Karlsruher Institut für Technologie

Hochperformante Humanoide Technologien

Robotics II: Humanoid Robotics
Chapter 2 – Building Humanoids

Tamim Asfour

http://www.humanoids.kit.edu

Chapter 2: Building Humanoids

- The history of humanoid robotics
- The DARPA Robotics Challenge
- Biomechanical models of the human body
- Mechatronics of humanoid robots

A Brief History of Humanoid Robotics

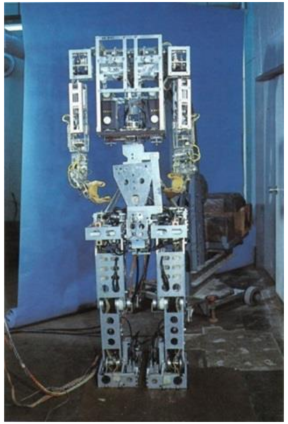
Famous Humanoid Robots (Unordered List)

Karlsruher Institut für Technologie

- **WABOT-1**
  Waseda University, Japan
- **Wabian**
  Waseda University, Japan
- **ASIMO**
  Honda, Japan
- **HRP-2**
  Kawada Industry, Japan
- **HRP-4C**
  Kawada Industry, Japan
- **Toyota Partner Robot**
  Toyota, Japan
- **HUBO**
  Korean Institute of Science and Technology, KIST, Korea
- **Petman**
  Boston Dynamics, USA
- **Atlas**
  Boston Dynamics, USA
- **Cog**
  MIT, USA
- **iCub**
  Italian Institute of Technology, Italy
- **Robonaut**
  NASA, USA
- **NAO**
  Aldebaran, France
- **REEM**
  PAL Robotics, Spain, United Arab Emirates
- **Justin**
  DLR, Germany
- **ARMAR**
  KIT, Germany
- ...

WABOT

- **WABOT-1** (1970 – 1973):
  - First Full-scale anthropomorphic robot of the world
  - Waseda University, Tokyo (Prof. Ichiro Kato)
  - WABOT is an acronym for **WA**seda ro**BOT**
  - Capabilities
    - Communication with persons in Japanese
    - Bipedal walking



- **WABOT-2** (1980 – 1984):
  - “Specialist robot" able to play the keyboard
  - Able to read musical score with its eye and play tunes on an electronic organ

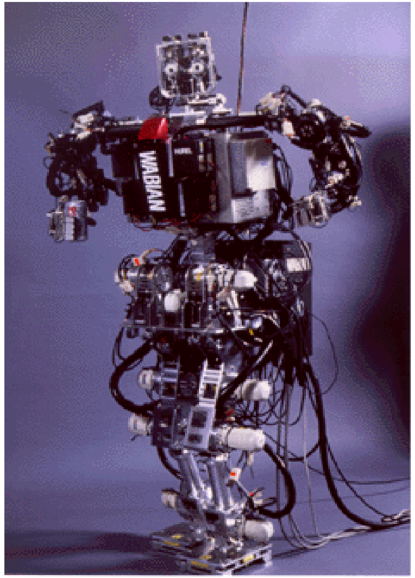
Wabian

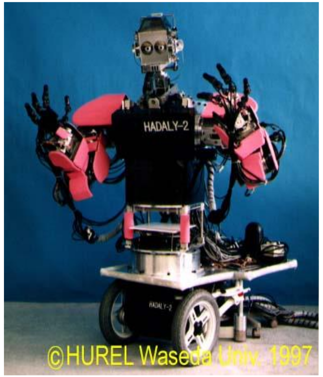
- Developed by Waseda University, Japan
- Current model: **Wabian-2R** (since 2006)
- Research interests:
  - Human motion simulation
  - Goal: robot should be the human's partner
  - Walking experiments with a walk-assist machine
- Sensors:
  - 6-axis force/torque sensors
  - Photo sensors
  - Magnetic encoders
  - Gyro sensor

Wabian

Waseda University, Tokyo, Japan

Hadaly-2





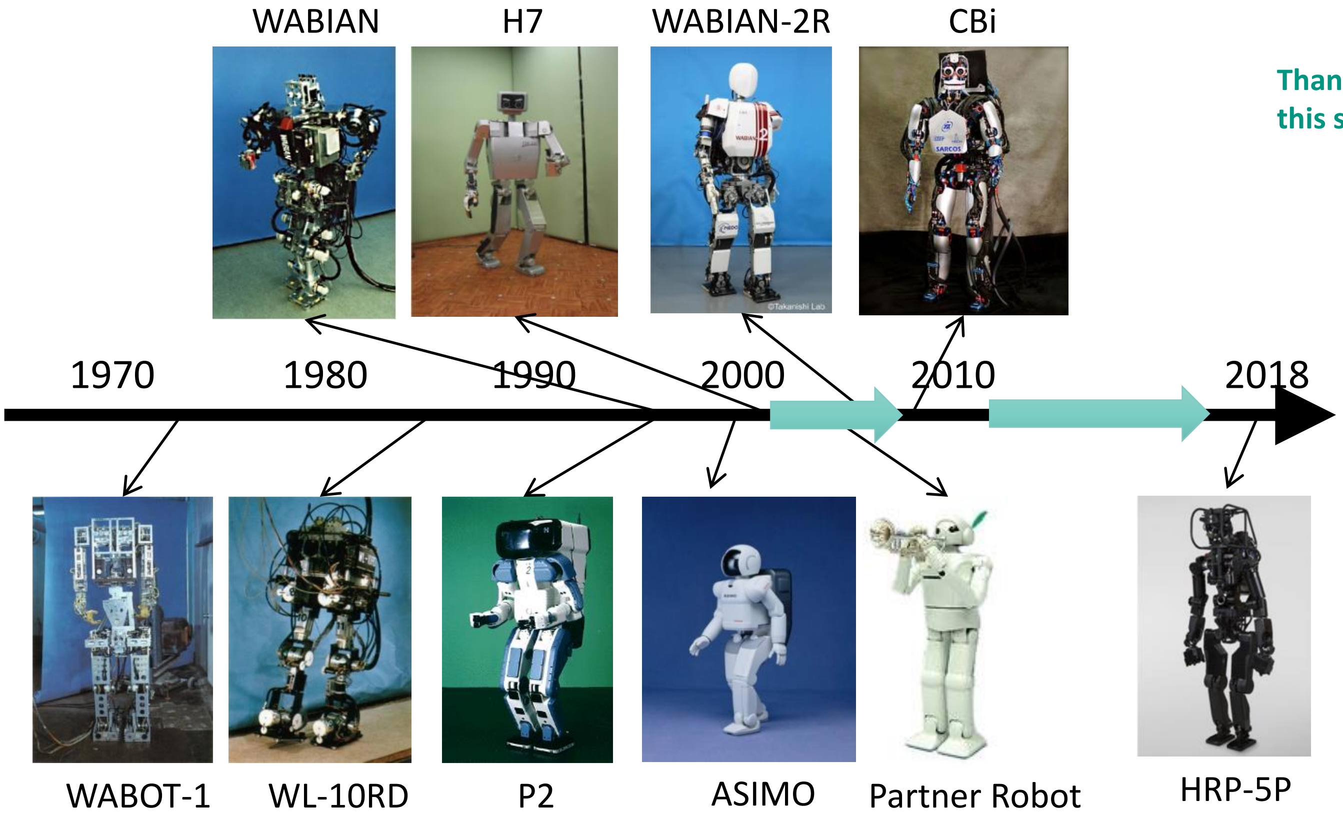
WABIAN

WABIAN-2

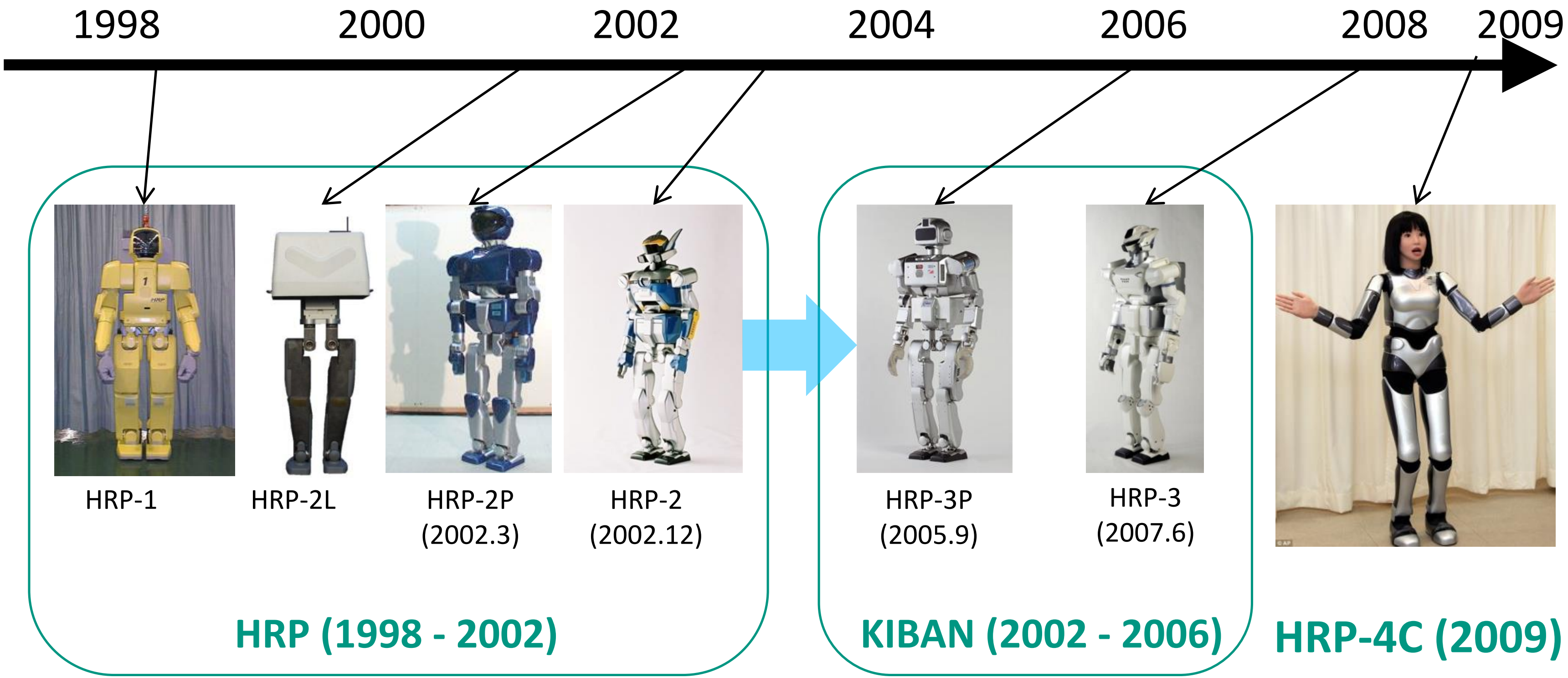
Ogura et al., "Human-like Walking with Knee Stretched, Heel-contact and Toe-off Motion by a Humanoid Robot", *IROS* (2006)

History of Humanoid Robotics in Japan

Thanks to Eiichi Yoshida for this slide!



HRP Series: From HRP-1 to HRP-4C



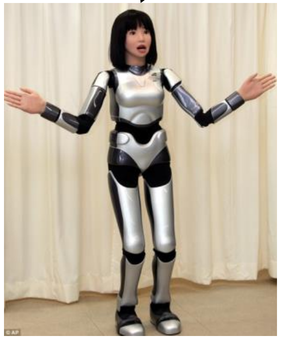
AIST: http://www.is.aist.go.jp/humanoid

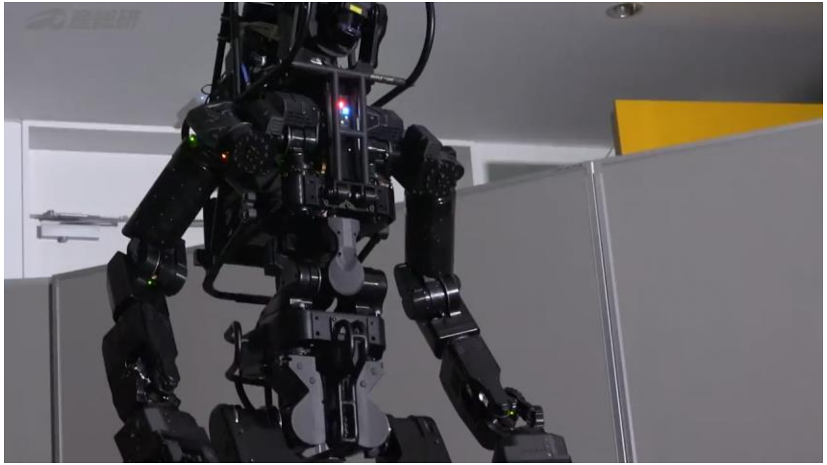
HRP = Humanoid Robotics Project

Thanks to Eiichi Yoshida for this slide!

HRP Series: From HRP-4C to HRP-5P

2009 2010 2018





HRP-4C (2009) **HRP-4 (2010)** **HRP-5P (2018)**

AIST: http://www.is.aist.go.jp/humanoid

Thanks to Eiichi Yoshida for this slide!

HRP-2 (2002)

HRP = Humanoid Robotics Project

- Developed by Kawada Industries (Japan), together with the Humanoid Research Group of National Institute of Advanced Industrial Science and Technology (AIST)
- In use in research labs worldwide
- Research areas include:
  - Walking (on uneven surfaces)
  - footstep planning
  - Tipping-over control
  - Grasping and manipulation
  - Human-interactive operations
- Height: 154 cm
- Weight: 58 kg
- 30 DoF







Kawada Industries: https://global.kawada.jp/

HRP-2 – Motion Planning and Control

Walking on uneven terrain
https://www.youtube.com/watch?v=IWG3dt9HELw

Walking through a wall (at LAAS)
https://www.youtube.com/watch?v=x0ASFOkd4I8

Standing up and panel assembly

HRP-2 – Human Motion Retargeting

Dancing

https://www.youtube.com/watch?v=6hLcz-c1Y-M

Humanoids 2005

Specifications of HRP-2

https://robots.ieee.org/robots/hrp2/

Dimensions	Height	1,540 [mm]
	Width	600 [mm]
	Depth	340 [mm]
Weight inc. batteries		58 [kg]
D.O.F.		Total 30 D.O.F.
	Head	2 D.O.F.
	Arm	2 Arms x 6 D.O.F.
	Hand	2 Hands x 1 D.O.F.
	Waist	2 D.O.F.
	Leg	2 Legs x 6 D.O.F.
Walking Speed		up to 2.0 [km/h]

Specifications of HRP-3

Dimensions	Height	1,606 [mm]
	Width	693 [mm]
	Depth	410 [mm]
Weight inc. batteries		68[kg]
D.O.F.		Total 42 D.O.F.
	Head	2 D.O.F.
	Arm	2 Arms x 7 D.O.F.
	Hand	2 Hands x 6 D.O.F.
	Waist	2 D.O.F.
	Leg	2 Legs x 6 D.O.F.

HRP-4C (2009) – Mimicking Human Movement

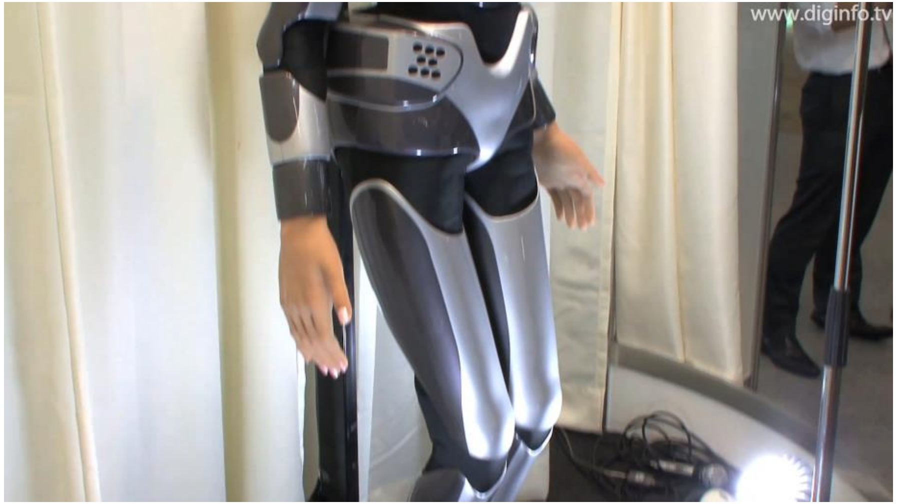
- Developed by **Kawada Industries**
- Shape and joints based on the 1997/1998 Japanese body dimension database
  - Average figure of a young Japanese female, realistic head
- Capabilities:
  - Human-like motion
  - Speech and ambient sound recognition
  - Singing, Dancing
  - Mimicking human facial and head movements
- Possible applications:
  - Entertainment industry
  - Human simulator for evaluation of devices
- Parameters
  - Height: 170 cm
  - Weight: 43 kg
  - 42 DoF

Specifications of HRP-4C

Height		1,580 [mm]
Weight inc. batteries		43 [kg]
D.O.F.		Total 42 D.O.F.
	Face	8 D.O.F.
	Neck	3 D.O.F.
	Arm	2 Arms × 6 D.O.F.
	Hand	2 Hands × 2 D.O.F.
	Waist	3 D.O.F.
	Leg	2 Legs × 6 D.O.F.
CPUs	Motion Controller	Pentium® M 1.6 [GHz]
	Speech Recognition	VIA C7® 1.0 [GHz]
Sensors	Joints	Incremental Encoder
	Sole	6-axes Force Sensor
	Body	Posture Sensor
	Head	Receiver of Bluetooth® Microphone
Batteries		NiMH DC 48V

See also: https://robots.ieee.org/robots/hrp4c/

HRP2 and HRP-4C



https://www.youtube.com/watch?v=_migLQ802Go

ASIMO

- Developed by Honda
- Asimo is acronym for: *Advanced Step in Innovative Mobility*
  - Also: asi (jap. *tomorrow*), mo (jap. *mobility*)
  - Japanese pronunciation: ashimo (jap. *also legs*)
- Capabilities:
  - Bipedal locomotion
  - Motion resembles human walking motion
- First generation introduced in 2000
- Latest generation (2014)
  - Weight: 50 kg
  - Height: 130 cm
  - 57 DoF

ASIMO

Honda Robots, Japan

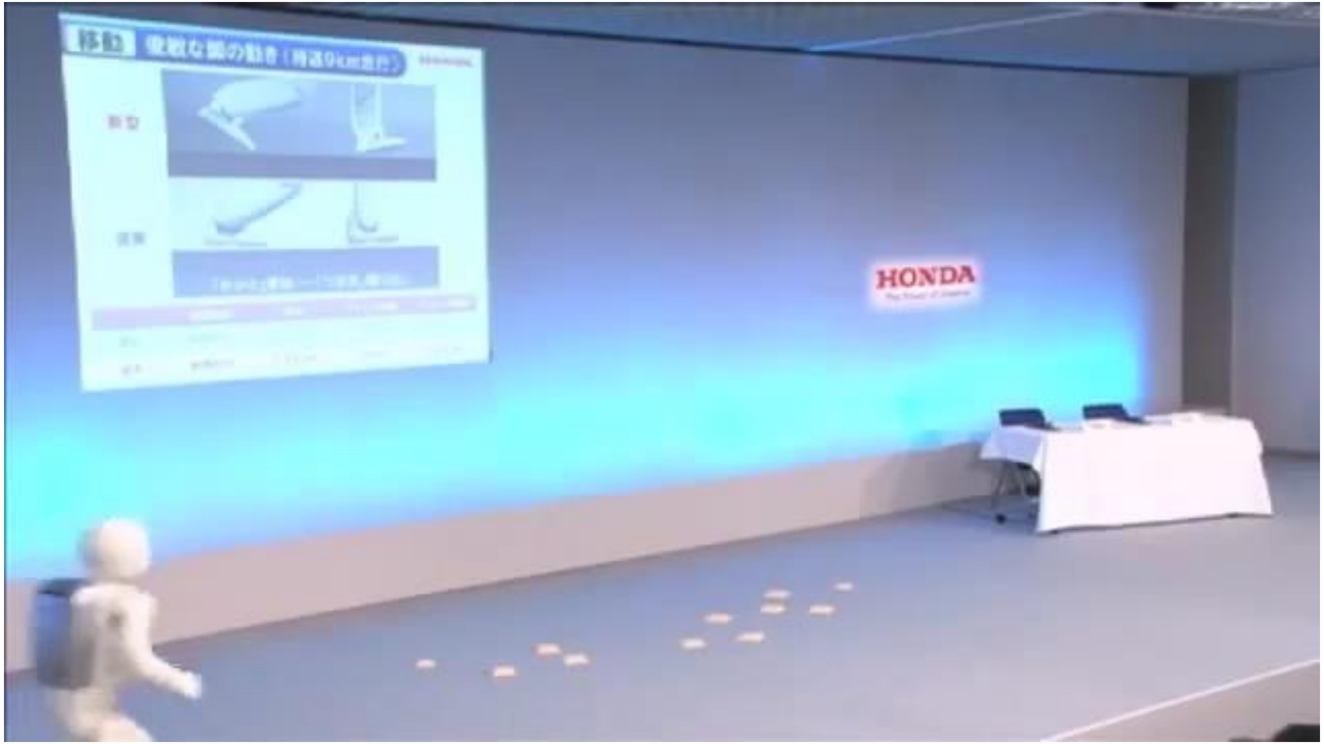
1986

https://www.youtube.com/watch?v=8psxACU1oSc

http://world.honda.com/ASIMO/history/history.html

2000

ASIMO, Nov. 2011



https://www.youtube.com/watch?v=Bmglbk_Op64

http://asimo.honda.com

Toyota Partner Robot

- Series of humanoid robots **starting in 2000**
- Latest version (2012):
  - Human Support Robot (HSR)
  - Able to pick up objects from tables and floor
  - Controllable via tablet PC
  - Height: 2.7 - 4.3 feet
  - Weight: 70 lbs
  - Speed: 1.8 mph
  - Visual sensors: Prosense (MS Kinect) and stereo cameras

From left to right: the walking type playing the trumpet, the wire type, i-Foot, TPR-ROBINA

22 Nov 2017 | 21:10 GMT

Toyota Gets Back Into Humanoid Robots With New T-HR3

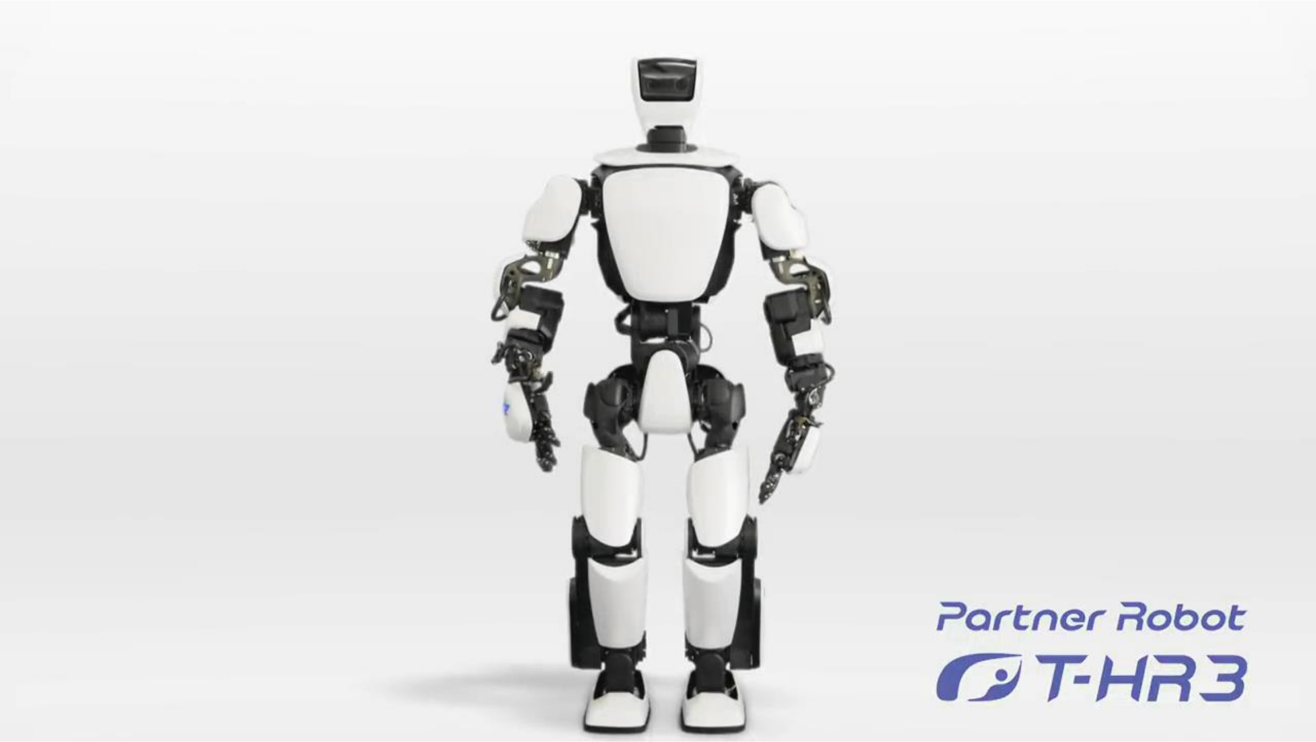
It's been about a decade, but Toyota is finally doing humanoid robots again

By **Evan Ackerman**

Image: Toyota

It's 1.5-meter tall, weighs 75 kilograms, and has 32 degrees of torque-controlled freedom plus a pair of 10 fingered hands. At first glance, it appears to be very capable, with excellent balance and coordination, and Toyota has decided to approach autonomy by keeping a human in the loop inside of a sophisticated, immersive "Master Maneuvering System."

Toyotas T-HR3 (Nov. 2017)



https://www.youtube.com/watch?v=jJYsOsoBIZU

Sony: SDR-3X, QRIO

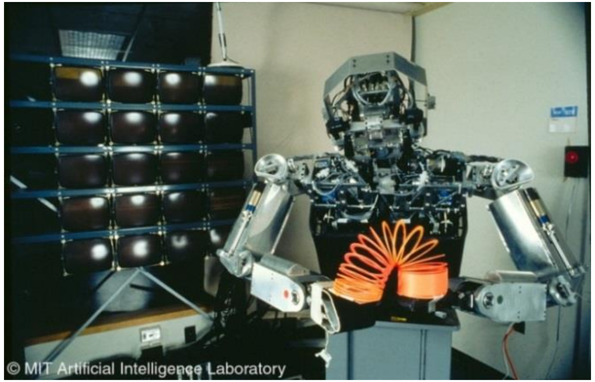
Sony Dream Robot (SDR-3X)

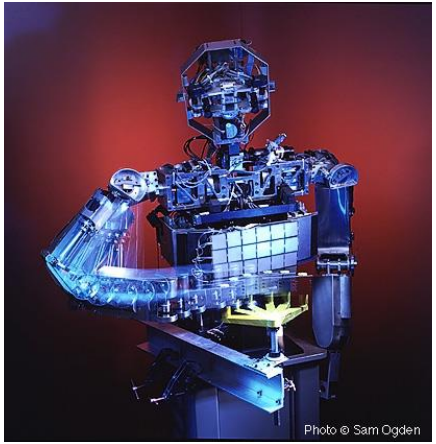
QRIO (until 2006)

https://www.sony.net/SonyInfo/CorporateInfo/History/sonyhistory-j.html

Cog – Cognition Information Processing

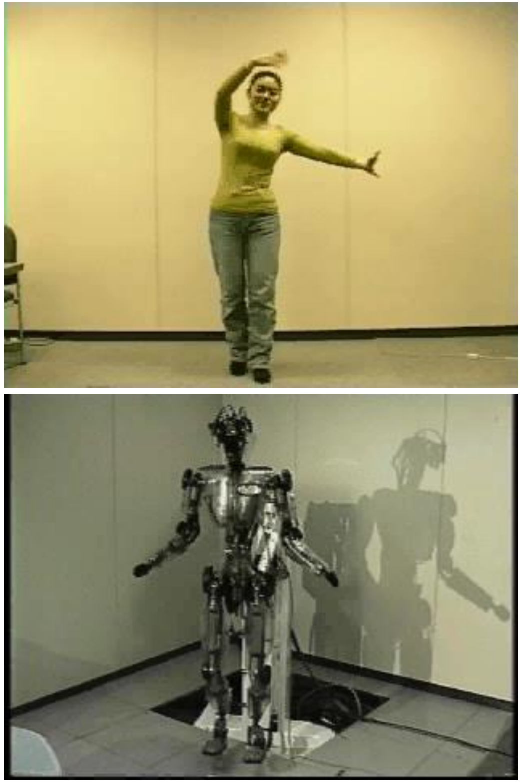
- MIT (Prof. Rodney Brooks)
- Developed 1994 - 2003
- Torso with head and arms
- Goal: Cognitive information processing
- Capabilities:
  - Recognition of people and objects
  - Learns how to move by handling objects.
- 22 DoF:
  - 6-DoF arms (2x)
  - 3-DoF torso
  - 4-DoF neck
  - 3-DoF eyes

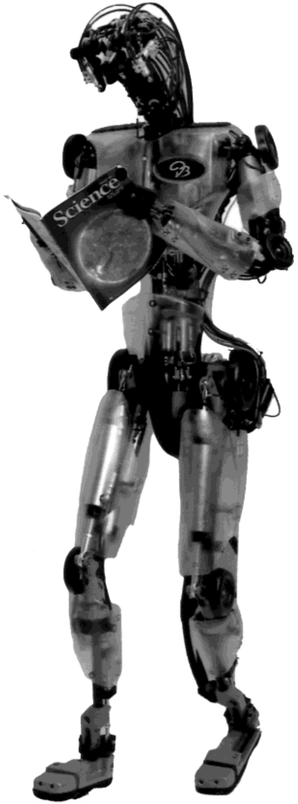


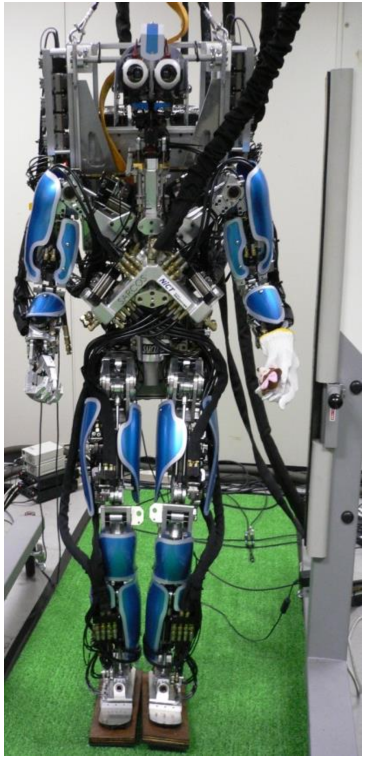


http://www.ai.mit.edu/projects/humanoid-robotics-group/cog/overview.html

Sarcos Robots at ATR – Study Cognition

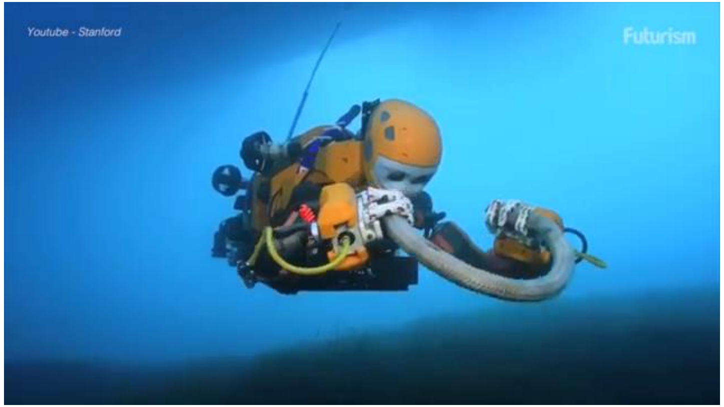

DB (Dynamic Brain)




CB (Computational Brain)

Ocean One – Haptic-based Interaction

- **Stanford** Robotics Lab team led by **Oussama Khatib**
- **Bimanual underwater humanoid robot** with haptic feedback
- "Robotic Avatar": Allows human pilots to explore the depths of the oceans
- Explored the wreck of "La Lune", the flagship of Louis XIV, 100 meters below the Mediterranean in 2016



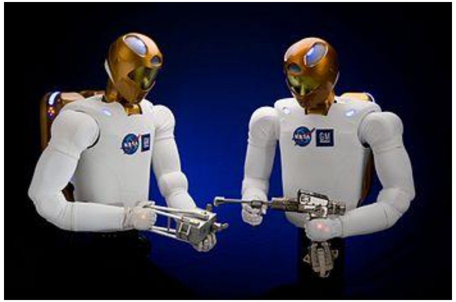
https://www.youtube.com/watch?v=TGXOs_aHPt4

http://khatib.stanford.edu/ocean-one.html

Robonaut – Humanoids for Space Applications

- NASA
- Introduced in 2002
- Objectives:
  - High dexterity, ability to use tools
  - Robot should work together with astronauts
  - Tele-operation
- Two generations: R1 and R2
- Several lower bodies
- One robot was in operation on the International Space Station
- 42 DoF
- More than 350 sensors

https://robonaut.jsc.nasa.gov/r2/



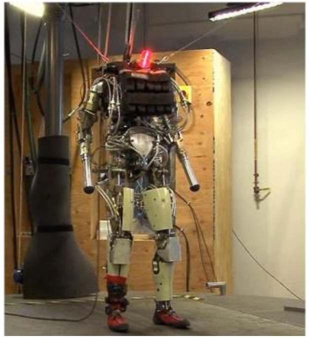
NASA Valkyrie – Space Applications

- NASA
- Introduced in 2013
- R5 aka Valkyrie
- Objectives:
  - Missions before humans arrive on a planet (i.e. Mars)
  - Work together with human teams (astronauts)
- Parameters
  - 187 cm
  - 129 kg
  - 44 DoF
- Participated in DARPA Robotics Challenge Trials

https://www.nasa.gov/

Petman (DARPA, Boston Dynamics)

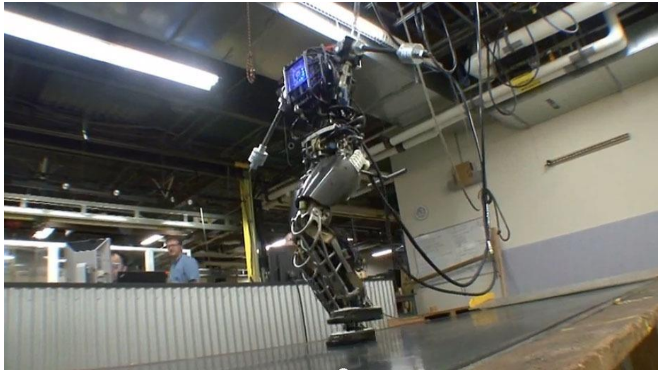
- Acronym for: Protection Ensemble Test Mannequin
- Developed by Boston Dynamics for the US army, funded by DARPA
- Introduced 2010
  - Humanoid robot for testing chemical protection suits for soldiers
  - Simulation how a soldier stresses protective clothing under realistic conditions.
- Capabilities:
  - Walking and balancing, bending and doing a variety of suit-stressing calisthenics during exposure to chemical warfare agents
  - Simulation of human physiology within the protective suit by controlling temperature, humidity and sweating
- Height: 175 cm, Weight: 80 kg



Petman (DARPA, Boston Dynamics)

Atlas (DARPA, Boston Dynamics)

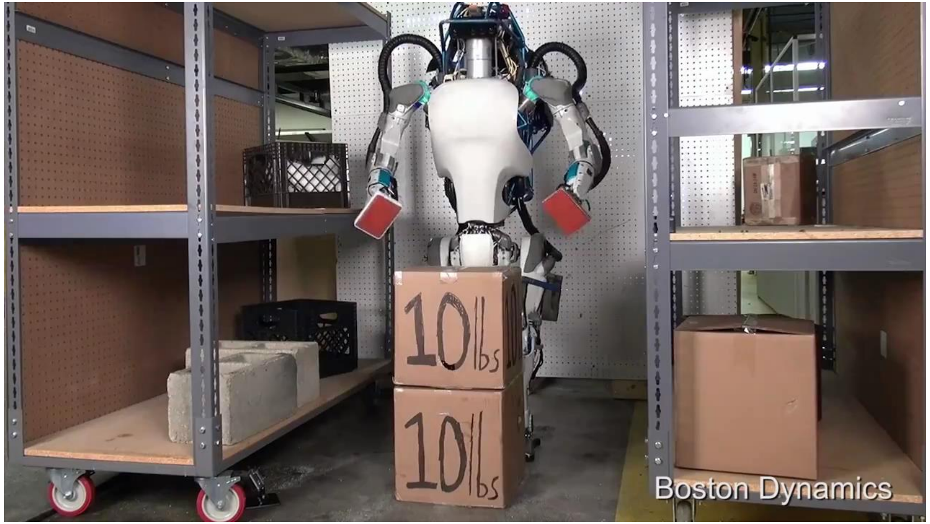
- Developed by **Boston Dynamics** for the US army, funded by DARPA, introduced 2013, based on Petman
- Capabilities:
  - Bipedal walking, leaving the upper limbs free to lift, carry and manipulate.
  - In challenging terrain, Atlas can climb using hands and feet.
- Some goals to achieve at **DARPA Robotics Challenge** 2015:
  - getting in and out of a vehicle; driving it; opening a door; using a power tool
- Intended for **search and rescue tasks**
- Parameters
  - Height: 180 cm
  - Weight: 150 kg
  - 28 DoF



Atlas at MIT (2013)

Boston Dynamics, August 15, 2015

Boston Dynamics Atlas, February 2016

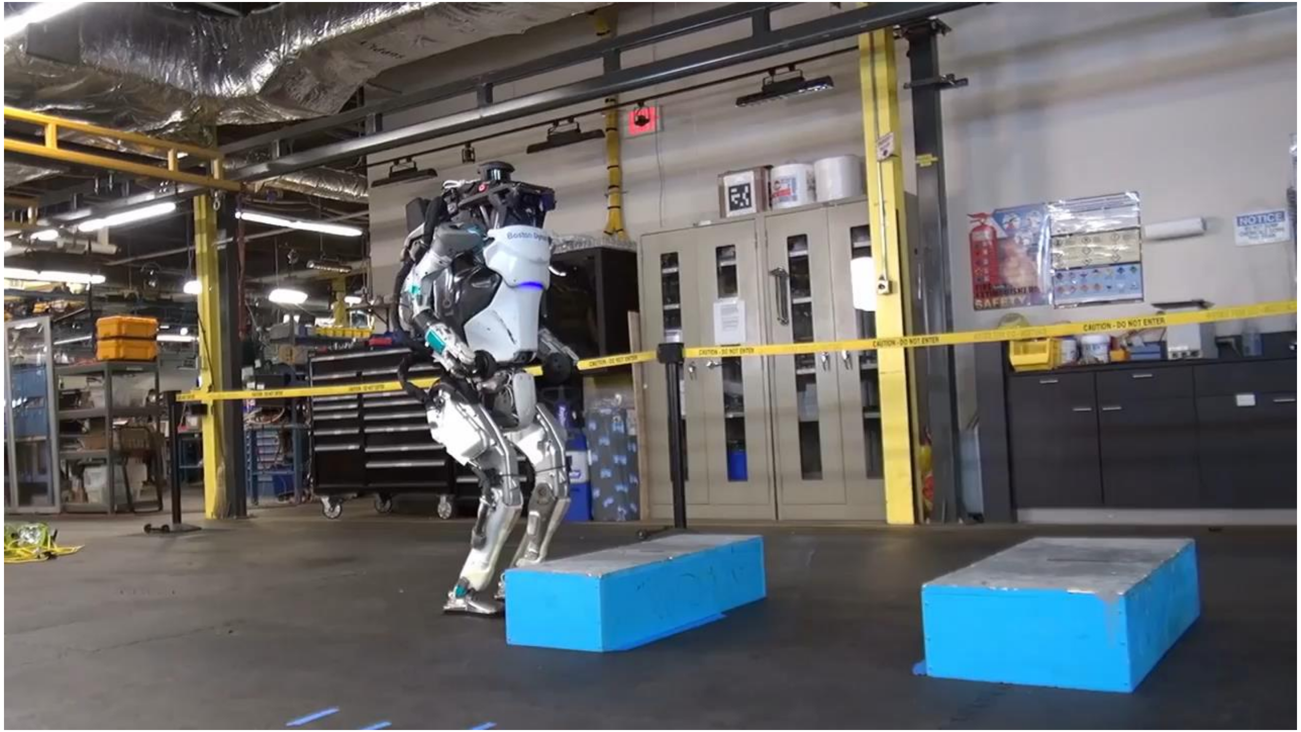


https://www.youtube.com/watch?v=rVlhMGQgDkY

Boston Dynamics Handle (Feb. 2017)

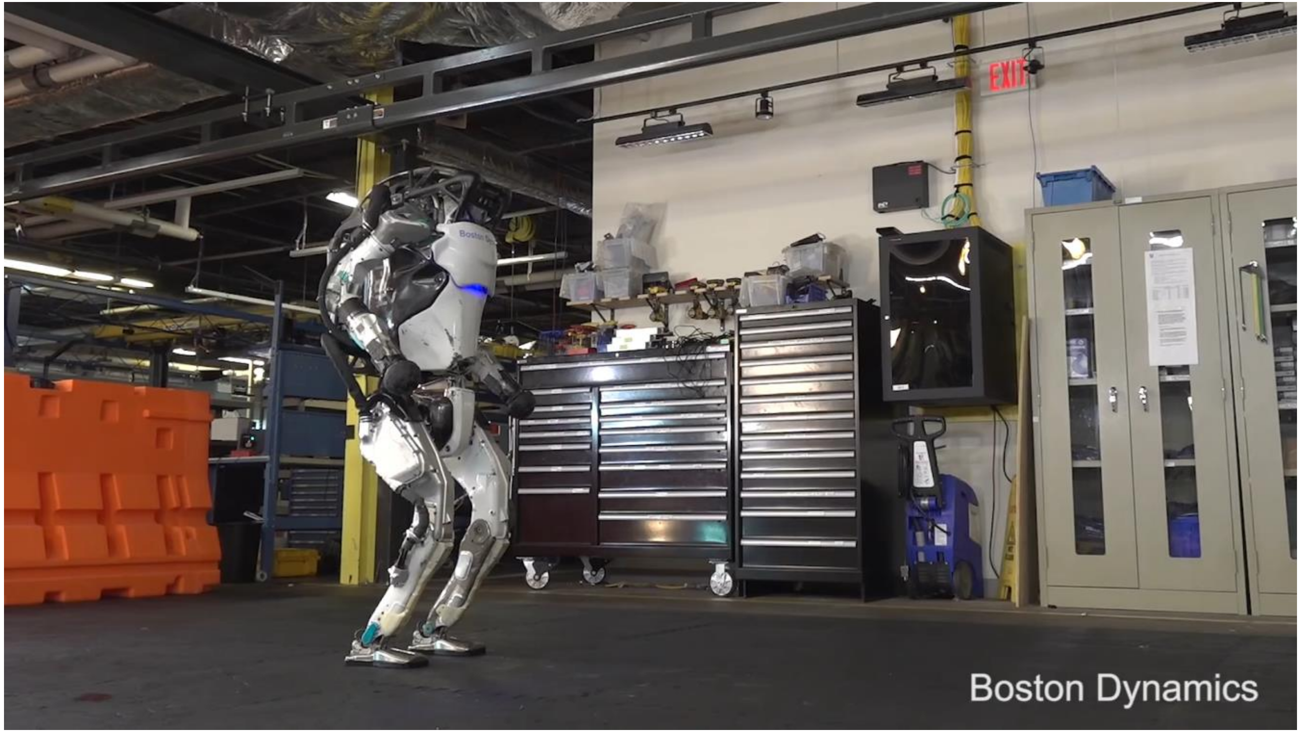
https://www.youtube.com/watch?v=-7xvqQeoA8c

Boston Dynamics Atlas (Nov. 2017)



https://www.youtube.com/watch?v=fRj34o4hN4I

Boston Dynamics Atlas (Sep. 2019)

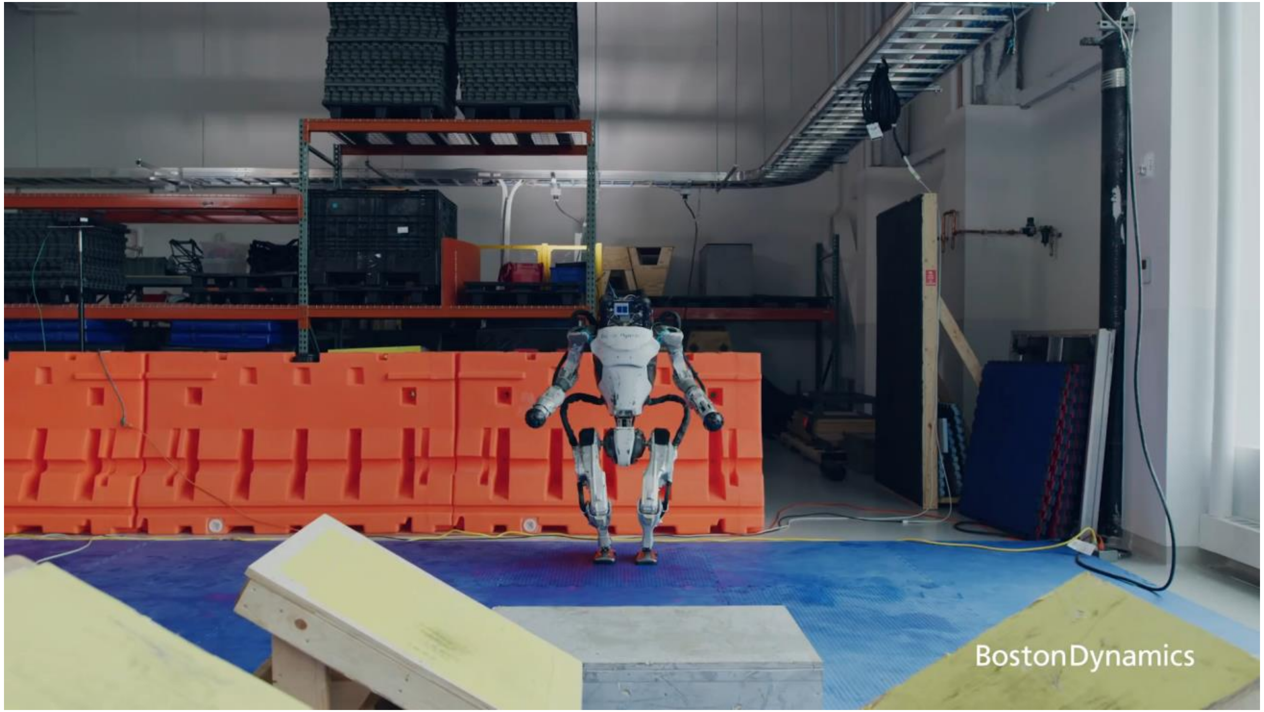


https://www.youtube.com/watch?v=_sBBaNYex3E

Boston Dynamics Atlas (Dec. 2020)

https://www.youtube.com/watch?v=fn3KWM1kuAw

Boston Dynamics Atlas (Aug. 2021)



https://www.youtube.com/watch?v=tF4DML7FIWk

Agility Robotics DIGIT – Humanoids as Workforce

https://www.youtube.com/watch?v=Jycdks836bY

Halodi Robotics EVEr3 – Houshold

https://www.youtube.com/watch?v=764ZMDOleDs

Baking Gingerbread Cookies

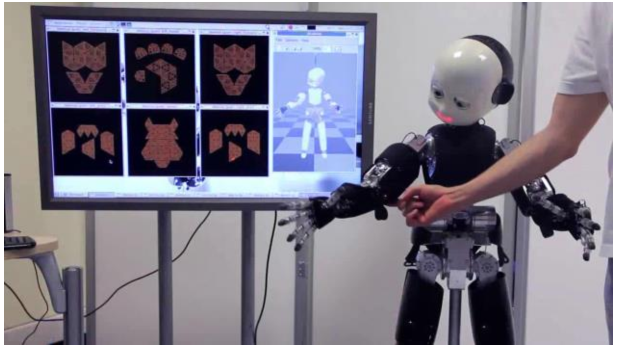
https://www.youtube.com/watch?v=bd-Ab90eljU

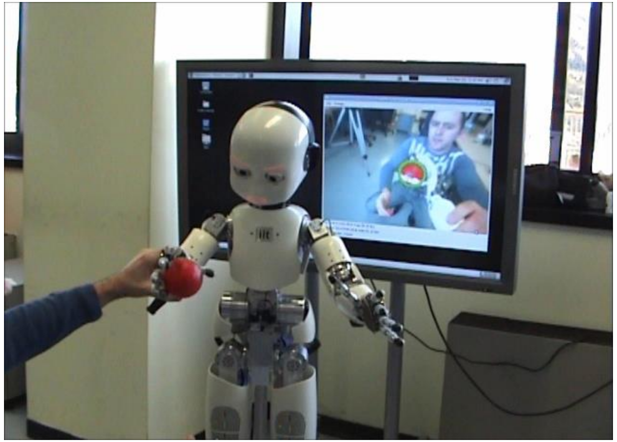
Carry a Box

iCub – Study Cognition

- Acronym for ***Cognitive Universal Body***
- Development **2004 - today**
- Designed by RobotCub Consortium of several European universities
- Built by **Italian Institute of Technology** (IIT)
- Dimensions similar to a 3 year old child
- Research interests:
  - Research on human cognition and artificial intelligence
  - Embodied cognition hypothesis: Human-like manipulation plays a vital role in the development of human cognition
  - The robot was designed to test this hypothesis by allowing cognitive learning scenarios to be acted out by an accurate reproduction of the perceptual system and articulation of a small child so that it could interact with the world in the same way that such a child does.
- Height: 100 cm, Weight: 22 kg, 53 DoF

https://www.iit.it/research/facilities/icub-tech





iCub

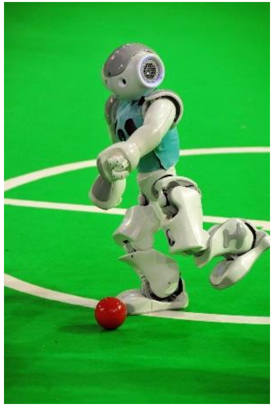
iCub is an open source international endeavour initially funded by the EU project RobotCub

- a full humanoid robot
- is 104cm, weighs 22 kg
- has 53 degrees of freedom
- can crawl, sit and manipulate
- open design as LGPL/GPL

Nao – Education and Entertainment

- Developed by Aldebaran Robotics, France (Now SoftBank Robotics)
- Introduced 2008, Nao Next Gen 2011
- Capabilities
  - Bipedal walking
  - Getting up from the floor
  - Facial and shape recognition
- Usage
  - Research and education
  - RoboCup robot soccer competitions
- Sensors
  - Ultrasound
  - HD Stereo cameras
- Height: 58 cm; Weight: 4.3 kg; 21 to 25 DoF

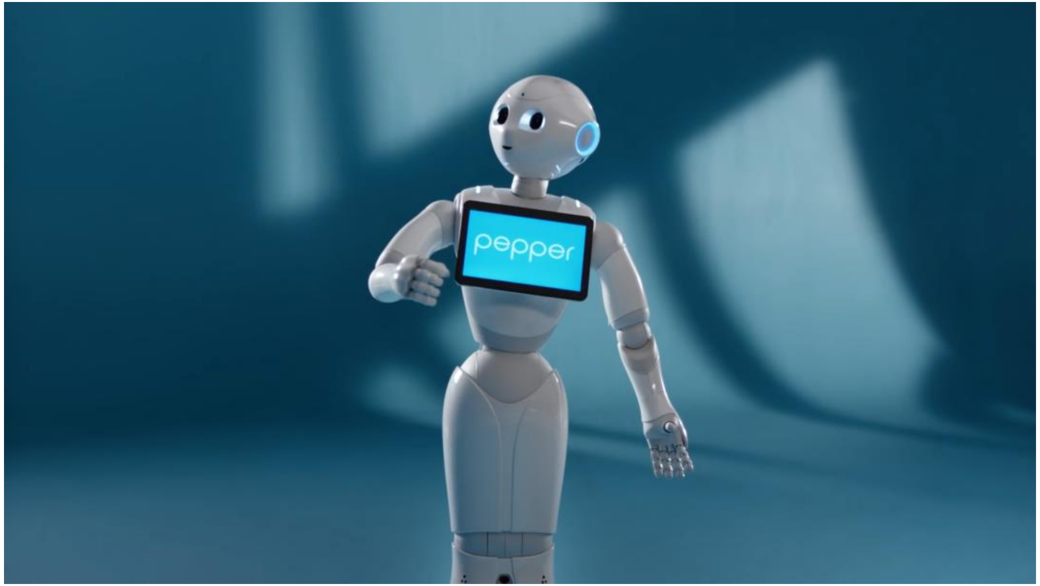
https://www.youtube.com/watch?v=H7K_Zh8syDU



https://de.wikipedia.org/wiki/RoboCup

Nao (2012)

Pepper – Social Interaction, Education, Entertainment



https://www.softbankrobotics.com/us/pepper

PAL Robotics

REEM-C

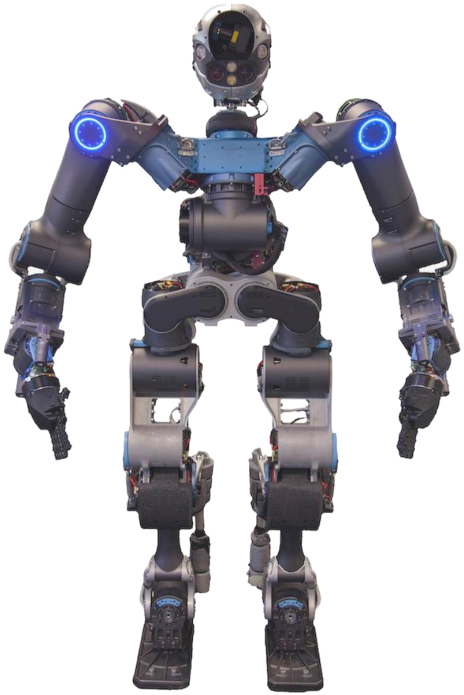
REEM

TALOS

http://pal-robotics.com/robot/

WALK-MAN – Mechatronics and Whole-Body Control

- Robot for disaster response; whole-body locomotion and manipulation
- Hardware was developed at IIT (Italian Institute of Technology) and University of Pisa
- 33 Degrees of Freedom (DoF):
  - 2 DoF neck
  - 2x7 DoF Arms
  - 3 DoF waist
  - 2 underactuated soft hands actuated by a single motor each
  - 2x6 DoF Legs
- Height: 185 cm; Weight: 118 kg
- Its first version was presented in 2015, the new version with a more powerful and lighter upper body in 2018.
- WALK-MAN participated in the DARPA Robotics Challenge



https://archive.darpa.mil/roboticschallenge/finalist/walk-man.html

KHR and HUBO

- Developed by the **Korea Advanced Institute of Science and Technology** (KAIST) and released on January 6, 2005
- Voice recognition and synthesis faculties
- Sophisticated vision in which its two eyes move independently of one another

	KHR-0 (2001)	KHR-1 (2002)	KHR-2 (2004)	HUBO (KHR-3) (2005)	Albert HUBO (2005)	HUBO 2 (KHR-4) (2008)	HUBO 2 Plus (2011)
Weight	29 kg	48 kg	56 kg	56 kg	57 kg	45 kg[3]	43 kg
Height	110 cm	120 cm	120 cm	125 cm	137 cm	125 cm	130 cm
Walking speed	-	1.0 km/h	1.2 km/h	1.25 km/h	1.25 km/h	1.5 km/h	1.5 km/h
Continuous operating time	-	-	-	60 minutes	60 minutes	120 minutes	120 minutes
Degrees of Freedom	12	21	41	41	66	40	38

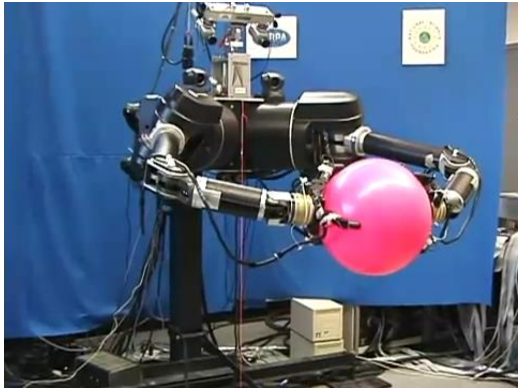
http://en.wikipedia.org/wiki/HUBO

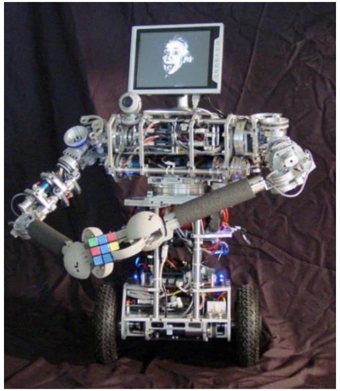
DASL
Drexel Autonomous Systems Lab
METlab

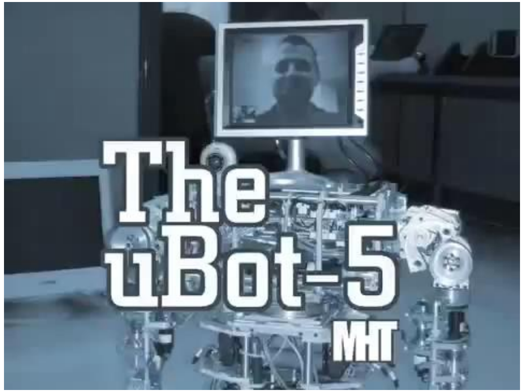
DRC HUBO: Winner of the DRC

Dexter and uBot

- **University of Massachusetts**
- **Dexter**
  - Bi-manual dexterity
  - Acquisition of concepts and cognitive representations from interaction with the world
- **uBot**
  - Mobile manipulation







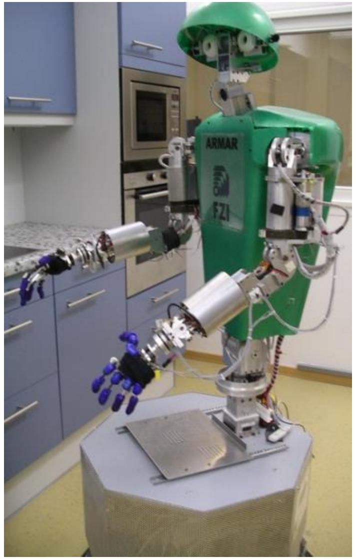
Justin and Toro – Mechatronics and Compliant Control

- **Deutsches Zentrum für Luft- und Raumfahrt** (DLR)
- Advanced mechatronics and compliance control

https://www.dlr.de/rm/desktopdefault.aspx/tabid-11864/

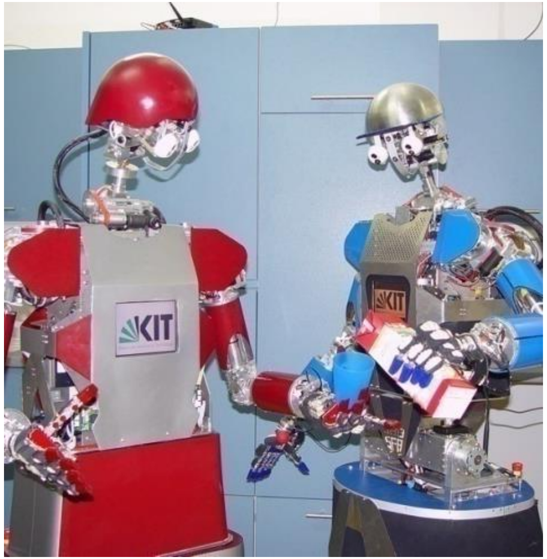
The ARMAR Humanoid Family

ARMAR
2000



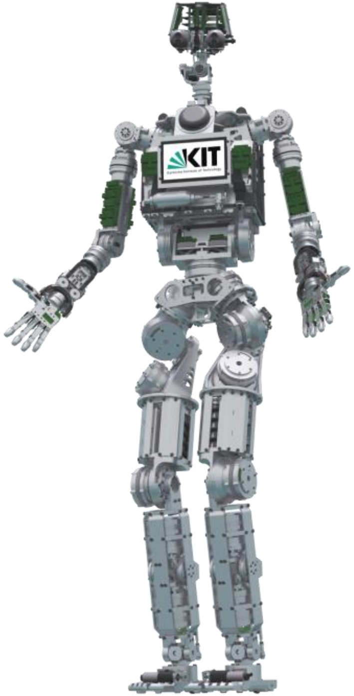
ARMAR-II
2002

ARMAR-IIIa
2006



ARMAR-IIIb
2008

The ARMAR Humanoid Family

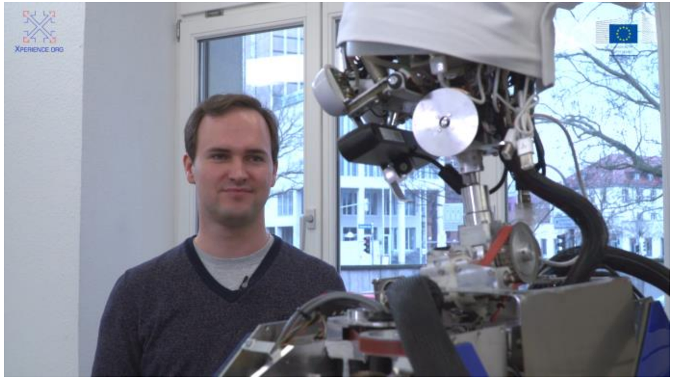


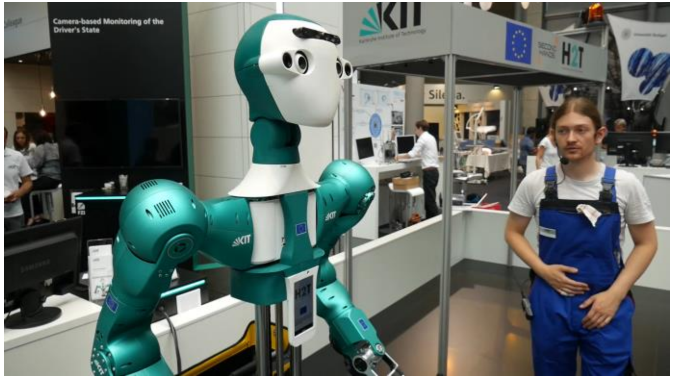
ARMAR-4
2011

ARMAR-6
2017

The ARMAR Humanoid Family

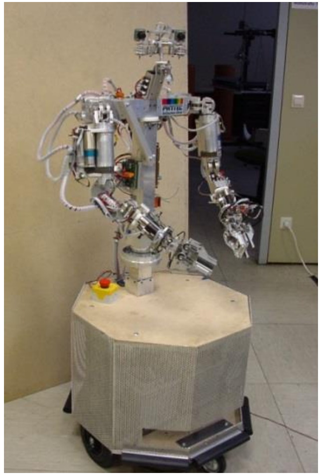
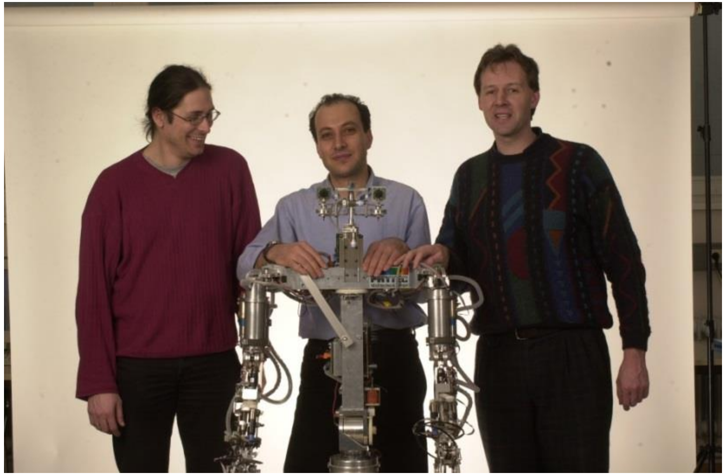
- Engineering Humanoids
- Grasping and manipulation
- Learning from human observation

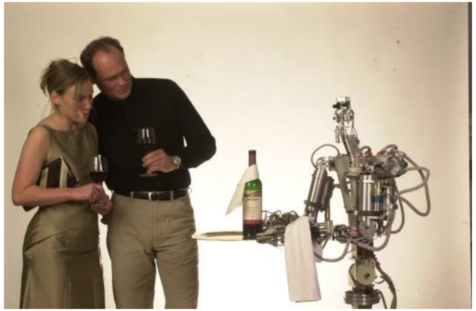
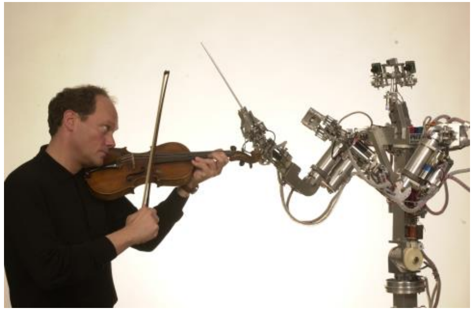




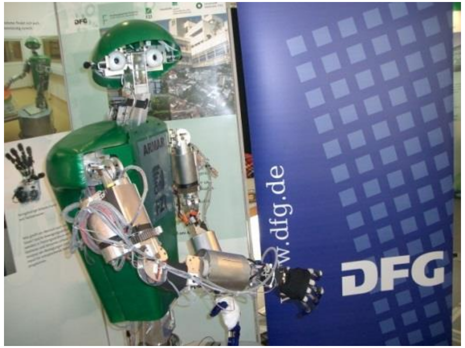
Asfour, T., Dillmann, R., Vahrenkamp, N., Do, M., Wächter, M., Mandery, C., Kaiser, P., Kröhnert, M. and Grotz, M., *The Karlsruhe ARMAR Humanoid Robot Family*, In: Goswami A., Vadakkepat P. (eds) Humanoid Robotics: A Reference, Springer Netherlands, 2017

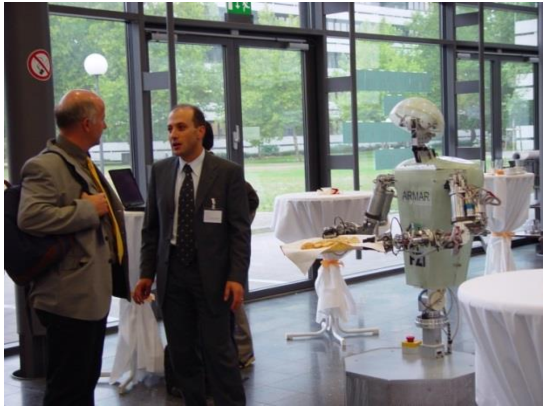
ARMAR-I (1999 – 2004)

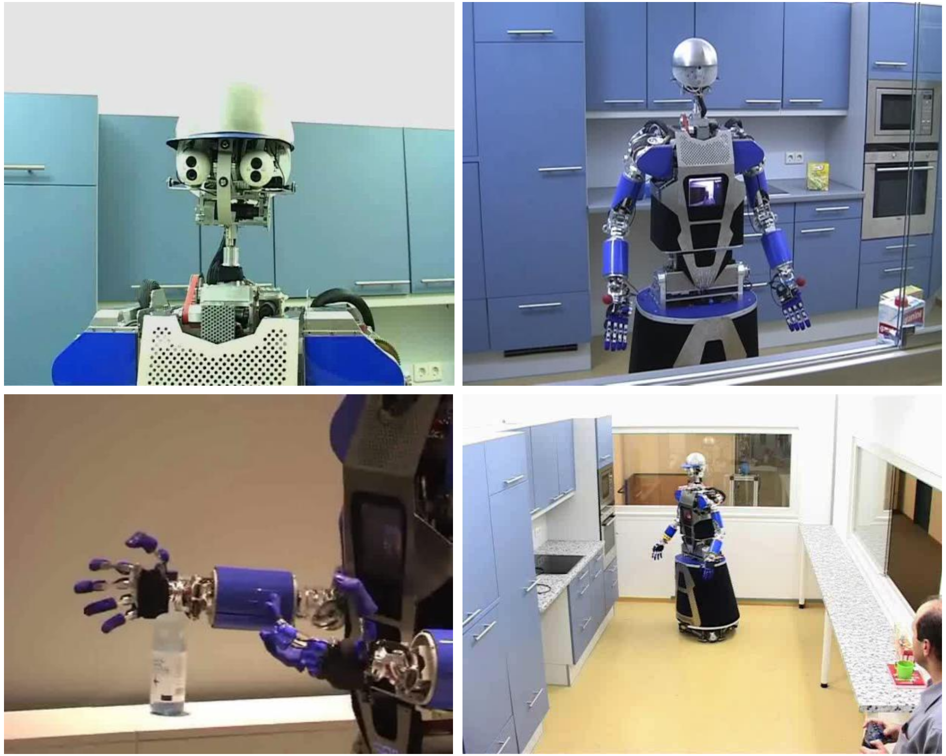

ARMAR-II (2003 – 2007)



ARMAR-IIIa and ARMAR-IIIb (2006 – Today)

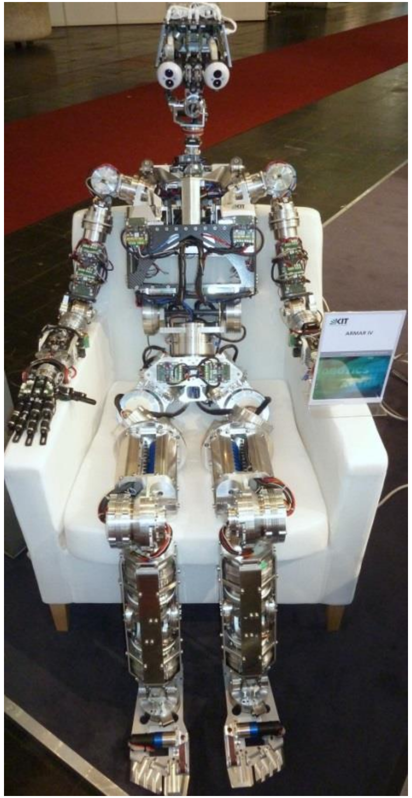
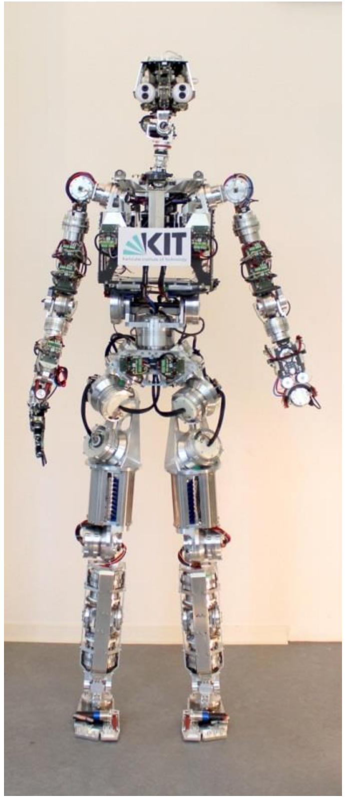
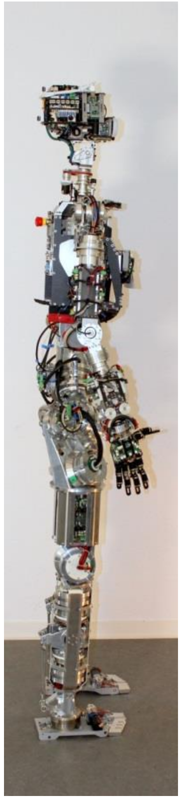
- **7 DoF head with foveated vision**
  - 2 cameras in each eye
  - 6 microphones
- **7 DoF arms**
  - Position, velocity and torque sensors
  - 6D FT-Sensors
  - Sensitive Skin
- **8 DoF hands**
  - Pneumatic actuators
  - Weight 250g
  - Holding force 2,5 kg
- **3 DoF torso**
  - 2 Embedded PCs
  - 10 DSP/FPGA Units
- **Holonomic mobile platform**
  - 3 laser scanner
  - 3 Embedded PCs
  - 2 Batteries
- **Weight: 150 kg**



Fully integrated humanoid system

ARMAR-4 (2011 - Today)

- 63 DoF
- 170 cm
- 70 kg
- Torque-controlled!

ARMAR-4: Mechano-Informatics

- Torque controlled
- 3 on-board embedded PCs
- 76 Microcontroller
- 6 CAN Buses
- 63 DoF
  - 41 electrically-driven
  - 22 pneumatically-driven (Hand)
- 238 Sensors
  - 4 Cameras
  - 6 Microphones
  - 4 6D-force-torque sensors
  - 2 IMUs
  - 128 position (incremental and absolute), torque and temperature sensors in arm, leg and hip joints
  - 18 position (incremental and absolute) sensors in head joints
  - 14 load cells in the feet
  - 22 encoders in hand joints
  - 20 pressure sensors in hand actuators
  - …

ARMAR-4

made@KIT

70 kg

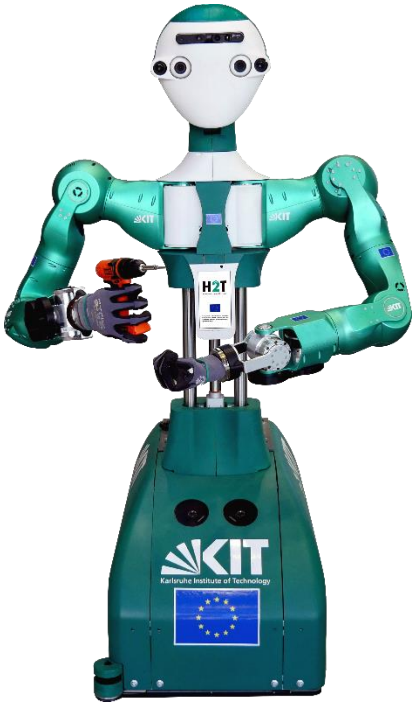
170 cm

More than mechatronics

ARMAR-6 (2017 - Today)

- 27 DOF
- 192 cm
- 160 kg

- **Torque-controlled!**



ARMAR-6: Mechano-Informatics

Karlsruher Institut für Technologie

- Torque controlled
- 4 on-board PCs, 1 GPU
- High-speed EtherCAT bus
- Payload
  - 10 kg per arm (extended arms)
  - 14 kg per arm (middle extension)
- 27 DOF
  - 8 DOF arms (2x)
  - 2 DOF hands (2x)
  - 2 DOF neck
  - 1 DOF torso (linear joint)
  - 4 mecanum wheels
  - Some joints have continuous rotation
- More than 200 sensors
  - 2 stereo camera systems
  - 1 depth camera
  - Position, torque, temperature and inertia sensors in each joint
  - 2 6D-force-torque sensors
  - 2 laser scanners
  - …

ARMAR-6

made@KIT

160 kg

192 cm

More than mechatronics

Chapter 2: Building Humanoids

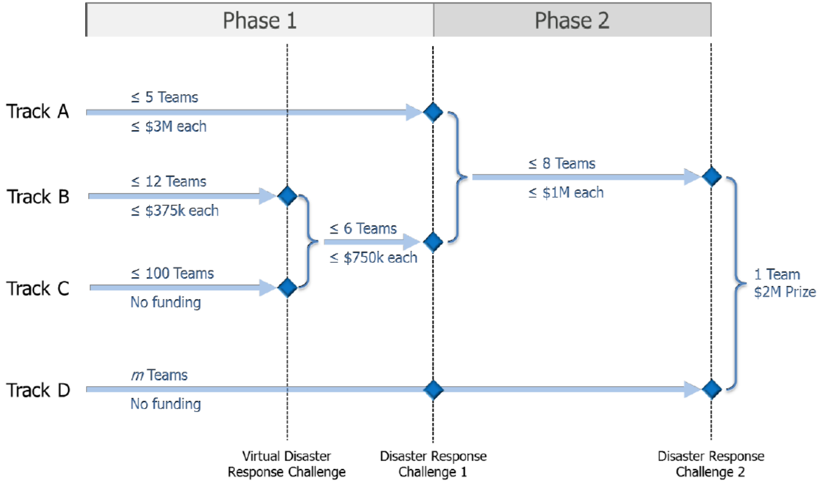
- The history of humanoid robotics
- **The DARPA Robotics Challenge**
- Biomechanical models of the human body
- Mechatronics of humanoid robots

THE DARPA ROBOTICS CHALLENGE (2012-2015)

https://en.wikipedia.org/wiki/DARPA_Robotics_Challenge

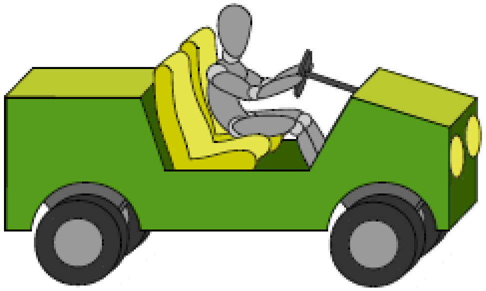
The DARPA Robotics Challenge

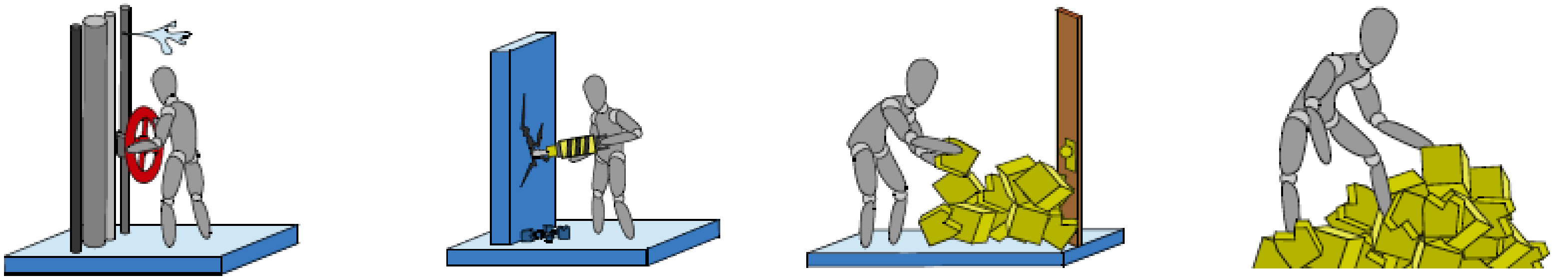
- Robot competition funded by the US Defense Advanced Research Projects Agency.
- Held from 2012 to 2015
- **Goal:** develop semi-autonomous ground robots that could do "complex tasks in dangerous, degraded, human-engineered environments”



The DARPA Robotics Challenge: Tasks

- Drive a utility vehicle
- Climb a 60 degree ship ladder
- Walk through 3 different door types
- Walk over a series of obstacles
- Clear wood and metal debris
- Turn on a drill and cut an opening in a wall
- Mate a hose to a spigot
- Turn 3 different industrial valves



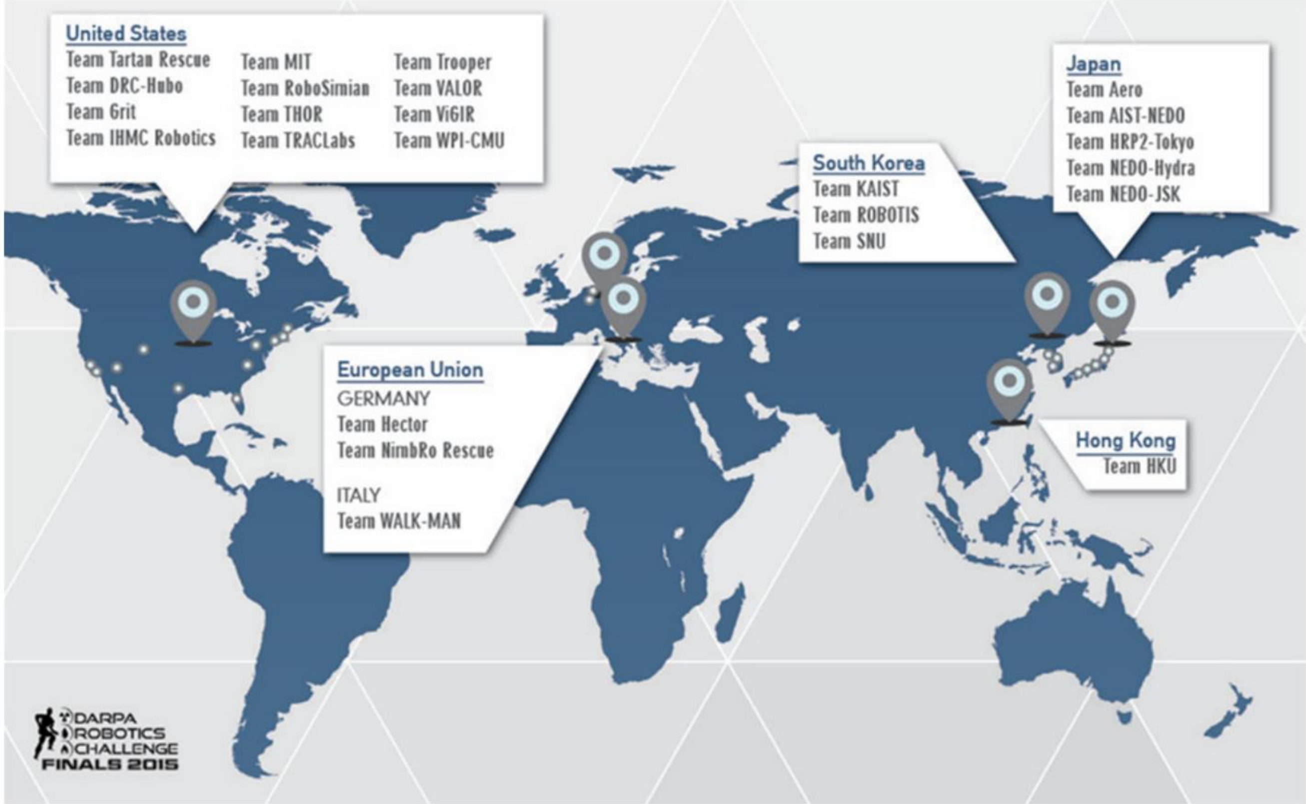


The DARPA Robotics Challenge: Teams (Phase 2)

- **TARTAN RESCUE**
- TEAM AERO (Japan)
- TEAM AIST-NEDO (Japan)
- TEAM DRC-HUBO AT UNLV (USA)
- TEAM GRIT (USA)
- TEAM HECTOR (Darmstadt, Germany)
- TEAM HKU (Hong Kong)
- TEAM HRP2-TOKYO
- **TEAM IHMC ROBOTICS**
- TEAM INTELLIGENT PIONEER (China)
- TEAM KAIST (South Korea)
- **TEAM MIT**
- TEAM NEDO-HYDRA (Japan)
- TEAM NEDO-JSK (Japan)
- TEAM NIMBRO RESCUE (Bonn, Germany)
- **TEAM ROBOSIMIAN**
- TEAM ROBOTIS (South Korea)
- TEAM SNU (South Korea)
- **TEAM THOR**
- **TEAM TRAC LABS**
- **TEAM TROOPER**
- TEAM VALOR (USA)
- **TEAM VIGIR**
- TEAM WALK-MAN (Italy)
- TEAM WPI-CMU (USA)

Bold: 8 finalists, DARPA funded (Tracks A and B)

The DARPA Robotics Challenge: Teams



The DARPA Robotics Challenge: Finals

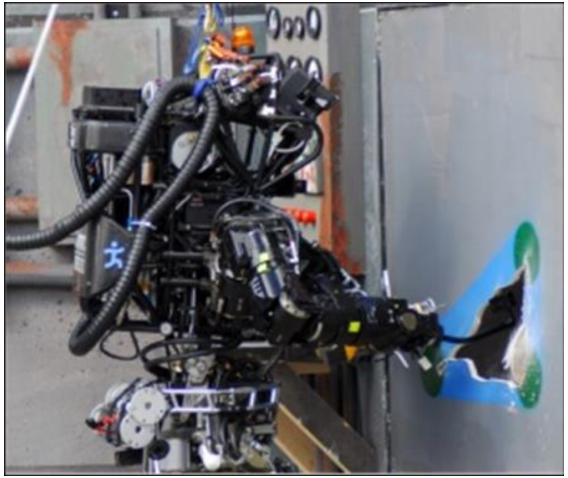
- The DRC finals on June 5-6, 2015 at Fairplex in Pomona, California.
- The event required robots to attempt a circuit of consecutive physical tasks, with degraded communications between the robots and their operators
- 25 of the top robotics organizations in the world gathered to compete for $3.5 million in prizes as they attempt a simulated disaster-response course.

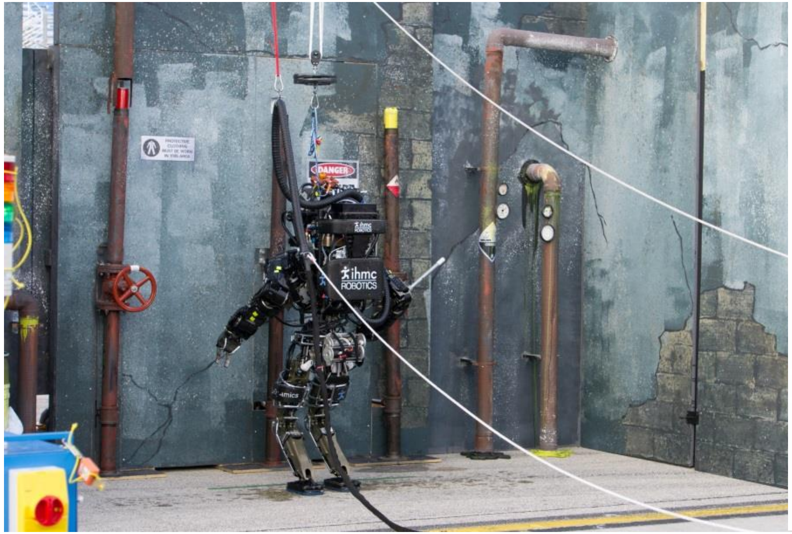
Winners

Position	Team	Final Score	Time (min)
1	TEAM KAIST	8	44:28
2	TEAM IHMC ROBOTICS	8	50:26
3	TARTAN RESCUE	8	55:15
4	TEAM NIMBRO RESCUE	7	34:00
5	TEAM ROBOSIMIAN	7	47:59
6	TEAM MIT	7	50:25
7	TEAM WPI-CMU	7	56:06
8	TEAM DRC-HUBO AT UNLV	6	57:41
9	TEAM TRACLABS	5	49:00
10	TEAM AIST-NEDO	5	52:30

Team IHMC Robotics

- Robot: ATLAS-Ian
- Florida Institute for Human & Machine Cognition
- Team leaders:
  - **Jerry Pratt**
  - **Matt Johnson**

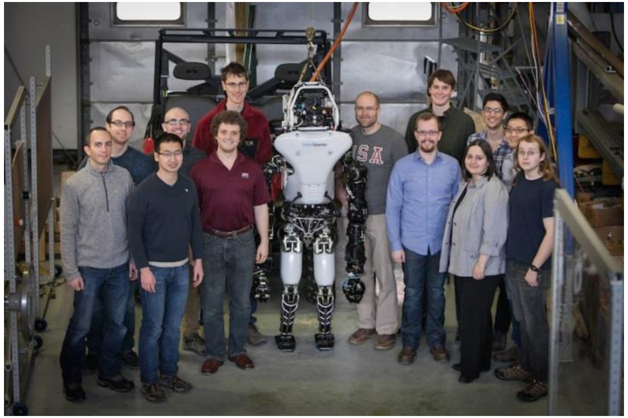




http://robots.ihmc.us

Team MIT

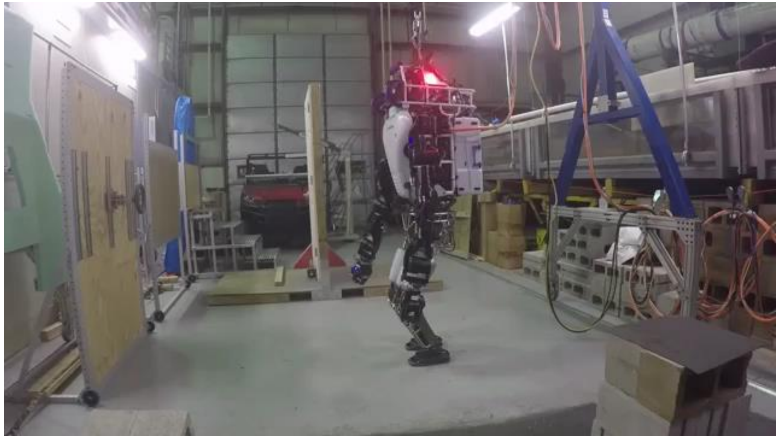
- Robot: Atlas - Helios
- MIT, Cambridge, MA
  - Team leader: **Russ Tedrake**
  - Sub Leads:
    - **Maurice Fallon** (perception)
    - **Scott Kuindersma** (planning and control),
    - **Pat Marion** (interface)
- http://drc.mit.edu



Team MIT

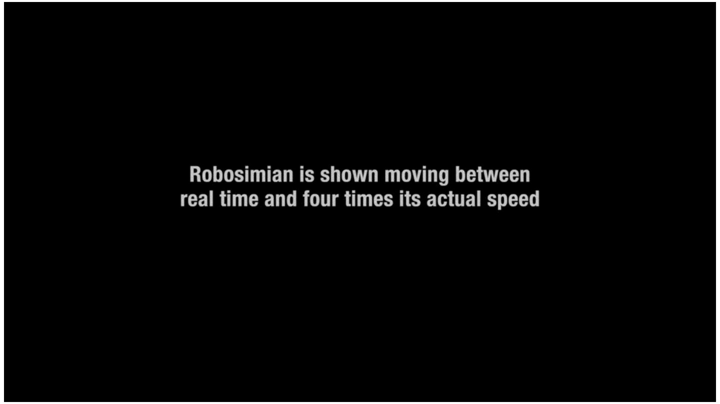
Whole-body grasping
https://www.youtube.com/watch?v=NeSTN1OxmtY

Fast walking
https://www.youtube.com/watch?v=n6cDjf6GZto



Team RoboSimian

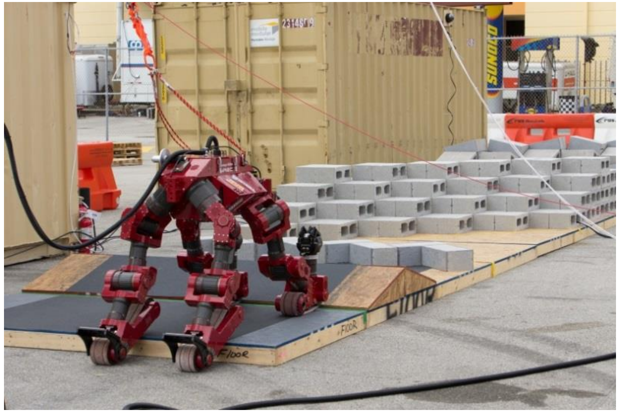
- Robot: RoboSimian
- NASA Jet Propulsion Lab
- Height: 164cm in bipedal pose
- Weight: 108kg
- Wingspan: 221cm



https://www.youtube.com/watch?v=dE3EascntYw

Team Tartan Rescue

- Robot: CHIMP „CMU Highly Intelligent Mobile Platform“
- Carnegie Mellon University (CMU), Pittsburgh
- Height: 5 feet and 2 inches
- Weight: 200kg
- Wingspan: ≈10 feet



https://www.nrec.ri.cmu.edu/solutions/defense/other-projects/tartan-rescue-team.html

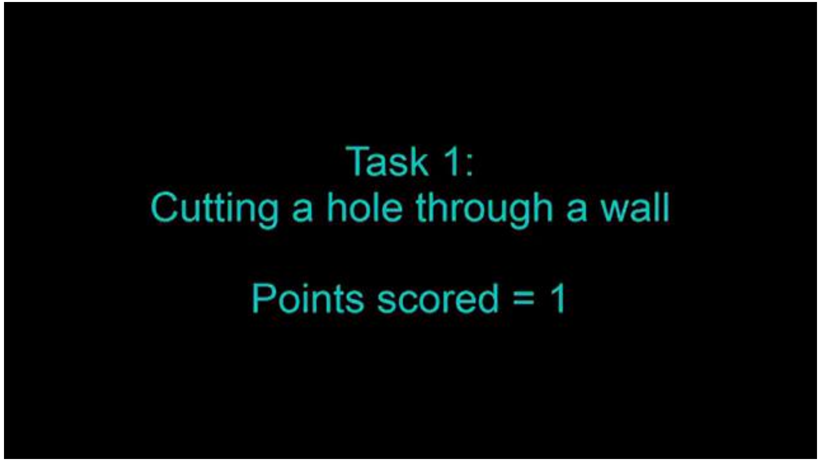
Team THOR

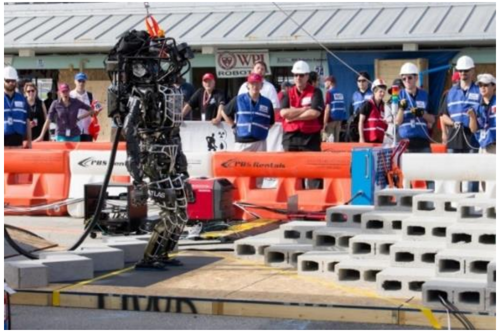
- Robot: THOR-OP (THOR = „Tactile Hazardous Operations Robot“)
- Virginia Tech
- Team leader: **Dennis Hong**
- Height: 178cm
- Weight: 65kg
- Wingspan: 208cm

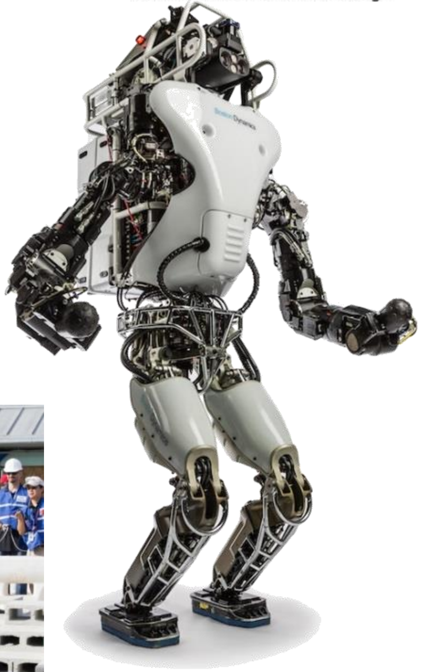
https://archive.darpa.mil/roboticschallenge/finalist/thor.html

Team TRACLabs

- Robot: Atlas - Hercules
- Webster, Texas
- Team leader: **David Kortenkamp**







https://www.youtube.com/playlist?list=PLmQko6gr2EvEYPqwDYmsxPN5kaxqUMEOo

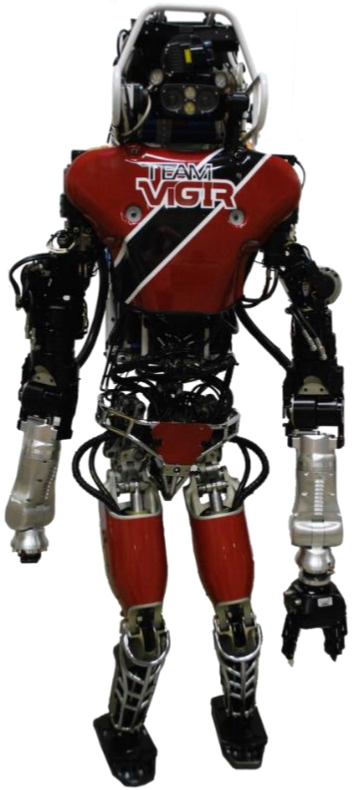
Team TROOPER

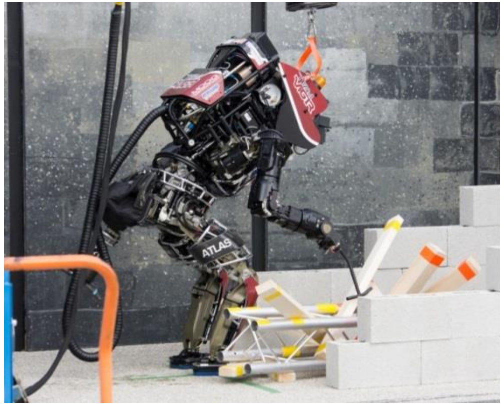
- Robot: Atlas - Leo
- Cherry Hill, NJ - Troy, NY - Philadelphia, PA
- Cooperation of:
  - Lockheed Martin
  - University of Pennsylvania
  - Rensselaer Polytechnic Institute

https://archive.darpa.mil/roboticschallenge/finalist/trooper.html

Team ViGIR

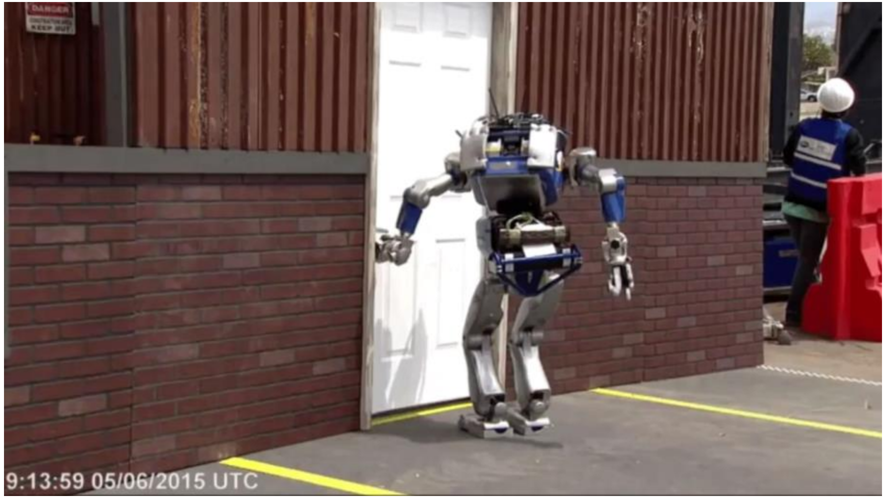
- Robot: Florian
- Cooperation of:
  - TORC Robotics
  - Virginia Tech
  - TU Darmstadt, Germany
  - Oregon State University



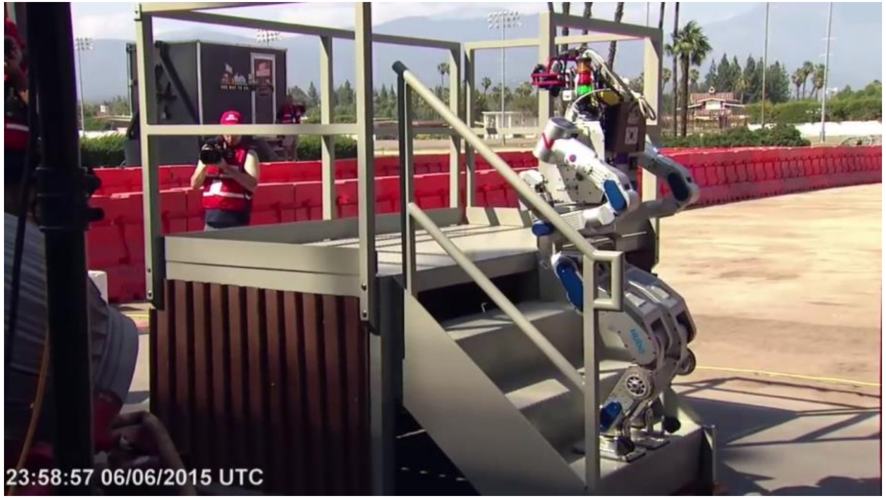


https://archive.darpa.mil/roboticschallenge/finalist/vigir.html

DRC – Humanoids and Doors ☺



Failures



Winner Team

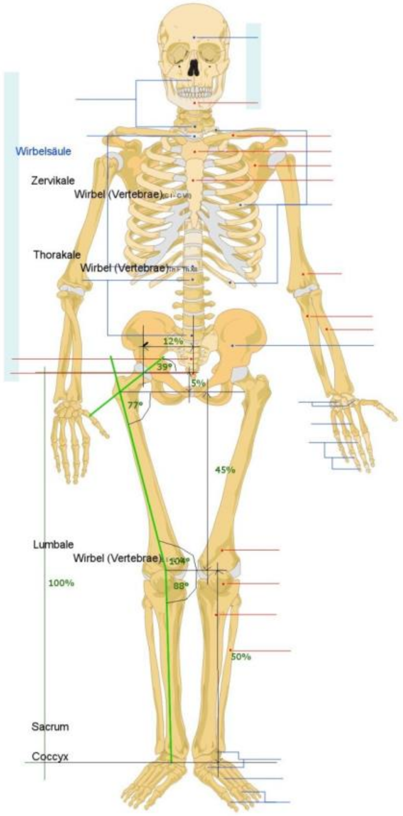
Atkeson, C., Babu, B., Banerjee, N., Berenson, D., Bove, C., Cui, X., DeDonato, M., Du, R., Feng, S., Franklin, P. et al. (2015). „No Falls, no Resets: Reliable Humanoid Behavior in the DARPA Robotics Challenge“. IEEE/RAS International Conference on Humanoid Robots (Humanoids)

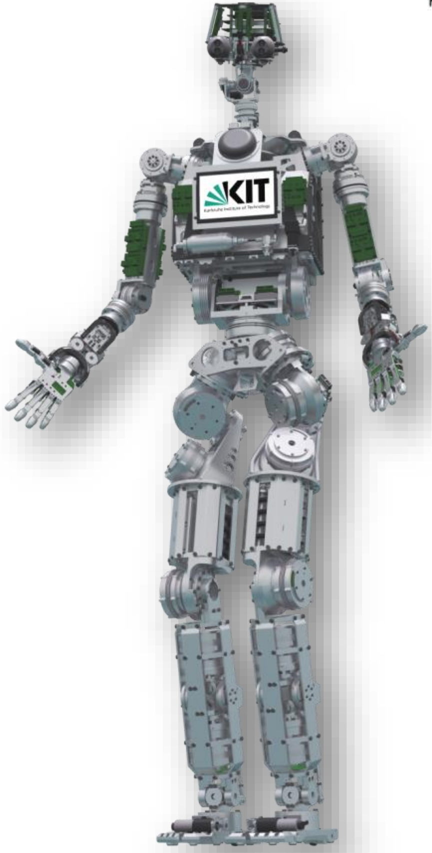
Chapter 2: Building Humanoids

- The history of humanoid robotics
- The DARPA Robotics Challenge
- **Biomechanical models of the human body**
- Mechatronics of humanoid robots

Biomechanical Models of the Human Body

From Human Body to Humanoid



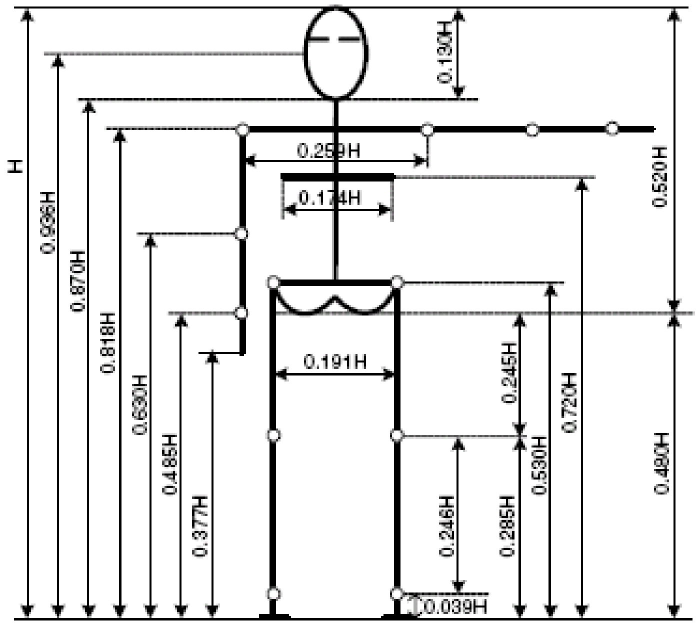


Models of the Human Body

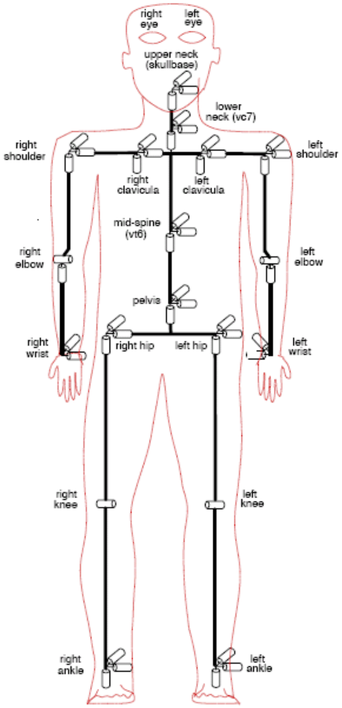
Models of the human body are used in …

- **human factors engineering**
  - Ergonomics
  - Work space design
  - Driver‘s cab
- **computer graphics**
  - Animation
  - Entertainment
  - Visualization
- **medical applications**
  - Rehabilitation
  - Human anatomy (e.g. http://www.visiblebody.com)
- **robotics**
  - Design of **anthropomorphic robots** (e.g. humanoids)
  - Design of **assistive robotics systems** (prosthesis and orthoses)
  - Learning from human observation

Human Body Model



D.A. Winter, "Biomechanics and Motor Control of Human Movement", John Wiley & Sons Inc. (1990)



P. Azad, T. Asfour, and R. Dillmann, "Toward an Unified Representation for Imitation of Human Motion on Humanoids", *IEEE International Conference on Robotics and Automation* (2007)

Master Motor Map (MMM) – Motivation

- **Goal:** Design of humanoid robots
  → **Models of body parts are needed**

- **Problem:** Various different systems for:
  - Human motion capture
  - Action recognition
  - Imitation learning
  - Visualization
  - Robotic action execution

  → **Unified representation is needed!**

Master Motor Map (MMM)

Red: Relevant for the exam

Karlsruher Institut für Technologie

- **Reference model of the human body**
  - For humanoid robot design
  - Imitation of human actions
  - Action recognition
  - Visualization of human movements
- **Interfaces and data structures** for the **transfer of motor knowledge** between different embodiments

C. Mandery, Ö. Terlemez, M. Do, N. Vahrenkamp and T. Asfour, "Unifying Representations and Large-Scale Whole-Body Motion Databases for Studying Human Motion" *IEEE Transactions on Robotics*, Vol. 32, No. 4, pp. 796 – 809 (2016)

O. Terlemez, S. Ulbrich, C. Mandery, M. Do, N. Vahrenkamp and T. Asfour, "Master Motor Map (MMM) – Framework and Toolkit for Capturing, Representing, and Reproducing Human Motion on Humanoid Robots", *IEEE/RAS International Conference on Humanoid Robots (Humanoids)* (2014)

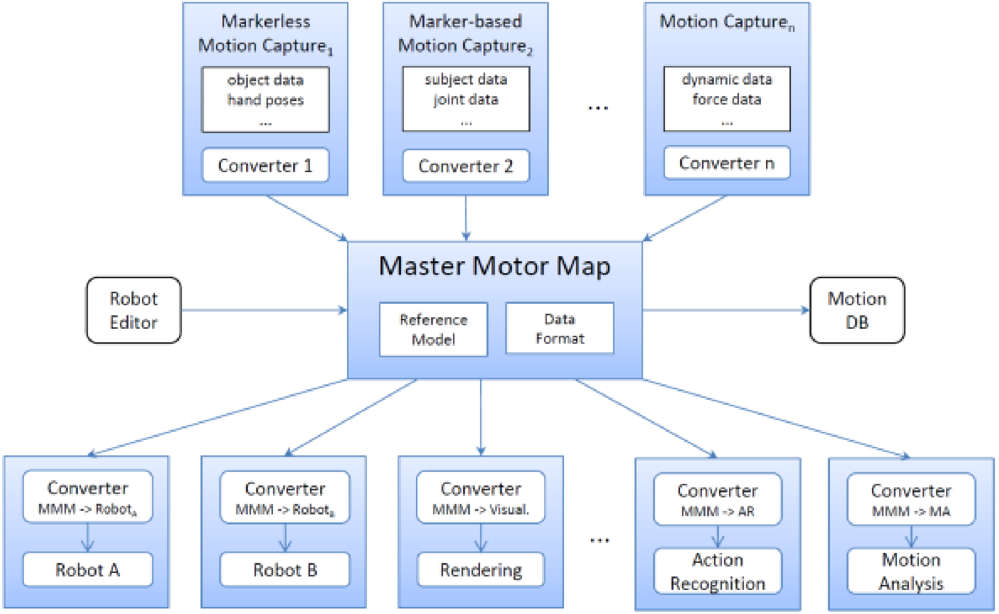
Pedram Azad, Tamim Asfour and Ruediger Dillmann, "Toward an Unified Representation for Imitation of Human Motion on Humanoids", *IEEE International Conference on Robotics and Automation* (2007)

The Master Motor Map (MMM)

Red: Relevant for the exam

Karlsruher Institut für Technologie

- **Unifying framework (Reference Model of the human body + Data Formats)** for capturing, representation, visualization and whole body human motion and mapping/converting to different embodiments



C. Mandery, Ö. Terlemez, M. Do, N. Vahrenkamp and T. Asfour, "Unifying Representations and Large-Scale Whole-Body Motion Databases for Studying Human Motion", *IEEE Transactions on Robotics*, Vol. 32, No. 4, pp. 796 - 809, (2016)

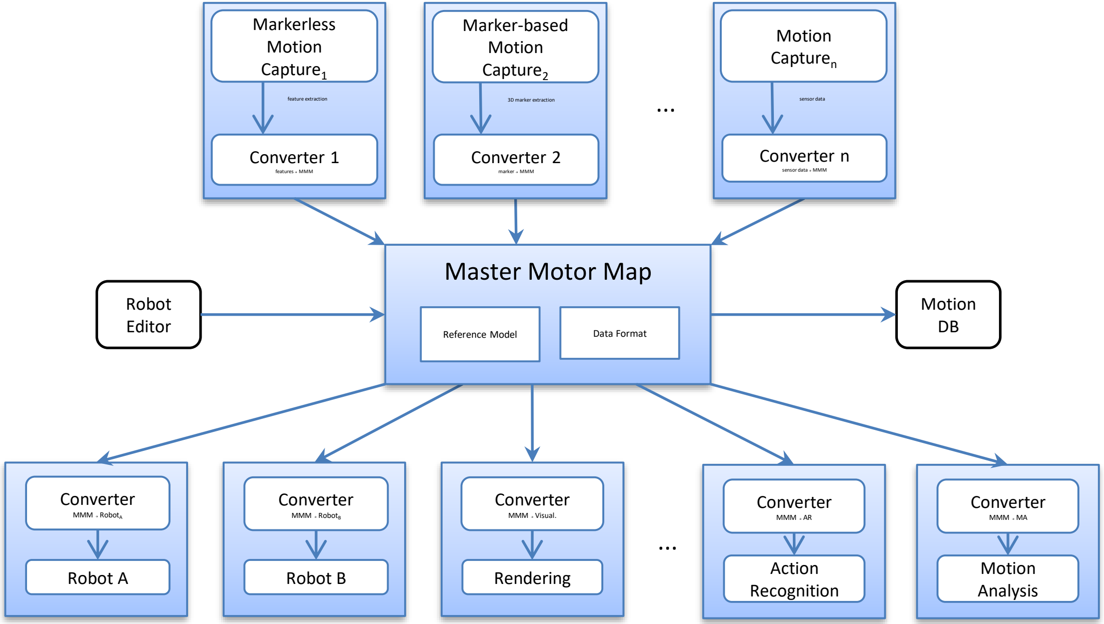
H2T

Master Motor Map (MMM)

- Replacement of any module (perception, recognition, visualization, reproduction) can be guaranteed by using the MMM as the exchange format

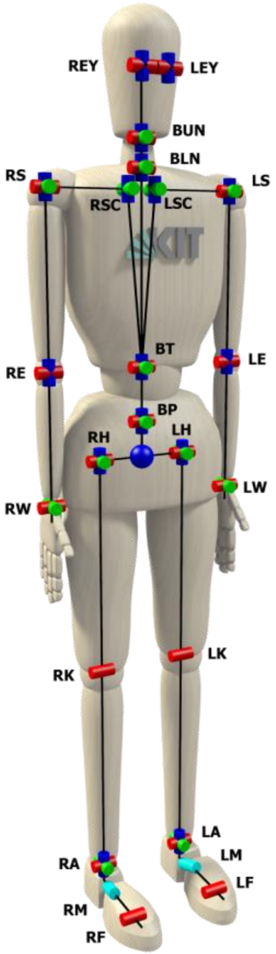
- All perceptive modules convert their output to the MMM format

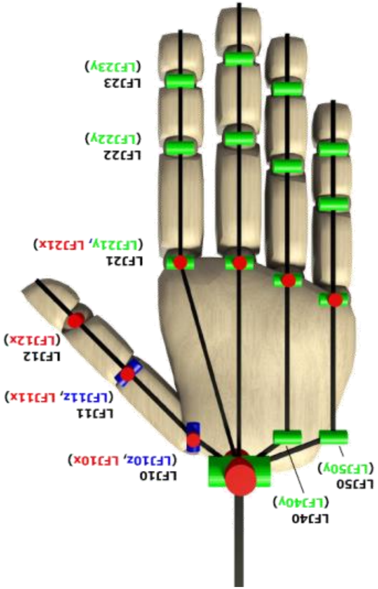
- All recognition and reproduction modules convert the MMM format to their specific internal representation



Master Motor Map (MMM)

- Reference model of the human body
  - **Kinematic model:** joints and segment lengths
  - **Dynamic model:** segment mass, center of mass and moments of inertia
  - **Statistic/anthropomorphic model:** segment properties (e.g. length, mass etc.) defined as a function (regression) of global parameters (e.g. body height, weight)
  - **104 DoFs**





Statistic/Anthropomorphic Model

Karlsruher Institut für Technologie

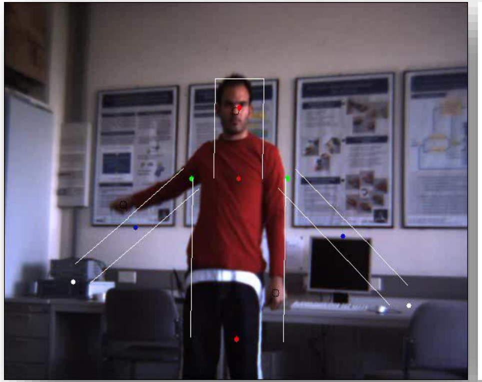
- Body segment properties (e.g. length, mass etc.) are defined as a function (regression) of certain global parameters (e.g. body height, weight etc.)
- Models have been discovered and verified by various researchers (see for example de Leva 1996, Winter 2005, Pronost et al., 2006)

D.A. Winter, "Biomechanics and Motor Control of Human Movement", John Wiley & Sons Inc. (1990)

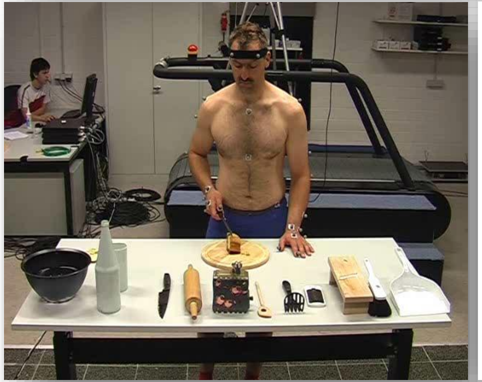
P. de Leva, "Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters", *J. of Biomechanics*, vol. 29, no. 9, pp. 1223 – 1230 (1996).

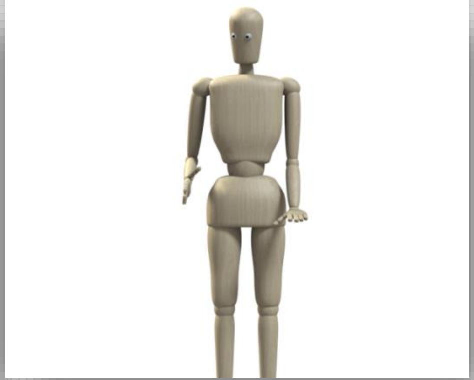
Motion Reproduction Using MMM

- Data from stereo-based markerless human motion capture system

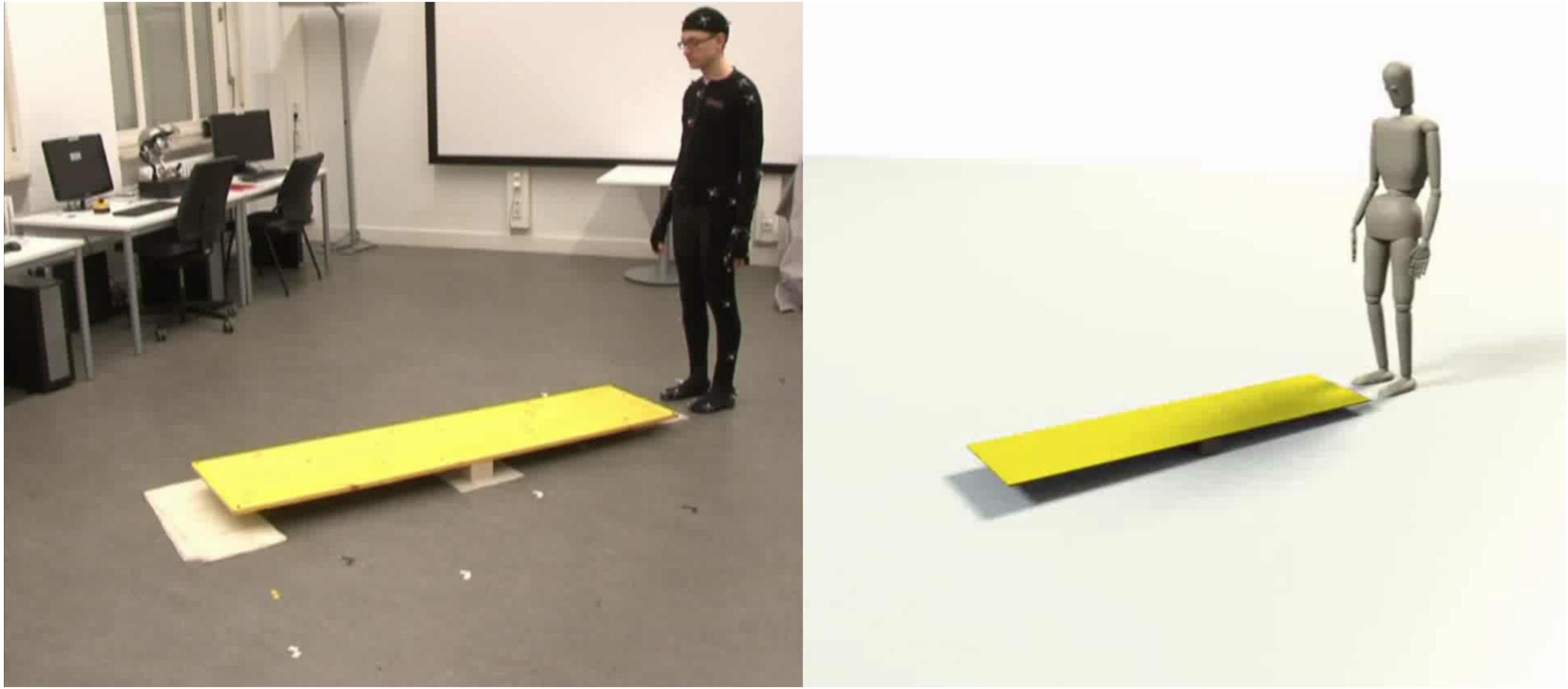


- Data from VICON system (SFB 588)

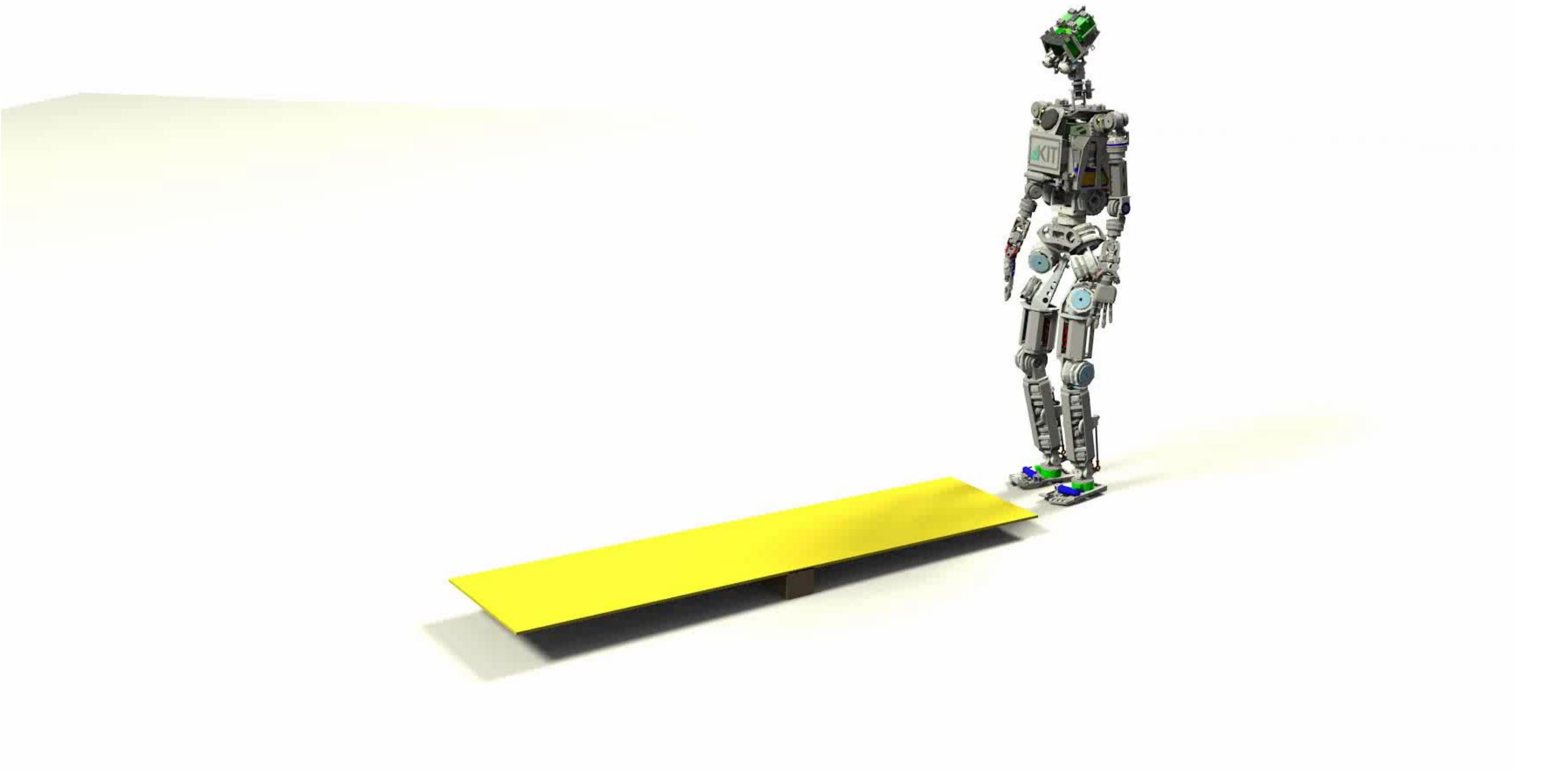




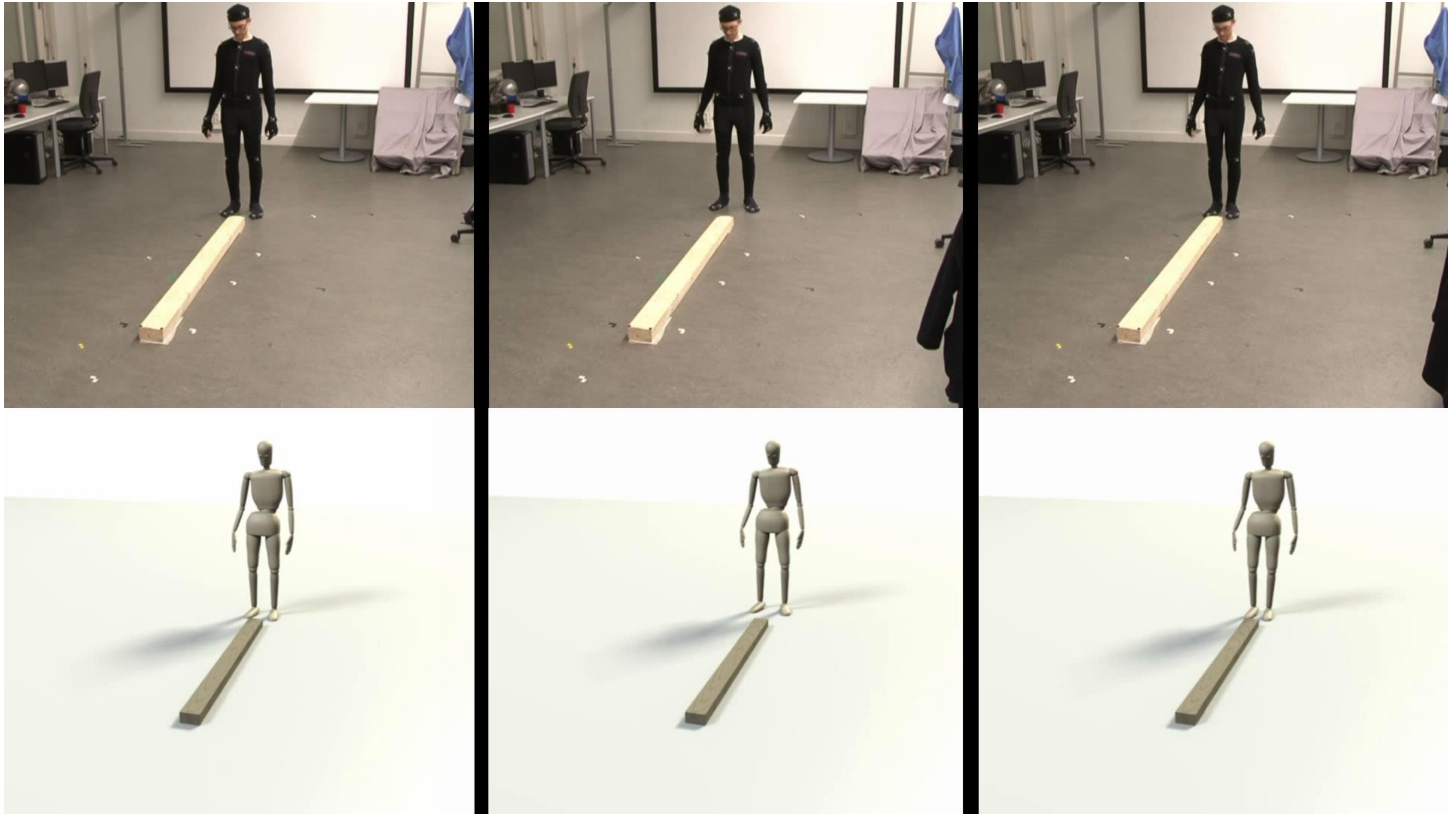
Motion Reproduction Using MMM



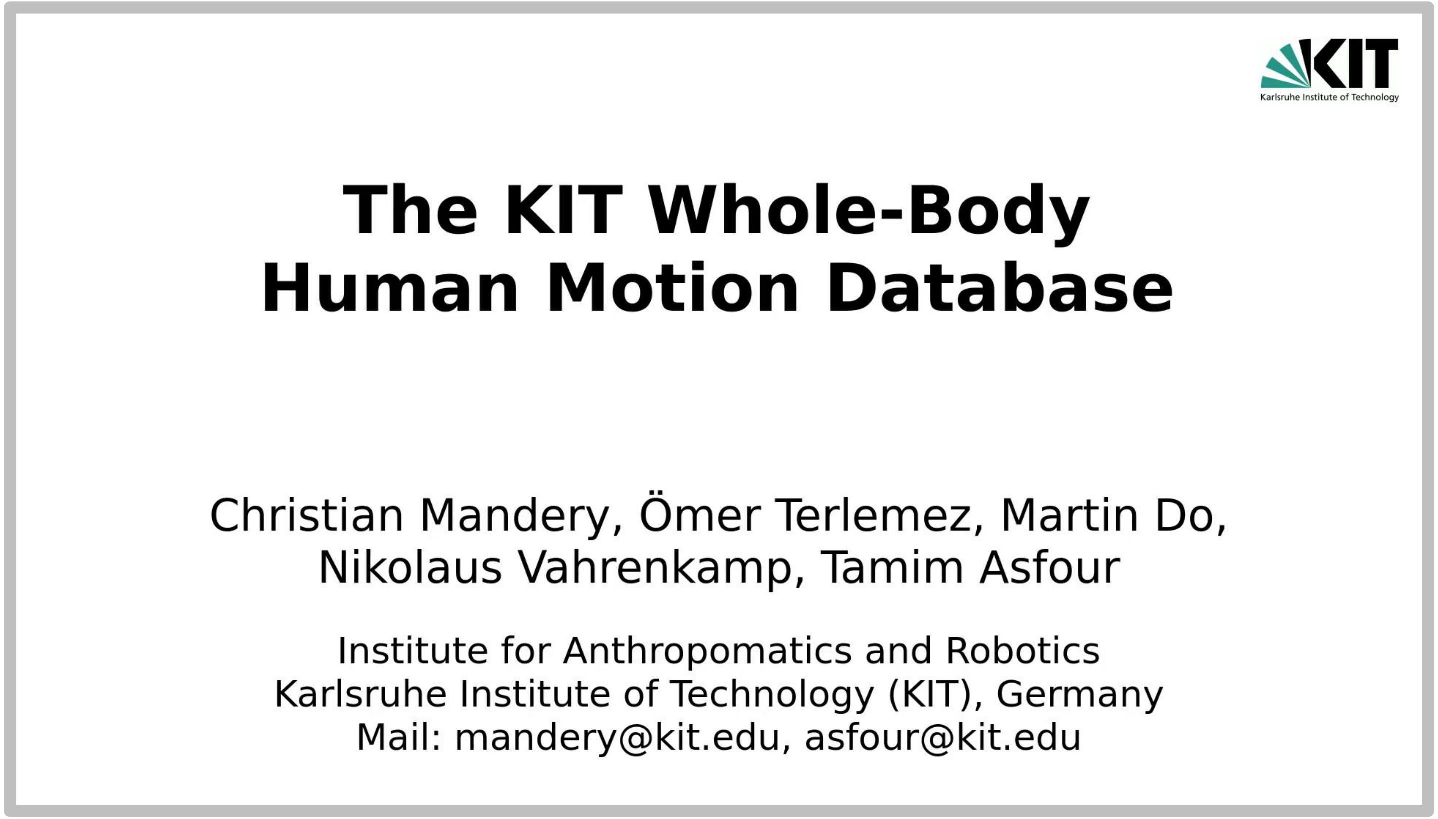
Motion Reproduction Using MMM



Motion Normalization Using the MMM (Video)



KIT Human Motion Database



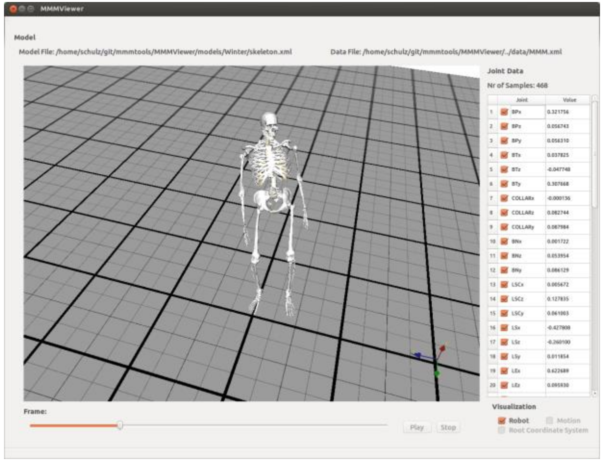
MMM Software and Documentation

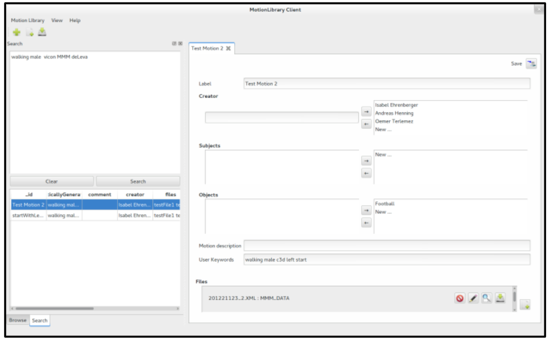
- MMM Software:
  - https://git.h2t.iar.kit.edu/sw/mmm/core
  - https://git.h2t.iar.kit.edu/sw/mmm/tools
- MMM Documentation:
  - http://mmm.humanoids.kit.edu
  - https://motion-database.humanoids.kit.edu/faq

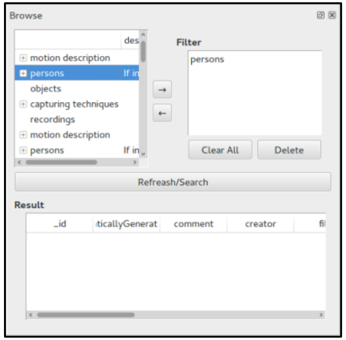
- **KIT Whole-Body Motion Database**
  - https://motion-database.humanoids.kit.edu

MMM Library & Tools

- **MMM Core**
  - C++ Library
  - I/O, XML, Raw Marker Data, Tools, Conversions
  - No dependencies (just Boost)
- **Mapping / Converter**
  - Vicon -> MMM model
  - MMM -> Robots (ARMAR III, ARMAR IV)
  - MMM -> Other robots (iCub, COMAN, HRP, …)
- **MMM Viewer**
  - 3D Model Viewer
  - MMM / Marker Data
  - Robots, Motions, Contacts, …
- **MMM Database**
  - Server
  - Client/Applications, Search, Web Frontend







References

Red: relevant for the exam

- **Our previous work on the MMM**

  - C. Mandery, Ö. Terlemez, M. Do, N. Vahrenkamp and T. Asfour, “Unifying Representations and Large-Scale Whole-Body Motion Databases for Studying Human Motion”, *IEEE Transactions on Robotics*, Vol. 32, No. 4, pp. 796 - 809, August (2016)
  - Ö. Terlemez, S. Ulbrich, C. Mandery, M. Do, N. Vahrenkamp and T. Asfour, “Master Motor Map (MMM) – Framework and Toolkit for Capturing, Representing, and Reproducing Human Motion on Humanoid Robots”, *IEEE/RAS International Conference on Humanoid Robots (Humanoids)* (2014)
  - C. Mandery, O. Terlemez, M. Do, N. Vahrenkamp and T. Asfour, “The KIT Whole-Body Human Motion Database”, *International Conference on Advanced Robotics (ICAR)* (2015)
  - S. Gärtner, M. Do, C. Simonidis, T. Asfour, W. Seemann and R. Dillmann, “Generation of Human-like Motion for Humanoid Robots Based on Marker-based Motion Capture Data”, *41th International Symposium on Robotics (ISR)*, pp. 1 – 8 (2010)
  - Pedram Azad, Tamim Asfour and Ruediger Dillmann, “Toward an Unified Representation for Imitation of Human Motion on Humanoids”, *IEEE International Conference on Robotics and Automation* (2007)

- **Others**

  - David A. Winter, “Biomechanics and Motor Control of Human Movement”, John Wiley & Sons, Inc. (2005)
  - P. de Leva, “Adjustments to Zatsiorsky-Seluyanov’s Segment Inertia Parameters”, *J. of Biomechanics*, vol. 29, no. 9, pp. 1223 – 1230 (1996)
  - Nicolas Pronost, Georges Dumont, “Validating re-targeted and interpolated locomotions by dynamics-based analysis”, *Proceedings of the 4th international conference on Computer graphics and interactive techniques in Australasia and Southeast Asia* (2006)
  - Michael Gleicher, “Retargetting Motion to New Characters”, *SIGGRAPH* (2008)

Chapter 2: Building Humanoids

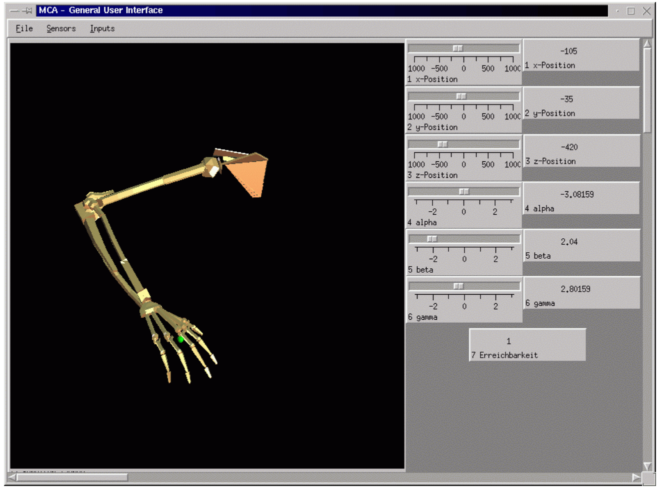
- The history of humanoid robotics
- The DARPA Robotics Challenge
- Biomechanical models of the human body
- **Mechatronics of humanoid robots**

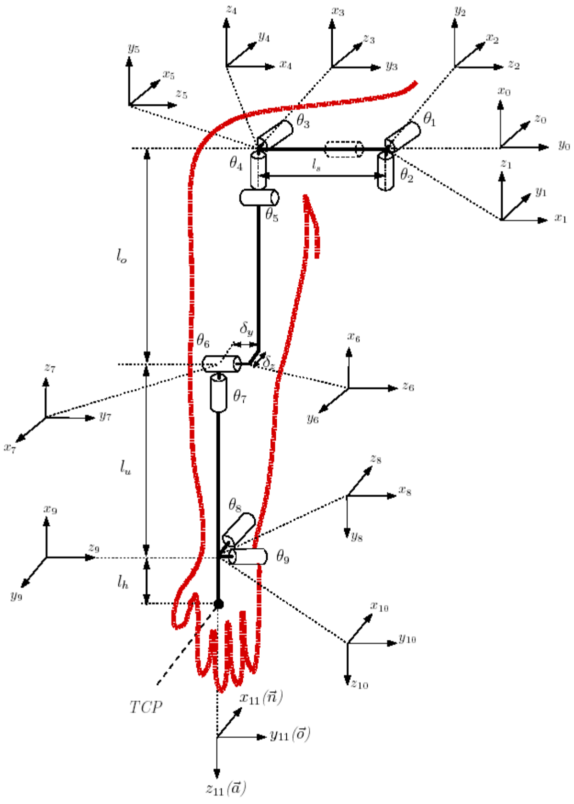
Mechatronics of humanoid robots

Examples based on the ARMAR Robots

Kinematic Model of the Human Shoulder-Arm System

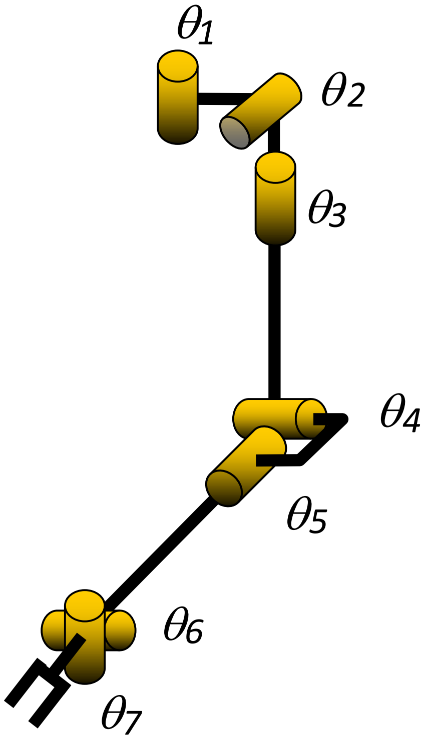
- 9 DoF
  - Shoulder: 5 DoF
  - Elbow: 2 DoF
  - Wrist: 2 DoF



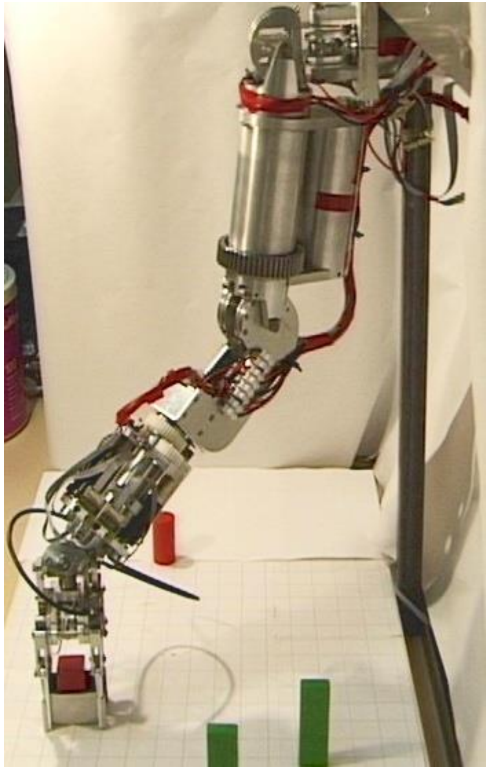


T. Asfour, „Sensomotorische Bewegungskoordination zur Handlungsausführung eines humanoiden Roboters“, *Dissertation*, Universität Karlsruhe (2003)

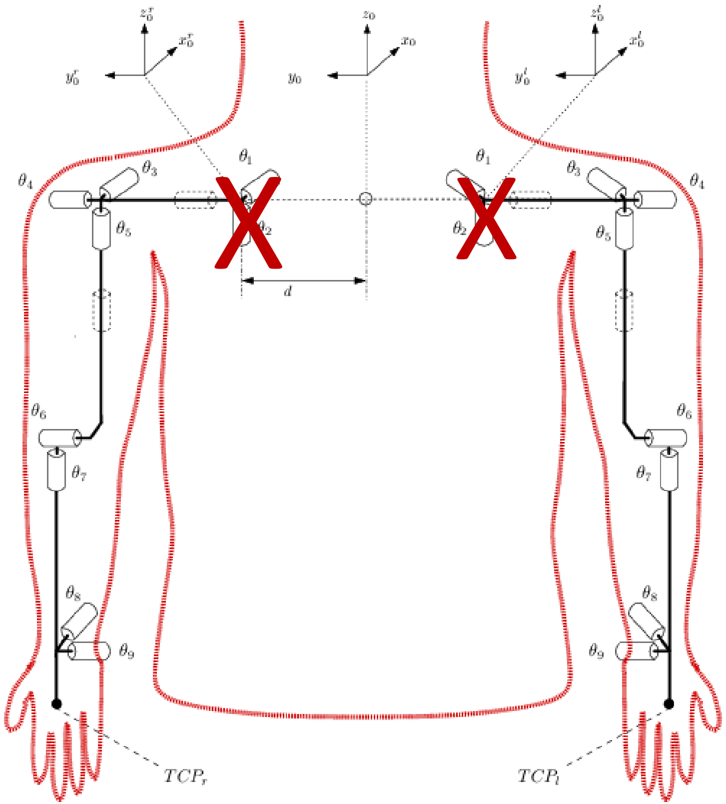
ARMAR-I: Kinematic Model (First Prototype)



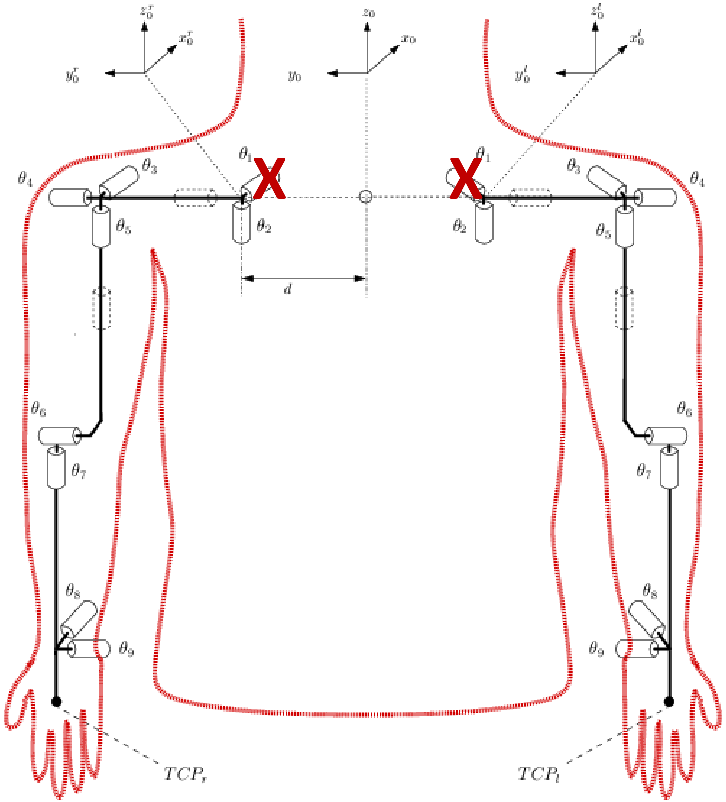
Joint		Motion Range
shoulder	θ_1	-45 ... 135
	θ_2	-90 ... 90
upperarm	θ_3	-160 ... 160
elbow	θ_4	0 ... 140
forearm	θ_5	-160 ... 160
wrist	θ_6	-45 ... 45
	θ_7	-45 ... 45



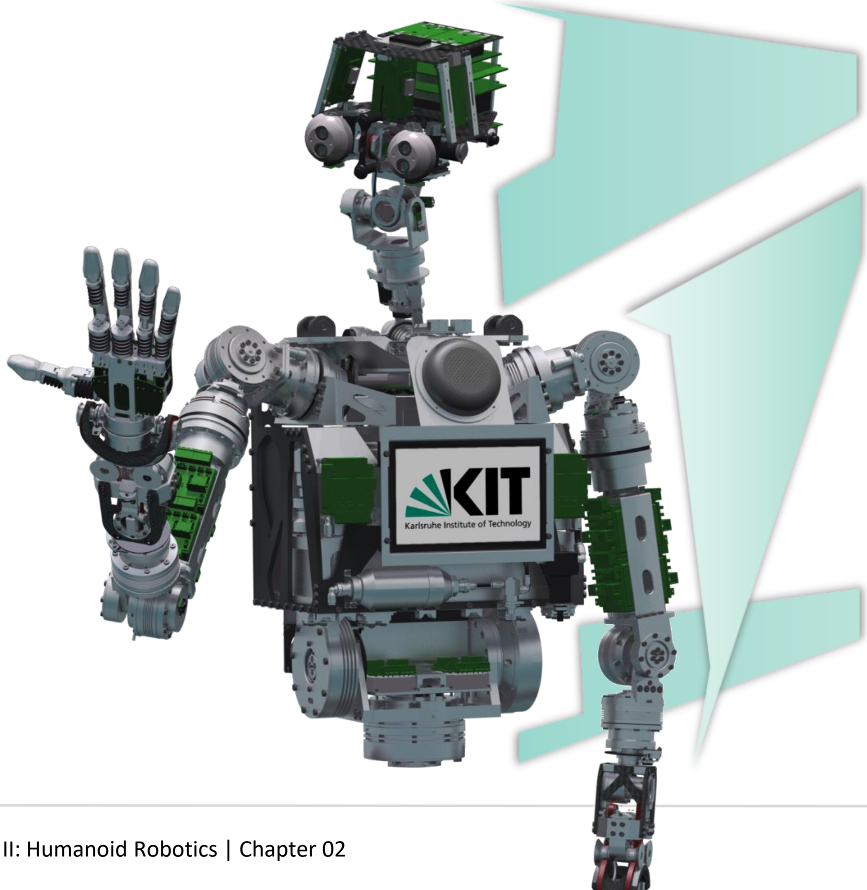
ARMAR-III: Kinematic Model



ARMAR-4: Kinematic Model



ARMAR-4: Upper Body

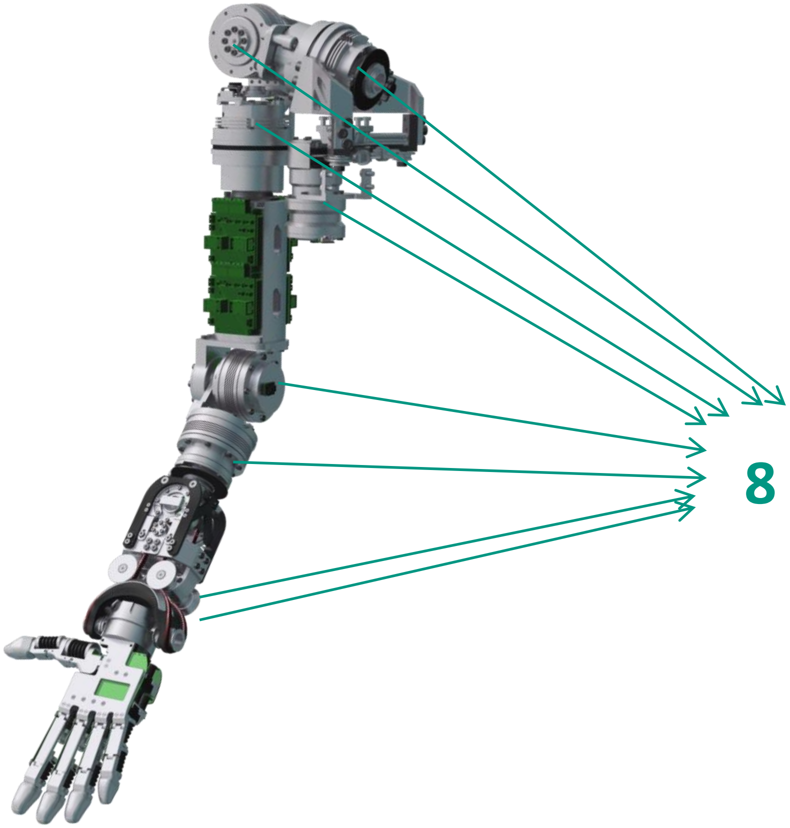


9 Degrees of Freedom

8 Degrees of Freedom

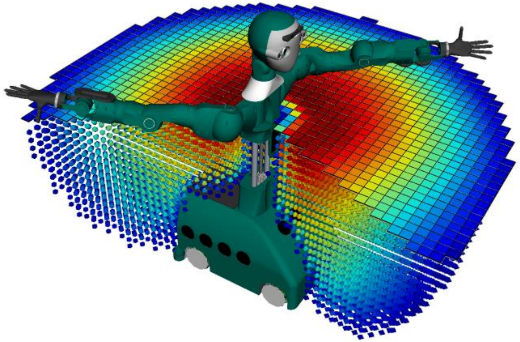
2 Degrees of Freedom

ARMAR-4: Arms



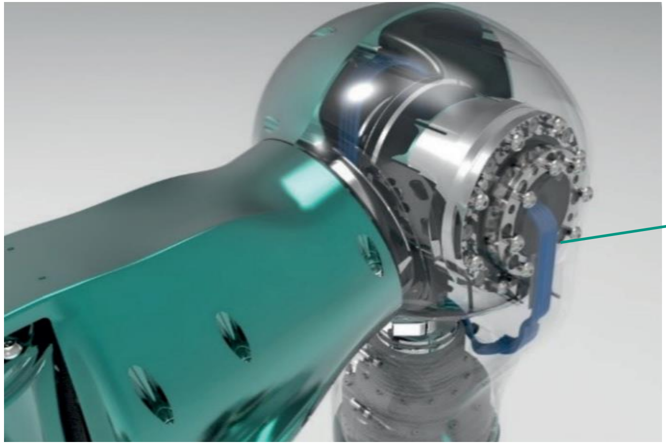
8 DoF

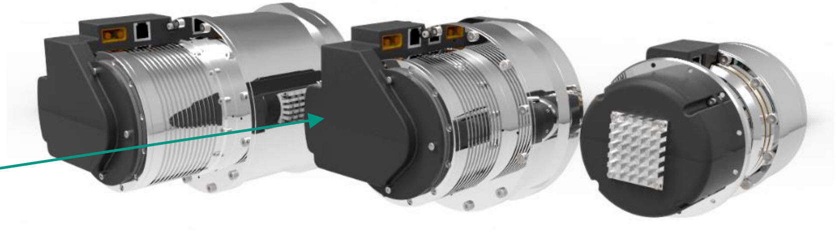
ARMAR-6: Dual-Arm System



- 8 DoF (each arm)
  - 4 Shoulder
  - 2 Elbow
  - 2 Wrist
- Continuous joint rotation
- Reach: 1.3 meters
- Payload: 10 - 12 kg

ARMAR-6: Arms



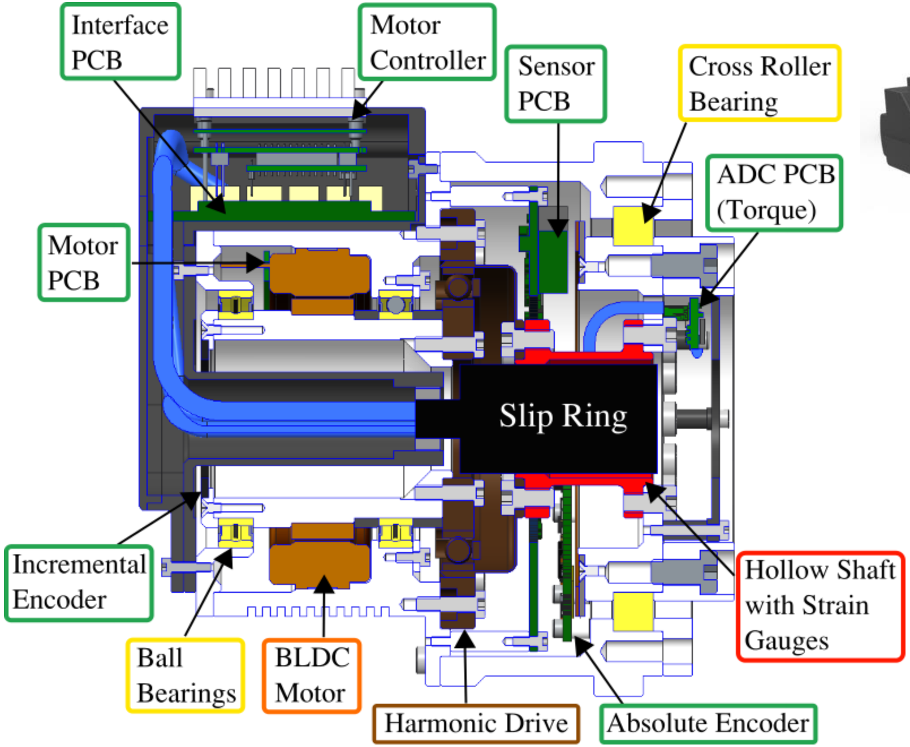


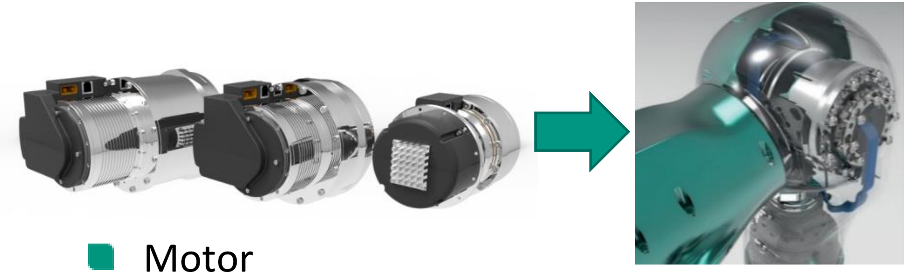
- **Arm**
  - 8 DoF (each)
    - 4 Shoulder, 2 Elbow, 2 Wrist
  - Continuous rotation
- **Hands**
  - Underactuated (2 Motors)
  - 14 DoF

ARMAR-6: Sensor-Actuator-Controller (SAC) Units

Humanoid Robot

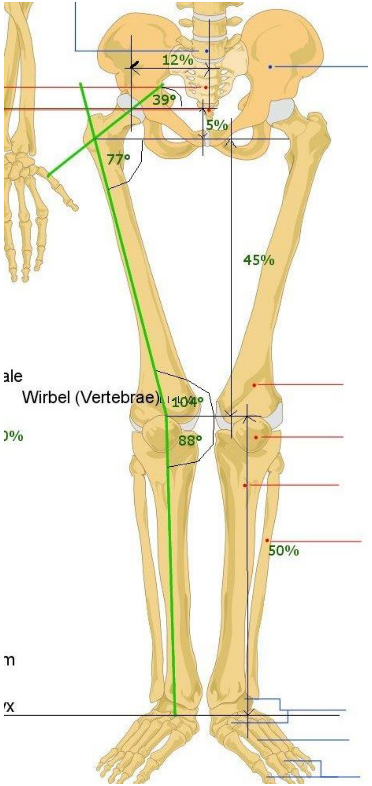
ARMAR-6: SAC Units: Subcomponents



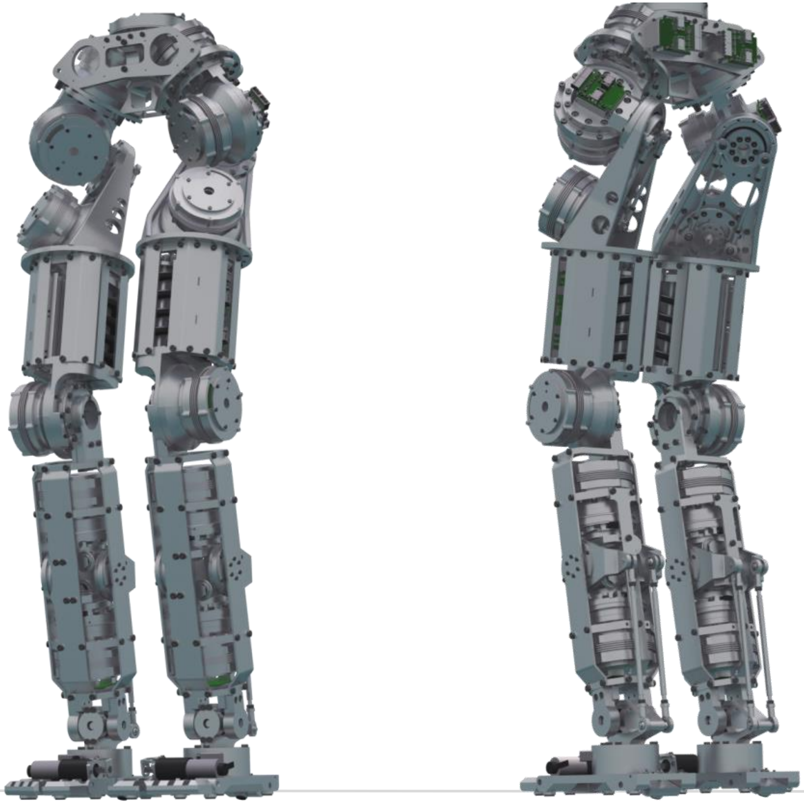


- Motor
- Gearbox (Harmonic Drive)
- Sensors
  - Torque
  - Position
    - Incremental
    - Absolute
  - IMU
  - Temperature (x5)
- **Control & communication electronics**
- Slip ring (continuous rotation)

ARMAR-4: Legs

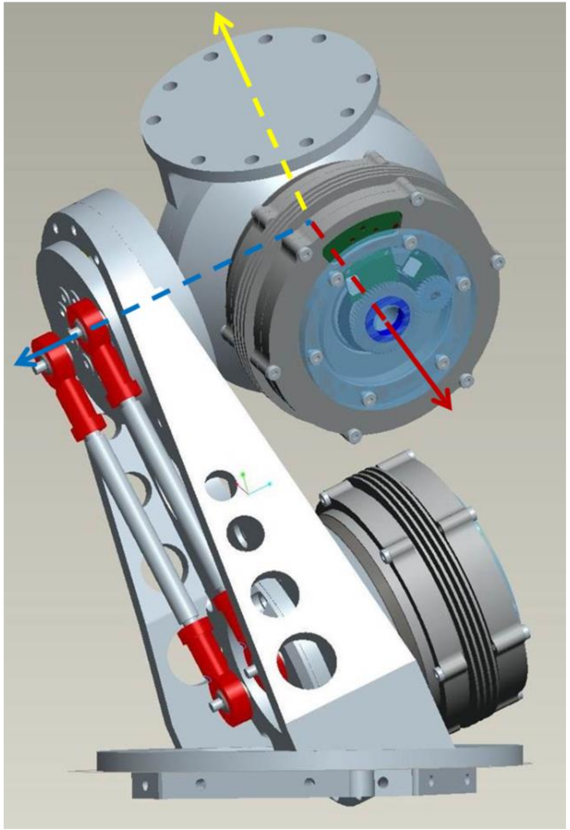


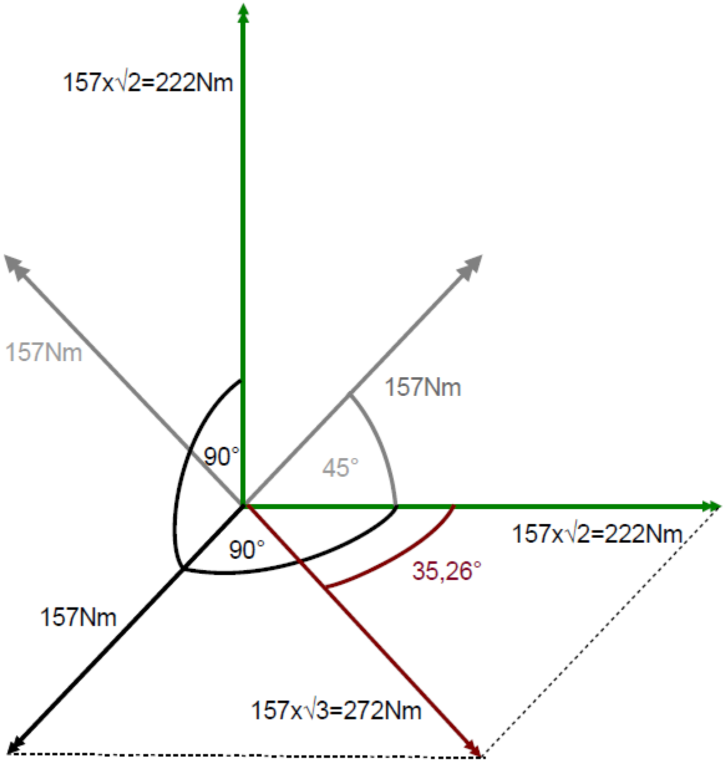
ARMAR-4: Legs



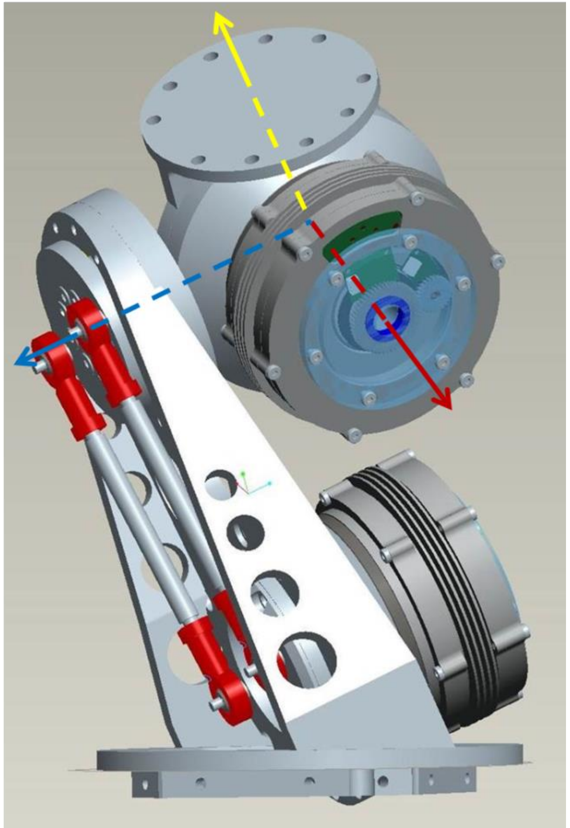
- **Legs**
  - 7 DoF
  - Energy storage in the knees by use of two springs
  - Differential kinematics in hip and ankle-joint
  - Uniform driving units in all joints with only 11 mechanical parts → Cost-reduction
  - Topology optimized hip
  - Weight per driving unit: 1300 g

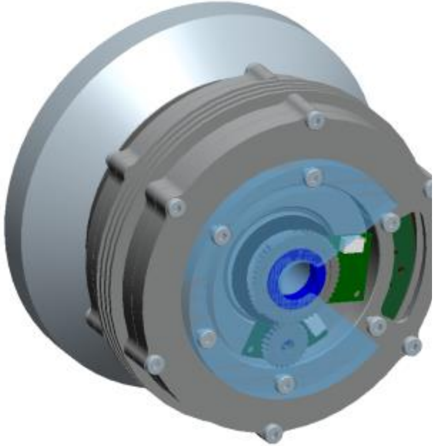
ARMAR-4: Hip Kinematics

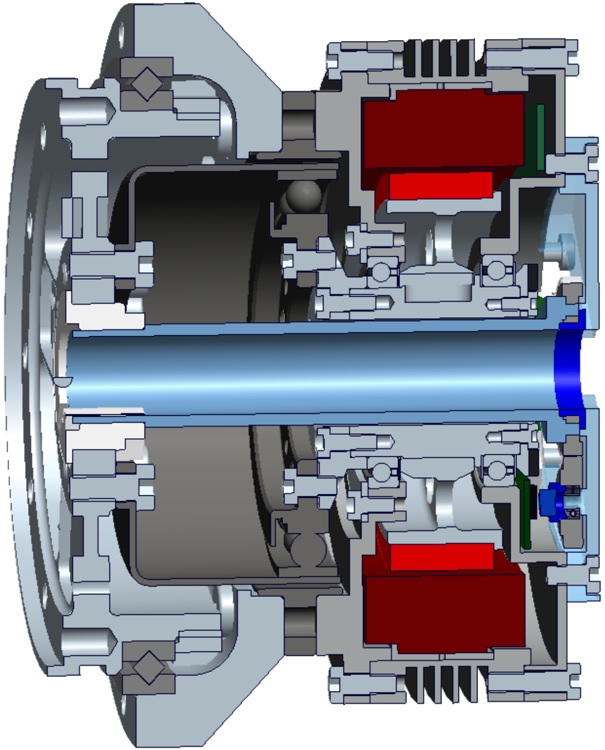




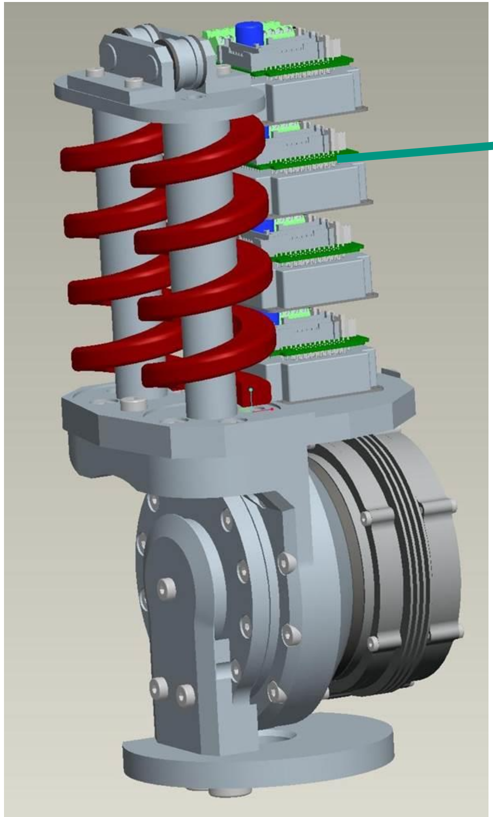
ARMAR-4: Hip / Upper Leg

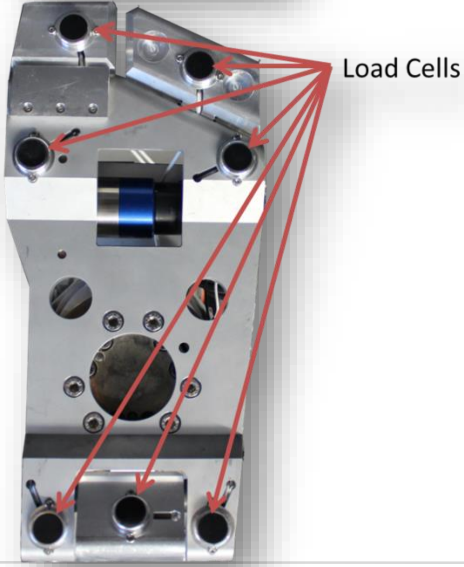






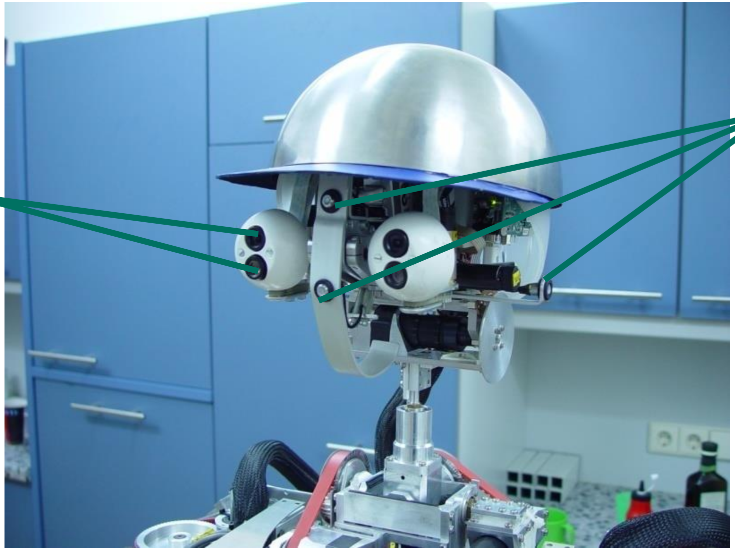
ARMAR-4: Knee / Lower Leg





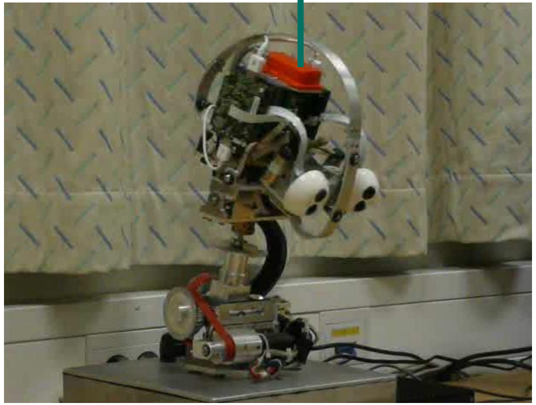
Karlsruhe Humanoid Head

Two cameras per eye
- wide-angle lens for peripheral vision
- narrow-angle lens for foveated vision



Six microphones and six channel microphone pre-amplifier with integrated phantom power supply

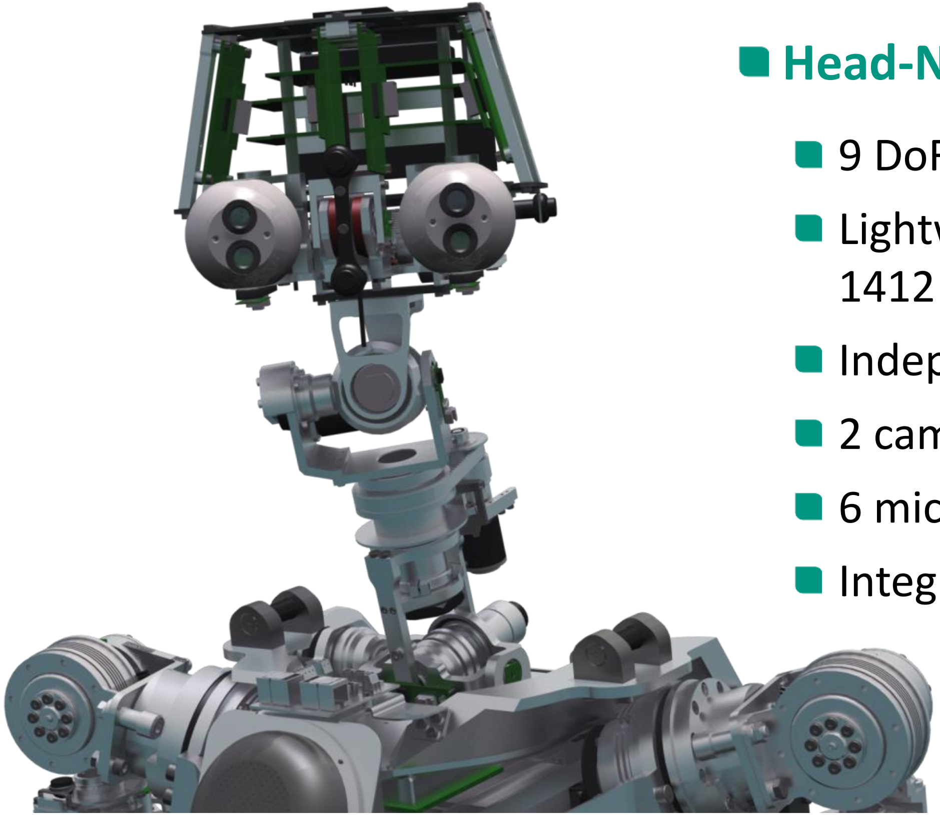
6D inertial sensor



7 DoF: 4 DoF neck and 3 DoF eyes

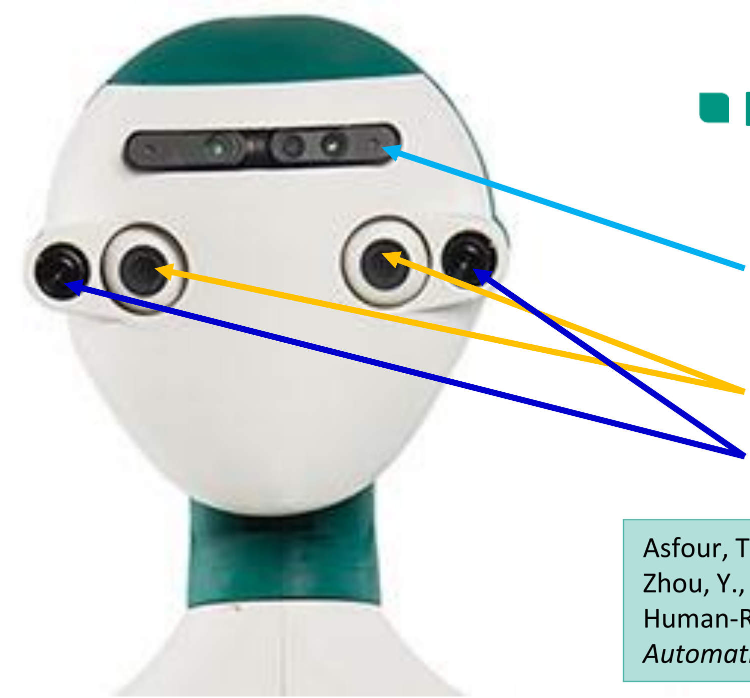
T. Asfour, K. Welke, P. Azad, A. Ude, R. Dillmann, **The Karlsruhe Humanoid Head**. In IEEE-RAS International Conference on Humanoid Robots, 2008

ARMAR-4: Head-Neck



- **Head-Neck**
  - 9 DoF
  - Lightweight design (weight of mechanics: 1412 g)
  - Independent eye pan/tilt movements
  - 2 cameras in each eyes
  - 6 microphones
  - Integrated computing power

ARMAR-6: Head-Neck

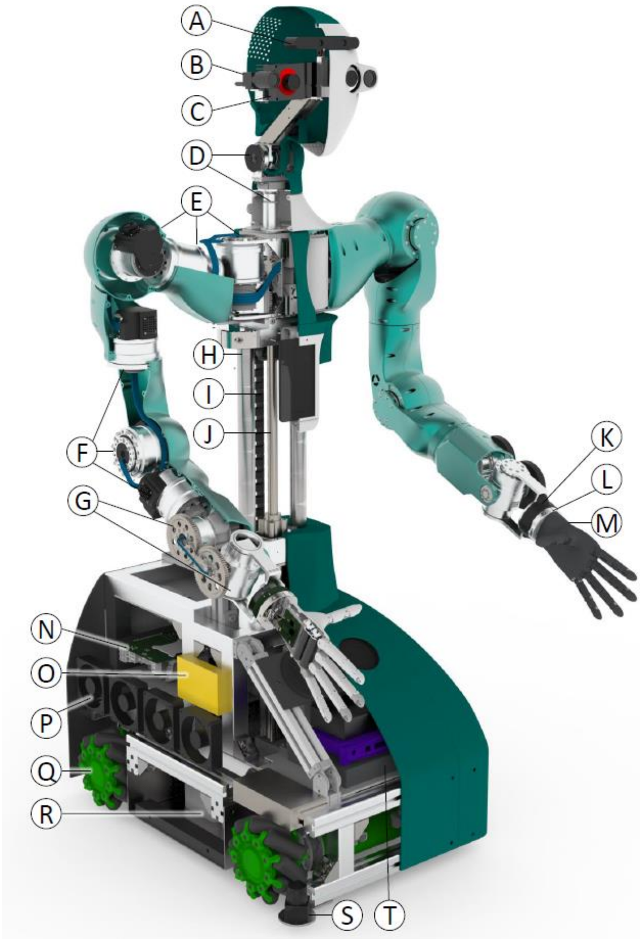


- **Head**
  - 2 DoF Neck
  - Primesense camera (RGB-D: Red Green Blue and Depth)
  - Roboception stereo camera system
  - Point Grey RGB USB stereo camera system

Asfour, T., Wächter, M., Kaul, L., Rader, S., Weiner, P., Ottenhaus, S., Grimm, R., Zhou, Y., Grotz, M. and Paus, F., „ARMAR-6: A High-Performance Humanoid for Human-Robot Collaboration in Real World Scenarios", *IEEE Robotics & Automation Magazine*, vol. 26, no. 4, pp. 108-121 (2019)

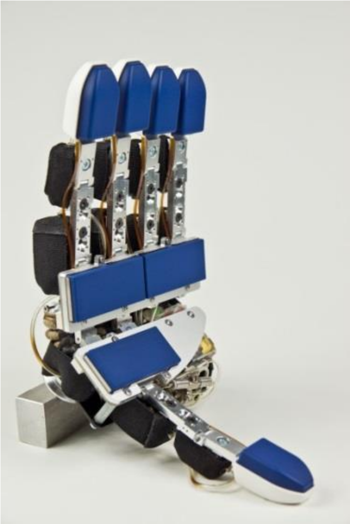
ARMAR-6: Overview

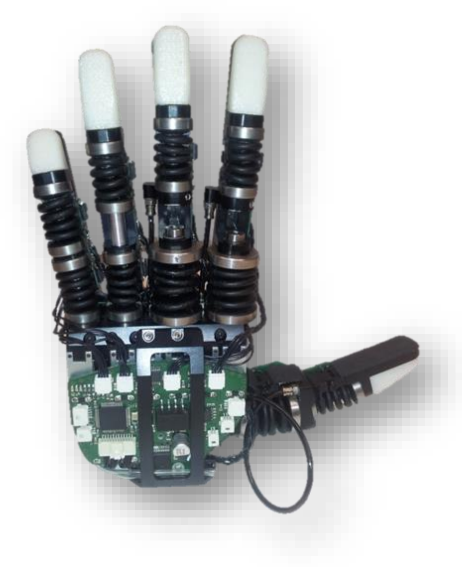
- (A) RGB-D Sensor
- (B) Stereo Vision System
- (C) Roboception
- (D) SAC Unit Neck (2)
- (E) SAC Unit Size L (2x3)
- (F) SAC Unit Size M (2x3)
- (G) SAC Unit Size S (2x2)
- (H) Linear Guide (2)
- (I) Energy Chain
- (J) Spindle Drive



- (K) 6D F/T Sensor (2)
- (L) Hand Adapter (2)
- (M) Five-Finger Hand (2)
- (N) 4 PC with GPU
- (O) Remote Emergency Stop
- (P) Cooling System
- (Q) Mecanum Wheel (4)
- (R) Battery Pack
- (S) Laser Scanner (2)
- (T) Sound System

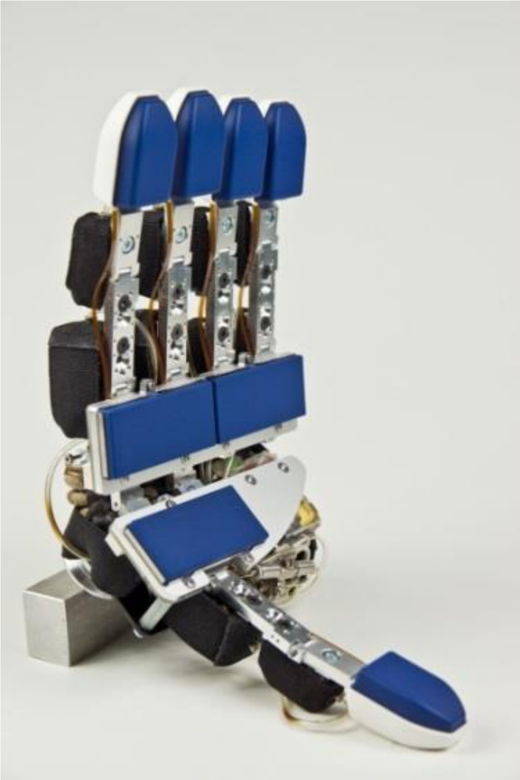
Hands





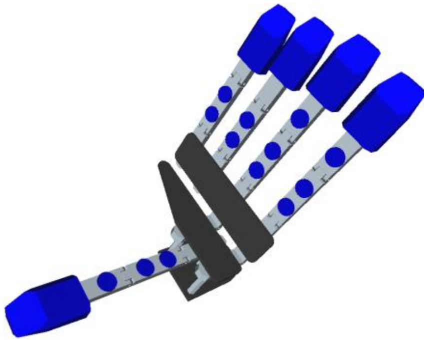
ARMAR-III: Hands (Version 2013)

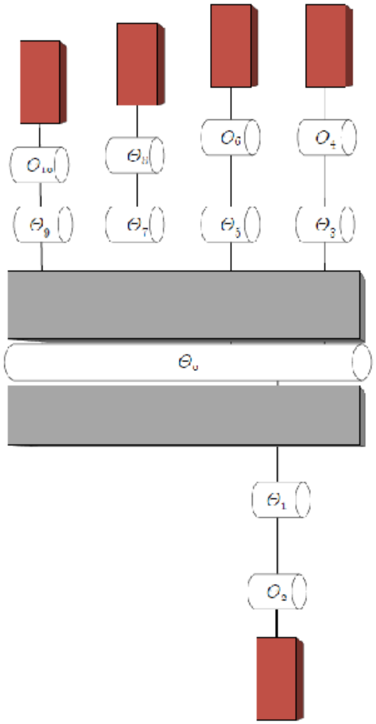
- New tactile sensor system
- 3 sensors in the palm
  - Tactile sensing matrix with 6x14 cells
- Novel sensor for each fingertip
  - Tactile sensing matrix 4x8 sensor cells
  - Curved surface
- 12 bit sensor signal resolution
- Spatial resolution of 3.8 mm
  - Enhances tactile pressure profiles with a high spatial accuracy
- Integrated signal processor
- USB Interface



ARMAR-III: Hands

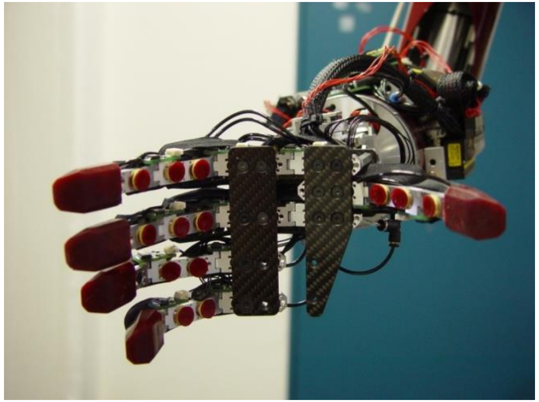
- **8 independent Degrees of Freedom**
  - 2 DoF per finger
    - For index, middle, thumb
  - 1 DoF in the palm
  - 1 DoF shared by pinkie and ring finger
- **Direct Kinematics**
- **Inverse Kinematics**
  - Virtual Model Control
  - Using a Physical simulation model (IPSA)
  - Compute velocity vectors from the difference between attractors and fingertip positions
  - Use simulated movements for the real hand
- Developed by **Stefan Schulz** and **Georg Bretthauer**





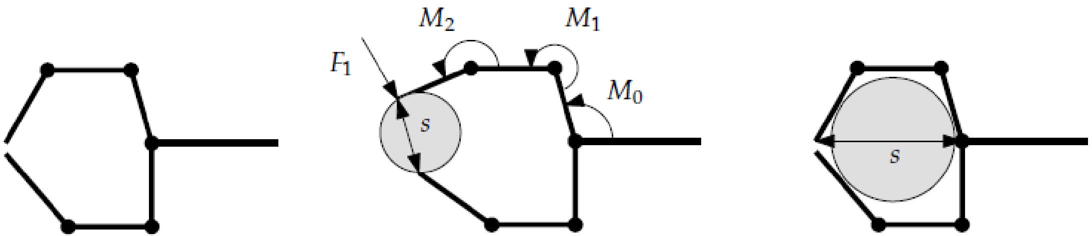
Karlsruhe 5-Finger Hand

- Carbon and aluminium structure
- **Fluid actuators**
  - Located directly at the joints
  - Pneumatically actuated
- Joint sensors
  - Located directly at the joints
  - Absolute joint angles
- Force position control
  - For arbitrary joint configurations
  - Not limited to a predefined set of hand preshapes
- Developed by **Dr. Stefan Schulz** **and** **Prof. Georg Bretthauer**



Contact Detection and Grasp Verification

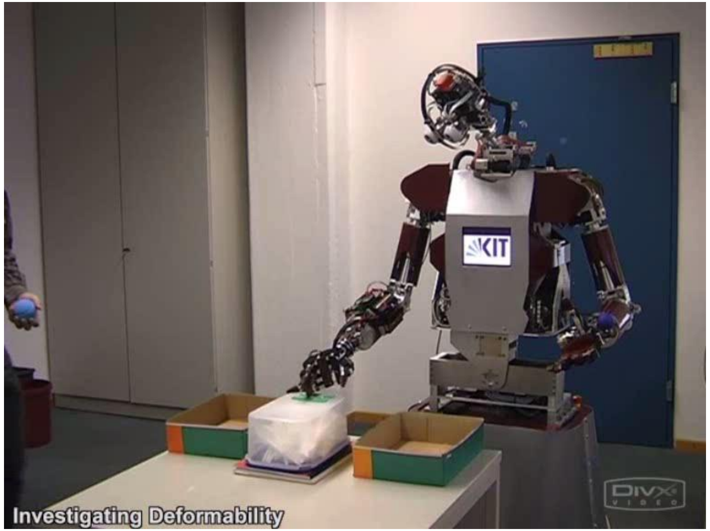
- **Contact Detection** using **joint torques**
  - Compute weighted sum of finger joint torques
  - Contact is detected when a threshold is surpassed
- **Object grasped successfully?**
  - Calculate distances:
    - between different fingertips (for precision grasps)
    - between fingertips and the palm (for power grasps)



Detection of Deformability

Deformable Objects can be detected:

- Grasp an object
- Verify that the grasp was successful
- Increase the joint torques
- Determine distances between the fingertips
  - Decreased distances indicate a deformable object

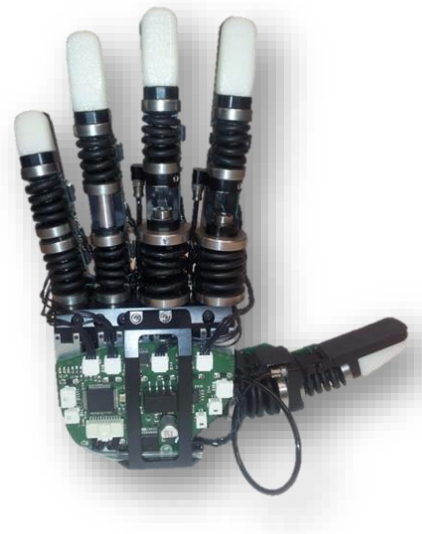


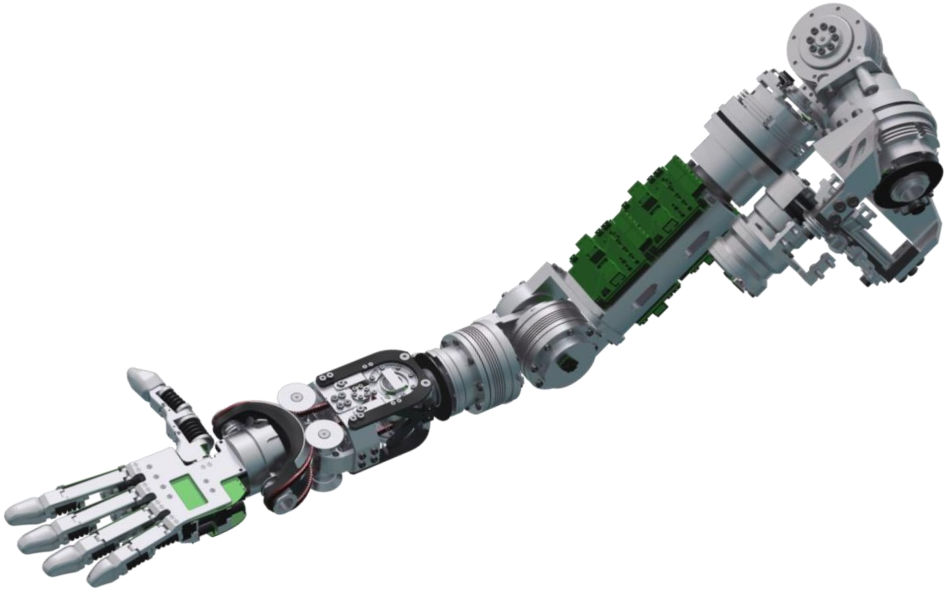
Verification of object deformability

A. Bierbaum, J. Schill, T. Asfour and R. Dillmann, "Force Position Control for a Pneumatic Anthropomorphic Hand", *International Conference on Humanoid Robots* (2009)

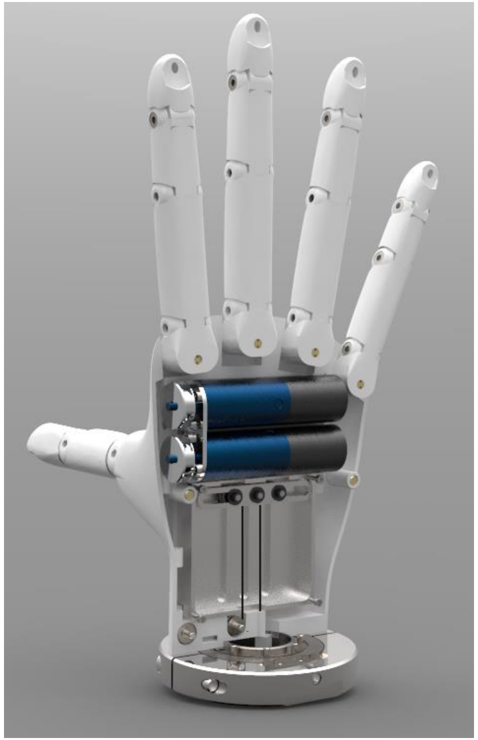
ARMAR-4: Hands

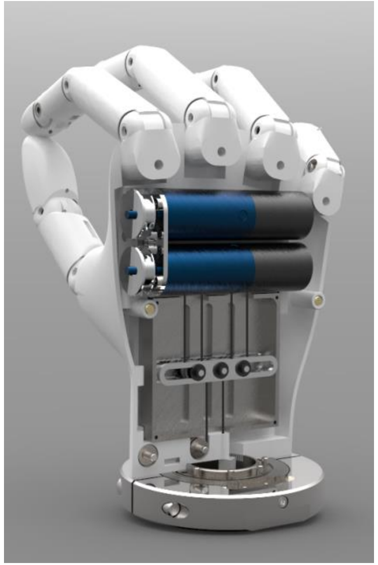
- 11 DoF
- Anthropomorphic 5-finger hand
- Bi-directional pneumatic actuators
- Integrated valves, angel- and pressure-sensors and electronic





ARMAR-6: Hands





- **Hands**
  - Underactuated (2 Motors)
  - 14 DoF

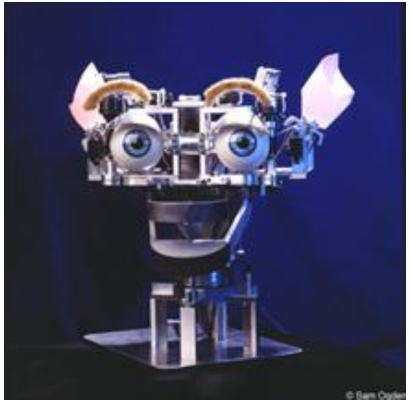
KIT Prosthetic Hand

- Cheap fabrication because of 3D prints
- 2 sizes:
  - 50. percentile male
  - 50. percentile female
- Underactuated (2 motors)
- Camera system in the palm allows object specific pregrasps
- Sensorized fingertips

KIT Prosthetic Hand

Neck and head

Other examples

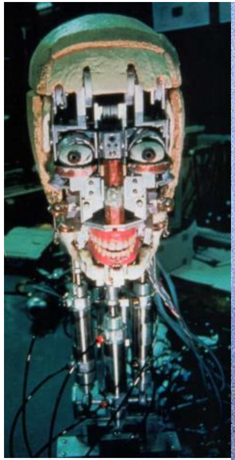


Kismet (MIT, USA)

Emotion expression: quiet, angry, sad, happy, surprise, displeasure, …

Roberta (Science University of Tokyo, Japan)

Emotion expression: sad, angry, happy, fear, surprise, displeasure



MAVERic (USC, USA)

2 cameras in each eye, saccadic eye movements

HRP-4C

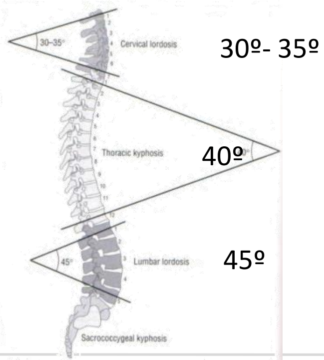
- HRP-4C (nicknamed Miim)
  - feminine-looking humanoid robot created by the National Institute of Advanced Industrial Science and Technology (AIST)

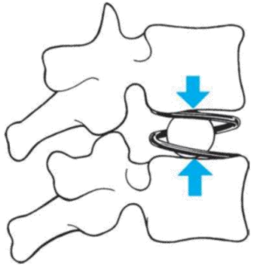
Joint name	DOF	Joint name	DOF
Eyebrows	1	Mouth	1
Eyelids	1	Upper lip	1
Eyeballs pan	1	Lower lip	1
Eyeballs tilt	1	Cheek	1
Total			8

Spine, legs and feet

The Spine (I): The Spine Structure

- 33 vertebrae
- Intervertebral disc (annulus fibrosus):
  - Resist compressive and torsional forces
  - Act as cushions to distribute stress (of increasing surface)
  - Vary size during daily activities, resulting in 15 to 25mm shorter column.
  - Flexible under low loads, stiff under high loads.
  - Mechanically, acts like a coil spring joining the vertebrae, and its nucleus acts as a ball bearing, where vertebrae roll over during flexion-extension



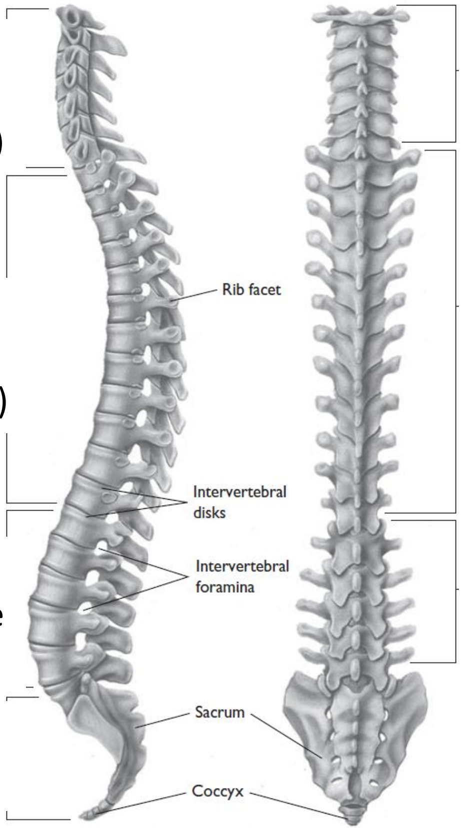


Cervical Vertebrae (C1, …, C7)

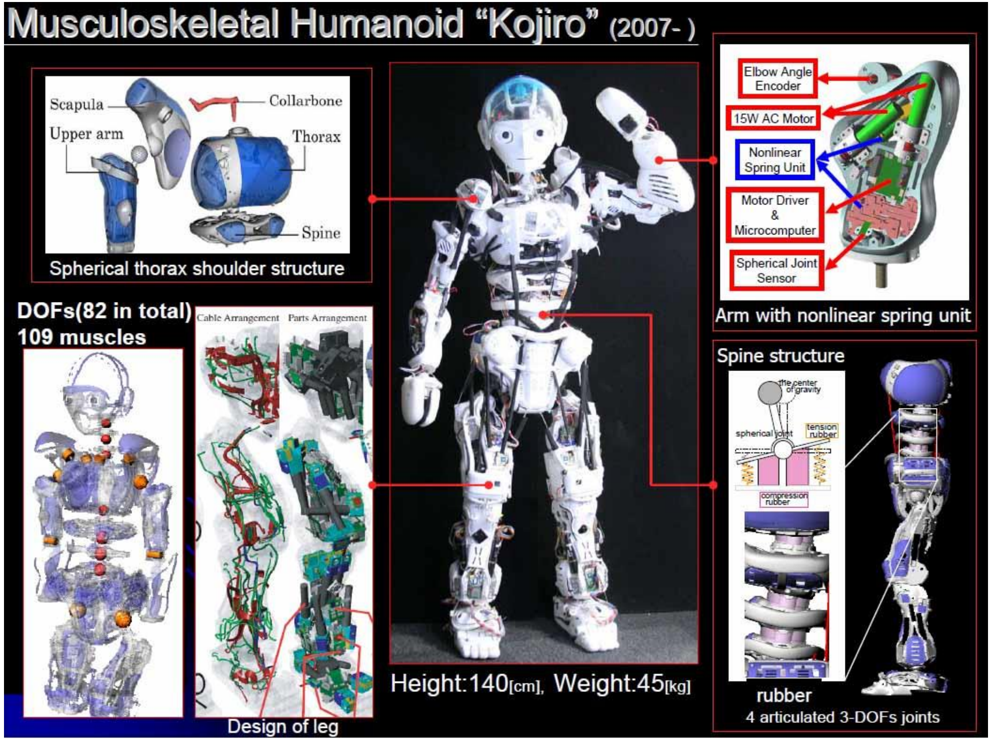
Thoracic Vertebrae (T1, …, T12)

Lumbar Vertebrae (L1 to L5)

Pelvic curvature



Shoulder-Arm in Kojiro

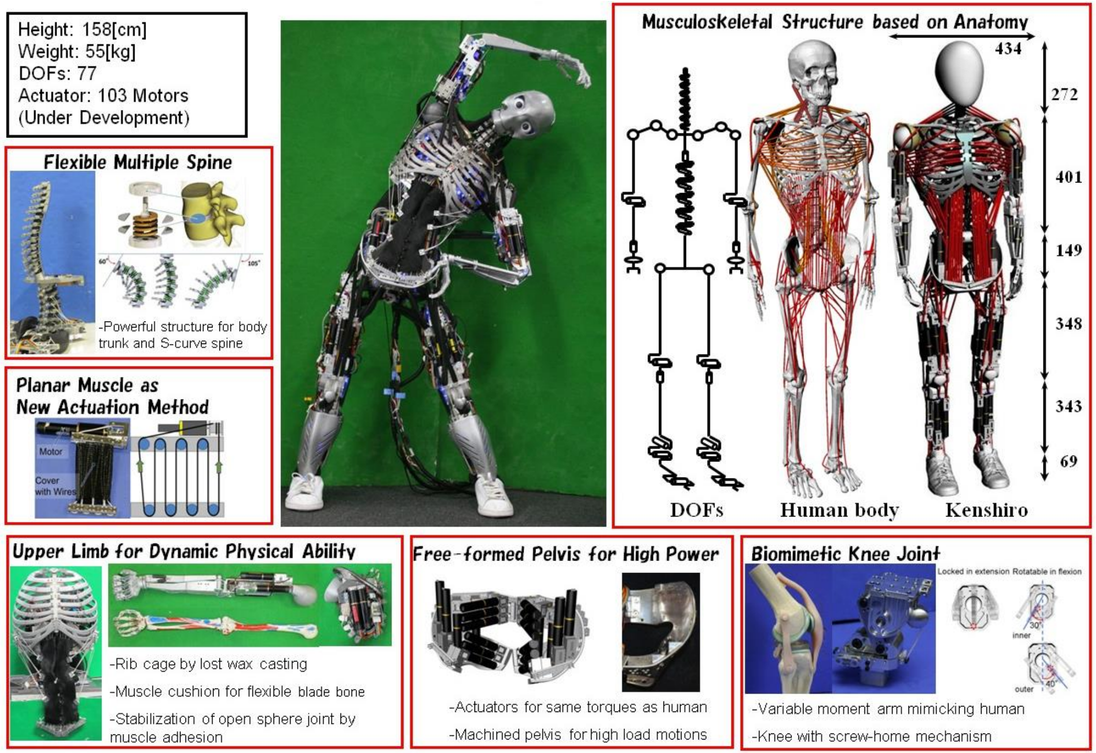


http://www.jsk.t-u-tokyo.ac.jp/~inaba/

University of Tokyo
Professor Masayuki Inaba

http://www.jsk.t.u-tokyo.ac.jp/~inaba/

Musculoskeletal Humanoid Kenshiro



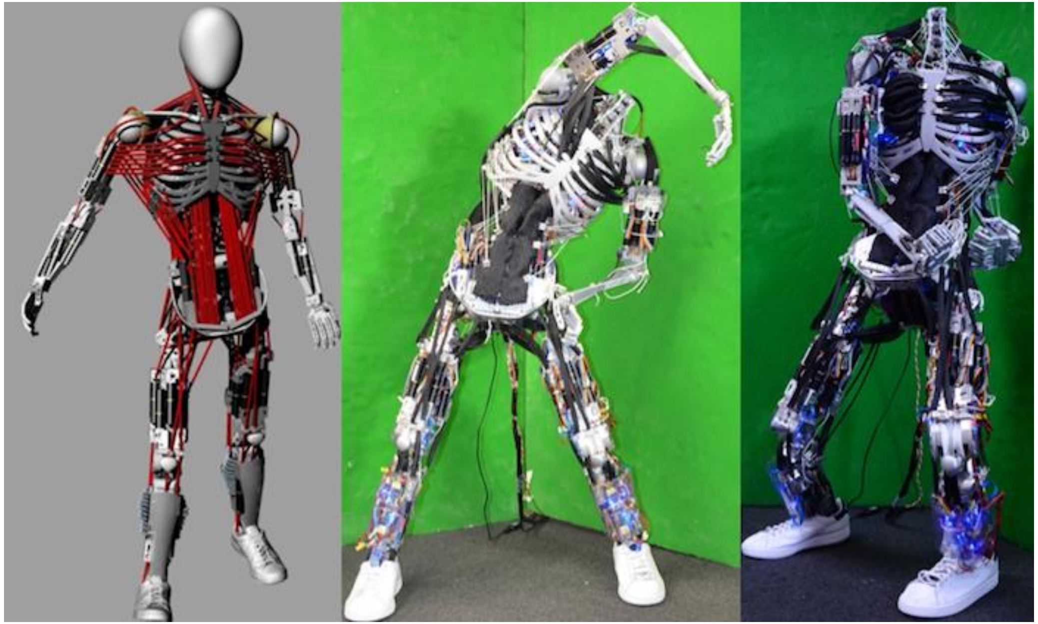
http://www.jsk.t.u-tokyo.ac.jp/research/kenshiro.html

University of Tokyo
Professor Masayuki Inaba

http://www.jsk.t.u-tokyo.ac.jp/~inaba/

Musculoskeletal Humanoid Kenshiro

- Kenshiro’s body mirrors almost all the major muscles in a human, with 160 pulley-like "muscles“, 50 in the legs, 76 in the trunk, 12 in the shoulder, and 22 in the neck.



Musculoskeletal Humanoid

Yuki Asano, Kei Okada and Masayuki Inaba, Design principles of a human mimetic humanoid: Humanoid platform to study human intelligence and internal body system, Science Robotics, 2017, https://robotics.sciencemag.org/content/2/13/eaaq0899

Chapter 2: Building Humanoids

- The history of humanoid robotics
- The DARPA Robotics Challenge
- Biomechanical models of the human body
- Mechatronics of humanoid robots