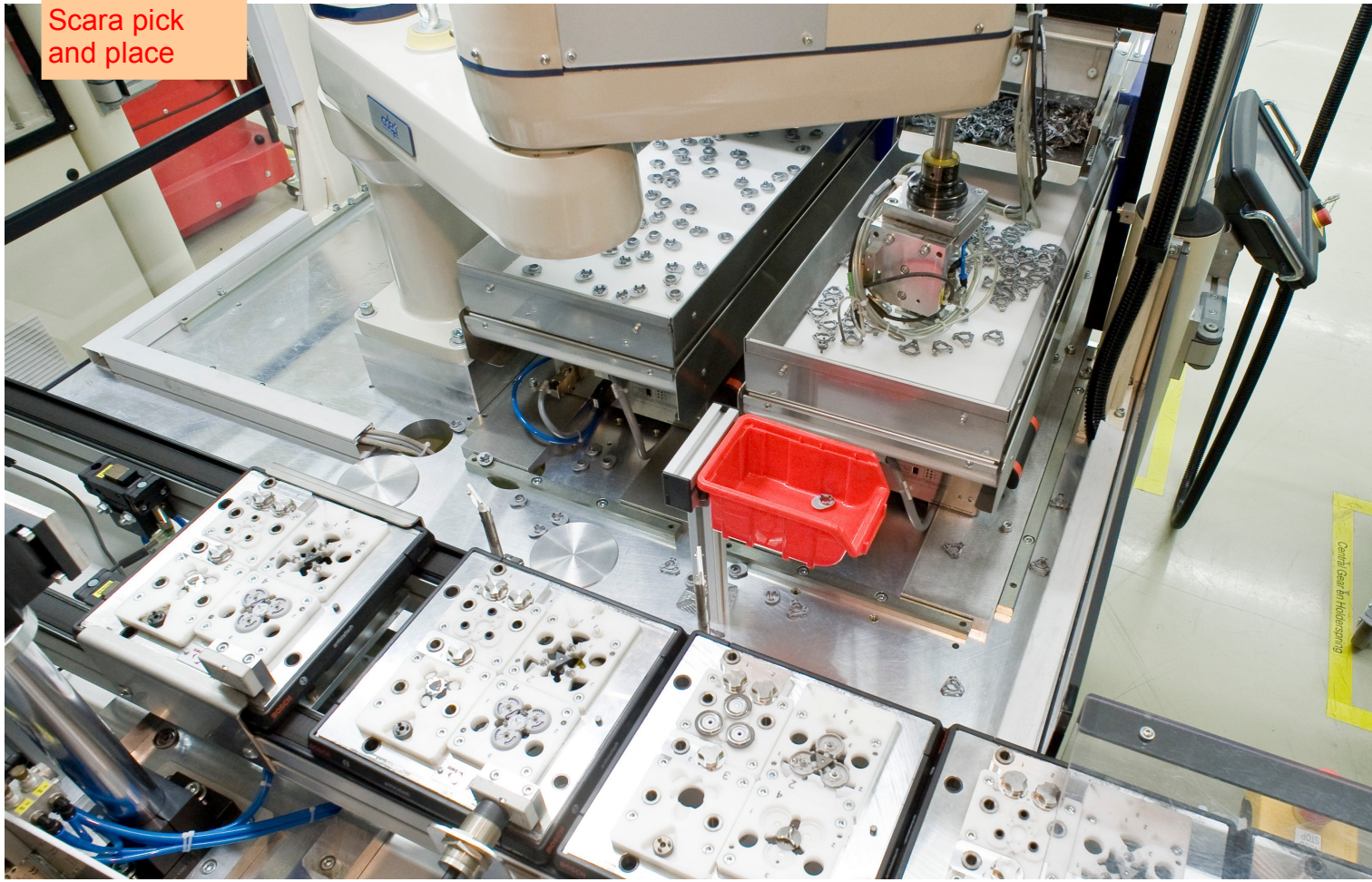
ADEPT
Scara pick and place



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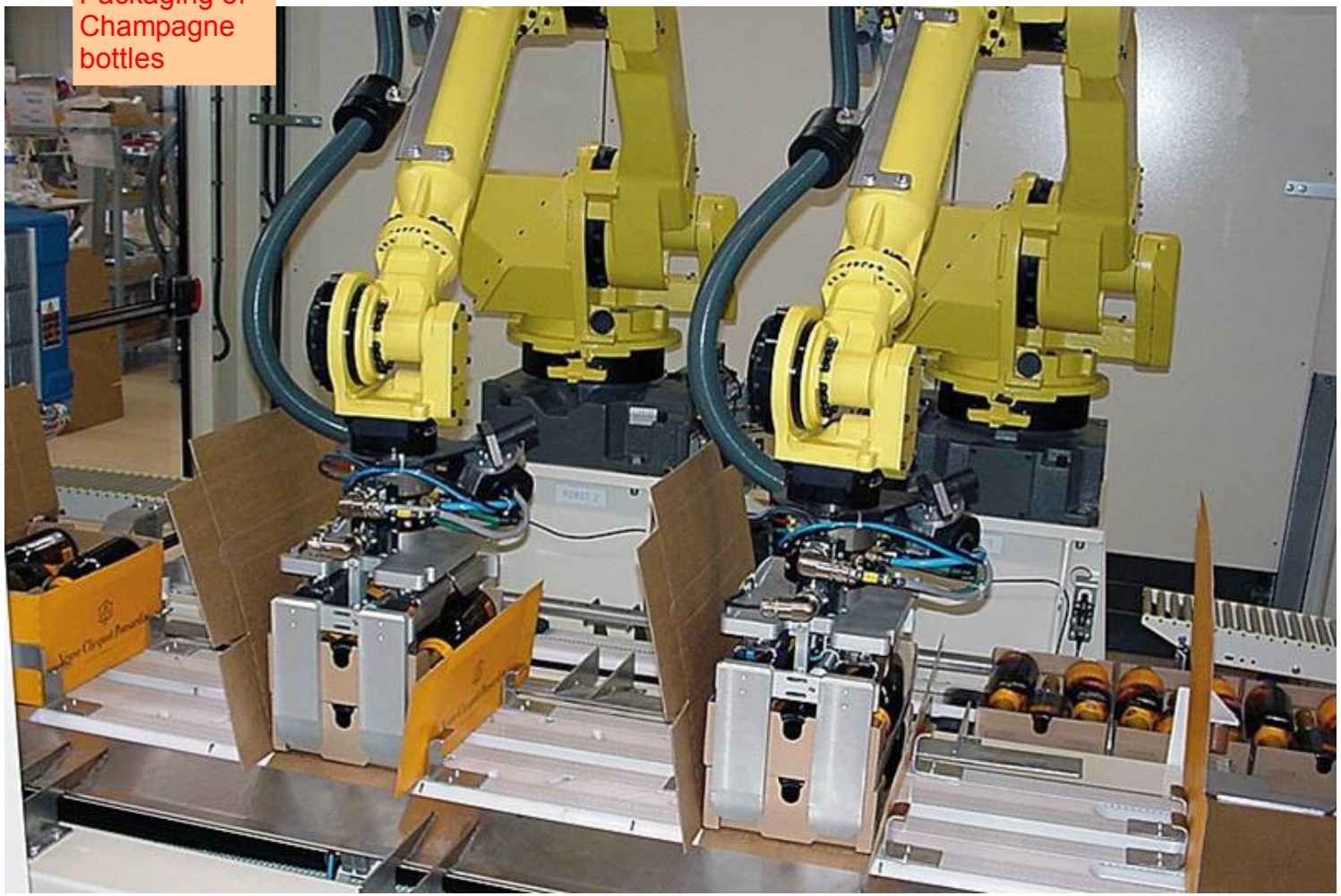
FANUC
Packaging of Champagne bottles



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KUKA
A robot collects pallets for stacking after nailing

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YASKAWA MOTOMAN
Automating plastic injection moulding

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REIS
Man collaborating with robot for soldering

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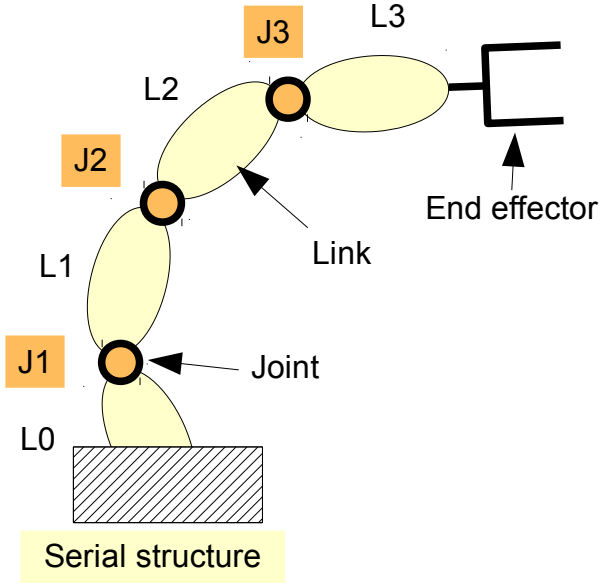
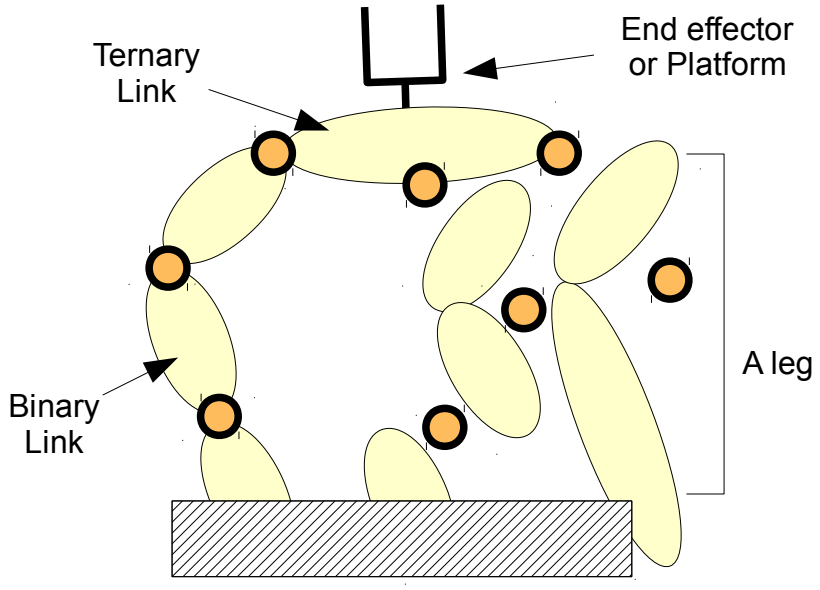
Structure of manipulators



Serial structure



Parallel structure

- ✔ Serial / Parallel / Hybrid structures
- ✔ Kinematical graph
- ✔ Models for representation of motions : Denavit-Hartenberg, TCS...

Modelling manipulators

- Model

x
Operational coordinates = **position** + **orientation** of end effector

Inverse geometric model

Direct geometric model

q
Articular coordinates = **position** or **orientation** of actuators

$\dot{x}$
Operational speeds

Inverse kinematic model

$$(\dot{x}) = \begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \end{pmatrix} = [J] \begin{pmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \\ \dot{q}_4 \\ \dot{q}_5 \\ \dot{q}_6 \end{pmatrix} = [J](\dot{q})$$

Direct kinematic model

$\dot{q}$
Articular speeds

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- Properties of robots:
  - ✔ Workspace
  - ✔ Singularities (come from conditioning of Jacobian J matrix)
  - ✔ Stiffness and precision
- Can be used for synthesis

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Poly-articulated Serial Manipulators

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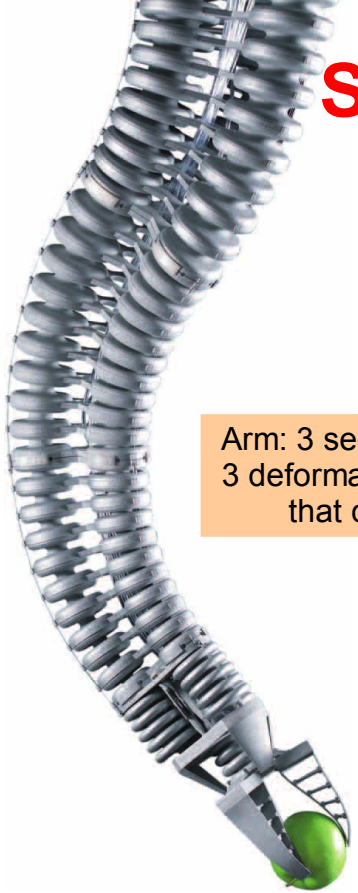
Kuka KR1000 Titan 6R
(L1000kg / R3.2m / r0.2mm)
www.kuka.com

Staubli RS80 Scara 2RPR
(L8kg / R0.8m / r0.01mm)
www.staubli.com

ABB IRB660 4R
(L250kg / R3.1m / r0.05mm)
www.abb.com

- ✔ Specifications :
- ✔ Load L (up to 1000kg)
- ✔ Reach R (up to 3m)
- ✔ Repeatability r (up to 0.01mm)

Soft Serial Manipulators



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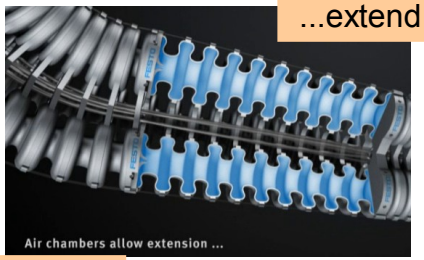
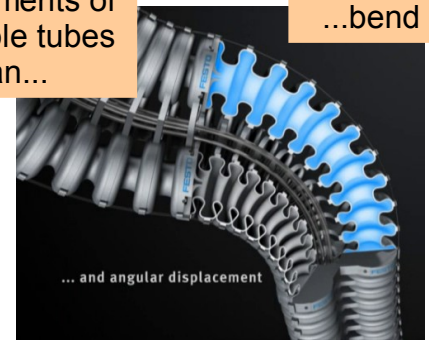
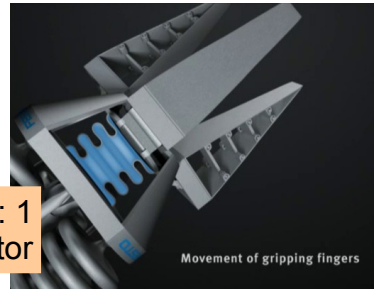


...extend

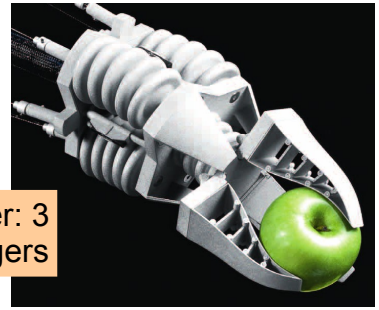
Arm: 3 segments of 3 deformable tubes that can...



...bend



Gripper: 1 central actuator



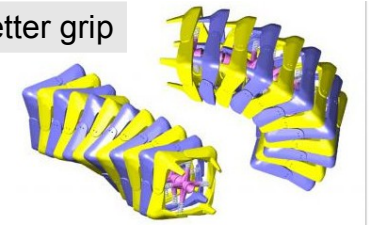
Gripper: 3 deformable fingers

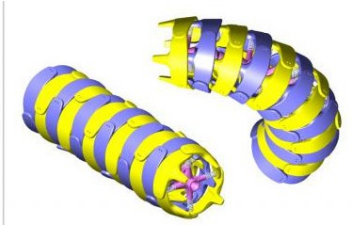
Festo Bionic Handling Assistant 2010
(3 segments + wrist + 3 finger gripper)
www.festo.com

- ✔ Biomimicry: elephant trunk, seahorse tail...
- ✔ Compliant struct. or more joints →
- ✔ Stiffness and precision ↓
- ✔ Control → more complex

Square vs circle for articulated tails (Clemson Univ.)
www.naturalengineering.org

Better grip





Stronger

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Inflatable Serial Manipulator

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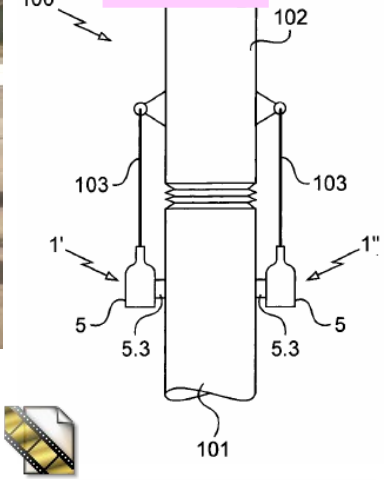
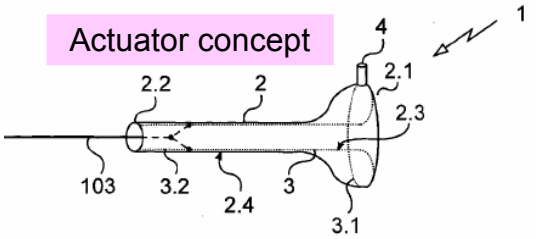
Warein Confection Technique
(L1kg / R5m / r10cm ?)
http://www.warein-sas.com

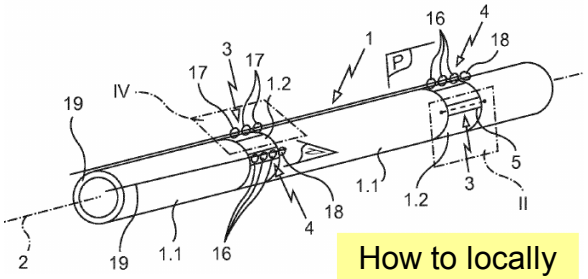
Use case



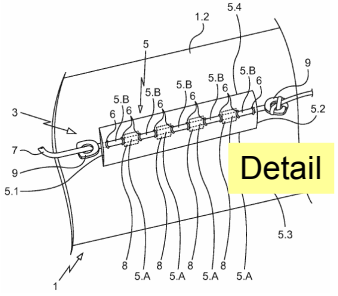
Actuator concept



Folding linear actuator
WO2015118085

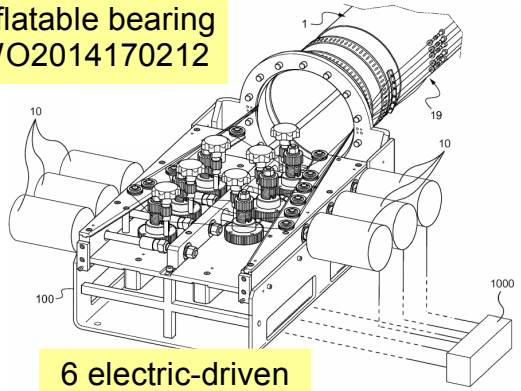


How to locally bend a tube ?



Detail

Inflatable bearing
WO2014170212



6 electric-driven cable actuators

- ✔ Robot mass = Payload mass (1kg)
- ✔ Low precision, long range (5m)
- ✔ Transportable by operator
- ✔ Tele-operated for inspection tasks
- ✔ Low risks for humans
- ✔ 2 patents

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Serial arms

- ✔ **Virtual Reality** applications
- ✔ Use robot **geometrical model**

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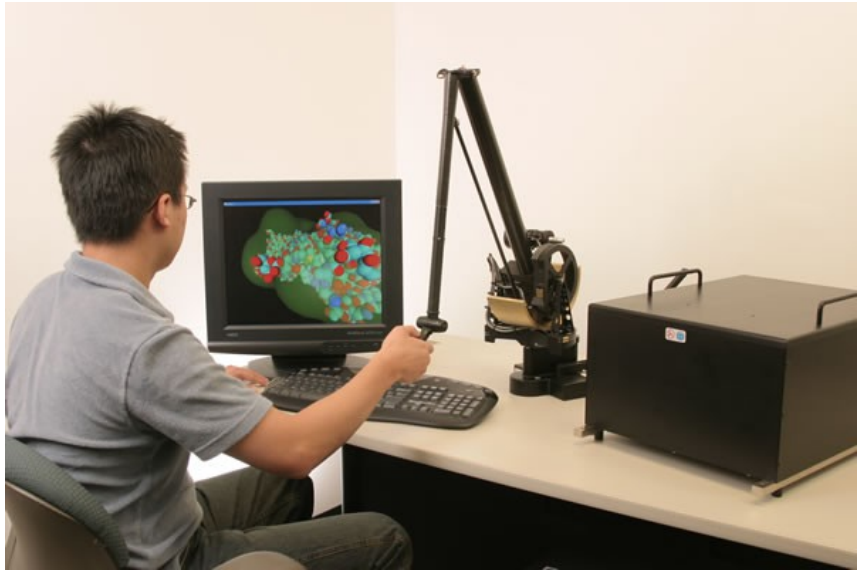
Sigma Measuring Arm
6kg, up to 5m range Accuracy +/- 25 μm
www.romer.com



Phantom 3.0
6 DOF, Accuracy 20 μm
Haptic rendering on 3 translations
20 N max, 3N nominal)
www.sensable.com

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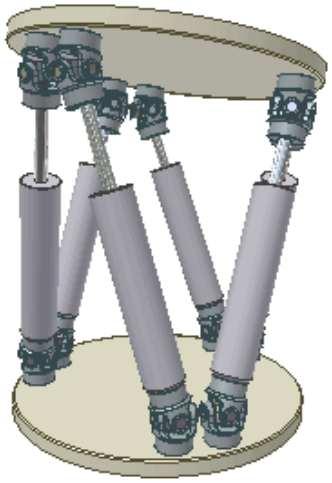
Parallel Manipulators

- ✔ Direct (reverse) geometric model is hard (easy) to solve
- ✔ Recent gain of popularity in industry

ABB IRB360 Delta 3 DOF
(L3kg / R0.4m / r0.1mm)
www.abb.com



Hexapod Gough-Stewart platform
Used for simulators / milling machines

Falcon joystick
3 leg parallel mechanis
www.novint.com

- ✔ Industrial applications are recent (simulator, positioning device, pick and place, milling machine)
- ✔ Small workspace but good precision
- ✔ Actuators on the frame → High accelerations (100g)
- ✔ High precision
- ✔ New structures are synthesized each year
- ✔ Resource on parallel machines: www.parallemic.org

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Isoglide 4 T3R1
A Decoupled Parallel Manipulator

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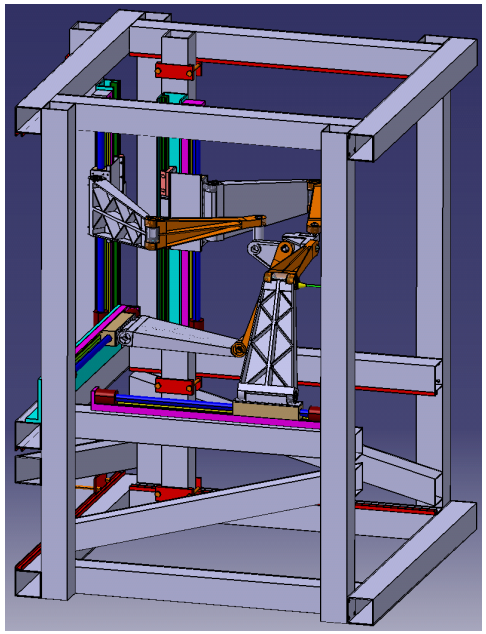
- ✔ Original idea of G. Gogu
- ✔ Isoglide family of robots
- ✔ Isoglide 4 T3R1 decoupled in translation
- ✔ Unitary Jacobian



IFMA INSTITUT FRANÇAIS DE MECANIQUE AVANCEE — LaMI

Isoglide 4 T3R1
www.ifma.fr/lami

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Surgery Manipulators

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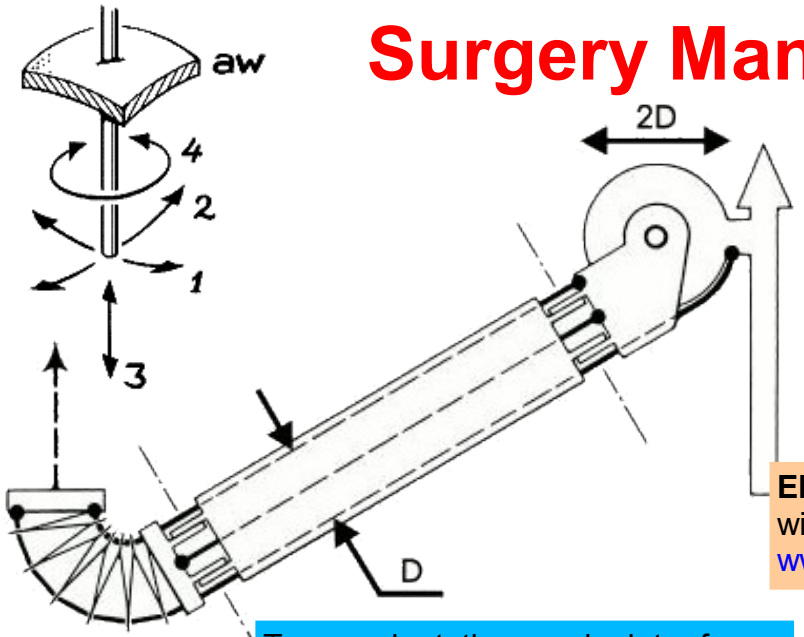
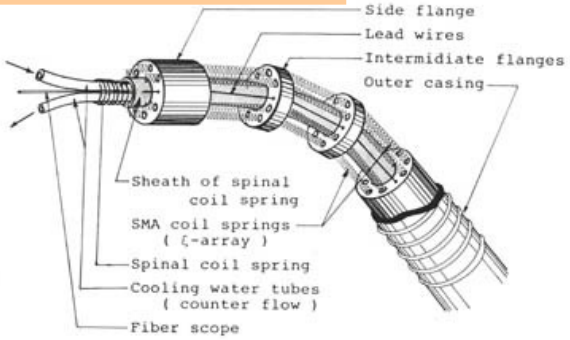
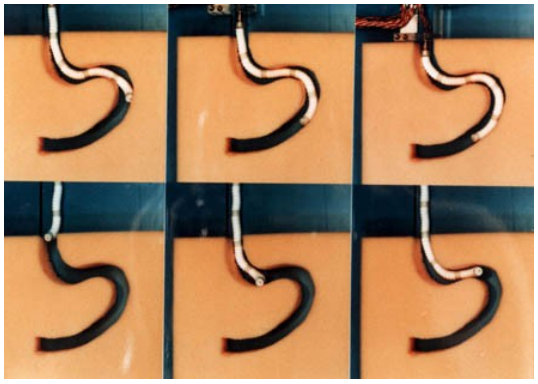


Elastor endoscope
with SMA actuators
www-robot.mes.titech.ac.jp

Trump orientating manipulator for laparoscopy
www-robot.mes.titech.ac.jp





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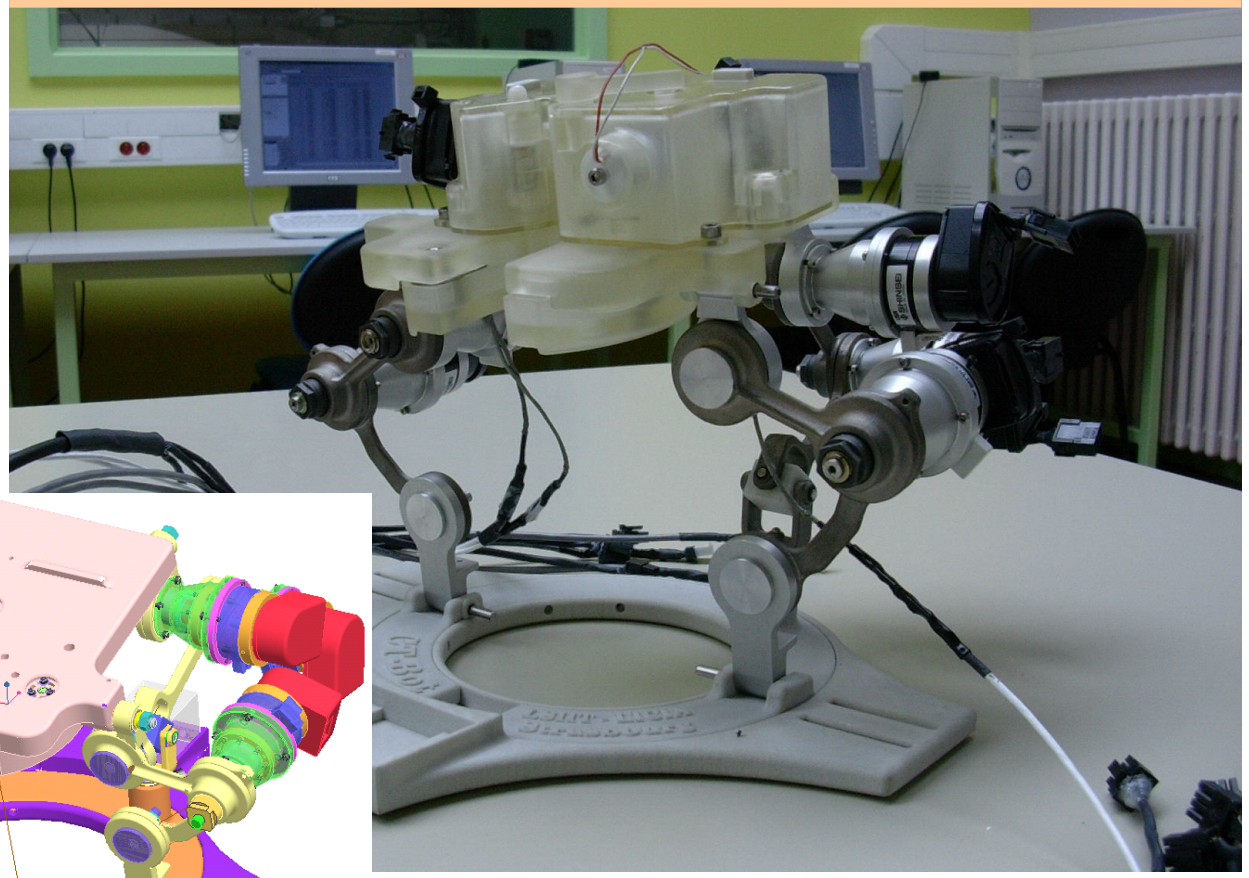
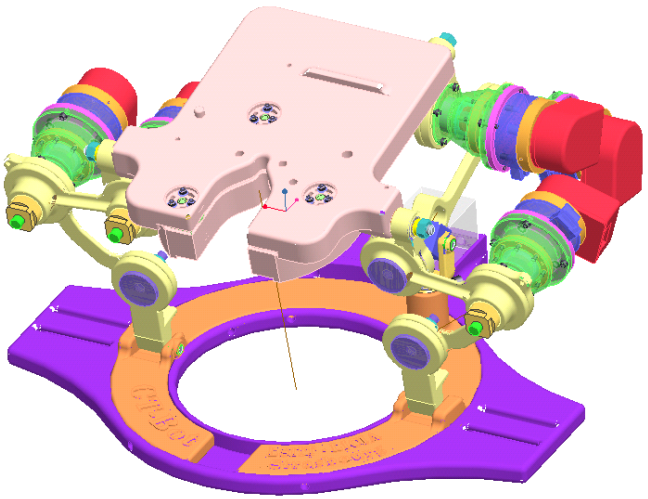
Surgery Manipulators

Robotics
State of the art 2015

- Robots
- Manipulators
  - Use cases
  - Modelling
  - Serial
  - Parallel
  - Surgery
- Mobile
- Humanoids
- Modular

CT-Bot
5DOF parallel robot for needle insertion guided by **C**omputer **T**omography
(the surgeon avoids to work among X-Rays)
lsiit.u-strasbg.fr





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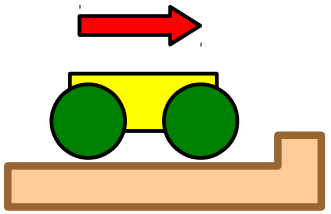
Robotics

State of the art 2015

- Robots
- Manipulators
- Mobile
- Humanoids
- Modular
- Conclusion

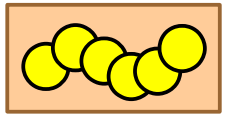
Mobile robots

Terrestrial vehicles

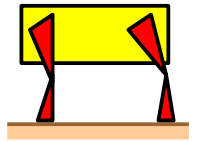


- ✔ **Wheeled** vehicles prevail (energetic efficiency ?)
- ✔ Blocked on **slope discontinuities** of the ground
- ✔ Legs / Tracks regain interest for **climbing**

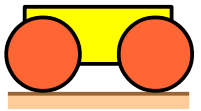
Interface with the ground



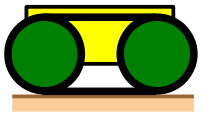
- ✔ **Crawler**
  - \+ multiples contacts, can cross obstacles & rough terrain
  - \- require high energy, moderate speed, complex control



- ✔ **Leg**
  - \+ can cross obstacles and go fast on rough terrain
  - \- contact discontinuity, energy cost, stability control



- ✔ **Wheel**
  - \+ fast on smooth surface, energy efficient
  - \- cannot climb obstacles or run on rough terrain



- ✔ **Track**
  - \+ permanent stability, high traction
  - \- high friction energy loss, particularly during steering

Steering

- ✔ Most of the vehicles have **non holonomic behaviour**

  E.g. a car cannot **go sideways** without a **manoeuvre**
  Going sideways is **non controlable**, although **possible**

- ✔ Holonomy is brought by **omnidirectional** propulsion

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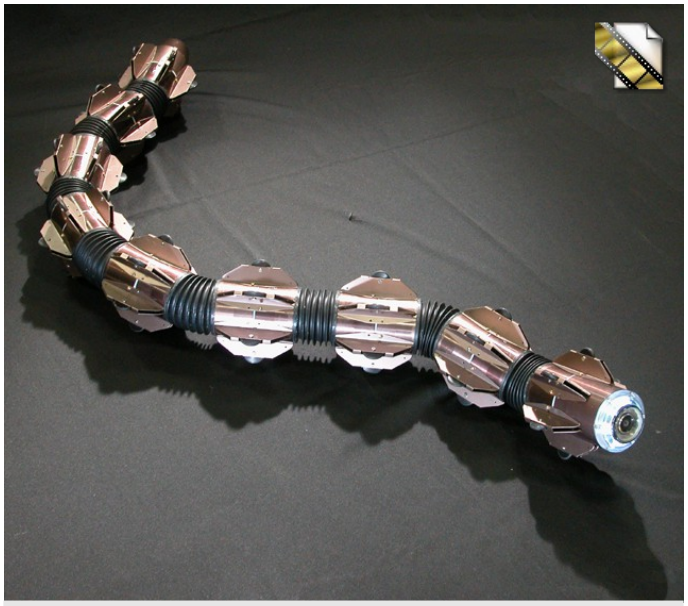
Crawling mobile robots

- ✔ Several **modes** (slide-pushing, peristaltism...)
- ✔ Suitable for inspection tasks (pipes...)
- ✔ **Solid ground** / **water**

Robotics
State of the art 2015

- Robots
- Manipulators
- Mobile
  - • Crawler
  - • Leg
  - • Wheel-Track
  - • Hybrid
  - • Special
- Humanoids
- Modular



Active Cord Mechanism ACM-R5
7.5kg, 1.7m long, 80mm diameter
Snake propulsion on ground and water
www-robot.mes.titech.ac.jp

Aiko
7kg, 1.5m long, 20 DOF, 2.5 Nm
Obstacle-aided locomotion, slidewinding
www.sintef.no

Mobile robots based on legs

- ✔ Bi / Quadri / Hexa / Octo
- ✔ Gait study based on nature
- ✔ Gait self-teaching

Robotics
State of the art 2015

- Robots
- Manipulators
- Mobile
  - Crawler
  - Leg
  - Wheel-Track
  - Hybrid
  - Special
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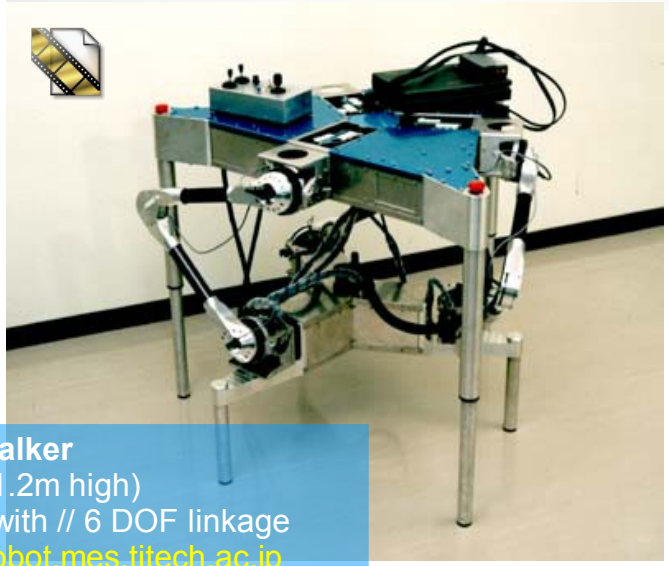
- Modular

Big Dog (75kg, 1m long, 6km/h, 35° slopes, 150kg payload)
www.bostondynamics.com

Resilient walker
Gait self-teaching
Functional damage compensation
ccsl.mae.cornell.edu



ParaWalker
(50kg,1.2m high)
Biped with // 6 DOF linkage
www-robot.mes.titech.ac.jp

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Mobile robots based on legs

Robotics
State of the art 2015

- Robots
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  - Crawler
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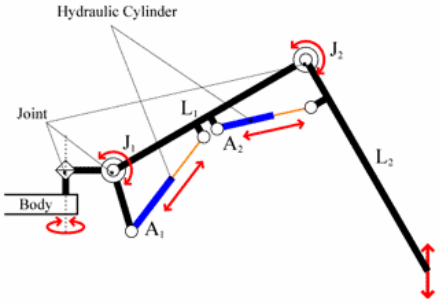
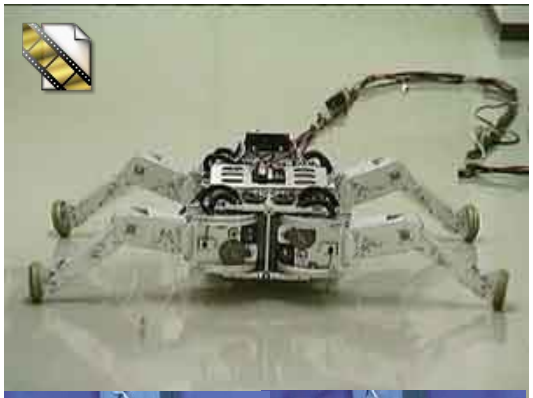
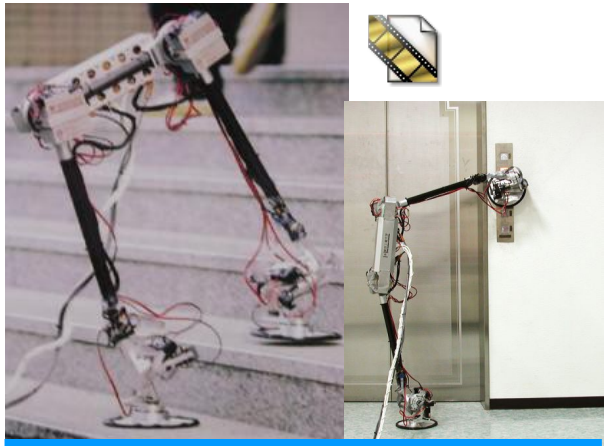
- Modular

Titan XI
(7000kg, leg 3.7m)
Climbing&heavy drilling
www-robot.mes.titech.ac.jp





Roller-Walker (24kg, 0.5m long)
Convertible wheels
Dual locomotion mode:
walking / roller-skating
www-robot.mes.titech.ac.jp



Yanboo III
(13kg,0.7m high)
Biped with suction/rolling effectors
Legs are manipulators
www-robot.mes.titech.ac.jp

Wheeled & tracked robots

- ✔ Wheel: energy efficient even when steering
- ✔ Only exception : **skid steering**

Robotics
State of the art 2015

- Robots
- Manipulators
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Pioneer P3-AT
Skid steering simple robot
www.mobilerobots.com

Nomad
Dual Ackermann steering strategy
www.frc.ri.cmu.edu/projects/lorax

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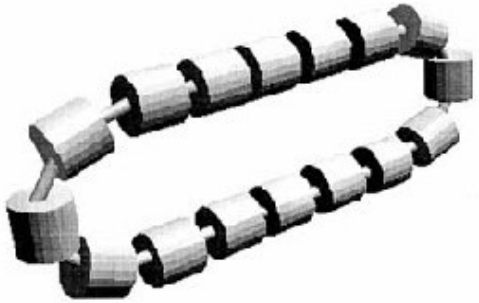
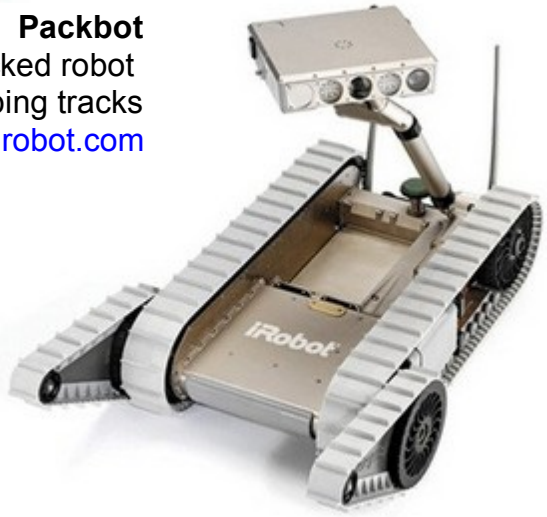
Wheeled & tracked robots

- Tracks: good traction but steering generates wear

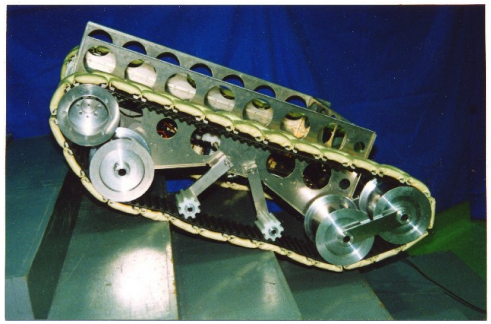


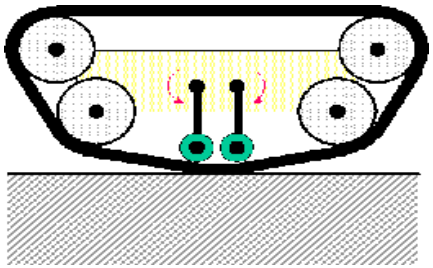
Packbot
Tracked robot
with auxilliary climbing tracks
www.irobot.com



Vuton
4 Omnidirectional tracks
Holonomic vehicle
www-robot.mes.titech.ac.jp

Xevius
Tracked robot
with reconfigurable polygon
www-robot.mes.titech.ac.jp





Robotics
State of the art 2015

- Robots
- Manipulators
- Mobile
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  - Leg
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Adaptative Wheeled Robots

- ✔ **Minimally actuated frame**, energy efficiency
- ✔ Simple control

Robotics
State of the art 2015

- Robots
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Rocky 7
Adaptative rocker-bogie structure
www-robotics.jpl.nasa.gov

Micro5
Climbing abilities via 5 wheels
www.mit.edu/~ykuroda

Adaptative Wheeled Robots

Robotics
State of the art 2015

- Robots
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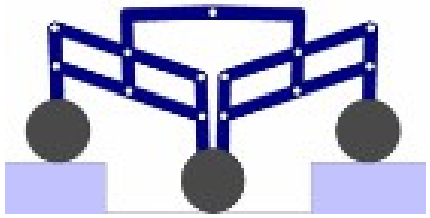
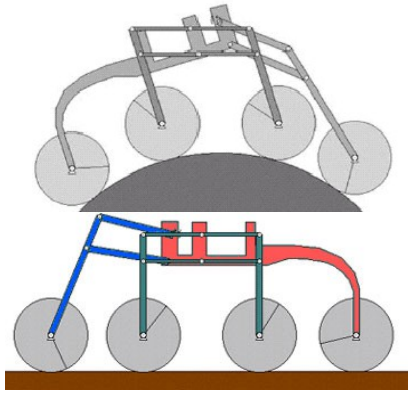
- Modular

Crab I
Adaptative parallel bogies
Obstacle climbing abilities
www.asl.ethz.ch



Shrimp
6 wheels on 2 // bogies
and 1 front linkage
www.asl.ethz.ch



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Hybrid multi-mode robots

- ✔ Highly **actuated** frame
- ✔ **Orientable tracks** for special modes of displacement

Robotics
State of the art 2015

- Robots
- Manipulators
- Mobile
  - Crawler
  - Leg
  - Wheel-Track
  - Hybrid
  - Special
- Humanoids
- Modular

Azimut
4 orientable tracks
www.gel.usherbrooke.ca/laborius

Helios VII
2 articulated tracks + 1 manipulating arm with hybrid grip/wheel end effector
www-robot.mes.titech.ac.jp

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Hybrid multi-mode robots

- ✔ **Highly actuated** frame
- ✔ Displacement modes: **peristaltic** crossing, obstacle **climbing**

Robotics
State of the art 2015

- Robots
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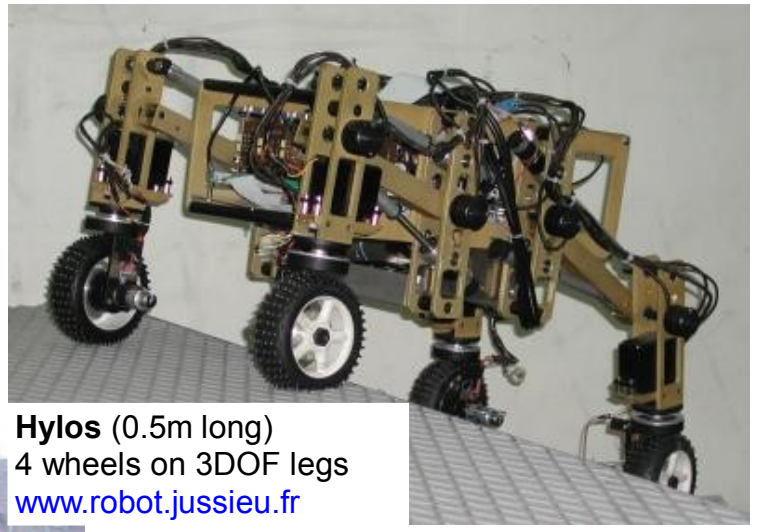
RobuROC 6 (150 kg, 1.5m long)
3 tiltable axles with passive warping
Able to turn on itself
Can climb obstacles
www.robosoft.fr



Hylos (0.5m long)
4 wheels on 3DOF legs
www.robot.jussieu.fr

Lama
Peristaltic crossing
of sandy areas
www.laas.fr

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A Hybrid multi-mode robot OpenWHEEL i3R

- ✔ OpenWHEEL **i3R** robot
- ✔ **Stable** obstacle climbing with **only 4** wheels
- ✔ Only one supplemental **central actuator**

Robotics
State of the art 2015

- Robots
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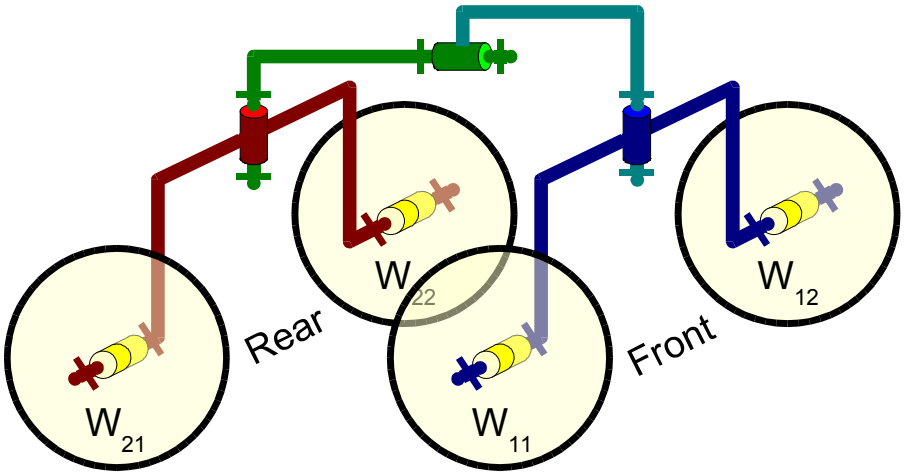
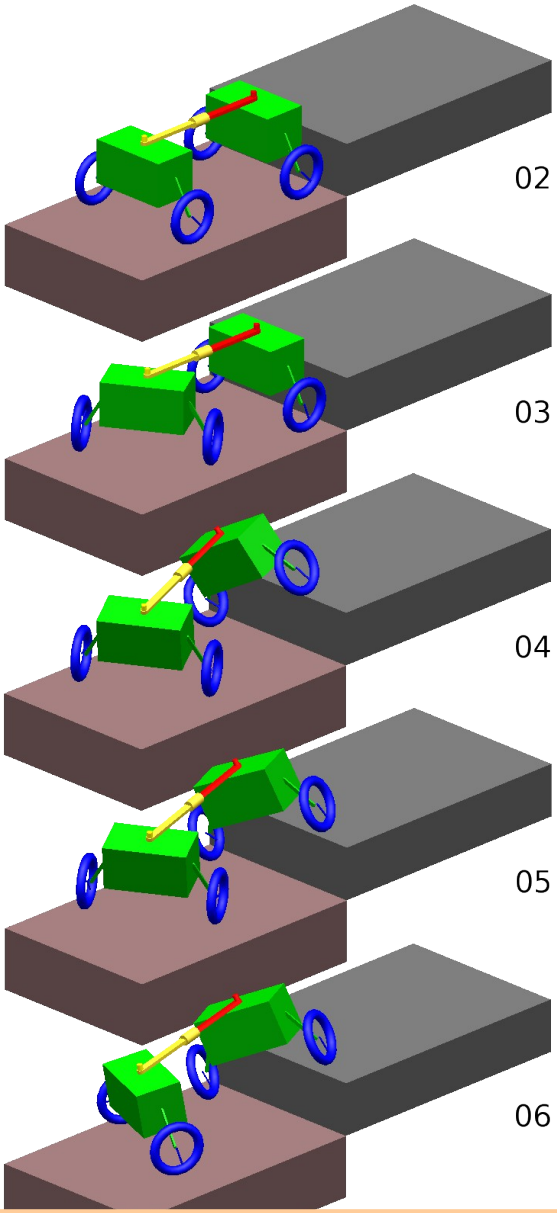
OpenWHEEL i3R
A big central actuator for warping





A stable **climbing process**
Multibody validation (Adams)

OpenWHEEL i3R
jc.fauroux.free.fr
www.ifma.fr/lami

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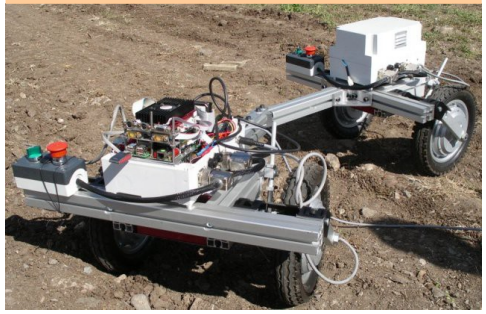
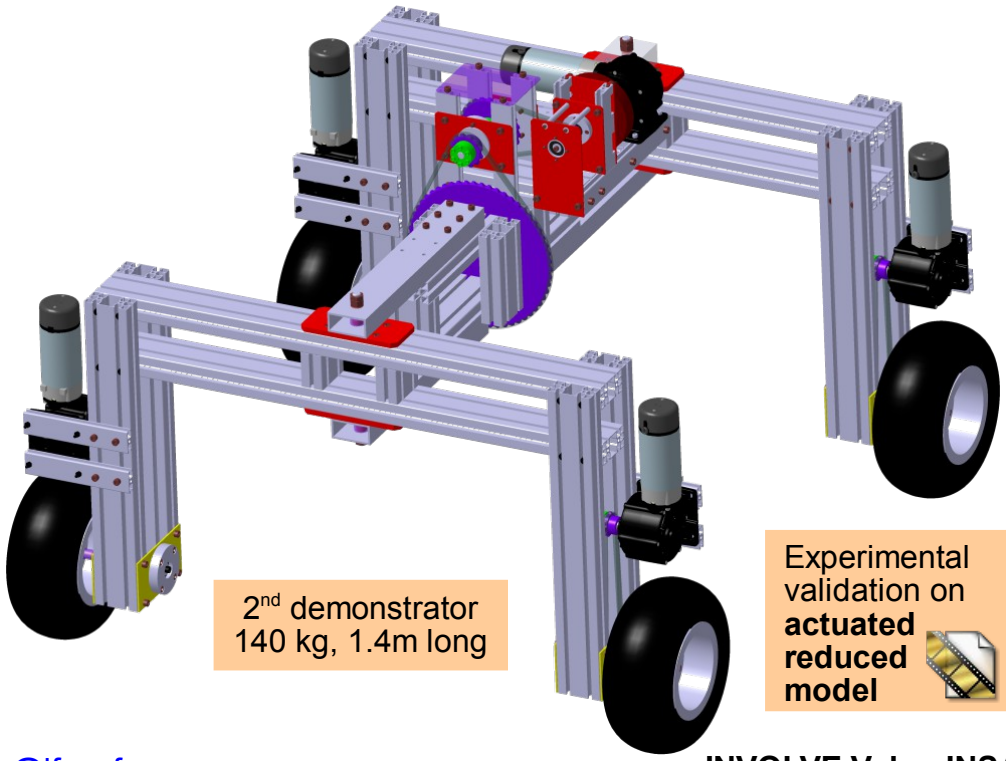
A Hybrid multi-mode robot OpenWHEEL i3R

- ✔ Climbing process in **19 stages**
- ✔ Climbs obstacles as high as **66%** of $Z_{\text{Centre of mass}}$

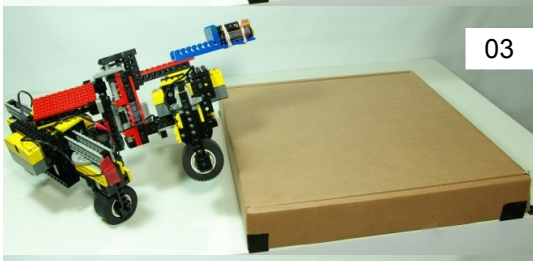
First demonstrator at scale 1:1

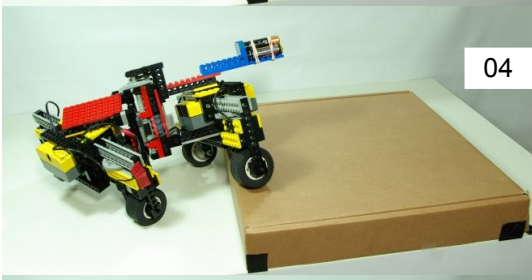




2nd demonstrator
140 kg, 1.4m long

Experimental validation on **actuated reduced model**





Robotics
State of the art 2015

- Robots
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- Modular

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Special robots

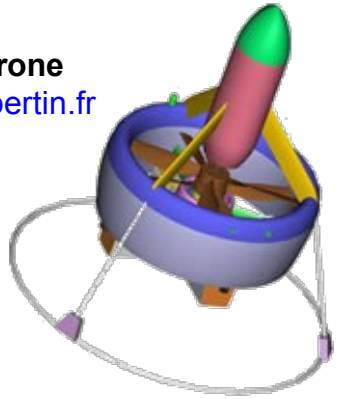
- ✔ Flying **drones** become popular
- ✔ Aero-terrestrial **cooperation**
- ✔ **Underwater** drones

Dragonfly Nanodrone
120mg, 6cm wide, 80mW
SMA actuators on the wings
www.silmach.com

BionicOpter
Span 63cm, 175g, 20Hz,
13 DDL: wing amplitude, freq, twist + head & tail motions
www.festo.com

Alistar 3000
5m long, 2800kg
Depth 3000m
www.eca.fr

Minidrone
www.bertin.fr



Seaglider
1.8m long, 52kg
Range 1000km
Depth 1000m
www.irobot.com

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Robotics
State of the art 2015

- Robots
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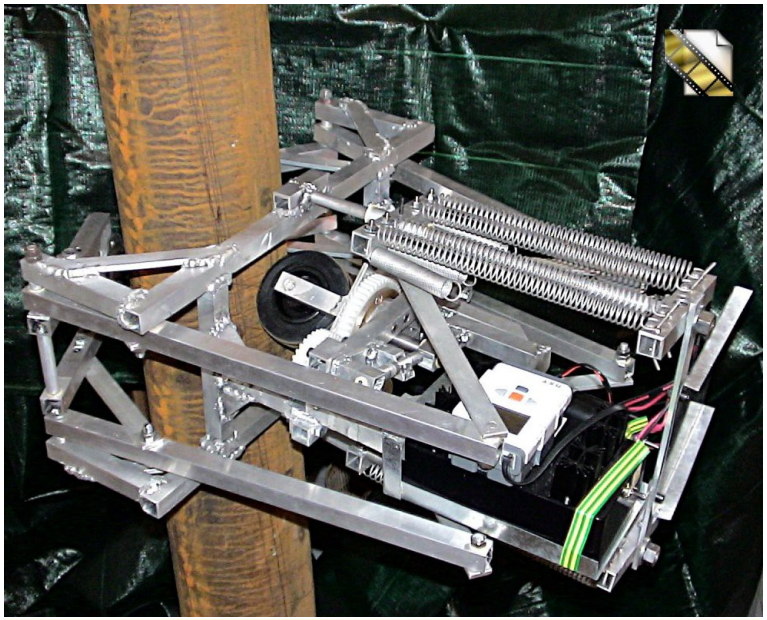
Special robots

✔ Pole climbing



Pobot V2
Pole climbing robot
Cannot fall, can turn around the pole
jc.fauroux.free.fr
www.ifma.fr/lami

✔ Pipe exploring

MagneBike
2 magnetic wheels with
anti-locking rollers
www.asl.ethz.ch

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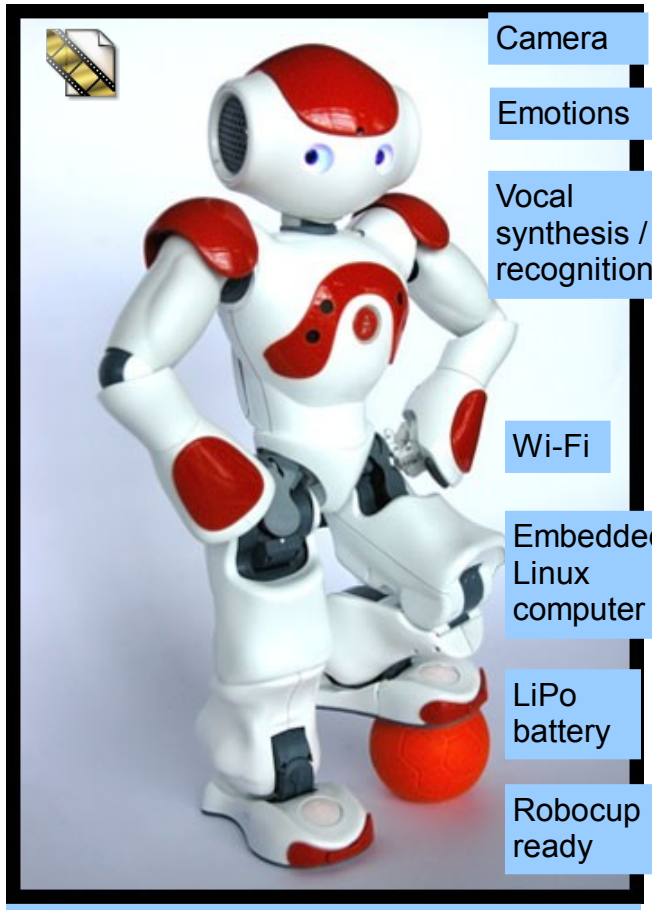
Human-like robots

- ✔ Humanoid = 1 **walking** robot + 2 **manipulators**
- ✔ New applications : **companion** robots

Asimo
24 DOF, 52 kg, 1.2m high
world.honda.com/ASIMO



Nao
25 DOF, 0.58m high, 3k€
www.aldebaran-robotics.com

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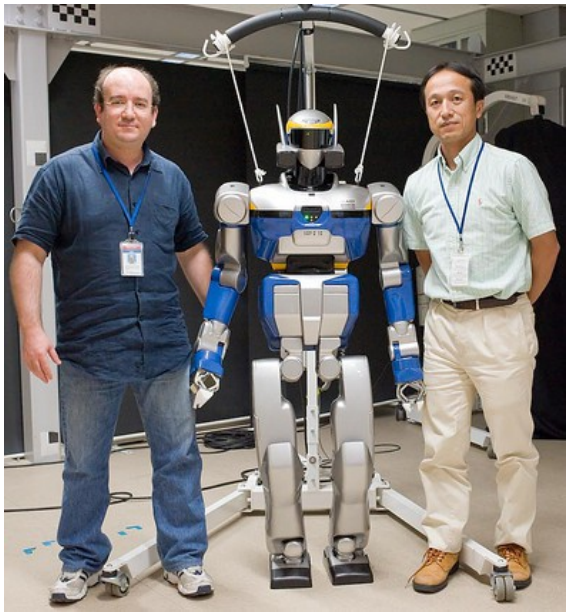
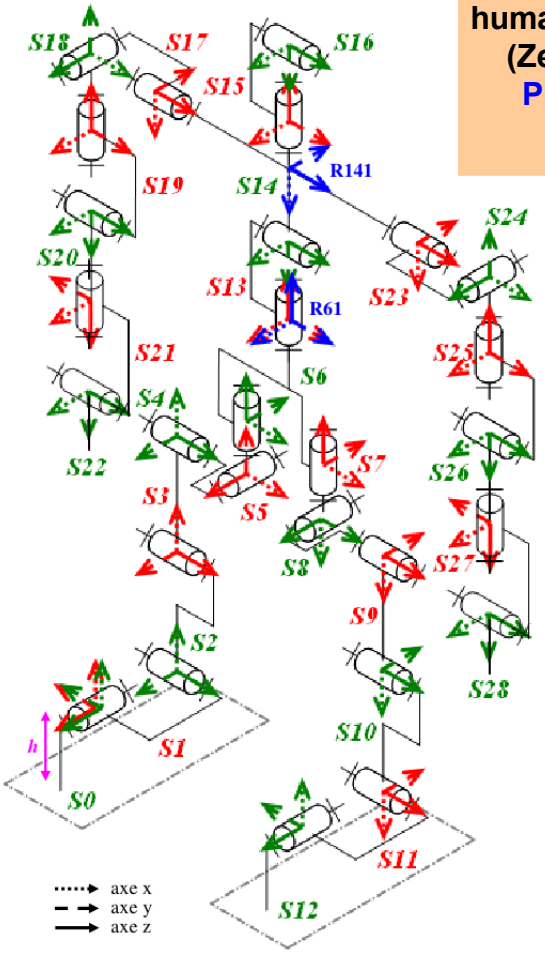
Human-like robots

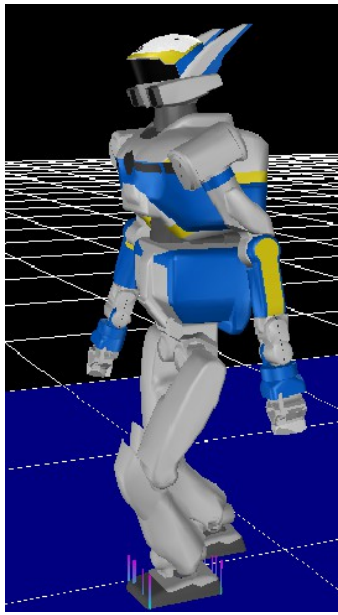
- **HRP-2** (Humanoïd Robotics Project)
- Japon : AIST, Kawada Industry
- Collaboration LAAS CNRS (2006+)

- 28DDL =
- 2x6 legs
- + 2x6 arms
- + 2 torso
- + 2 head
- 1,54m 58 kg

Dynamic control of humanoïd robots by ZMP (Zero Moment Point)
PHD Antoine EON, Poitiers 2009







Robotics
State of the art 2015

- Robots
- Manipulators
- Mobile
- Humanoids
  - Human-like
  - Exo-skeletons
- Modular
- Conclusion

Exo-skeletons

- ✔ Bio-compatible
- ✔ **Haptic** device + Force **amplifier**
- ✔ Specialized on a limb (arm/leg)

Robotics
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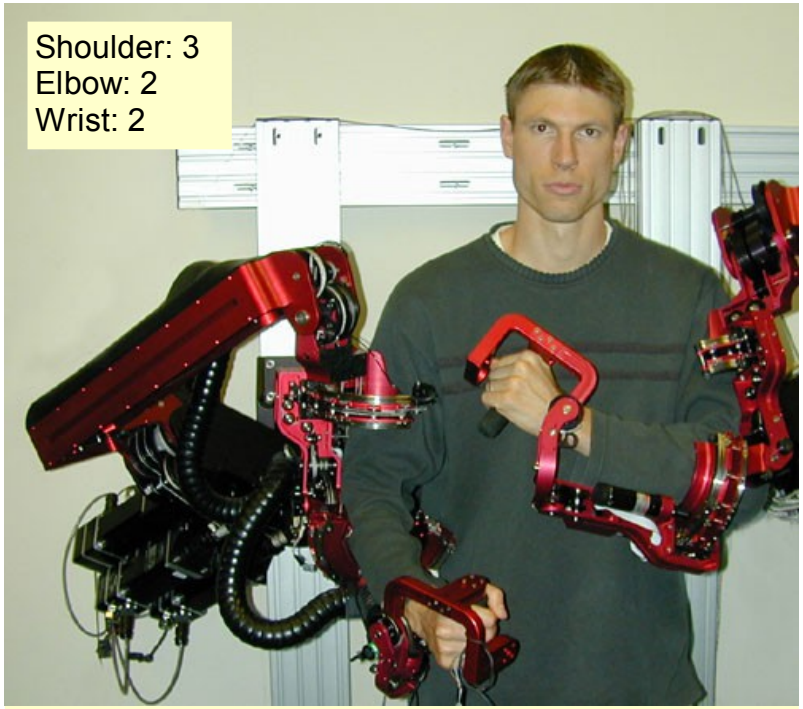
- Modular
- Conclusion



Wearable robotics - Exoskeleton
7DOF, Neural control
brl.ee.washington.edu

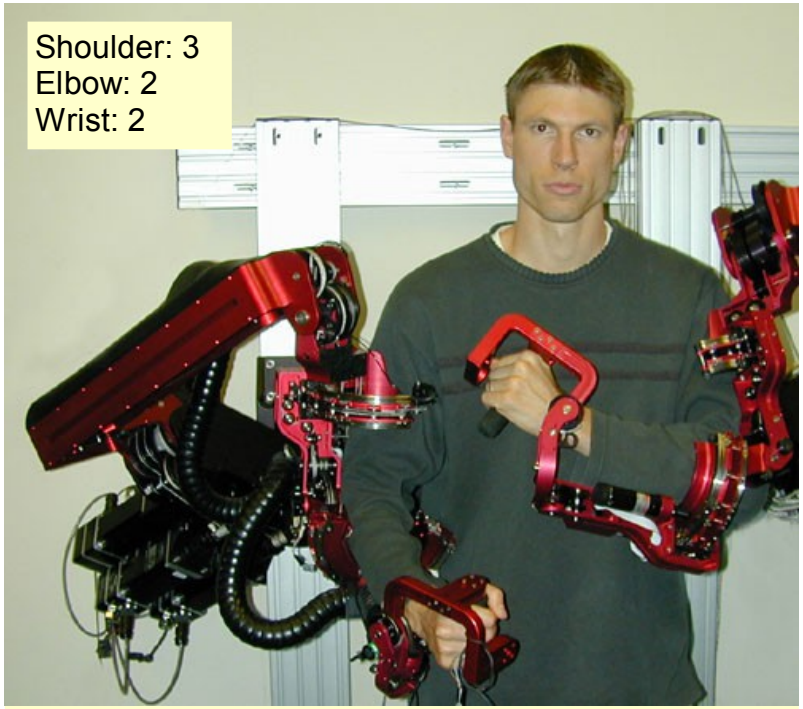
ReWalk robotic suit
For walking / lifting from seat
www.argomedtec.com

Exo-skeletons

- ✔ Bio-compatible
- ✔ **Haptic** device + Force **amplifier**
- ✔ Specialized on a limb (arm/leg)

Robotics
State of the art 2015

- Robots
- Manipulators
- Mobile
- Humanoids
  - Human-like
  - Exo-skeletons
- Modular
- Conclusion



Wearable robotics - Exoskeleton
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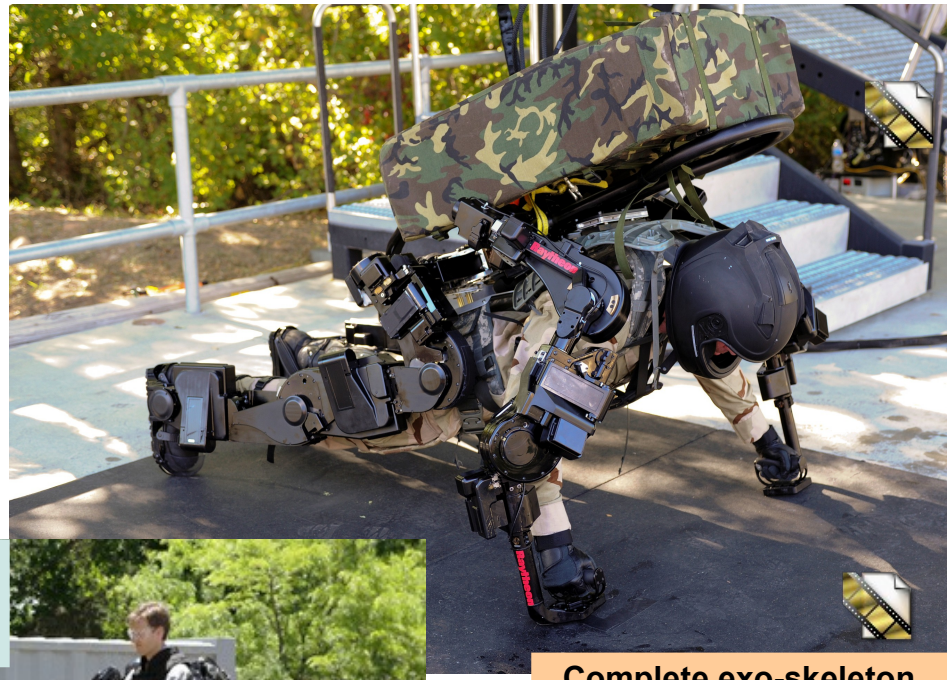
Exo-skeletons

- ✔ Military applications (Raytheon Sarcos)
- ✔ **Force feedback** for delicate tasks



Complete exo-skeleton XOS2
Lower and upper limbs
www.raytheon.com

Dual manipulatorBigArm
2x100kg at a distance of 2m
www.raytheon.com

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Modular Robotics Kits

- ✔ From toys to industry
- ✔ Cost-effective / maintainability

Robotics
State of the art 2015

- Robots
- Manipulators
- Mobile
- Humanoids
- Modular
  - • Kit approach
  - • Self-reconfig.
- Conclusion

Mindstorms NXT
Control box, Bluetooth,
3 actuators 2W 50Ncm
Sensors (contact / sound / US / light / ...)
mindstorms.lego.com

Ranked 1st and 2nd in France 2007. Source : www.robopolis.com

Bioloid
Servomotors AX12 150 Ncm
Sensors (distance / light / heat / ...)
www.robotis.com

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Robotics

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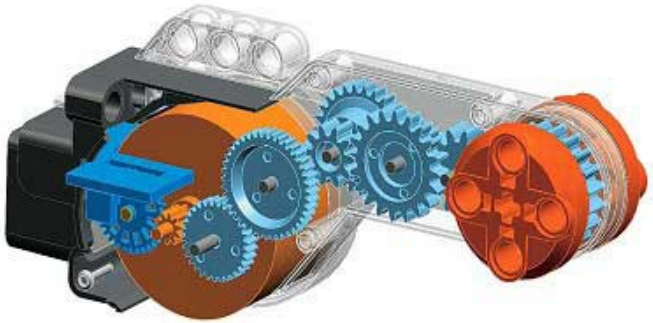
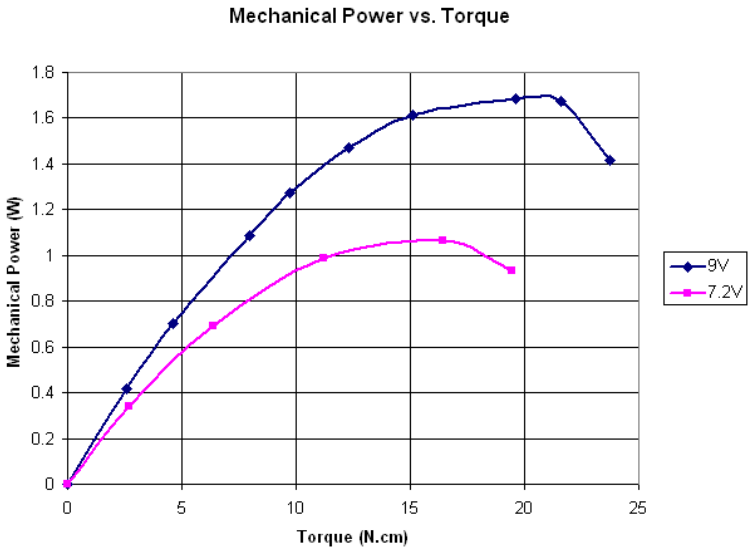
Mindstorms : case study

- An open and expandable architecture
  - Atmel **32-bit ARM** processor at 48MHz, 256 Kb flash
  - **Bluetooth** / USB2
  - 3 motors outputs / 4 sensor inputs / multiplexers with daisy chain
  - Only **one controller** required
  - Closed loop control with access to PID parameters
  - **Powerful** 9V actuators (5W)
  - Many **sensors** : contact, angular, distance (US), 3D accelerometer to measure tilting
- A dynamic community
  - Experimental actuator characterization
  - **www.philohome.com**





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Mindstorms : Sensors (1/2)

Robotics

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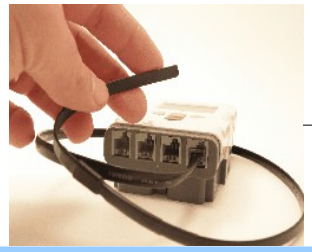
Angle incremental coder (1°)
www.hitechnic.com



Flex sensor (1° acc.)
Dexterindustries.com

Camera 88x144@30Hz
www.mindsensors.com

WIFI remote (digital/analog)
www.mindsensors.com

Sensor type	lego.com	codatex.com	dexterindustries.com	hitechnic.com	humarobotics.com	mindsensors.com	vernier.com
Locating							
Contact	X					X	
Distance US	X						
Distance IR						X	
Accelerometer				X		X	X
Angle				X			
Flexion			X				X
Gyrometer				X			
IMU			X				
GPS			X				
Magnetic compass			X	X			X
Force							X
Vision						X	
Communication							
RFID		X					
USB HID						X	
Wifi			X		X		
Zigbee			X				
Remote control						X	

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Mindstorms : Sensors (2/2)

Robotics

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Sensor multiplexer
www.hitechnic.com

Motor multiplexer
www.hitechnic.com

Dswitch
Dexterindustries.com

NXT adapter
www.vernier.com

Sensor type	lego.com	codatex.com	dexterindustries.com	hitechnic.com	humarobotics.com	mindsensors.com	vernier.com
Infrastructure							
Clock						X	
Sensor multiplexer				X		X	
Actuator multiplexer						X	
Servomotor control						X	
AC control			X				
Solar power	X		X				
Various sensors							
Current							X
Power						X	
Anemometer							X
Barometer				X			X
Color	X			X		X	X
Sound	X						X
Temperature			X				X
Moisture							X
Turbidity							X
Flow							X
Pressure			X			X	X
Dissolved oxygen							X
pH							X

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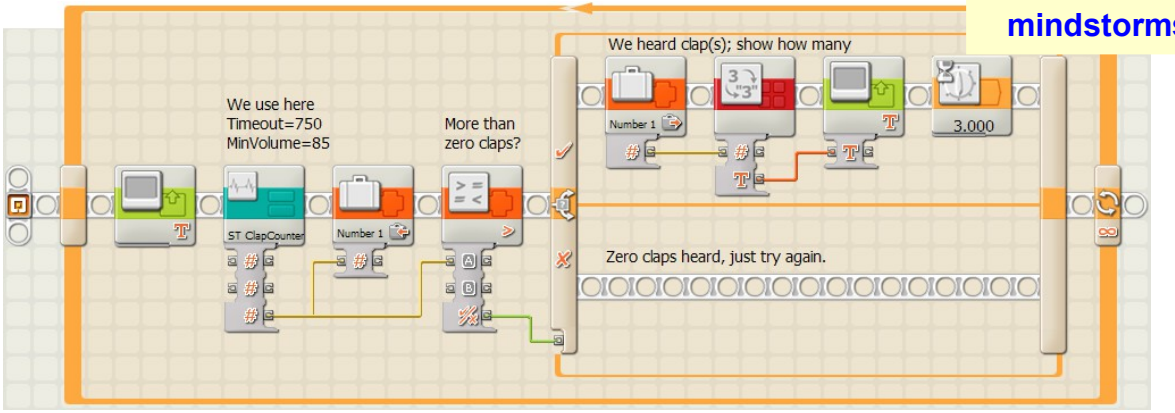
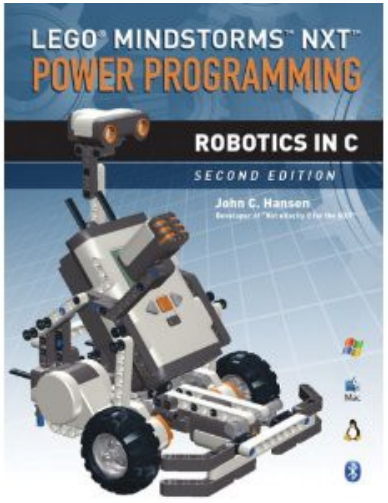
Mindstorms : native OSes

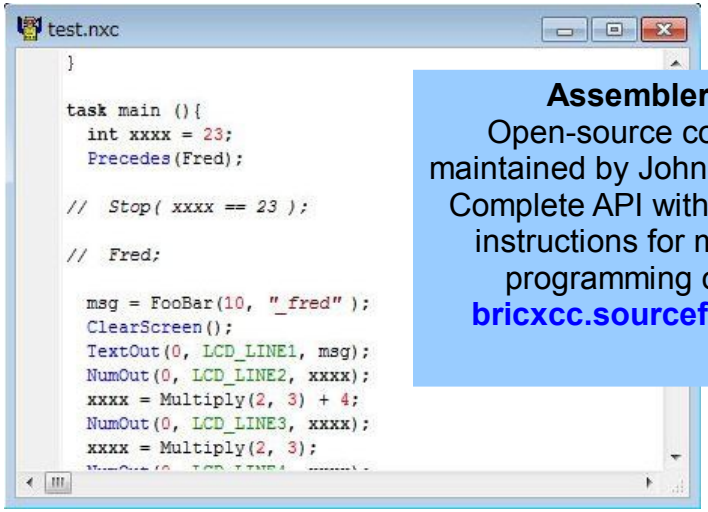
- NXT-G Labview like language

Graphical language based on wired blocks
mindstorms.lego.com



- NBC / NXC Assembler and C compilers





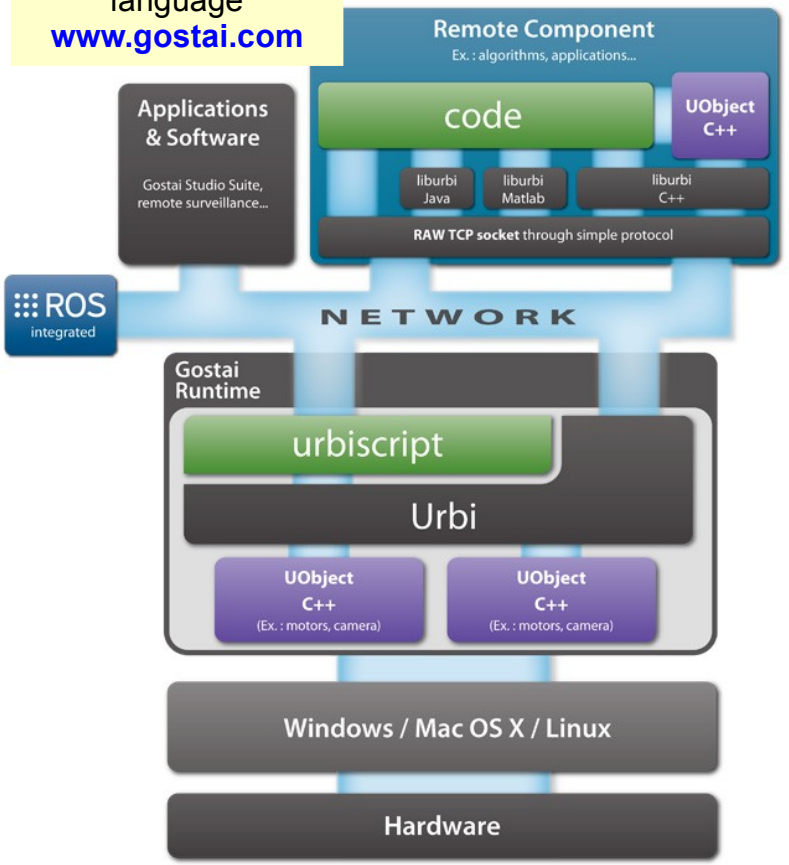
Assembler / C
Open-source compilers maintained by John C. Hansen. Complete API with additional instructions for multi-task programming of NXT
bricxcc.sourceforge.net

- Others: RobotC, LejOS (Java)...

Mindstorms : neutral OSes

- ✔ Principle : one program for several hardware architectures → maintainability
- ✔ GOSTAI Urbi :
  - **Open Source**
  - **Multi-OS**: Linux / Mac OS / Windows
  - **Multi-hardware** : NXT / Bioloid / Spykee / Aibo / Nao / Segway / ...
  - Event **orchestration script** Urbiscript with graphical programming
  - **C++ component** UObject
  - **Network** connection
  - **Abstraction level**: "jumping" means different control laws for Aibo & Nao but is represented by the same Urbi function

Open source Urbi language
www.gostai.com



- ✔ ROS (Robot Operating System) www.ros.org
- ✔ Microsoft Robotics studio (closed source)

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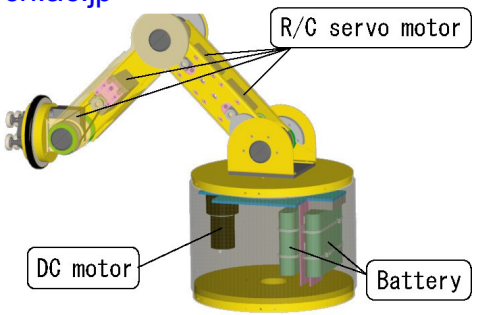
Self-reconfigurable robots

✔ Robot with detachable limbs

SMC Rover and **UniRover**
6 wheels on detachable legs
www-robot.mes.titech.ac.jp



✔ Self-attaching modules
✔ Towards auto-replication / cloning

M-TRAN III
Self reconfigurable robot
Locomotion and Adaptation
unit.aist.go.jp/is

The next step: robot **breeding**

Molecube
Auto-cloning
ccsl.mae.cornell.edu

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Conclusion

- Manipulators
  - ✔ **Serial** manipulators reached industrial **maturity**
  - ✔ **Parallel and hybrid** architectures may improve **dynamics** and **precision**
- Mobile robots
  - ✔ No locomotion mode is perfect
  - ✔ Improved architectures: engines **distributed** on the wheels, **wheels on legs**
  - ✔ Innovative architectures already exist (e.g. for **spatial** robots)
- Humanoids
  - ✔ **Realism** and **energetic autonomy**
  - ✔ Companion robots with improved **interaction** and **expressivity**
- Modular robots
  - ✔ Modularity for **reliable** and **cost-effective** building of **anything**
  - ✔ Control via portable software development kits, limb and behavior libraries

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