Karlsruhe Institute of Technology

H2T High Performance Humanoid Technologies

Engineering humanoids that grasp, learn from human and experience, and perceive time

Tamim Asfour

http://www.humanoids.kit.edu

Institute for Anthropomatics and Robotics, High Performance Humanoid Technologies

Karlsruhe Institute of Technology

High Performance Humanoid Technologies

On Dualities, Force and Time in Robotics

Tamim Asfour

http://www.humanoids.kit.edu

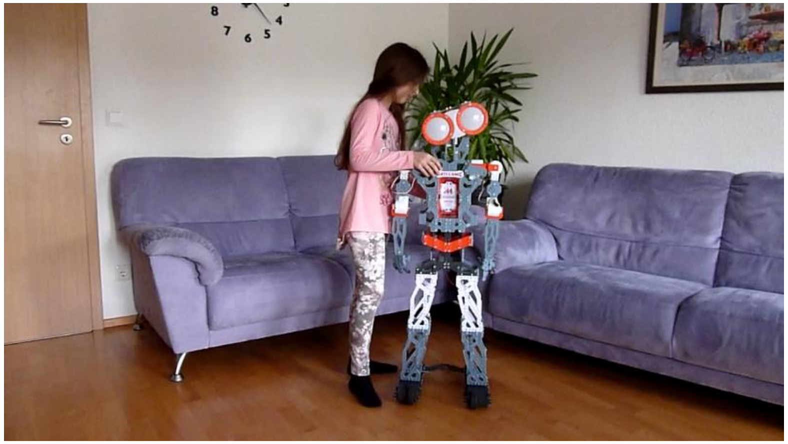
Institute for Anthropomatics and Robotics, High Performance Humanoid Technologies

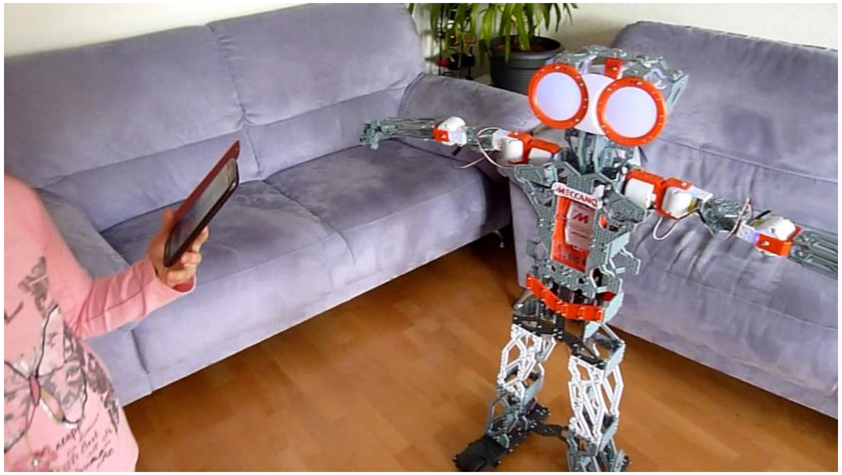
My team

Humanoids@KIT

Chiara‘s robot Tomy

- **Tomy:** 1200 parts , 7 motors, 250 EURO
- Tomy assembled by Chiara
- **Chiara:** 9 years old
- **Tomy's skills:** speech interface, kinesthetic teaching, annotating motions sequences via speech, control via smart phone, upper body tracking and imitation, … lots of fun!





Humanoids in the real world

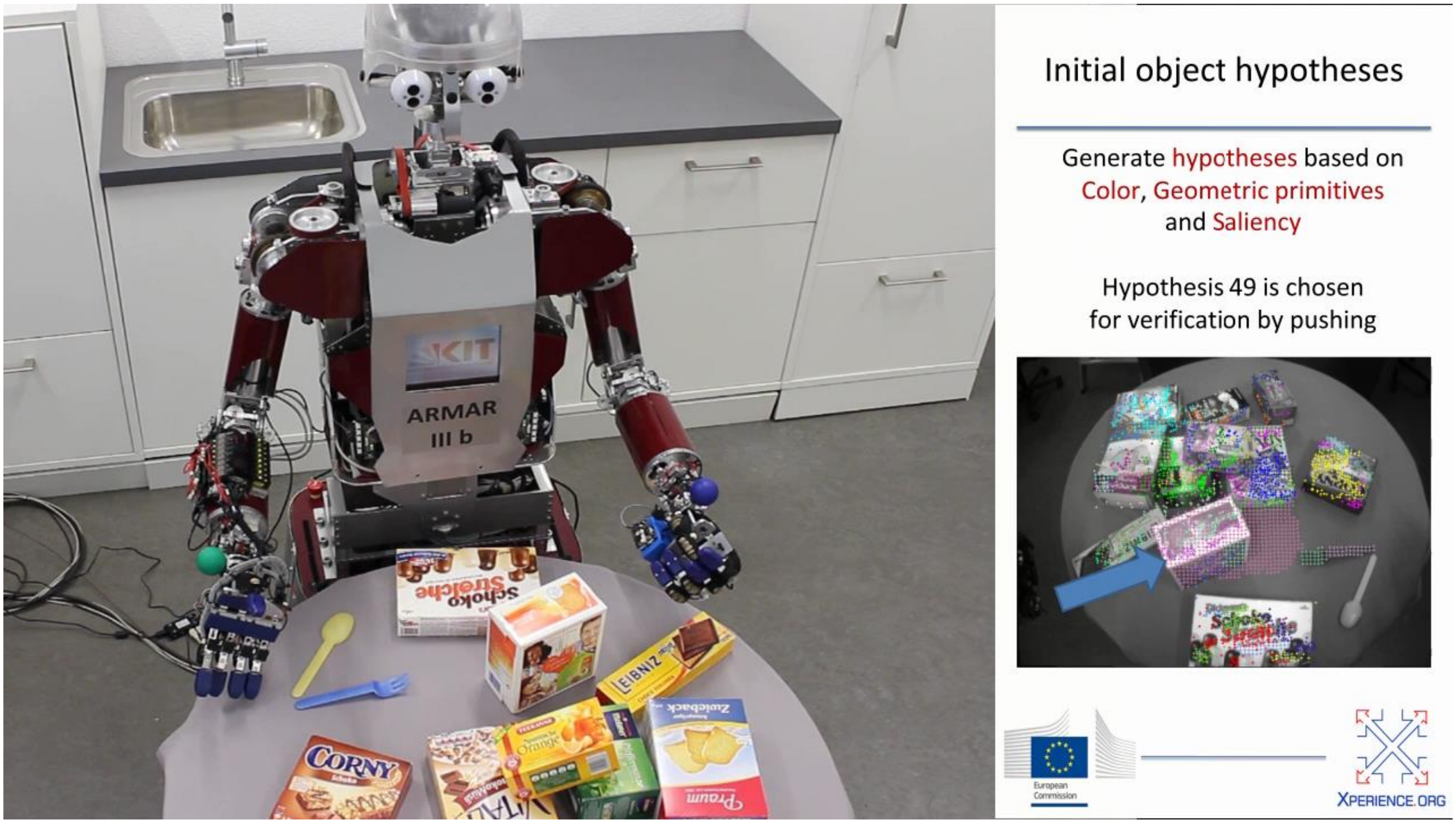
- Engineering Humanoids
- Grasping and manipulation
- Learning for human observation
- Natural Interaction and communication

© SFB 588

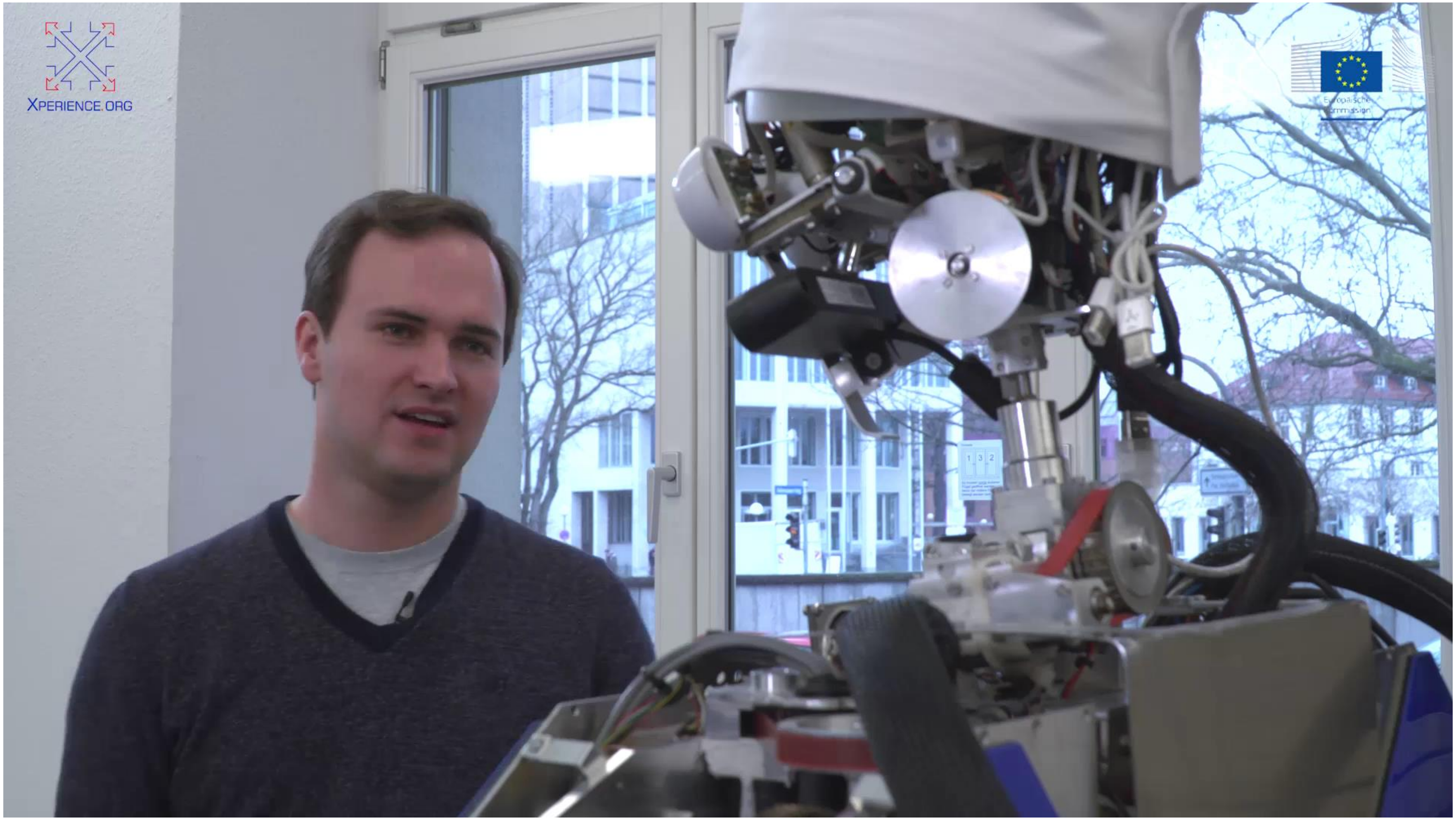
ARMAR-III in the RoboKITchen

45 minutes, more than 2000 times since February 3, 2008

Combining action, vision and haptics for grasping

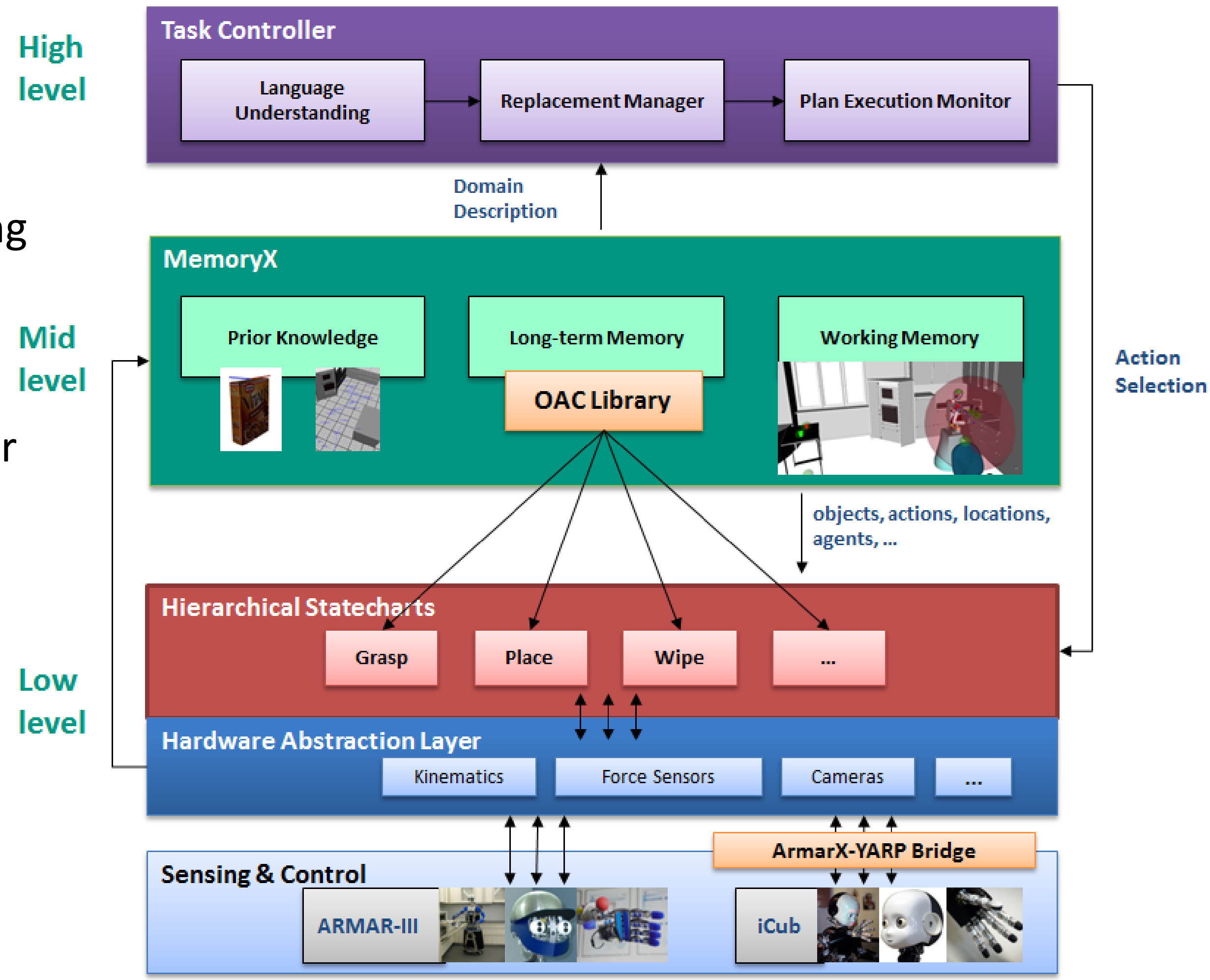


Integrating language, planning and execution with OACs



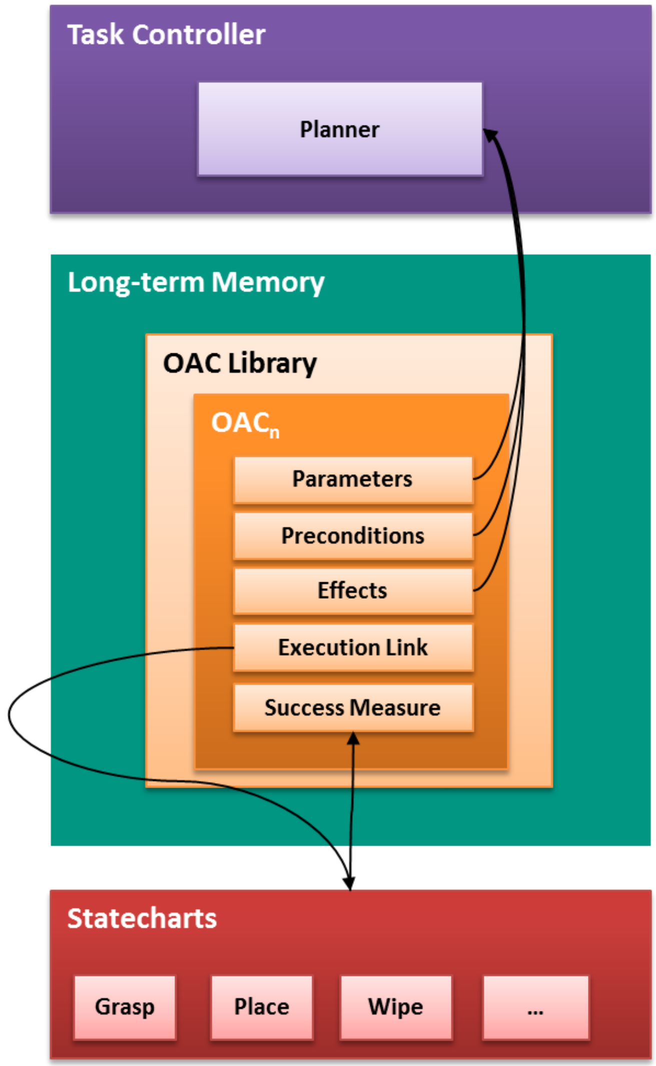
The ARMAR Architecture (inspired by Xperience)

- **High-level:**
  - Natural language understanding, reasoning and planning
- **Mid-Level:**
  - MemoryX: mediator between sensorimotor data and symbolic knowledge
- **Low-Level:**
  - Execution
  - Hardware Abstraction Layer (HAL)
  - ArmarX-YARP bridge

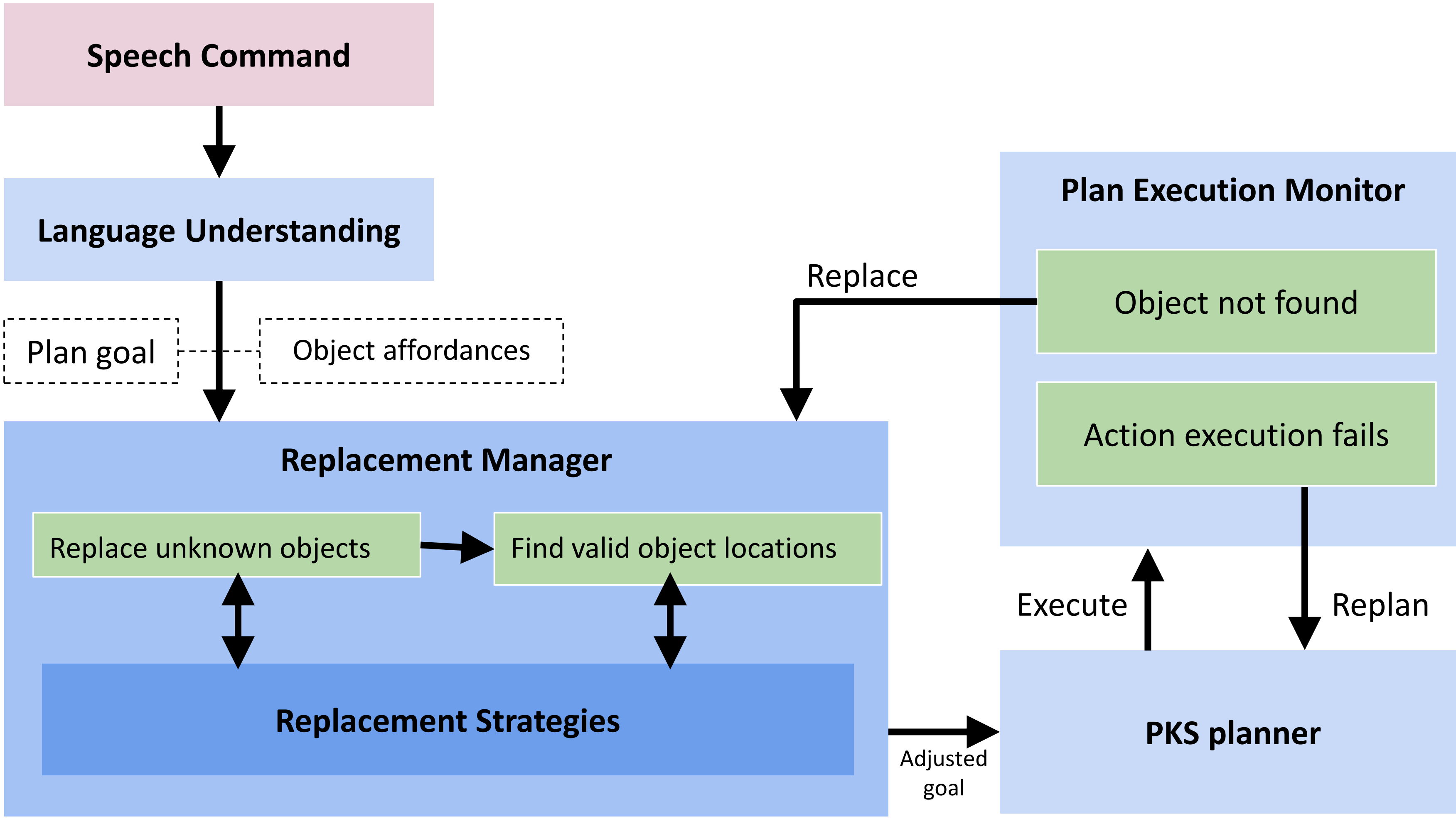


Task execution with OACs

- OAC library as part of long-term memory
- Each OAC consist of
  - ID
  - Specific parameters
  - Preconditions for planning
  - Effects
  - Link to a hierarchical statechart
  - statistics about execution
- Instantiated OACs in the working memory for the current task



NLU, Planning and Bootstrapping mechanisms

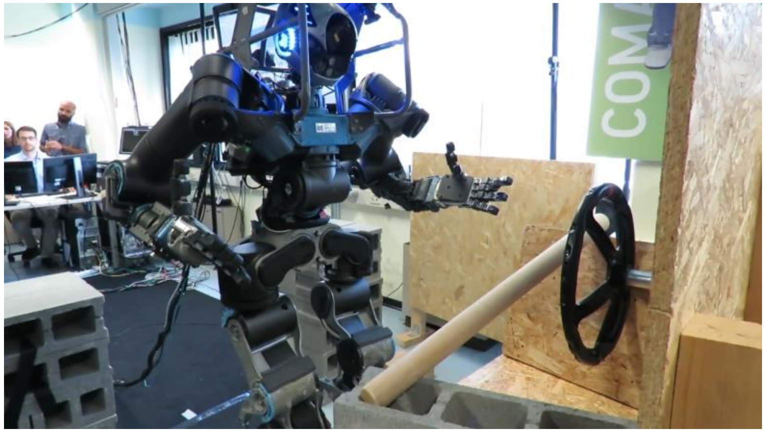
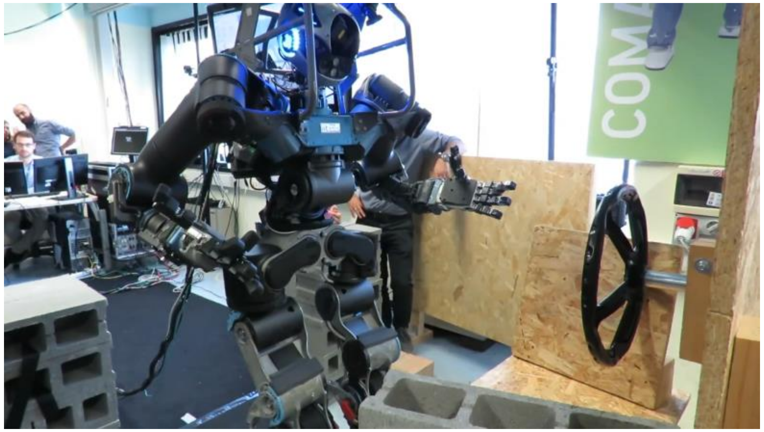
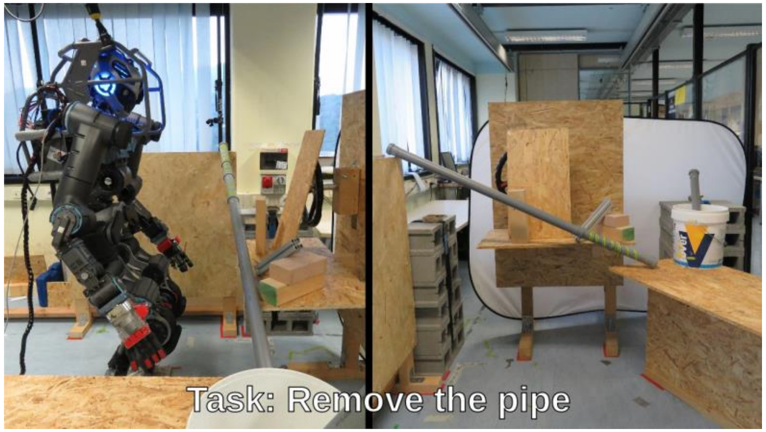


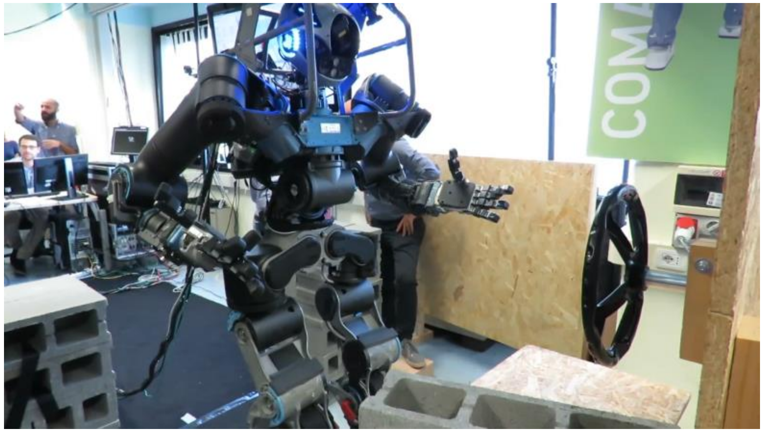
The ArmarX Software

- Event-driven component-based robot software development environment
- Open Source robot software development environment
- Code and documentation
  - Source code: https://gitlab.com/ArmarX
  - Documentation: https://armarx.humanoids.kit.edu

Loco-manipulation tasks on WALK-MAN

- Semi-public demo at project review
- MultiSense SL **stereo camera**

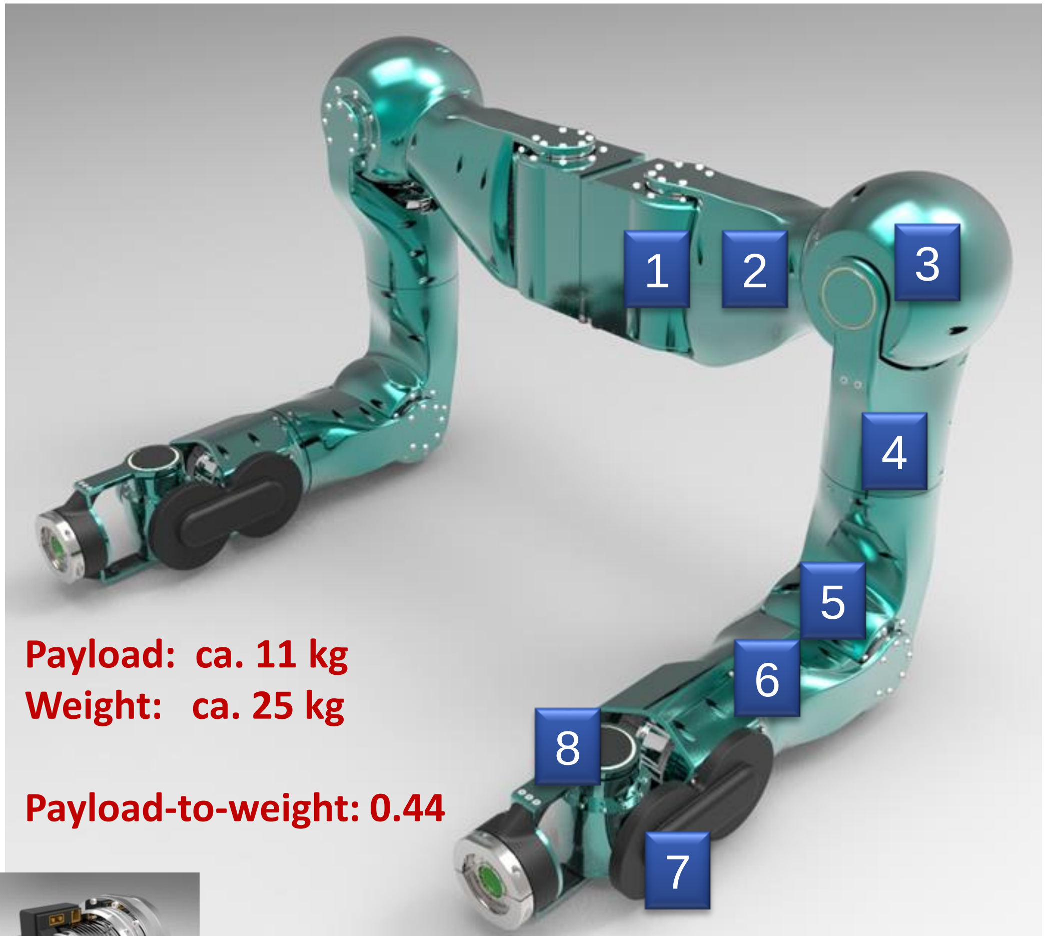






What‘s next?

- **SecondHands: A robot assistant for industrial maintenance**
  - 5 years project in Horizon 2020 (2015 – 2020)
  - Ocado, KIT, Sapienza, EPFL, UCL
- Provide help to maintenance technicians in a warehouse environment
- Advancement in the automation of the relatively unexplored domain of production machine maintenance
- Reduction of production machinery maintenance costs

ARMAR robot technologies in warehouses

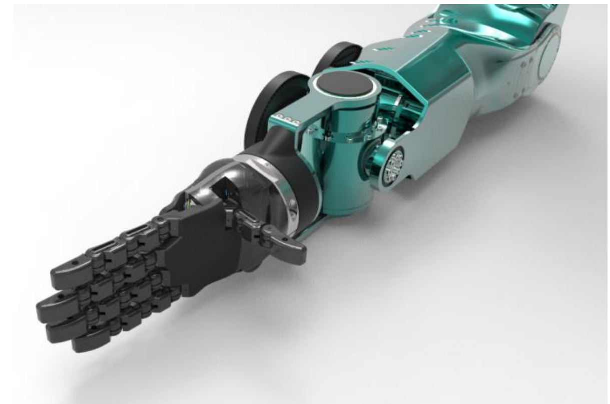


Payload: ca. 11 kg
Weight: ca. 25 kg

Payload-to-weight: 0.44

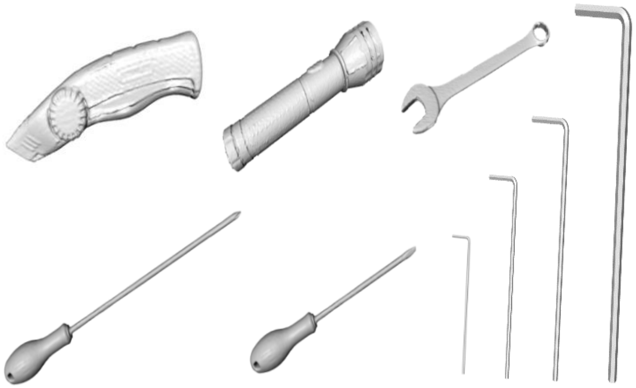
Joint	Max. Torque	speed
1	176 Nm	79°/s
2	176 Nm	79°/s
3	176 Nm	79°/s
4	100 Nm	132°/s
5	100 Nm	132°/s
6	100 Nm*	132°/s
7	34 Nm	206°/s
8	34 Nm	206°/s

ARMAR robot technologies in warehouses

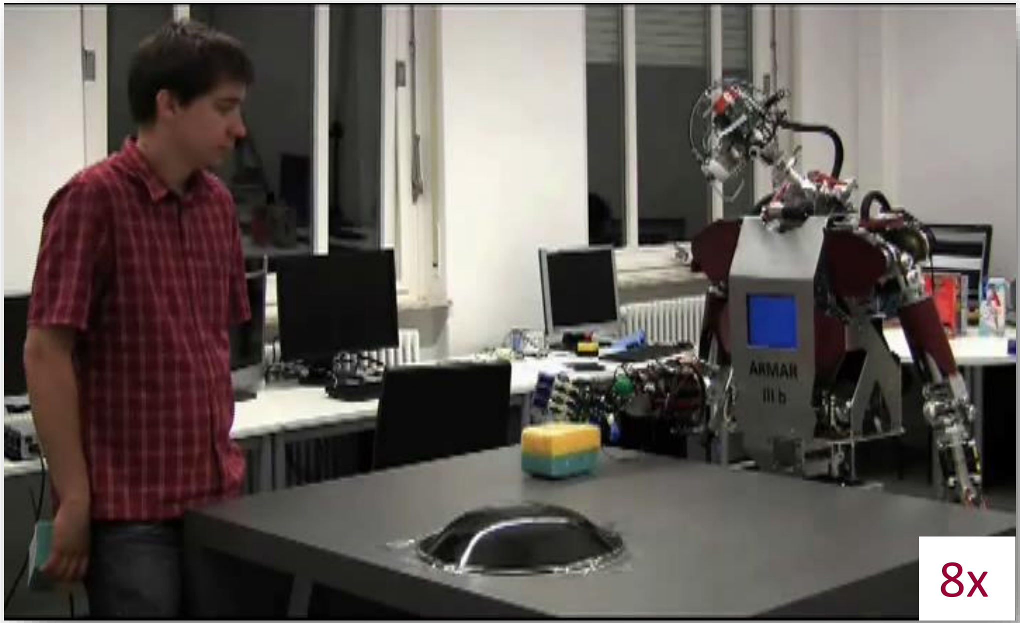


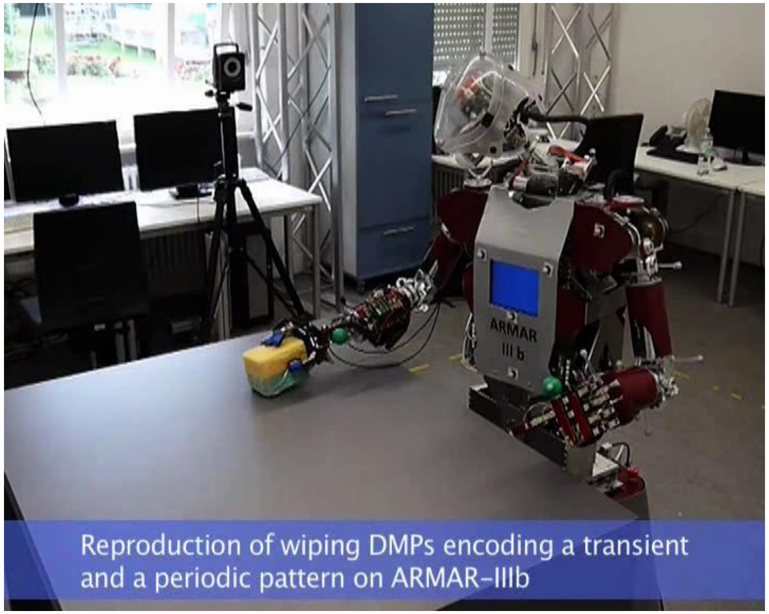
Maintenance objects/tools

- Object/tools models
  - AllanKey.xml
  - AllanKey2.xml
  - AllanKey3.xml
  - Cutter.xml
  - Flashlight.xml
  - Screwdriver-Red-smaller.xml
  - Screwdriver-cross.xml
  - Wrench.xml
  - Pliers.xml
  - …
- See KIT object database
  http://object-database.humanoids.kit.edu



Learning from human observation



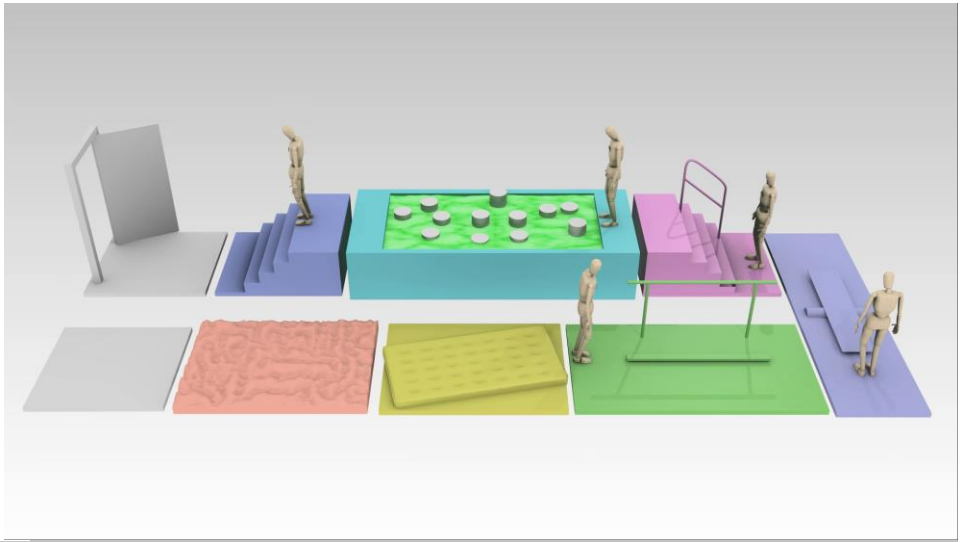


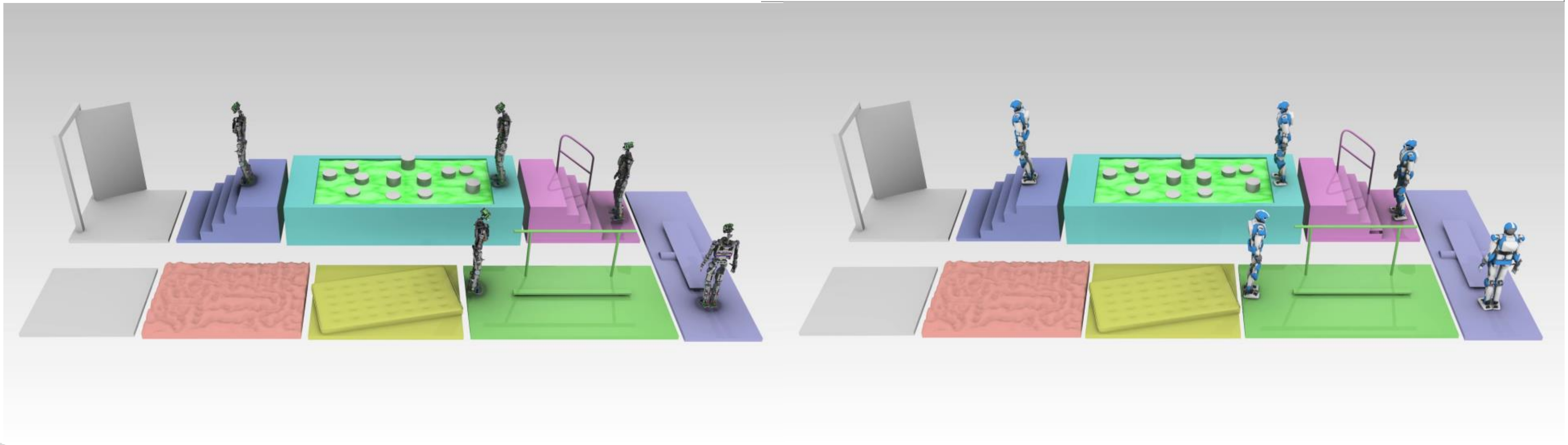
Learning from observation – prepare the dough

KIT whole-body human motion database

https://motion-database.humanoids.kit.edu/

The KIT whole-body human motion database





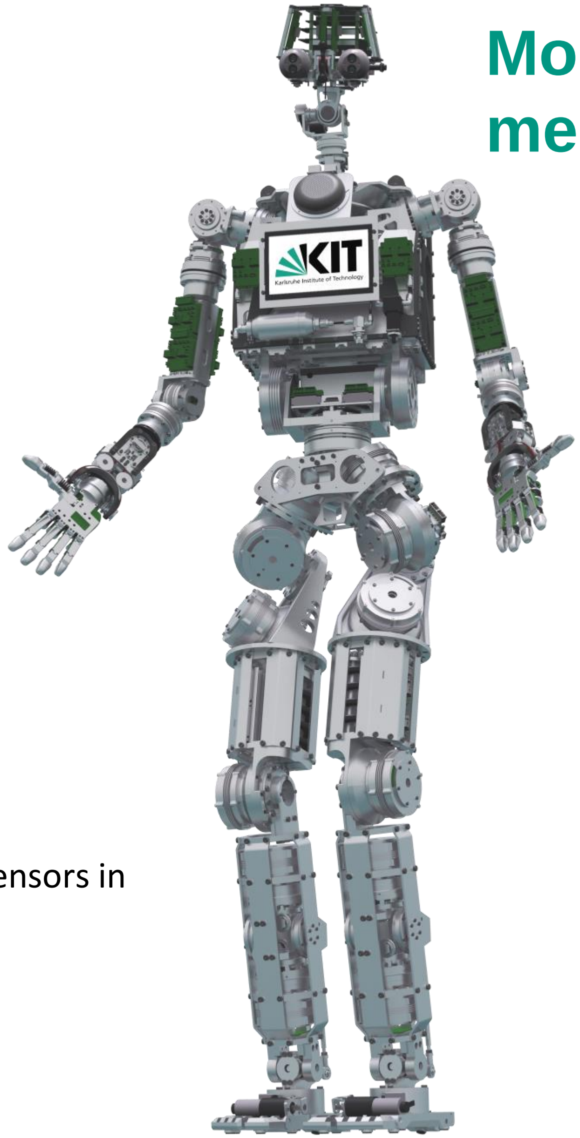
mocap → MMM → robot model → real robot

ARMAR-IV: 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
  - …



More than mechatronics

ARMAR-IV

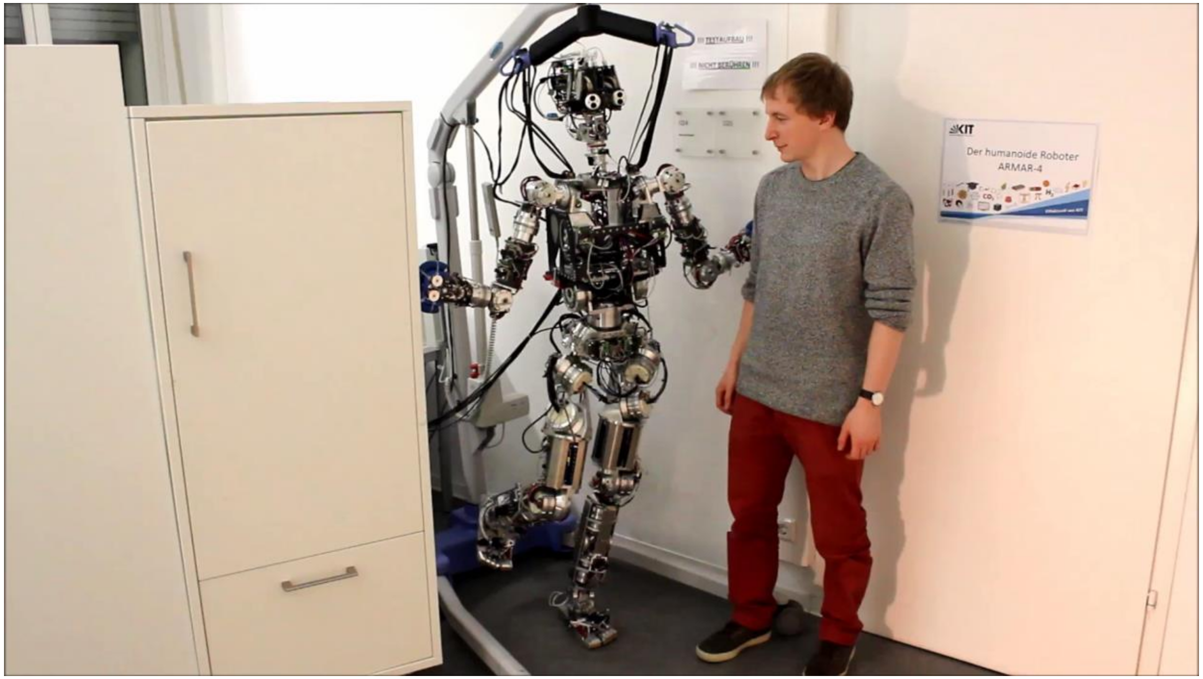
made@KIT

70 kg

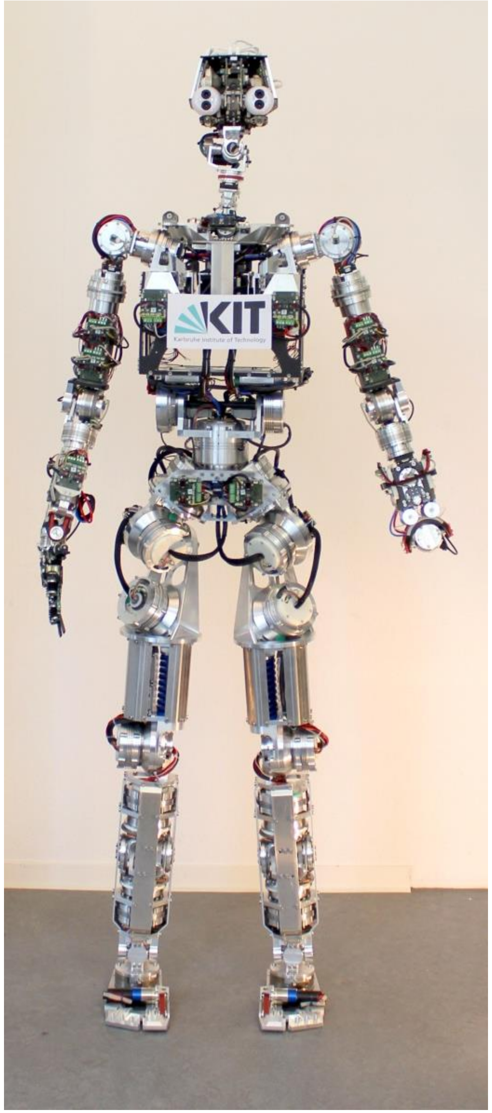
170 cm

ARMAR-IV

- 63 DOF
- Torque-controlled!



Multi-contact active compliance balancing controller



Duality

Duality - Boolean Algebra

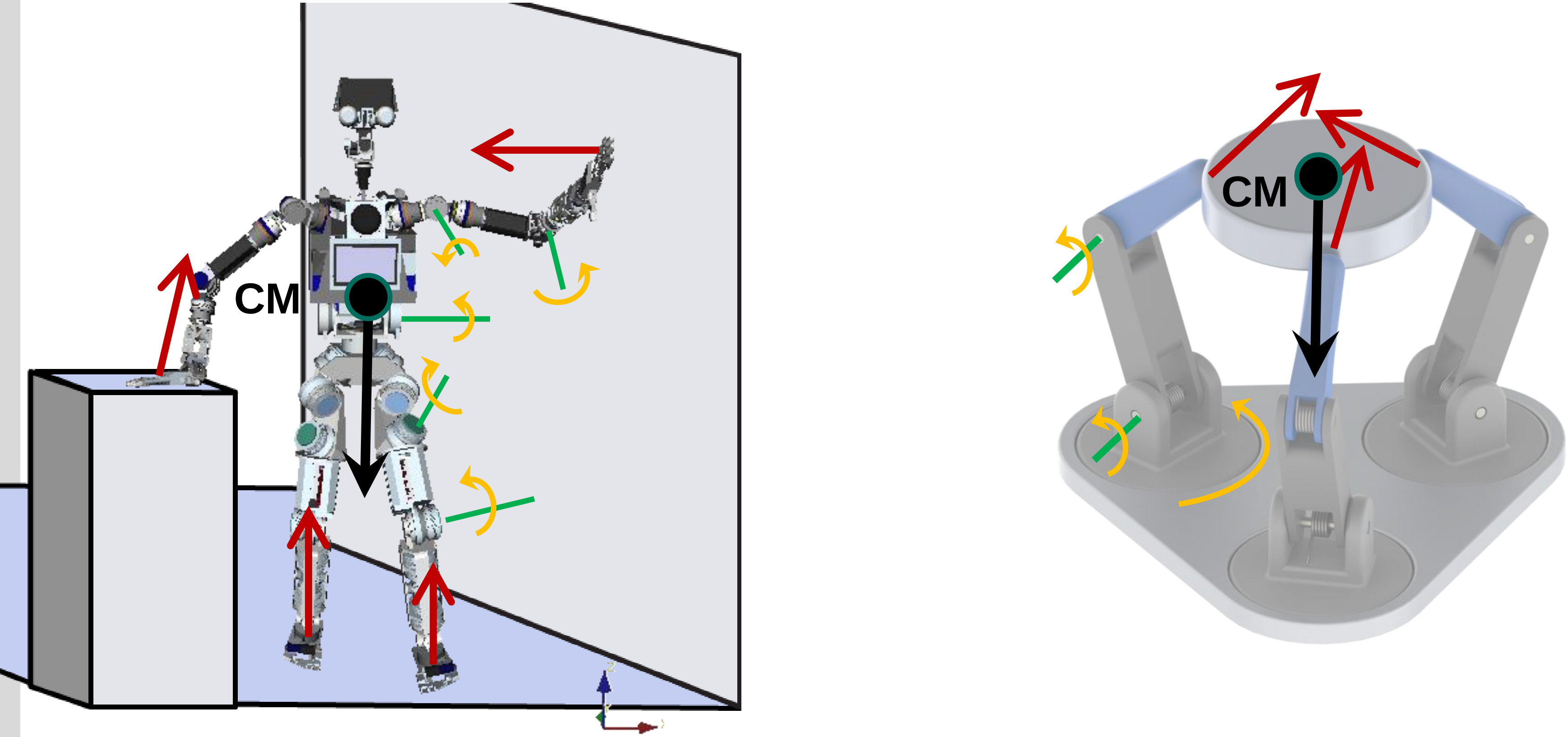
$$\wedge \leftrightarrow \vee \qquad 0 \leftrightarrow 1$$
$$a \leftrightarrow a \qquad \overline{a} \leftrightarrow \overline{a}$$

$$\begin{aligned}
a \wedge a &\overset{H3}{=} (a \wedge a) \vee 0 \\
&\overset{H4}{=} (a \wedge a) \vee (a \wedge \overline{a}) \\
&\overset{H2}{=} a \wedge (a \vee \overline{a}) \\
&\overset{H4}{=} a \wedge 1 \\
&\overset{H3}{=} a \qquad \text{q.e.d.}
\end{aligned}$$

$$\begin{aligned}
a \vee a &\overset{H3}{=} (a \vee a) \wedge 1 \\
&\overset{H4}{=} (a \vee a) \wedge (a \vee \overline{a}) \\
&\overset{H2}{=} a \vee (a \wedge \overline{a}) \\
&\overset{H4}{=} a \vee 0 \\
&\overset{H3}{=} a \qquad \text{q.e.d.}
\end{aligned}$$

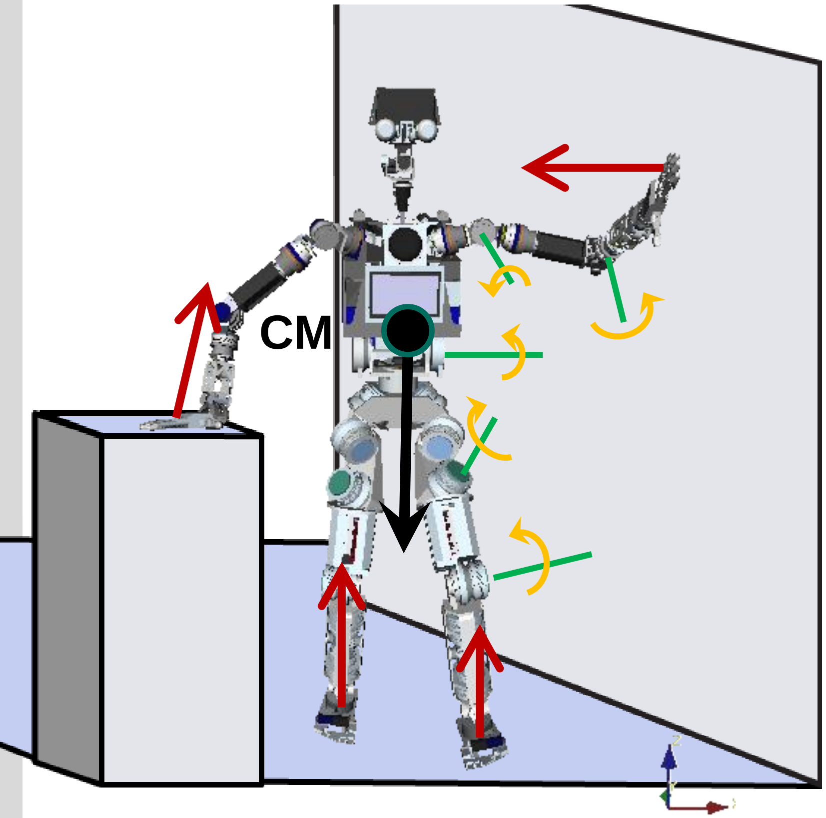
The duality of grasping and balancing

Equilibrium is reached by balancing similar sets of forces



Ground reaction forces	↔	Fingertip forces
Weight of the body (CM)	↔	Weight of the object (CM)
Torques on the joints	↔	Torques on the joints

The duality of grasping and balancing



Concepts of grasping can be applied to loco-manipulation

$$\mathbf{G}^T\mathbf{T} = \mathbf{J}_H\dot{\Theta}$$
$$\mathbf{J}_H^T\lambda_f = \tau$$
$$-\mathbf{G}\lambda_f = \mathbf{W}$$
$$\lambda_f \in \mathscr{F}$$

Balance ⟷ Stable grasp

Step planning ⟷ Grasp synthesis

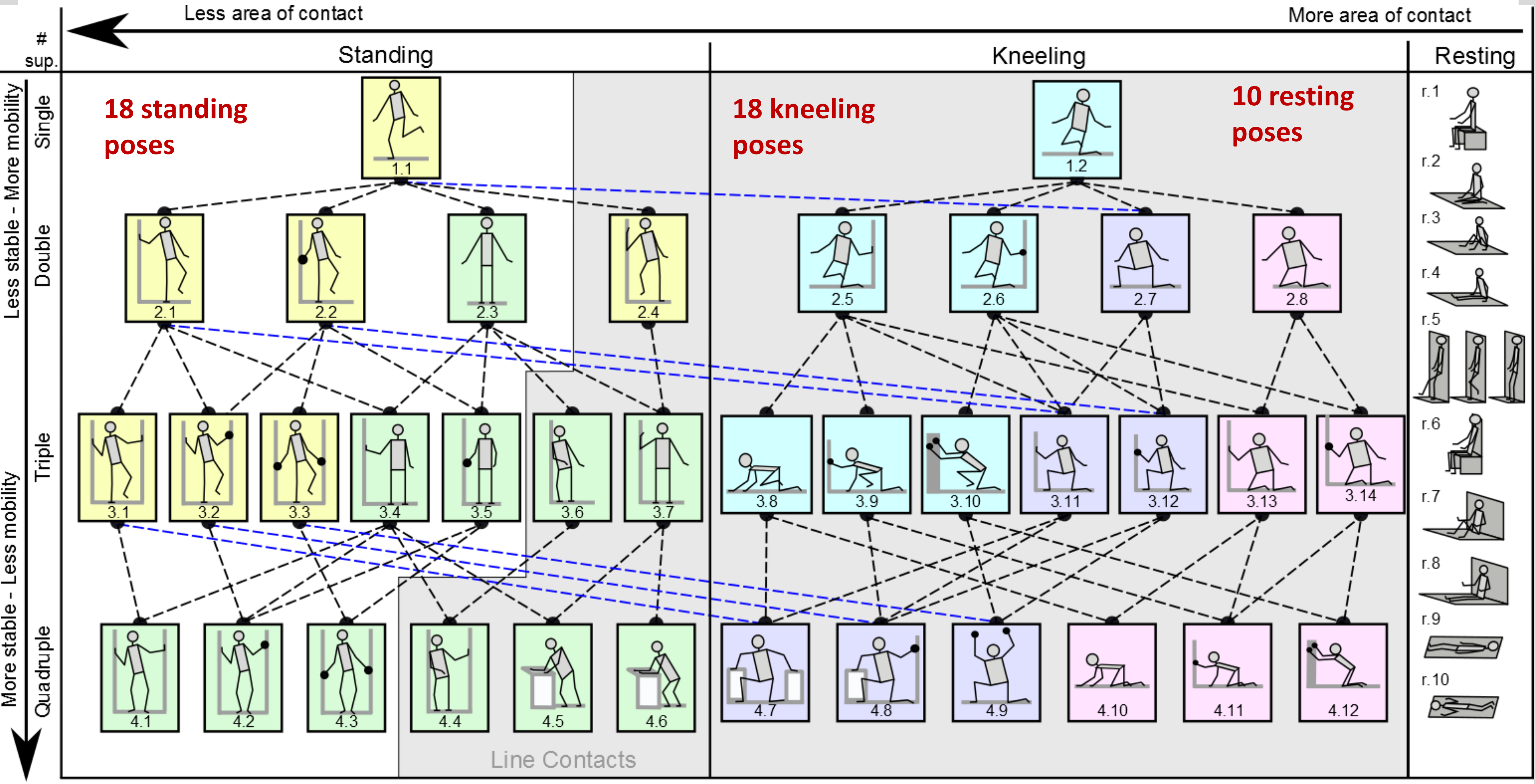
On the Duality of grasping and balancing

Selection of support pose	⟷	Grasp selection
Selection of contact points	⟷	Grasp synthesis
Classification of support poses possibilities	⟷	**Grasping taxonomies**

M. R. Cutkosky, 1989 | N. Kamakura, 1989 | T. Feix et al, 2009 | Bollock et al. 2013

- Applications of grasping taxonomies
  - Benchmark to test robot hand abilities
  - Simplify grasp synthesis
  - Inspire hand design
  - Optimization of synergies: Formulation of dexterity/functionality as number of achievable grasps for maximization
  - Guide autonomous grasp selection

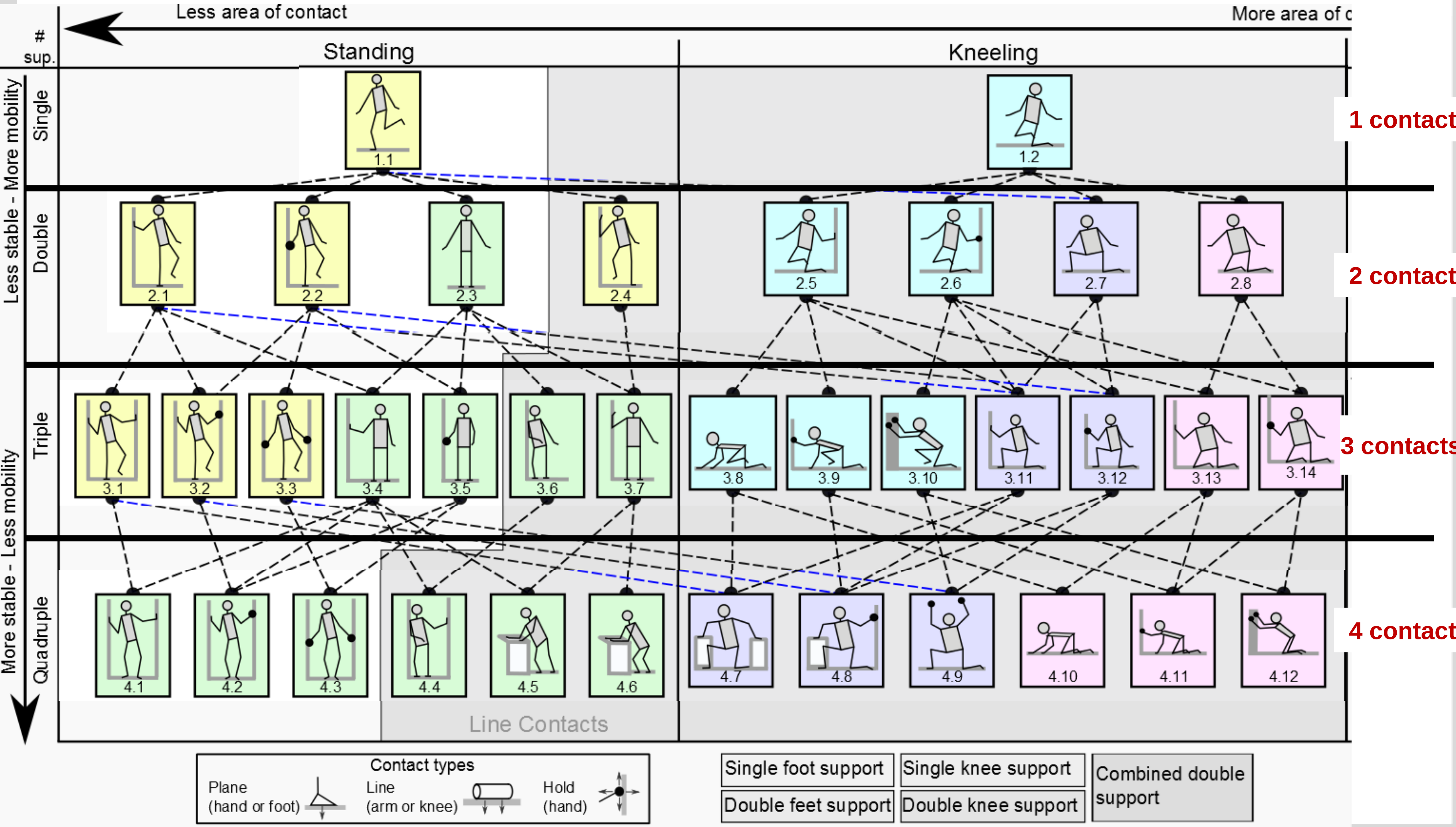
Taxonomy of whole-body poses



Total: 46 classes

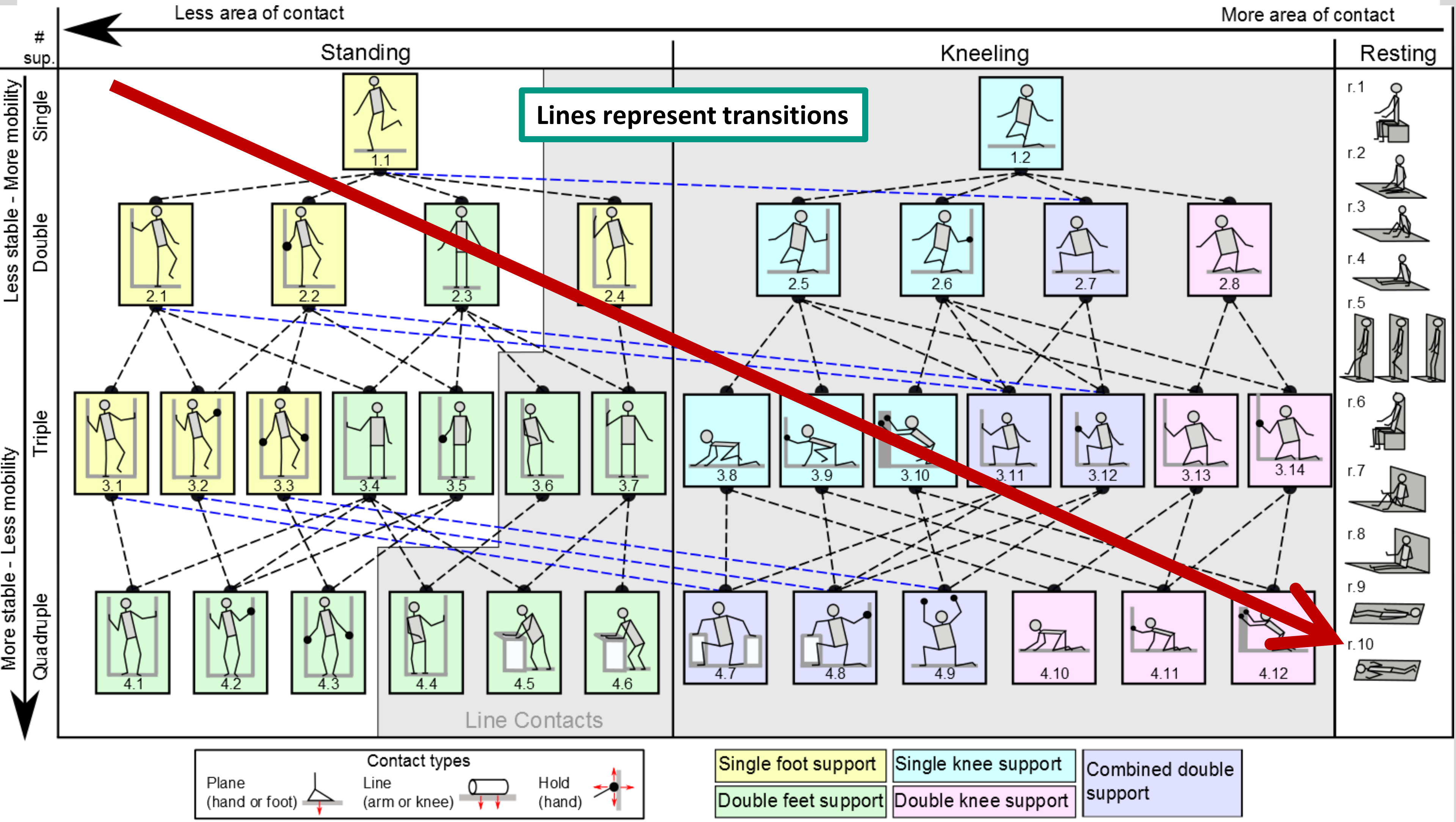
Borras and Asfour, IROS 2015

Taxonomy of whole-body poses



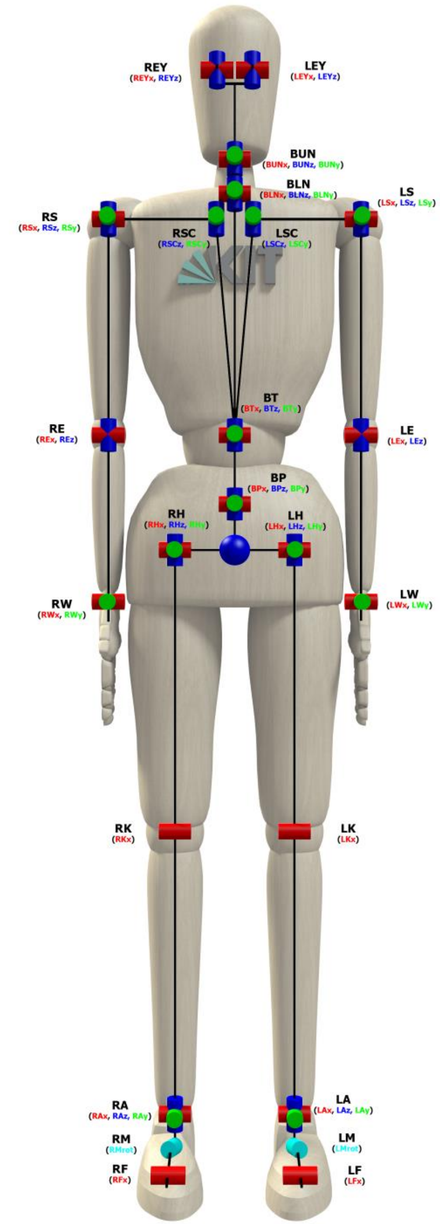
Borras and Asfour, IROS 2015

Taxonomy of whole-body poses



Validation of the taxonomy

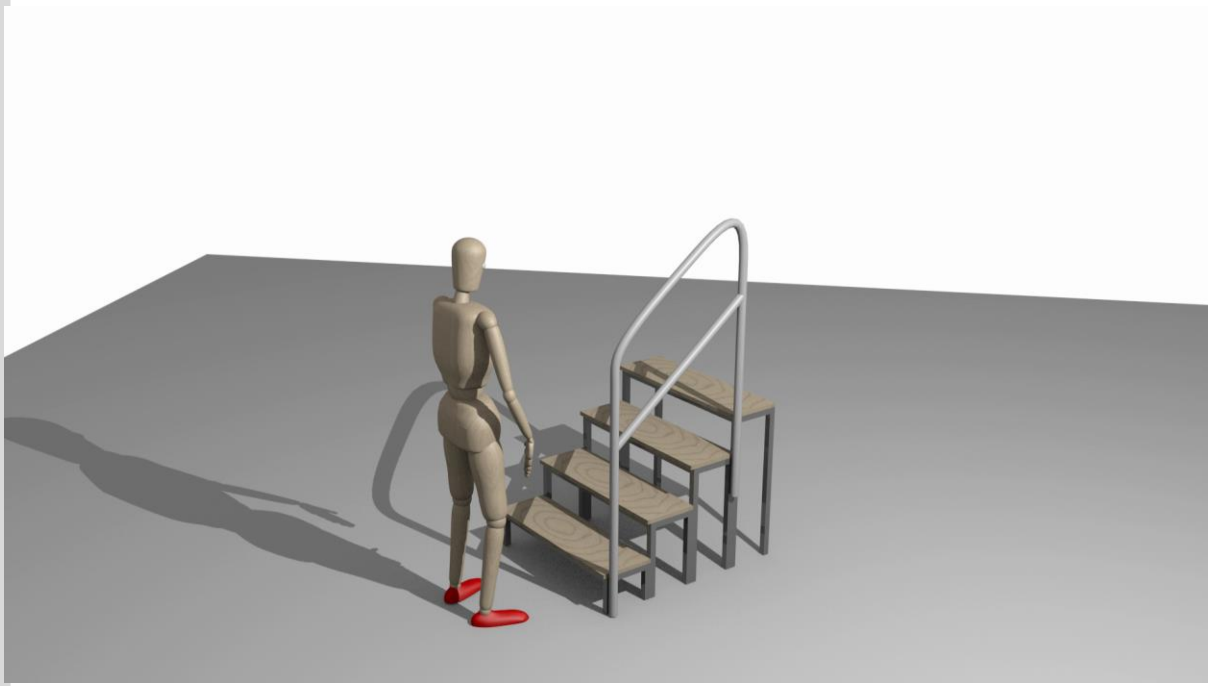
- Analyses of different human loco-manipulation tasks with supports
- Reference model of the human body (Master Motor Map: MMM) with 104 DOF
- Motion capture data mapped to reference model of the human body (MMM)
- Automatic segmentation to detect support poses and transitions
- Automatic generation of a taxonomy of the poses and their transitions in the motion data



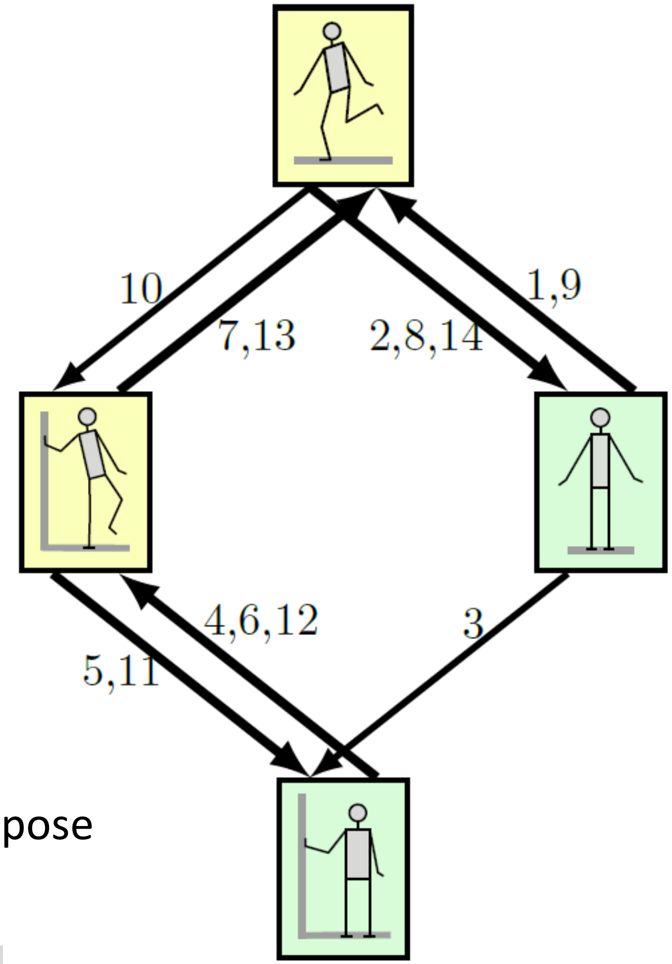
Analysis of pose transitions

Going upstairs with a handle

Detection of support contacts highlighted in red

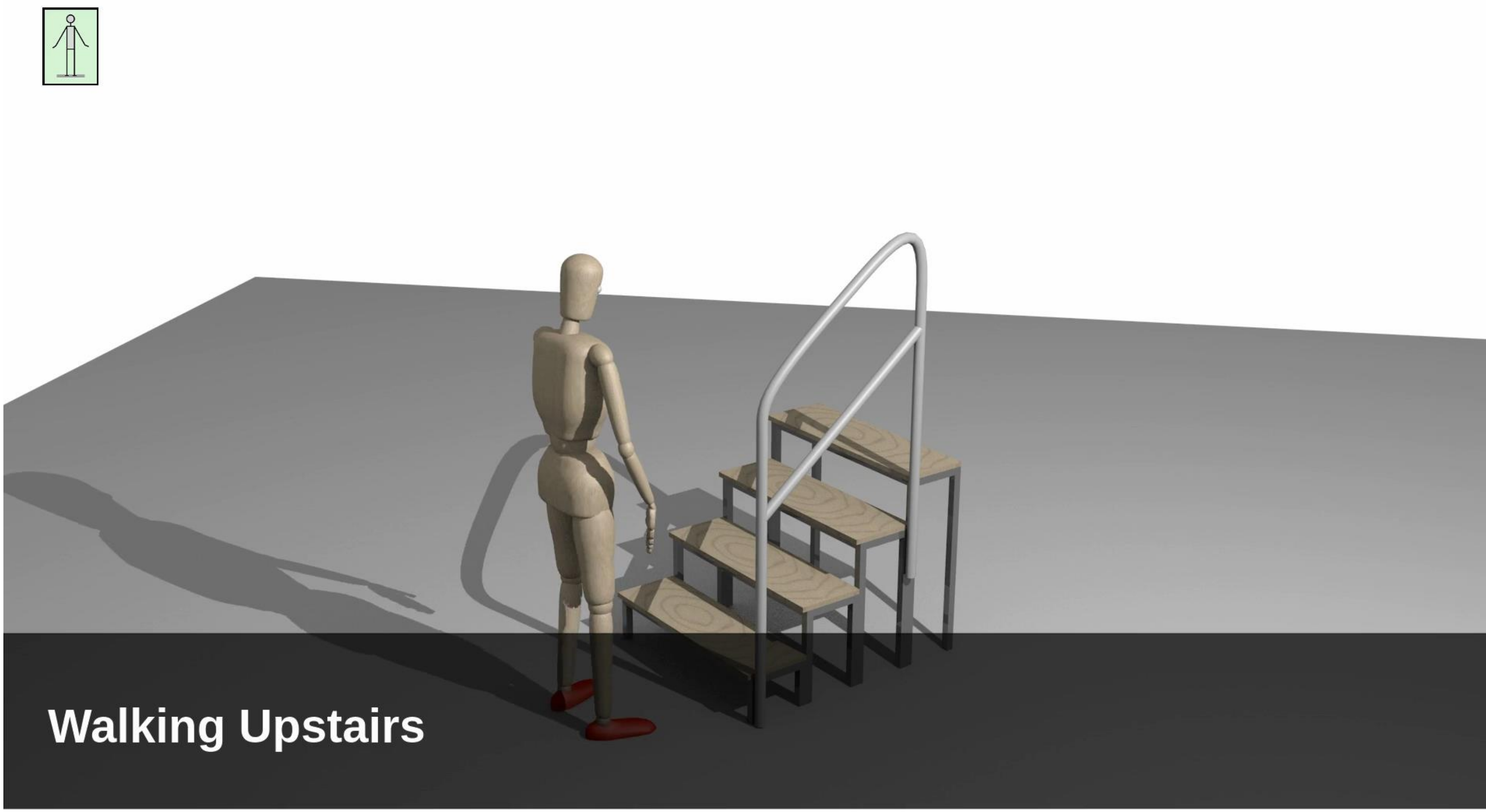


Generated graph of transitions:

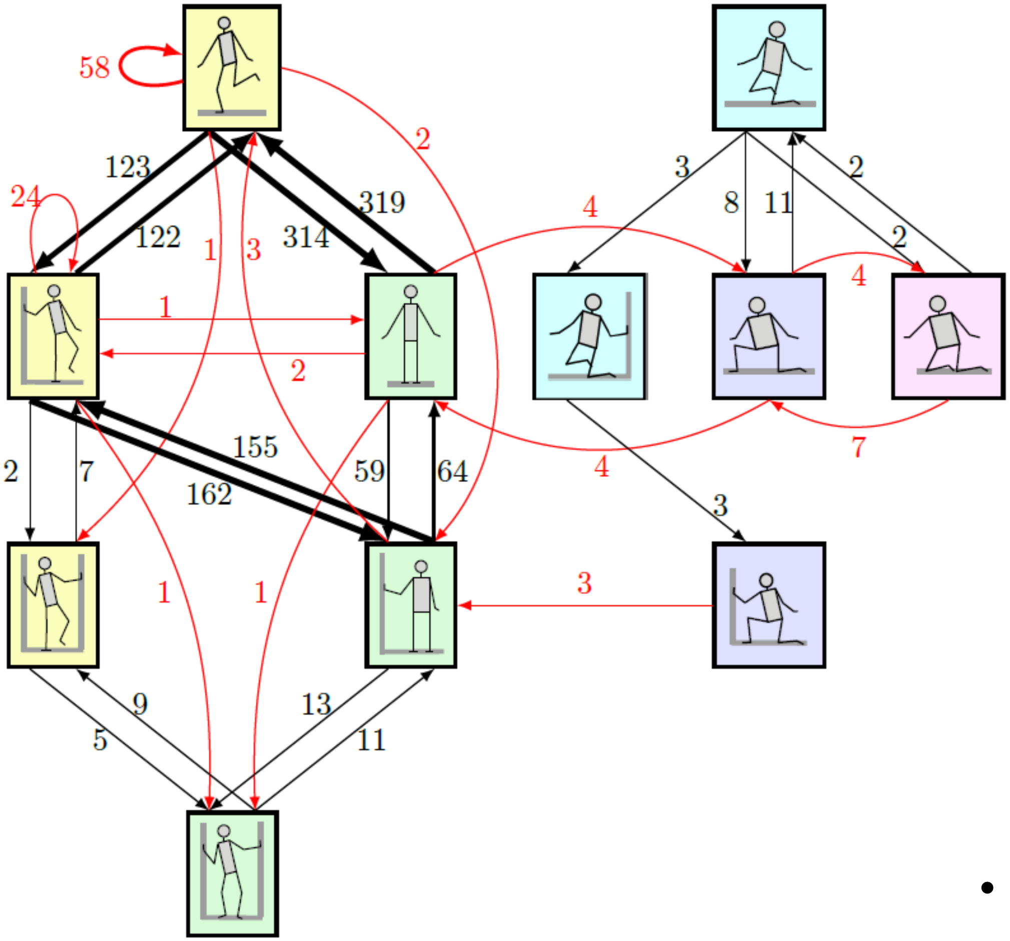


Subject swings left leg with a *right foot – right hand* support pose

Analysis of whole-body loco-manipulation tasks



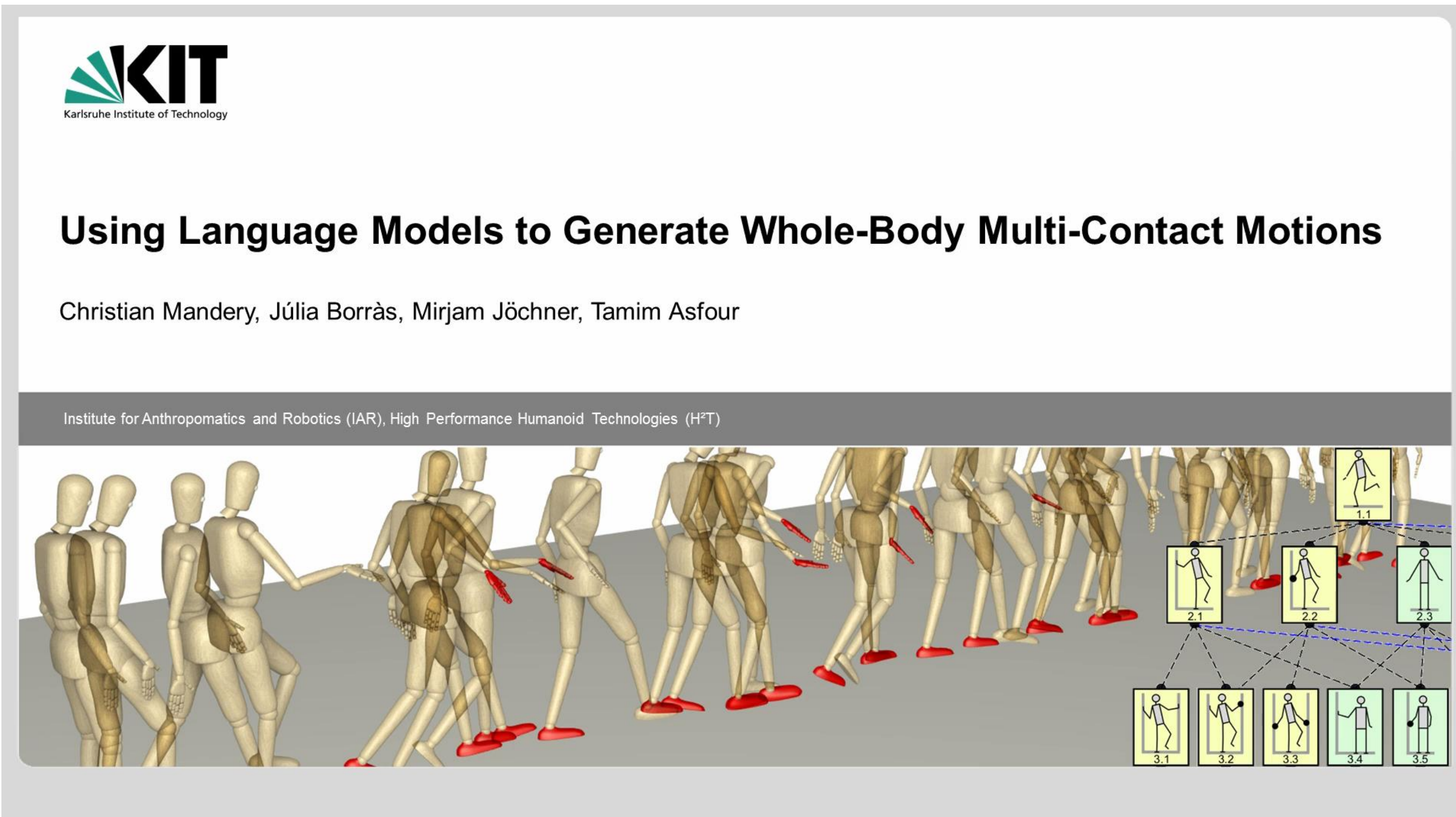
Data-driven validation of the taxonomy



- Total of **121** motions processed
  - **Locomotion**
    - Upstairs/downstairs with handle
    - Walk with handle
    - Walk avoiding obstacles using hand supports
  - **Loco-manipulation**
    - Lean to reach/place/wipe
    - Bimanual pick and place of big objects
  - **Balancing**
    - push recovery
    - recovery due to lost balance
  - **Kneeling motions**
- 4,5% of poses missed (all double foot supports (the looping edges))

Whole-body motion based on the taxonomy

- **n-gram language model**: Statistical approach to learning conditional transition probabilities between whole-body shape poses



Software and documentation: MMM, Motion DB

- KIT Whole-Body Motion Database
  - https://motion-database.humanoids.kit.edu
- MMM:
  - https://gitlab.com/mastermotormap/mmmcore
  - https://gitlab.com/mastermotormap/mmmtools
- Dokumentation:
  - http://mmm.humanoids.kit.edu
  - https://motion-database.humanoids.kit.edu/faq
- KIT Object database
  - http://h2t-projects.webarchiv.kit.edu/Projects/ObjectModelsWebUI/

Lessons learnt in 16 years

Robotics is the science of integration

The “X” in robotics

- It is not the “X” in Self-X (self-organization, self-repair, self-refinement, …)
- It is not the “X” in Co-X (co-habiter, co-worker, co-protector, …)
- It is not the state variable in dynamical systems

Unfortunately, it is the value by which we have to speed up robot movies to make robots behave/move in a human-like way

- **X > 1**

It’s all about Force

Force

Role of force

- Force is key element for interaction with the physical world.

- Human infant motor control studies also indicate that early manipulation relies on contact and force, with other senses being incorporated in control later in the development.

- **Claim:**
  - Objects, agents and their actions can be described based on a new concept of sensorimotor force fields (SFF) that provides a unified representation and computational mechanism for solving robotics tasks (grasping and manipulation, balancing, …).
  - SSF result from the integrated mapping of action and sensory modalities such as position, pressure, tactile, audio and vision sensory data to the **force space**.

Action and agent

- Action
  - Action represented by the force fields that generate it
  - Dynamic systems; attractor landscapes

- Agents = Embodiment
  - Sensorimotor maps of the body schema; tool use
  - Based on proprioception (and vision and haptic)

Perception - Physical laws

- Duality between force and position has been demonstrated in the robotics in the form of position-force control mechanisms (Newton's law)

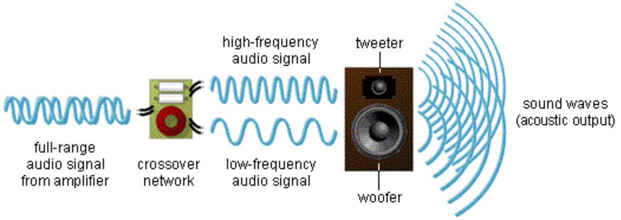
$$F = m \cdot \ddot{x}$$

- Pressure is the amount of force acting perpendicularly per unit area

$$F = A \cdot P$$

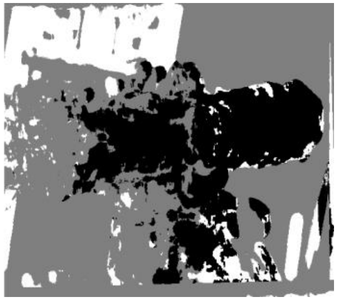
- Haptic: contact, pressure, proprioception, temperature, vibration
  - Superposition ?

- Audio: loudness proportional to force (e.g. knocking)



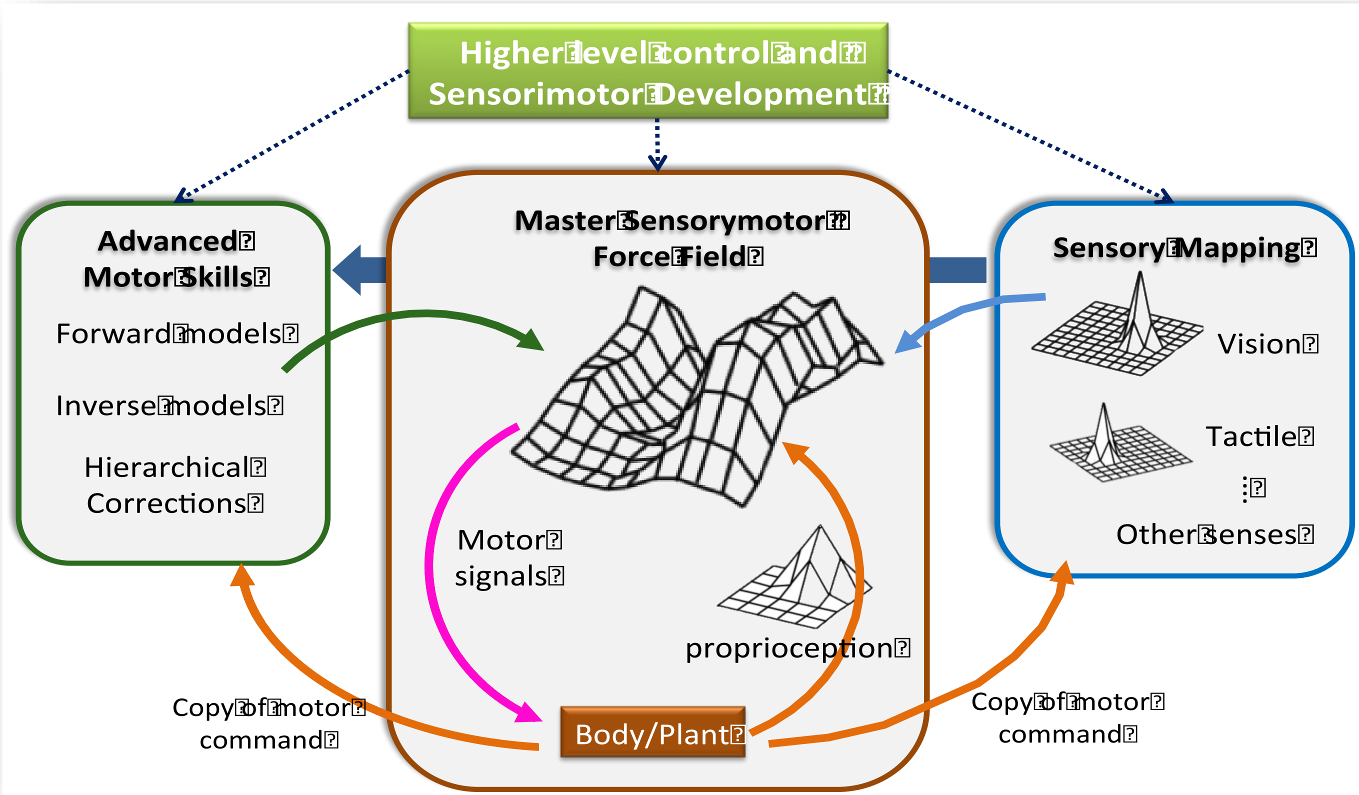
Perception - Physical laws

- Vision
  - Depth → position
  - Colors
  - Intensity
  - Saliency
  - Attention
  - Motion → see action
  - Shape features
  - ….



Sensorimotor Force Fields (SFF)

From X to force and torque!
From pixels, voxels, taxels, … to forces and torques



SFF - force4all

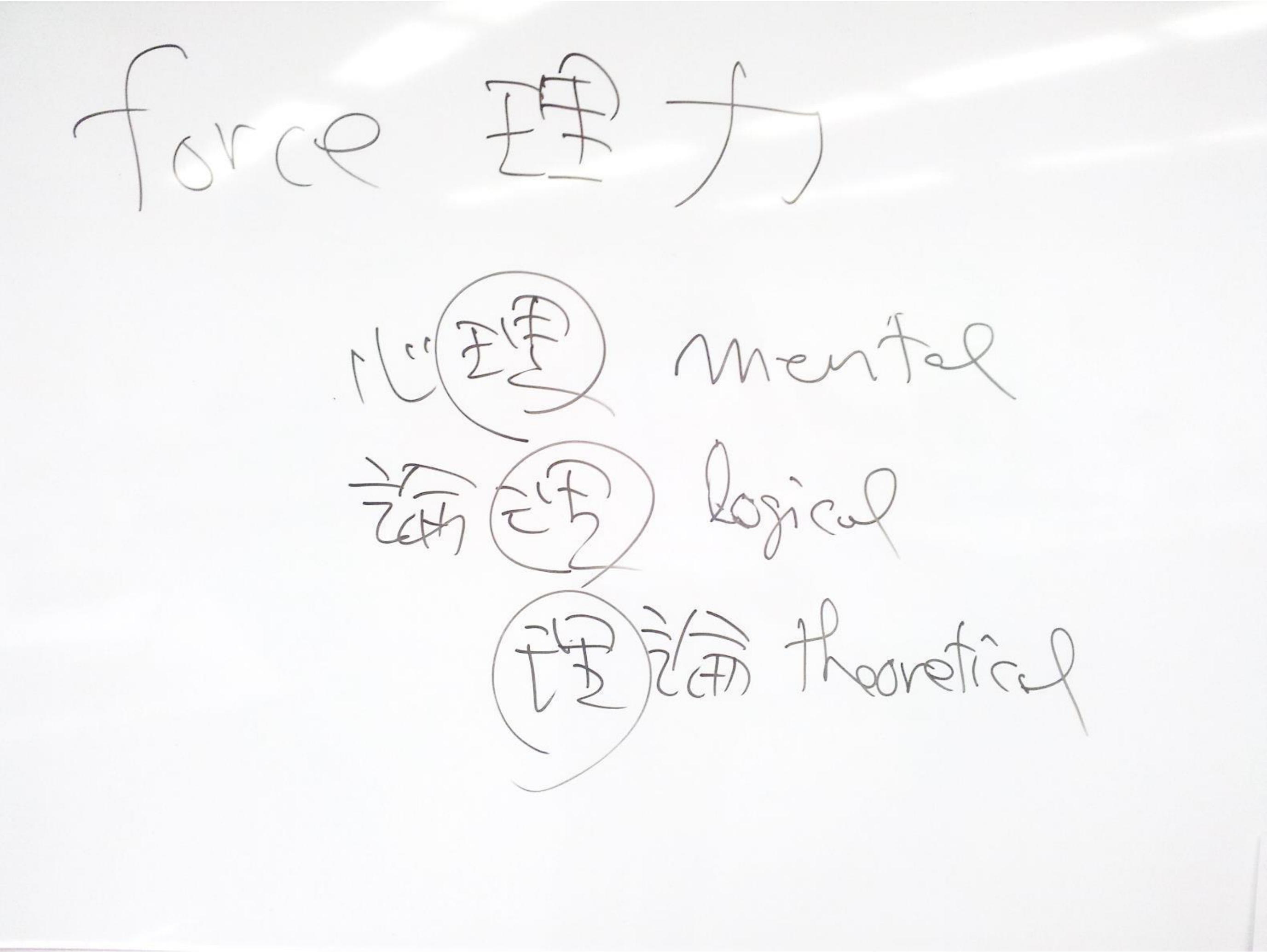
- Co-joint Object-Action representation in the force space (force-based OACs) → Robot "machine code" in the force space

- Research questions:
  - Definition of laws and rules for mapping of different sensory modalities into SFF.
  - Mathematical and algorithmic modeling of SSFs.
  - Operators and arithmetics for SFF: interaction of different SSFs resulting from different sensory modalities or action.
  - Formulation of robotics tasks based on the SSF representation
  - Compilers from natural language task description to the force space
  - Which robotics tasks? Grasping, Balancing, …

It is not only about Newton forces

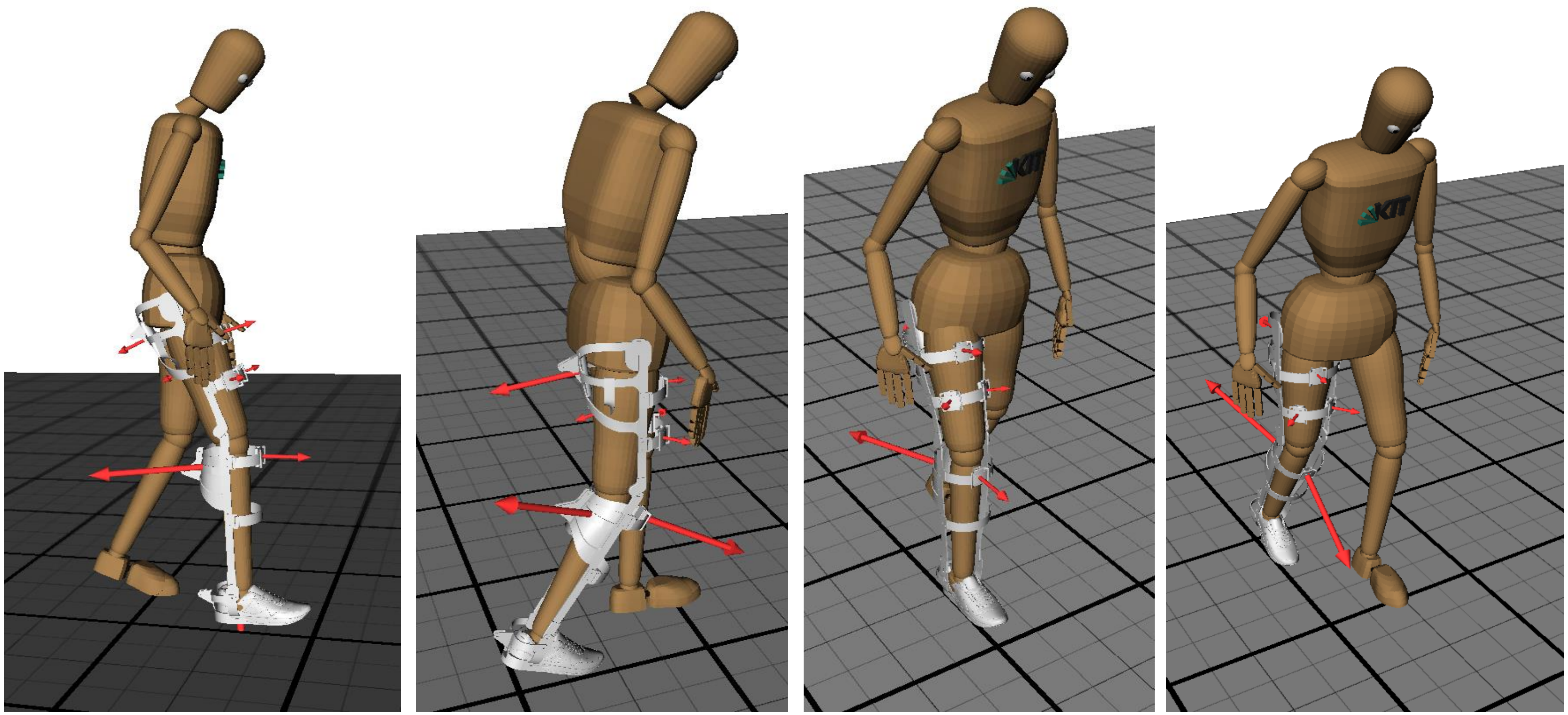
- Mental forces
- Logical forces
- Theoretical forces
- Physical forces
- ...

Force in Japanese culture

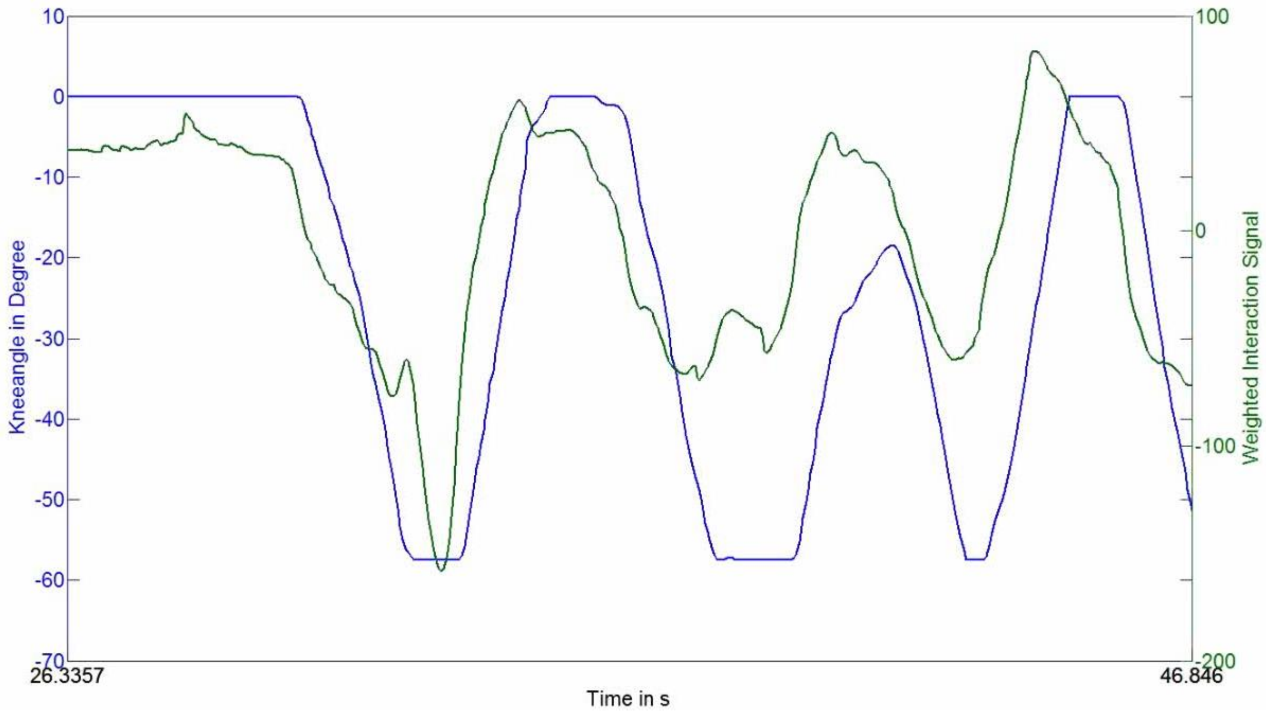


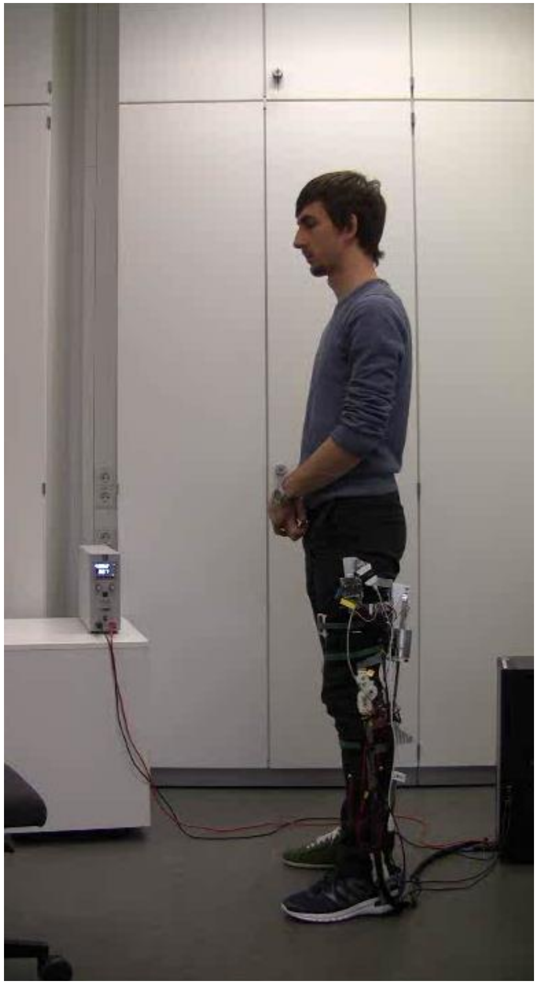
Force-based Human-EXO interface

- **Feel the muscle activation (non invasive)**
- Learn human-suit interaction force pattern and use them for motion prediction



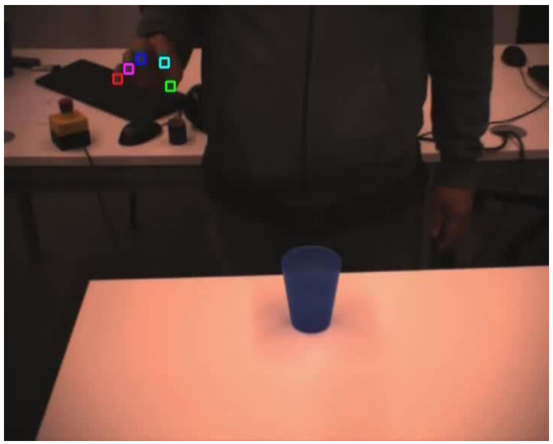
ARMAR-5: Interface to the human body

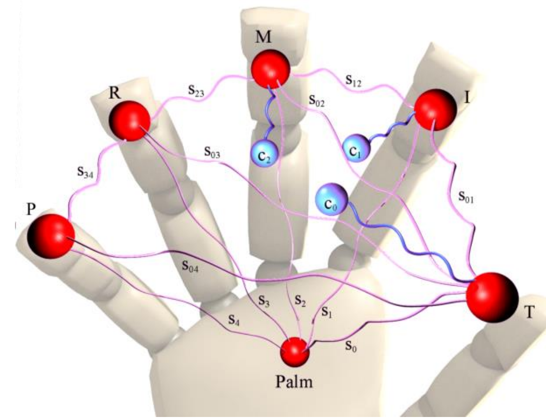




Other examples

- SFFs for grasp recognition and reproduction





- A. Kheddar (CNRS/LIRMM) and A. Argyros (FORTH)
  - Towards Force Sensing From Vision: Observing hand-object interactions to infer manipulation forces, CVPR 2015

- Gentiane Venture
  - Emotion recognition based on force

Important

- It is not only about the an EXO interfaces
- It is not only about physical forces (contact forces, ….)

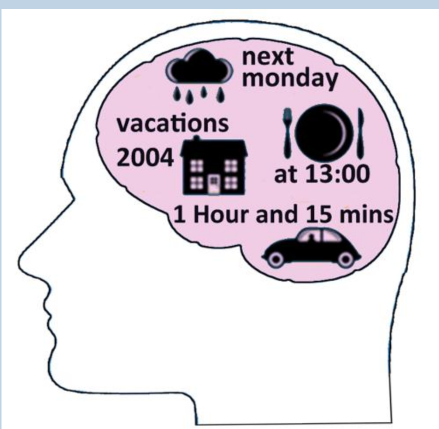
- **It is about the force space as unifying representation for sensorimotor experience and cognitive capabilities**

Time

Time is vital

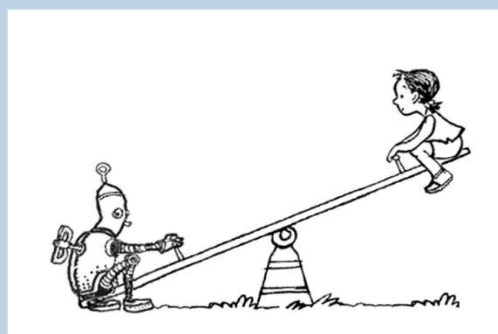
Knowing

- Knowledge hierarchies
- Episodic memory (what, where, when), forgetting
- Time-based: Past recall, future imagination



Doing

- Short-term: Fluency in HRI (e.g. turn taking)
- Long-term: constraints in action planning, habits.
- Multiple tasks coordination



Being

- Self identity over time
- Low level consciousness: perceive internal, environment changes
- High-level consciousness: link self to historical times

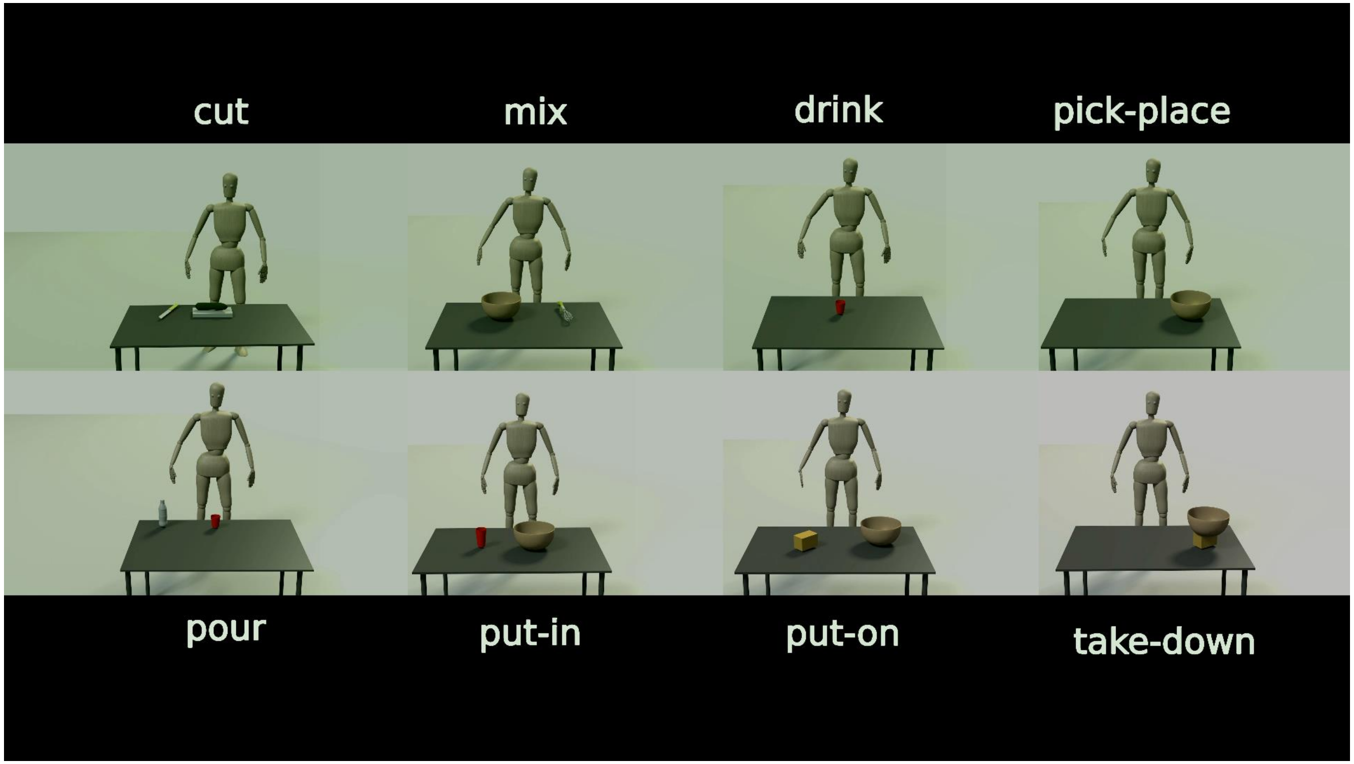
H2T

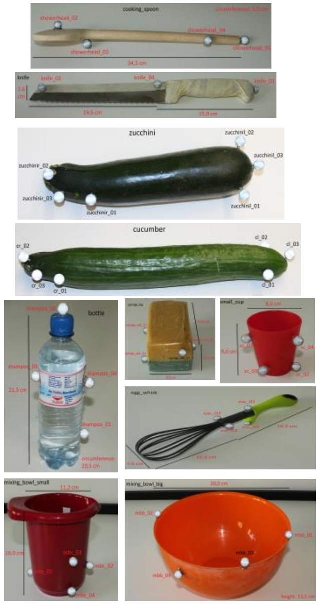
Time in Robotics

Past	Present	Future
• Experience	• Current world state	• Prediction

- Time is fundamental for the implementation of **episodic memories**

KIT Manipulation Action Dataset



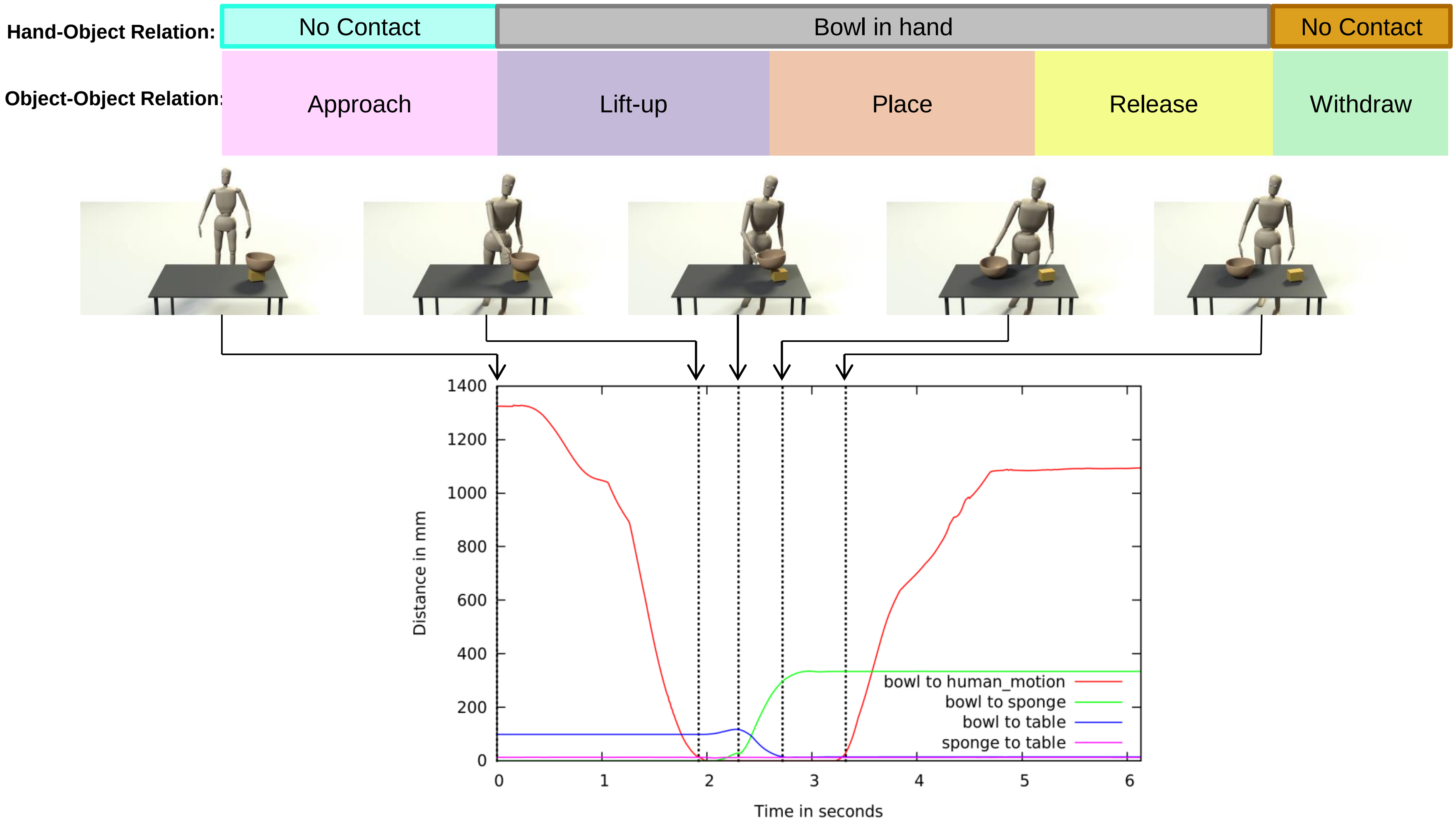


10 Different Objects

- In total 70 demonstrations of 8 different manipulation actions

Level I : Semantic Segmentation

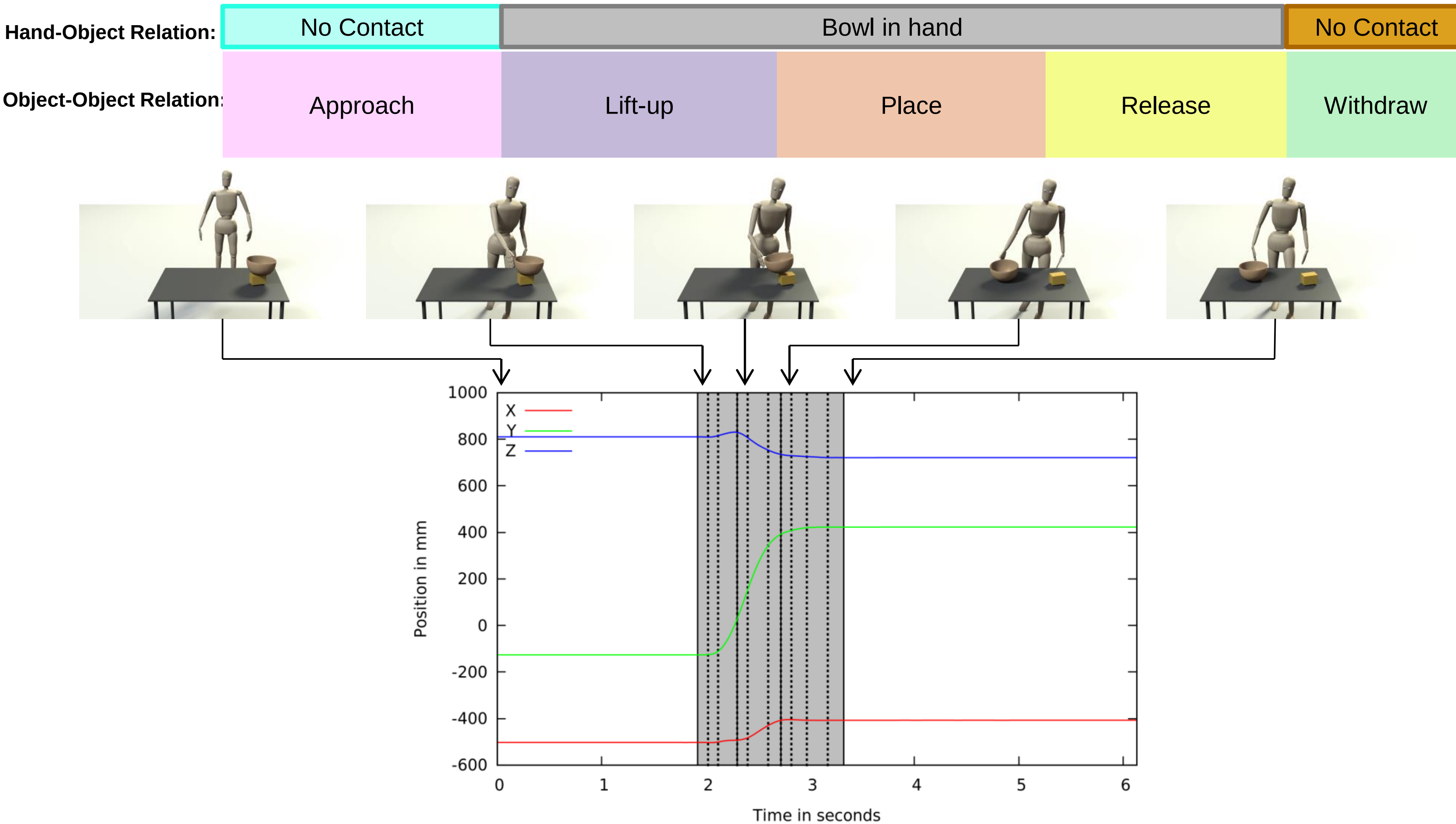
Hierarchical Segmentation



Semantic Distance Profile

Level II : Motion Segmentation

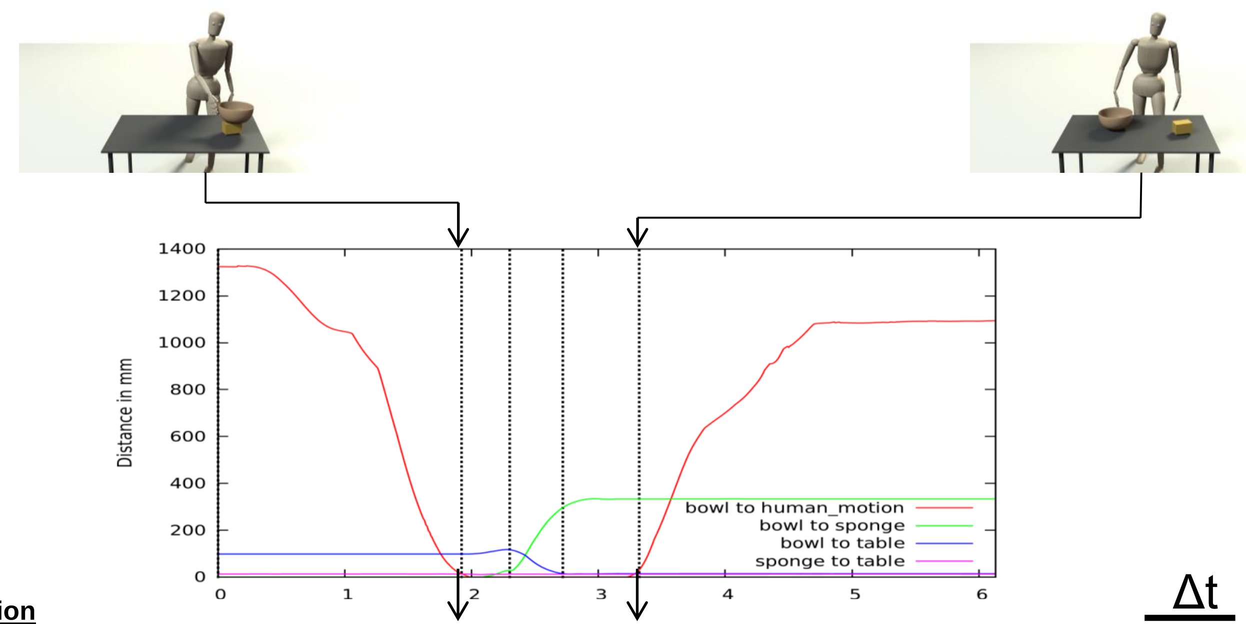
Hierarchical Segmentation



Trajectory of the Bowl

Perception of Time: Put-on Action

No Contact	Bowl in hand	No Contact

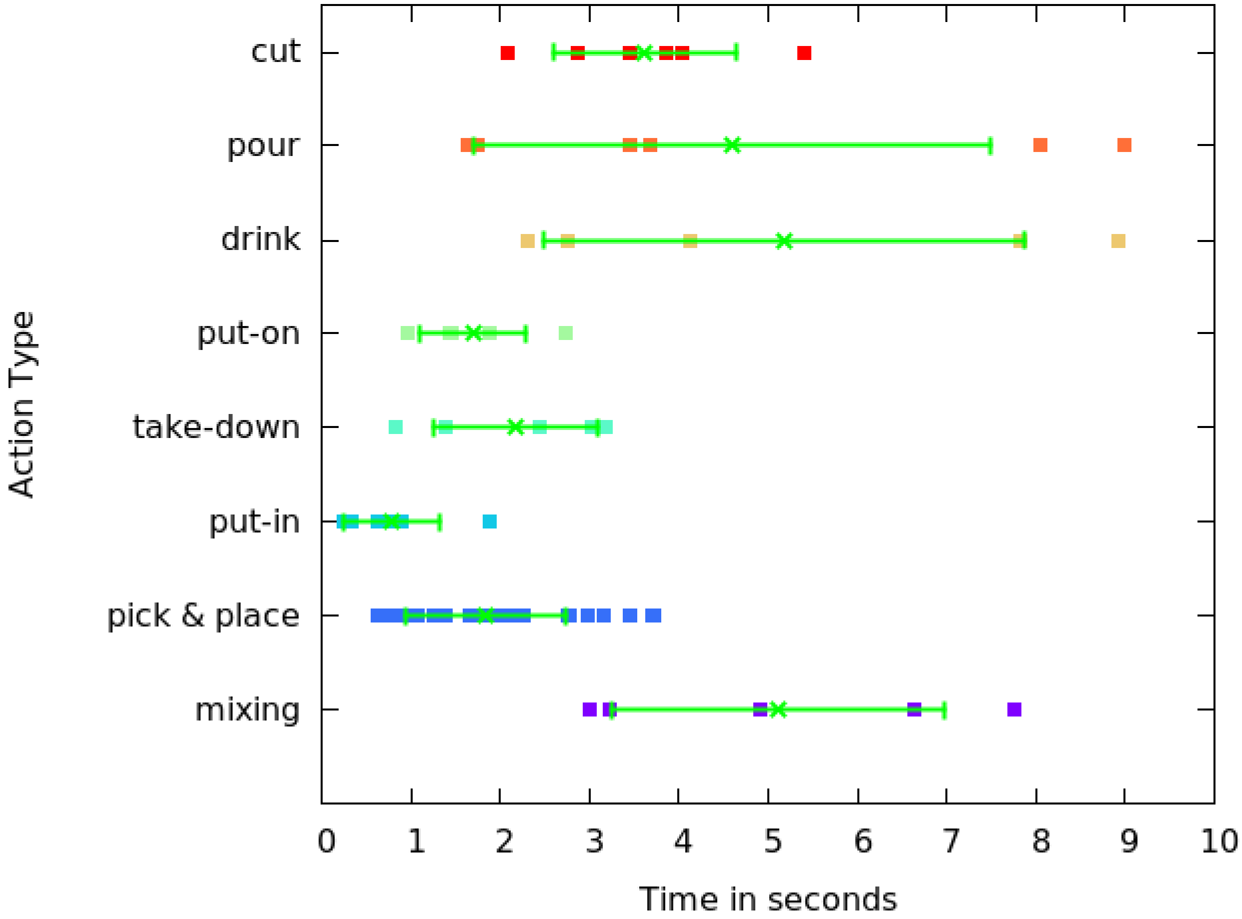


Put-on Action						Δt
Version I:	1.9	0.4	0.4	0.6	2.8	1.4 sec
Version II:	2.1	1.0	0.6	0.9	3.2	2.5 sec
Version III:	2.8	0.9	1.2	1.0	3.0	3.1 sec
Version IV:	1.7	0.4	0.4	0.1	2.1	0.9 sec
Version V:	1.8	0.7	1.2	1.1	3.1	3.0 sec

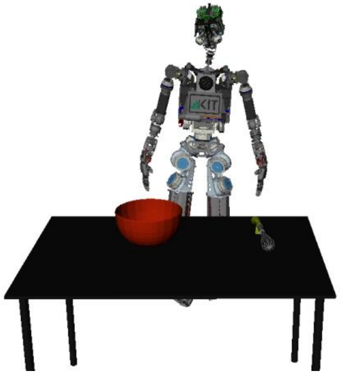
Δt

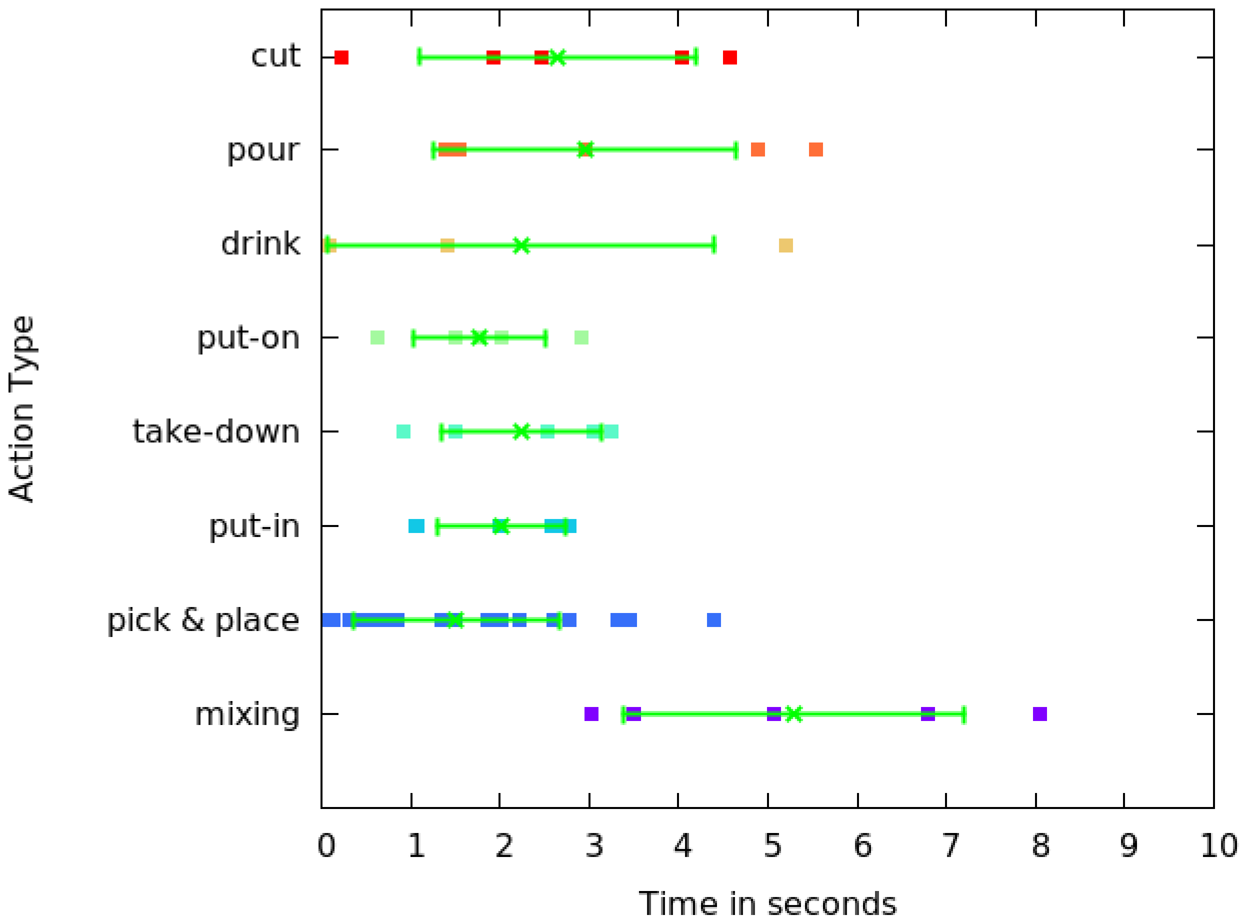
Mean : 2.1 sec Std: 0.9

Perception of Time: Human Demonstration



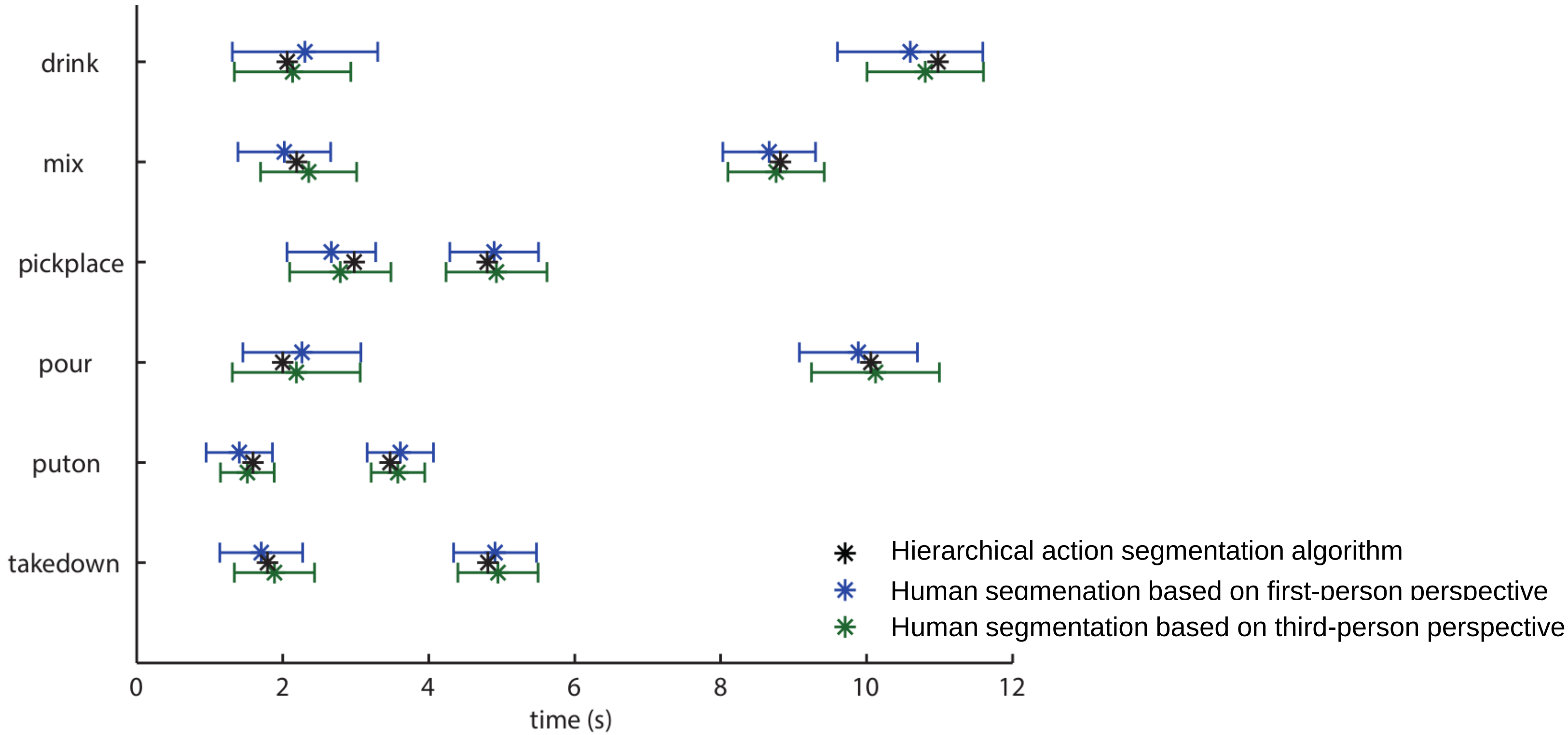
Perception of Time: ARMAR-4 Imitation





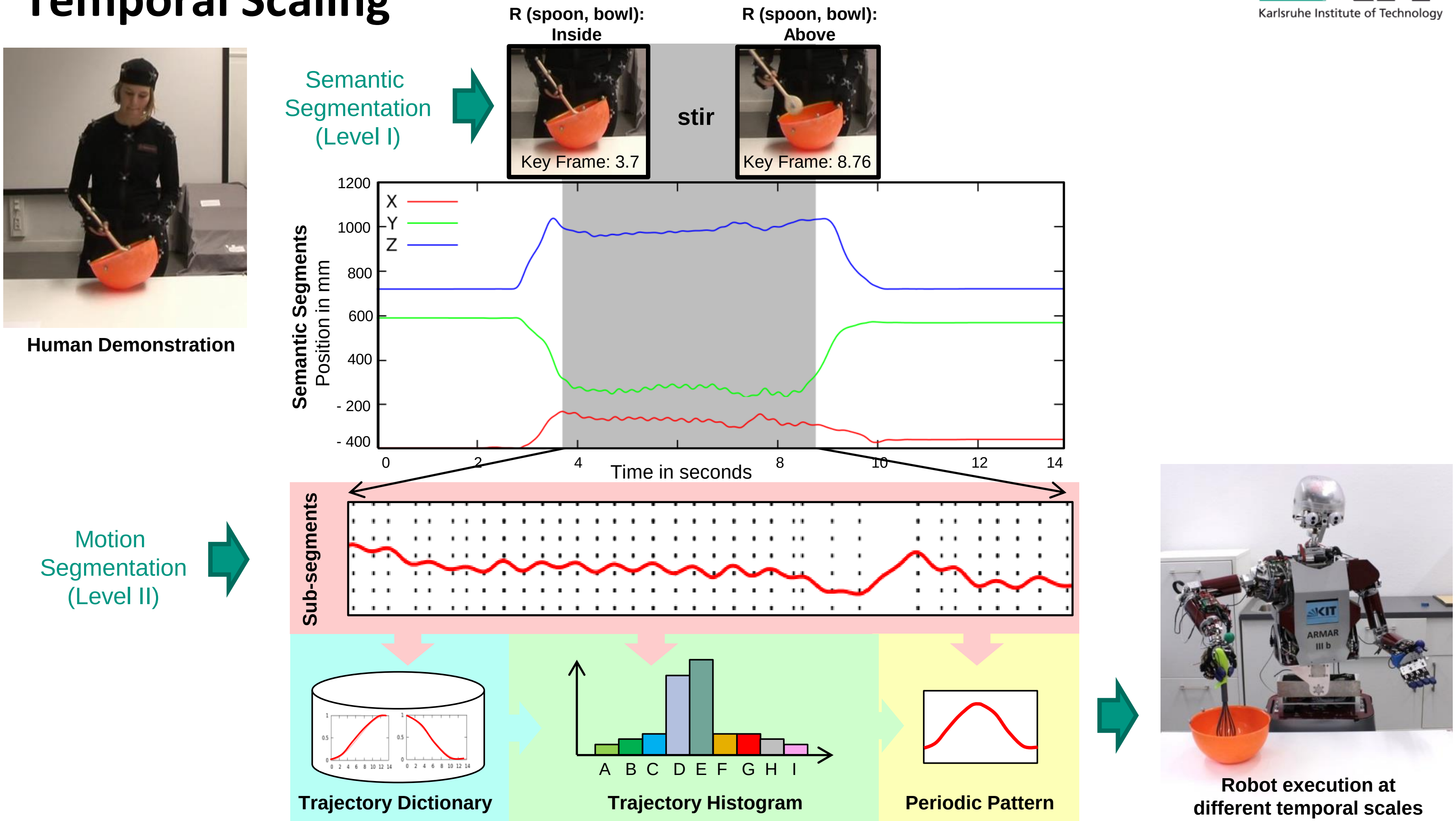
Perception of Time: Psychological Experiments

- Psychological experiments support our new semantic action segmentation hypothesis
- Collaboration with the University of Groningen (Hedderik van Rijn, Experimental Psychology & Statistical Methods and Psychometrics)



Schlichting al. “Temporal Context Influences the Perceived Duration of Everyday Actions“, Under Review, 2016

Temporal Scaling

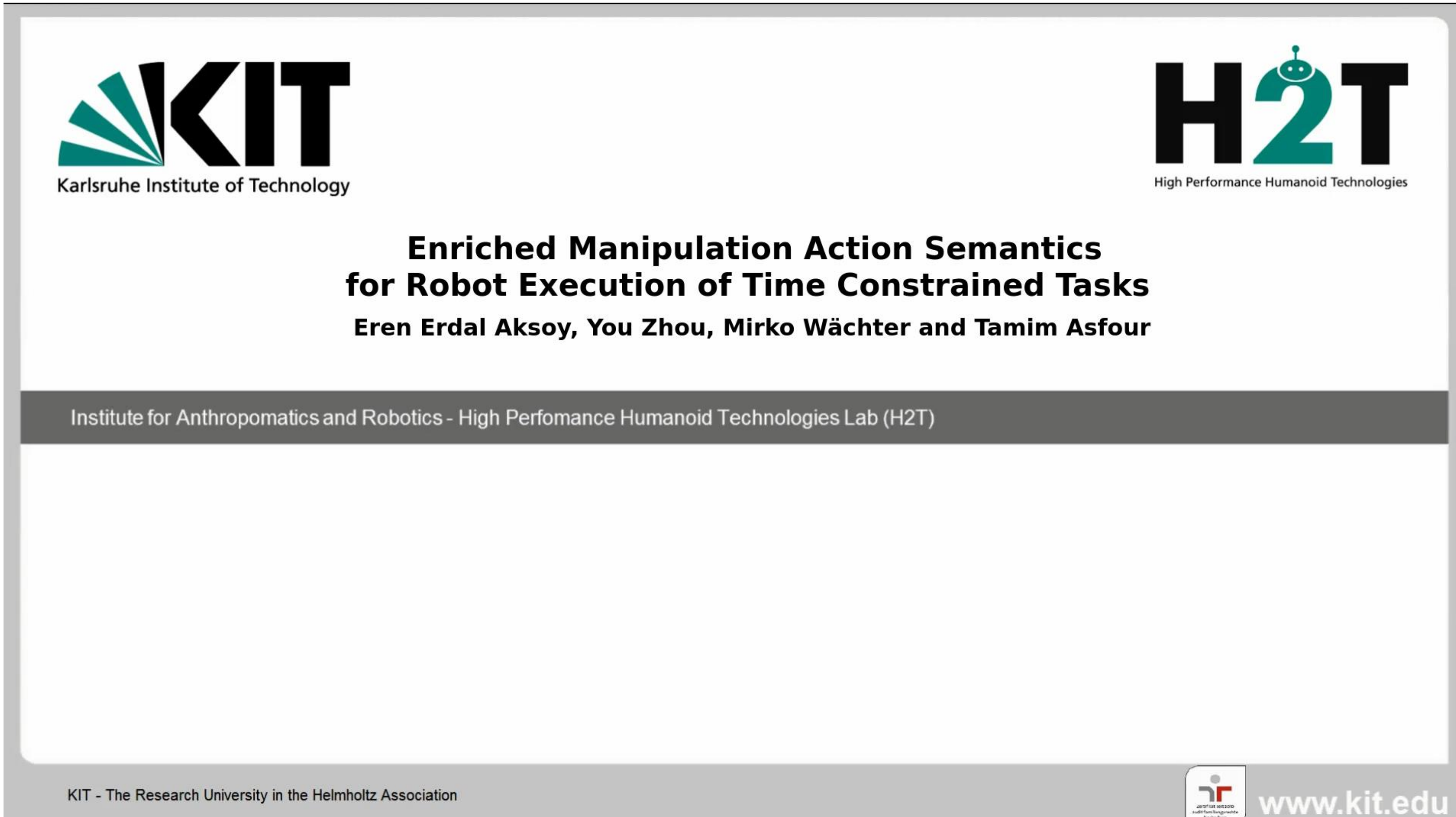


Based on the Dynamic Time Warping Distance Measure

CLASS-WISE AVERAGE PERIODICITY MEASURES.

Stir	*Pick Place*	*Put In*	*Take Down*	*Put On*	*Drink*	*Pour*	*Cut*
0.67	0.0	0.0	0.0	0.0	0.0	0.0	**0.5**

Temporal Scaling



Breakthroughs in robotics since ~2000 – my view

- Progress driven by
  - **„Cool“ new hardware**
    - Robot mechatronics:
      DLR/KUKA LWR, NAO, UR, iCub, youBot, FRANKA EMIKA, …
    - Sensors:
      Kinect, …
    - Computing power:
      many-core systems, GPUs, …
  - **Large amount of data** (thanks to better hardware)

Thanks to ...

- **German Research Foundation (DFG)**
  - SFB 588 www.sfb588.uni-karlsruhe.de (2001 - 2012)
  - SPP 1527 autonomous-learning.org (2010 -)
  - SFB/TR 89 www.invasic.de (2009 -)
- **European Union**
  - IMAGINE (2017- 2020)
  - SecondHands www.secondhands.eu (2015-2019)
  - TimeStorm www.timestrom.eu (2015-2018)
  - I-Support www.i-support.eu (2015-2017)
  - Walk-Man www.walk-man.eu (2013-2017)
  - KoroiBot www.koroibot.eu (2013-2016)
  - Xperience www.xperience.org (2012-2015)
  - GRASP www.grasp-project.eu (2008-2012)
  - PACO-PLUS www.paco-plus.org (2006-2011)
- **Federal Ministry of Education and Research (BMBF)**
  - INOPRO (2016-2021)
- **Karlsruhe Institute of Technology (KIT)**
  - Professorship "Humanoid Robotic Systems"
  - Heidelberg-Karlsruhe Research Partnership (HEiKA)

Thanks for your attention

Karlsruhe Institute of Technology

May the force be with you!