Karlsruhe Institute of Technology

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

My motivation

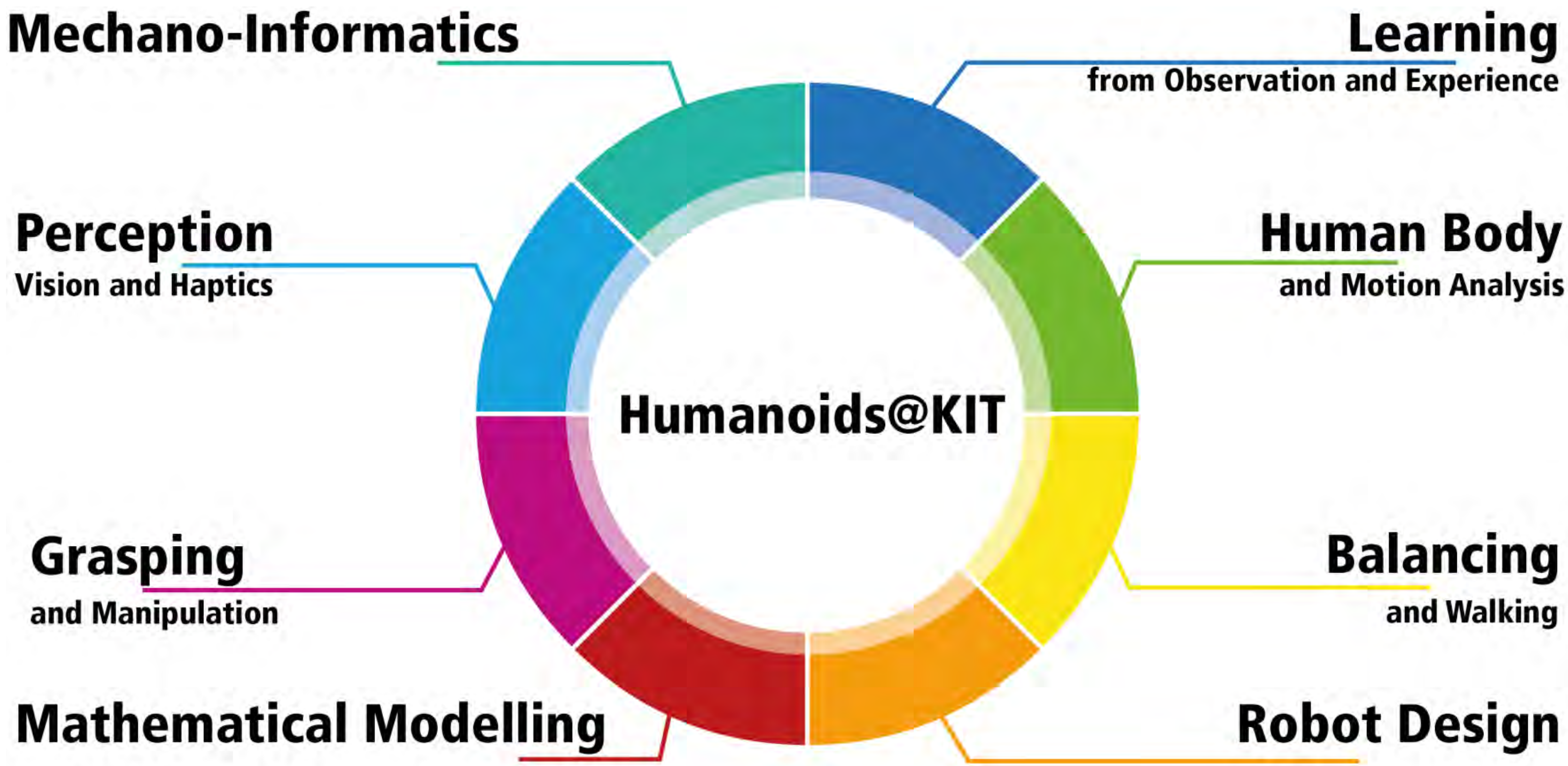
Humanoid Technologies for Humans

- Versatile systems that act and interact in made-for-human environments and use made-for-human tools
- Assistants and companions for people in different ages, situations, and environments to improve the quality of life
- Key technologies for future robotic systems
- Experimental platforms “bodies” to study theories about humans

My team

Humanoids@KIT

H^2T Research Topics



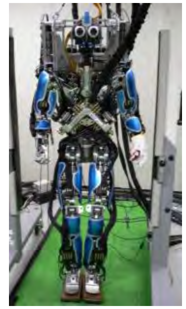
Humanoid robotics has made progress !

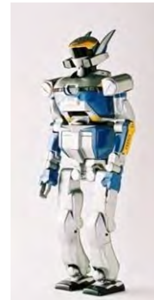

WABOT-1


P2


ASIMO


DB


CB

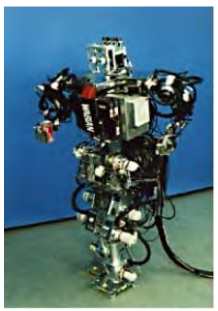

HRP-2


HRP-4


HRP-4C


ARMAR-IV

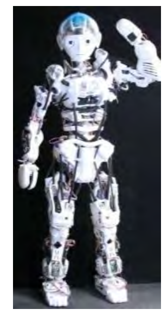

Toro


WABIAN


Twendy-one


ARMAR-III


iCub


kojiro


Partner Robot


HUBO


Lola


KOBIAN

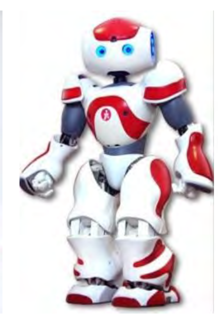

Cog


Petman


Atlas

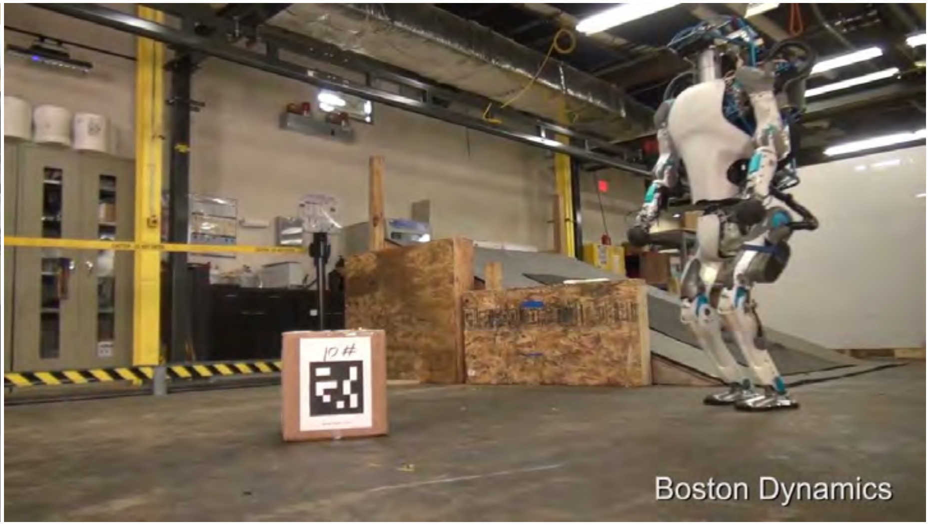

Robonaut


Justin

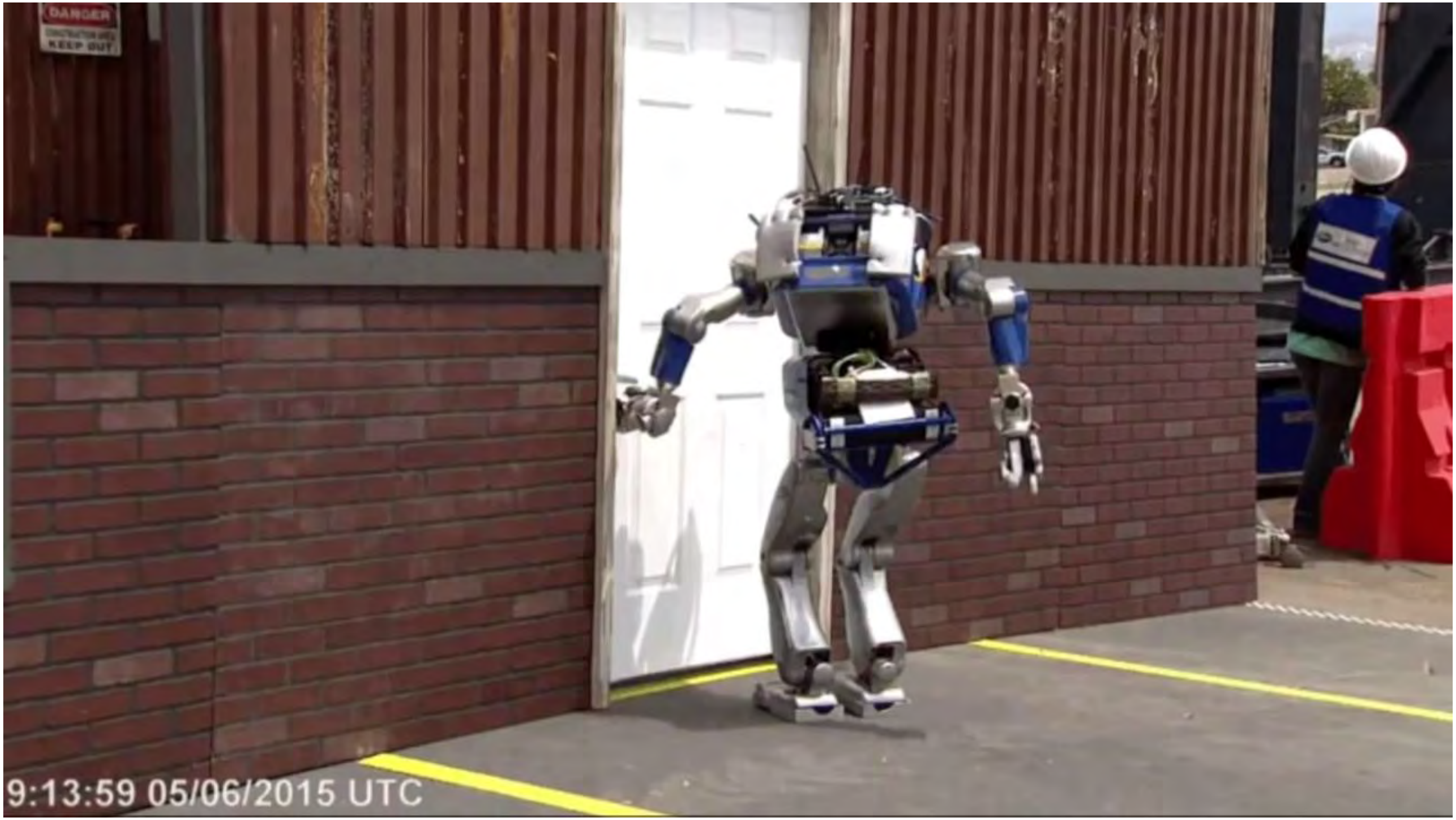

NAO


DARwIN-OP

Boston Dynamics Atlas



Humanoids vs. Doors

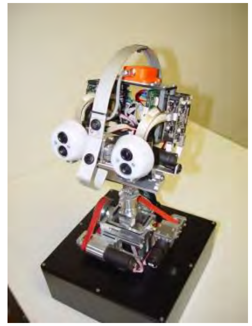


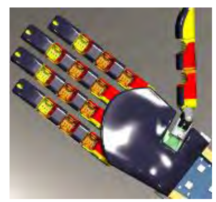
Humanoids in the real world

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

Die ARMAR Roboterfamilie







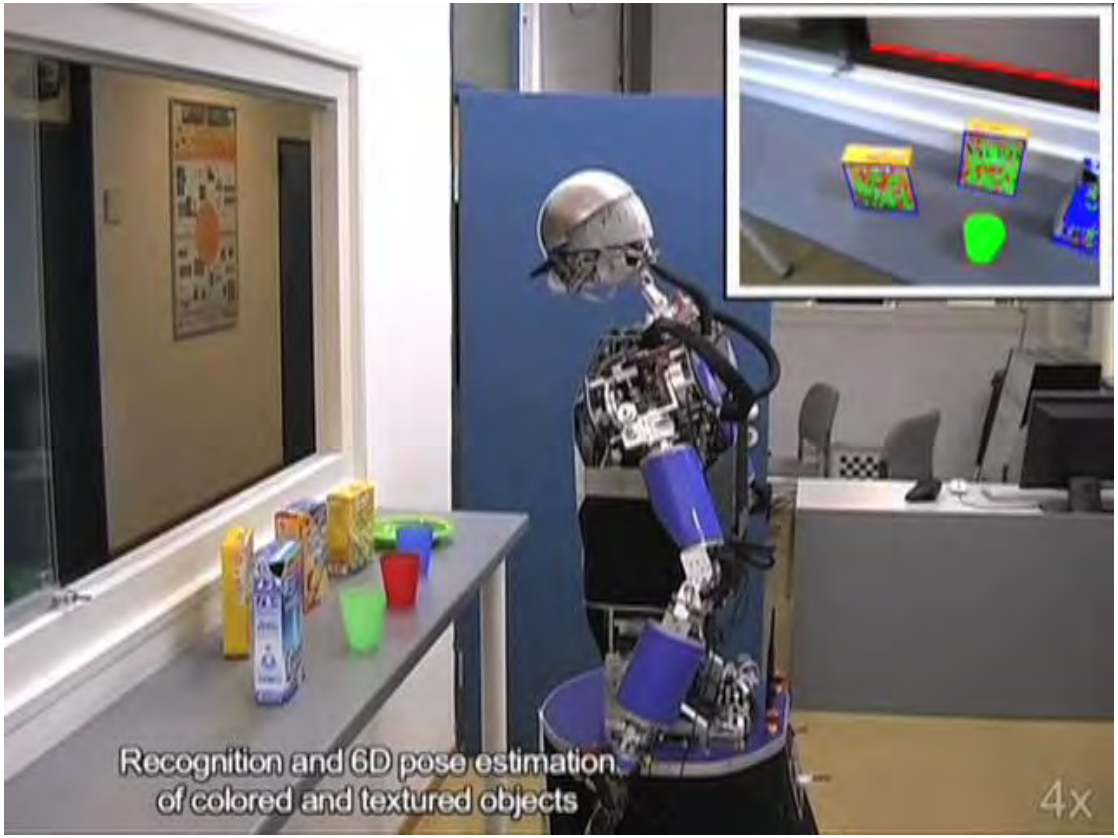
ARMAR-IIIa and ARMAR-IIIb

- 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-III in the RoboKITchen

- Object recognition and localization
- Vision-based grasping
- Hybrid position/force control
- Combining force and vision for opening and closing door tasks
- Collision-free navigation
- Vision-based self-localisation
- Multimodal human-robot dialogs
- Continuous speech recognition
- Learning new objects, persons and words
- Audio-visual tracking and localization
- …

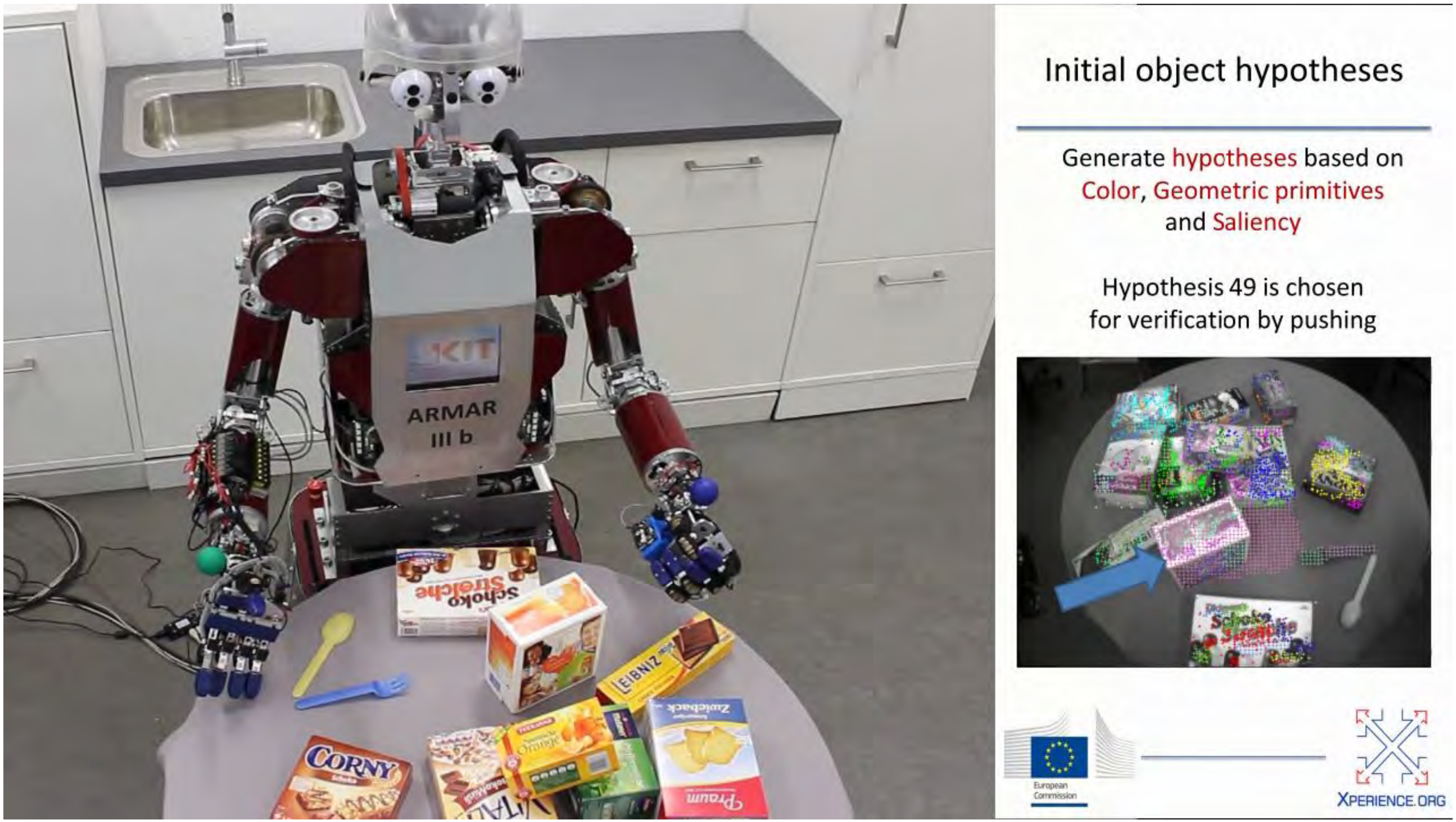


45 minutes, more than 2500 times since February 3, 2008

Discover, segment, learn and grasp unknown objects

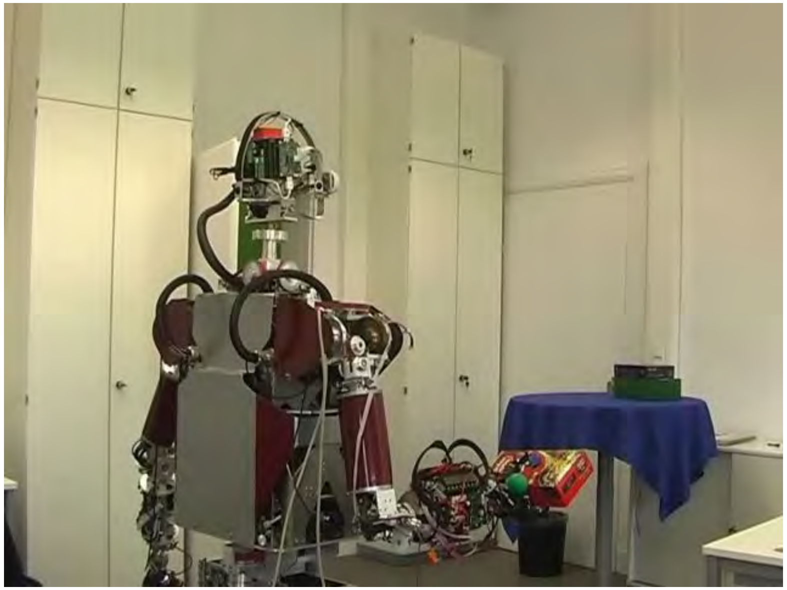
ICRA2014, ICRA 2012, Humanoids 2011, 2012 Adaptive Behavior 2013

Combining action, vision and haptics for grasping



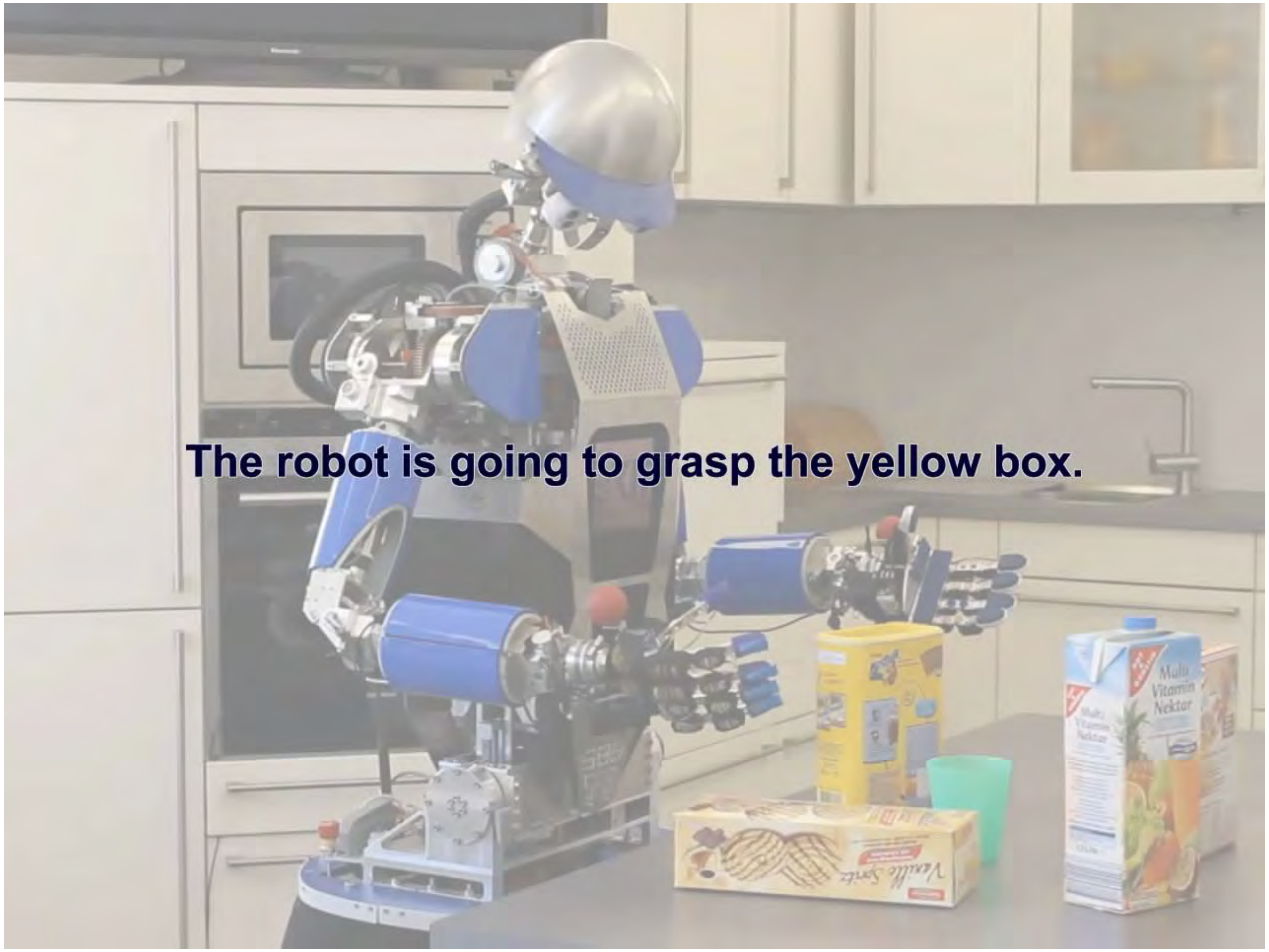
Object learning by manipulation and visual search

- Scene memory
  - Integration of object hypotheses in an ego-centric representation
- Active Search
  - Object search using perspective and foveal cameras of the head



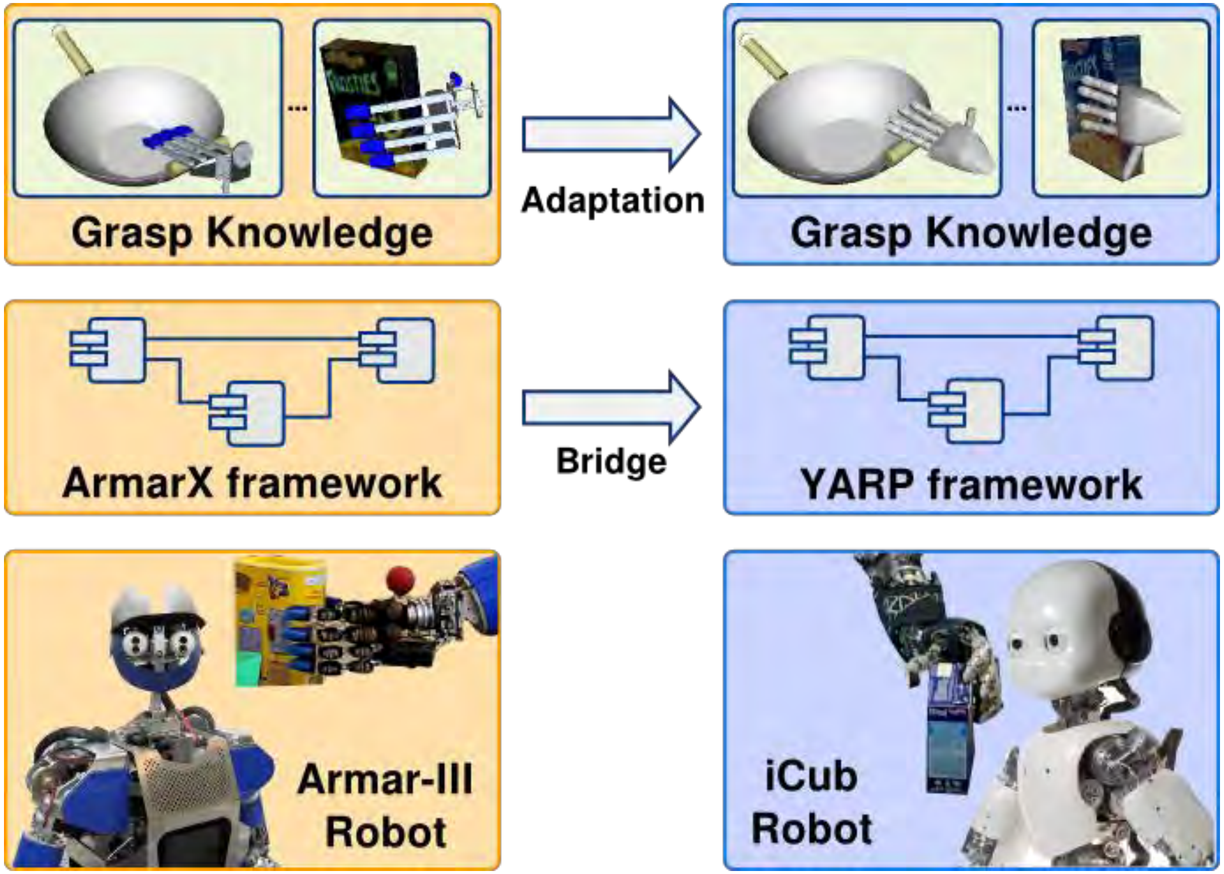
ICRA 2010
Humanoids 2009
ICRA 2009

Visual collision detection for reactive grasping



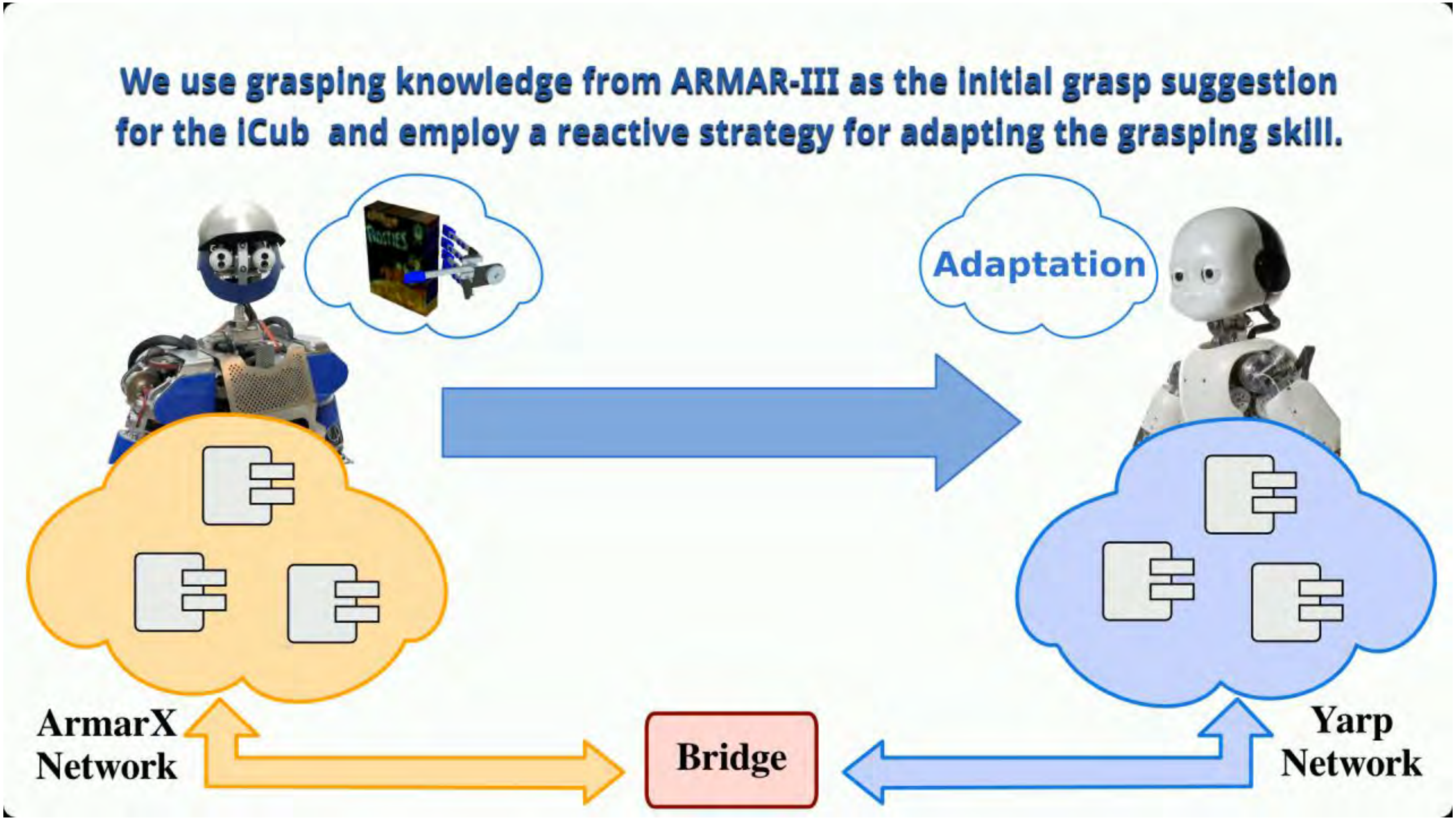
Humanoids 2014

Transferring Object Grasping Knowledge to iCub



A. Paikan, D. Schiebener, M. Wächter, T. Asfour, G. Metta and L. Natale, Transferring Object Grasping Knowledge and Skill Across Different Robotic Platforms, ICAR 2015

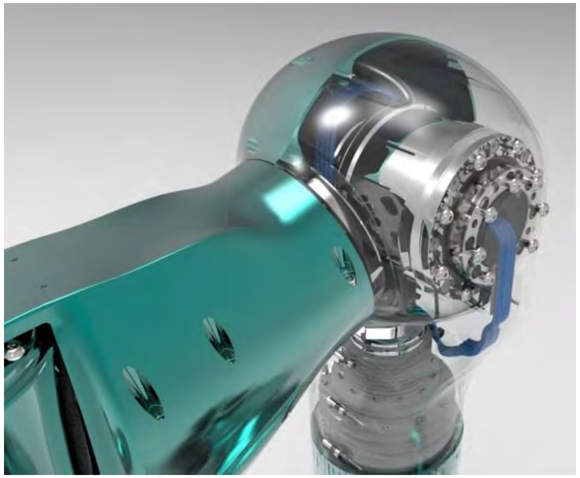
Transferring Object Grasping Knowledge to iCub



ARMAR robot technologies in warehouses

- **SecondHands: A robot assistant for industrial maintenance**
  - 5 years project in Horizon 2020 (2015 – 2019)
  - 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



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

Humanoids in the real world

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

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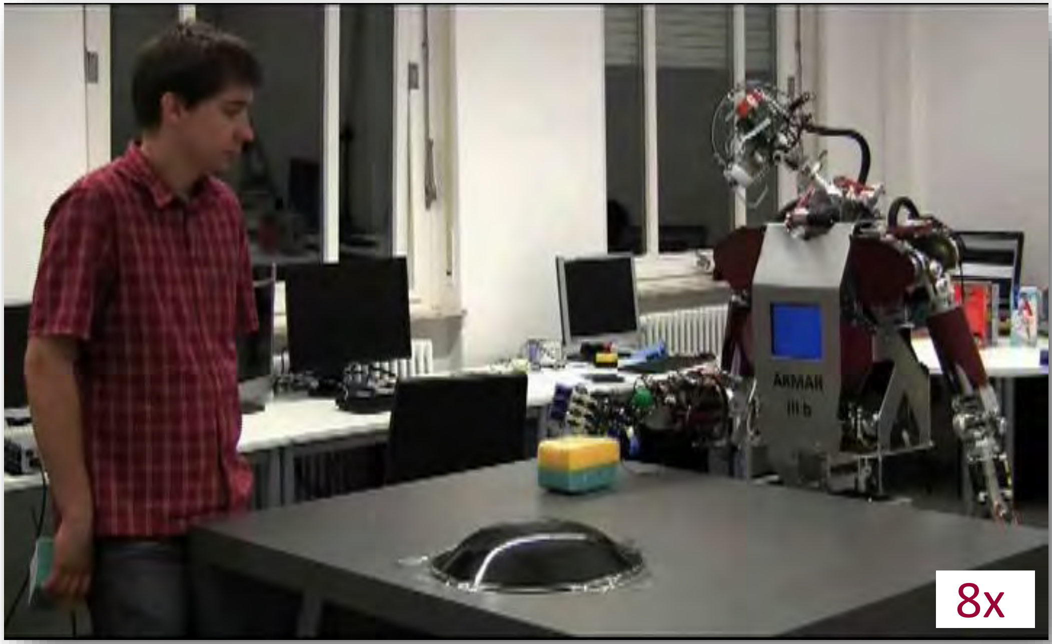
Learning from observation

- Building a library of motion primitives
- Dynamic movement primitives (DMP) for discrete and periodic movements



Humanoids 2006, IJHR 2008, Humanoids 2007, ICRA 2009, Humanoids 2009, TRO 2010, Humanoids 2012, IROS 2013, RAS 2015

Dynamic Movement Primitives (DMPs)

A DMP consists of two parts:

$$\dot{s}(t) = \text{Canonical}(t, s), \tag{1}$$

$$\dot{y}(t) = \text{Transform}(t, y) + \text{Perturbation}(s). \tag{2}$$

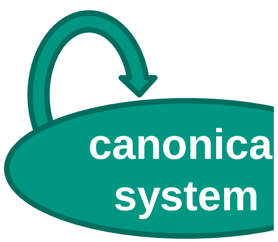
- The Canonical system
  - State of the DMP in time
  - Drives the perturbation to control the transformation system
- The Transformation system
  - Generates the motion of the robot according to the state of the canonical system

$$f(u) =$$

$$\xrightarrow{\hat{y}, \hat{\dot{y}}, \hat{\ddot{y}}}$$

n-dimension

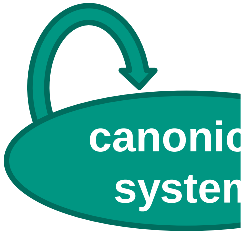
$f_{\text{target}}^{(1)}$



$y_n, \dot{y}_n, \ddot{y}_n$

n-dimension

$$\boldsymbol{w}_i$$



On discrete and periodic motion primitives

- Observation: **periodic motions start with a discrete part**

    - Stirring – first move the hand to the vessel containing the liquid.
    - Wiping – first move the hand to the surface to be wiped.
    - Peeling – first bring the peeler to the potato.
    - Cutting – first move the hand to the object.
    - Walking – first step vs. all other steps.
    - Juggling – bringing the balls into the air vs. juggling itself.

  We call this non-periodic part the transient.

- Encode the periodic movement and all corresponding transients into a single dynamical system (DMP)

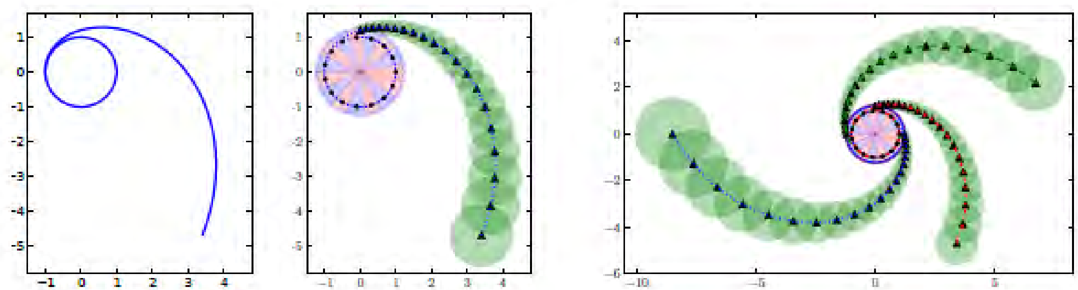
Humanoids 2012

Two dimensional canonical system

- $s(t) := (\varphi(t), r(t))$ in $\mathbf{R}\times(0,\infty)$ for φ, r solution of

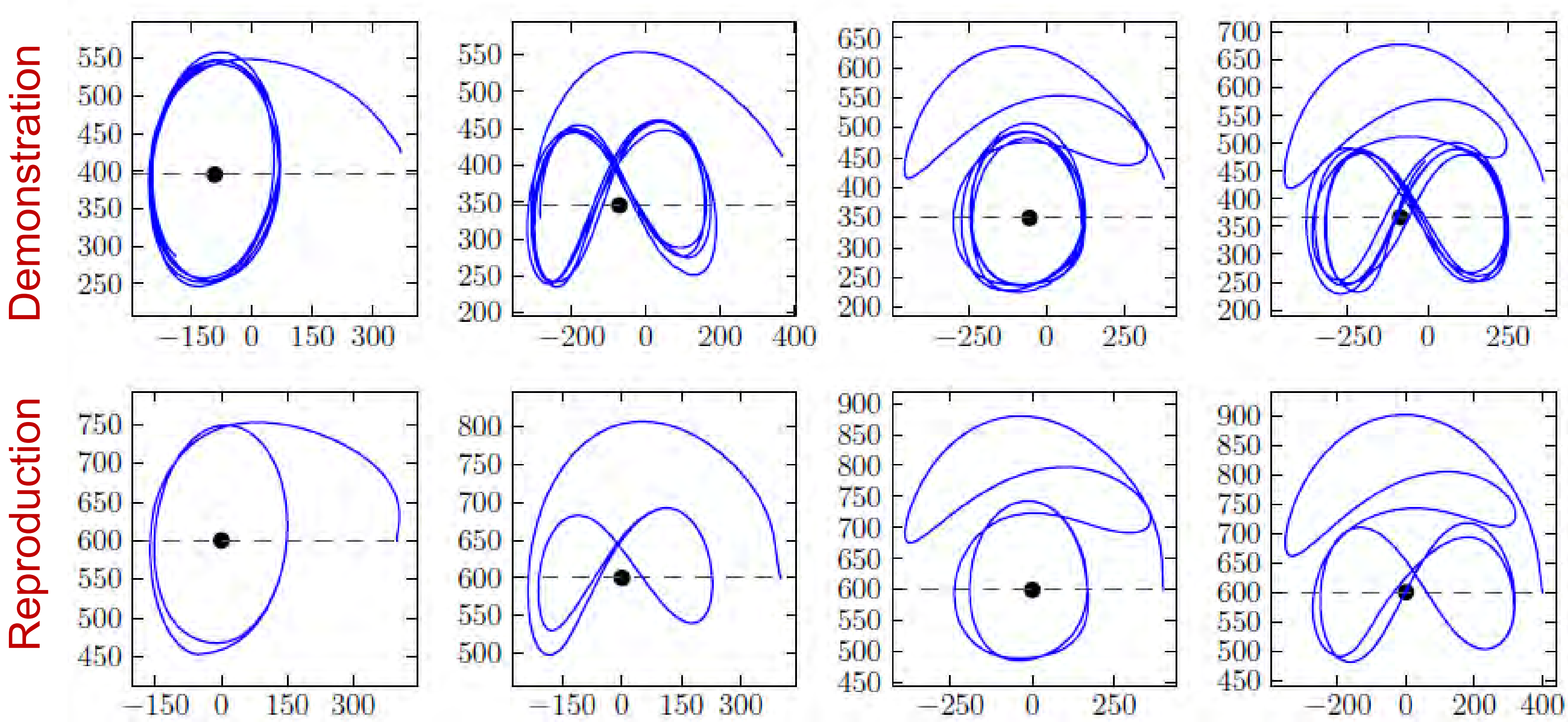
$$\begin{cases} \dot{\phi} = \Omega, \\ \dot{r} = \eta(\mu^\alpha - r^\alpha) r^\beta, \\ \phi(0) = \phi_0, \; r(0) = r_0 \end{cases}$$

- ψ_j "living" outside the limit cycle (transient).
- φ_i "living" on the limit circle (periodic pattern).

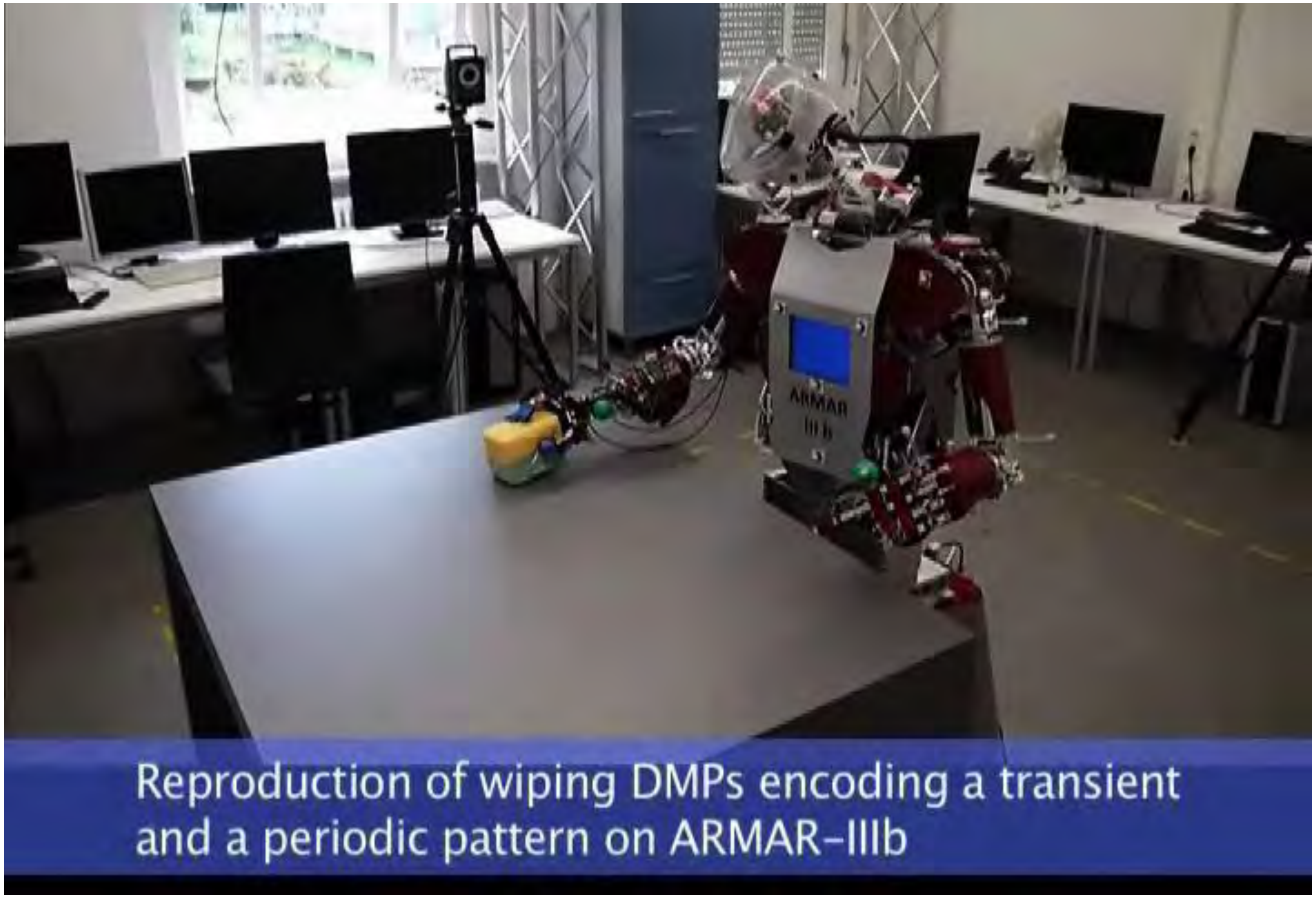


- Each transient has its separate set of basis functions ψ_j.

Evaluation



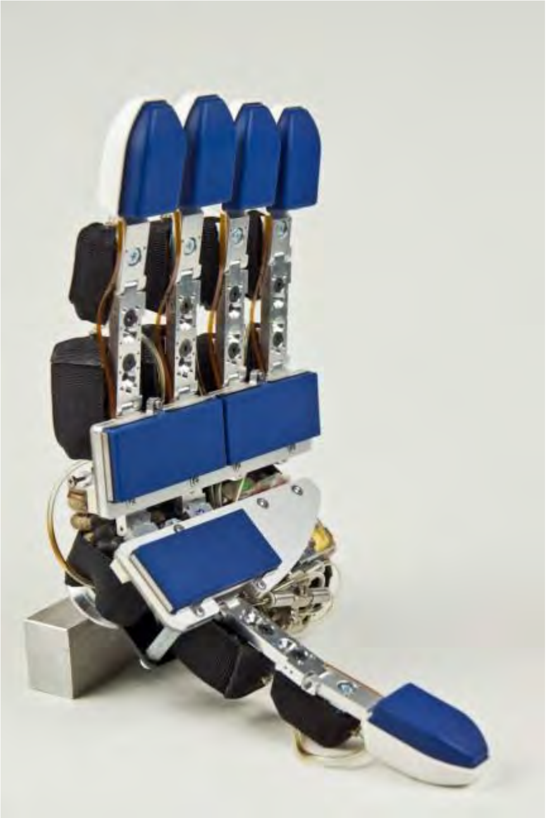
Periodic and transient motions



Humanoids 2012

Learn to wipe

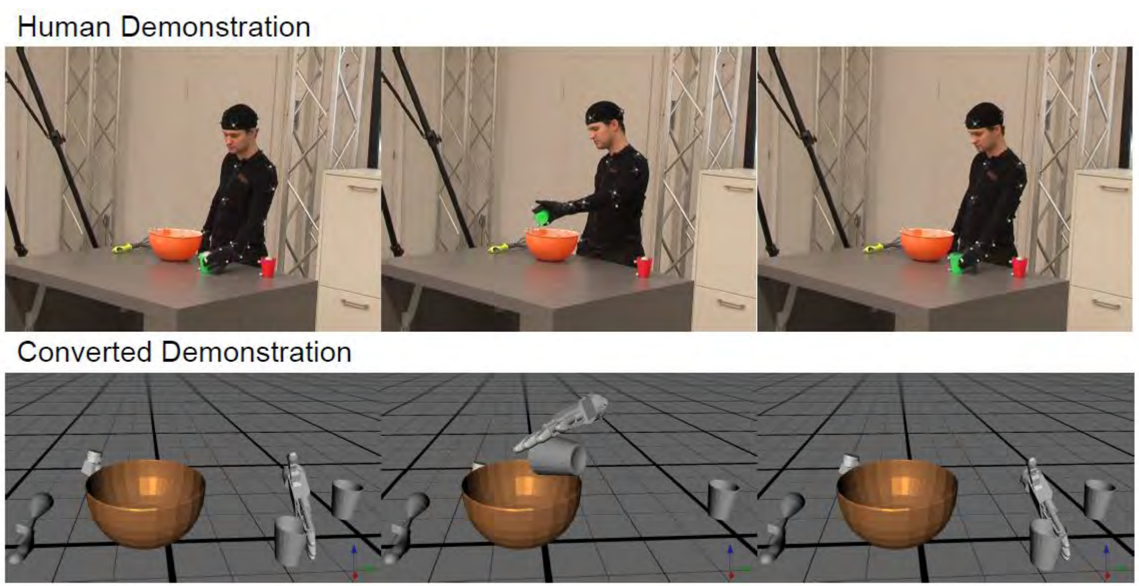
- Learning associations between object properties and action parameter
  → Object-Action Complexes (OACs)



ICRA 2014

Understanding human demonstration

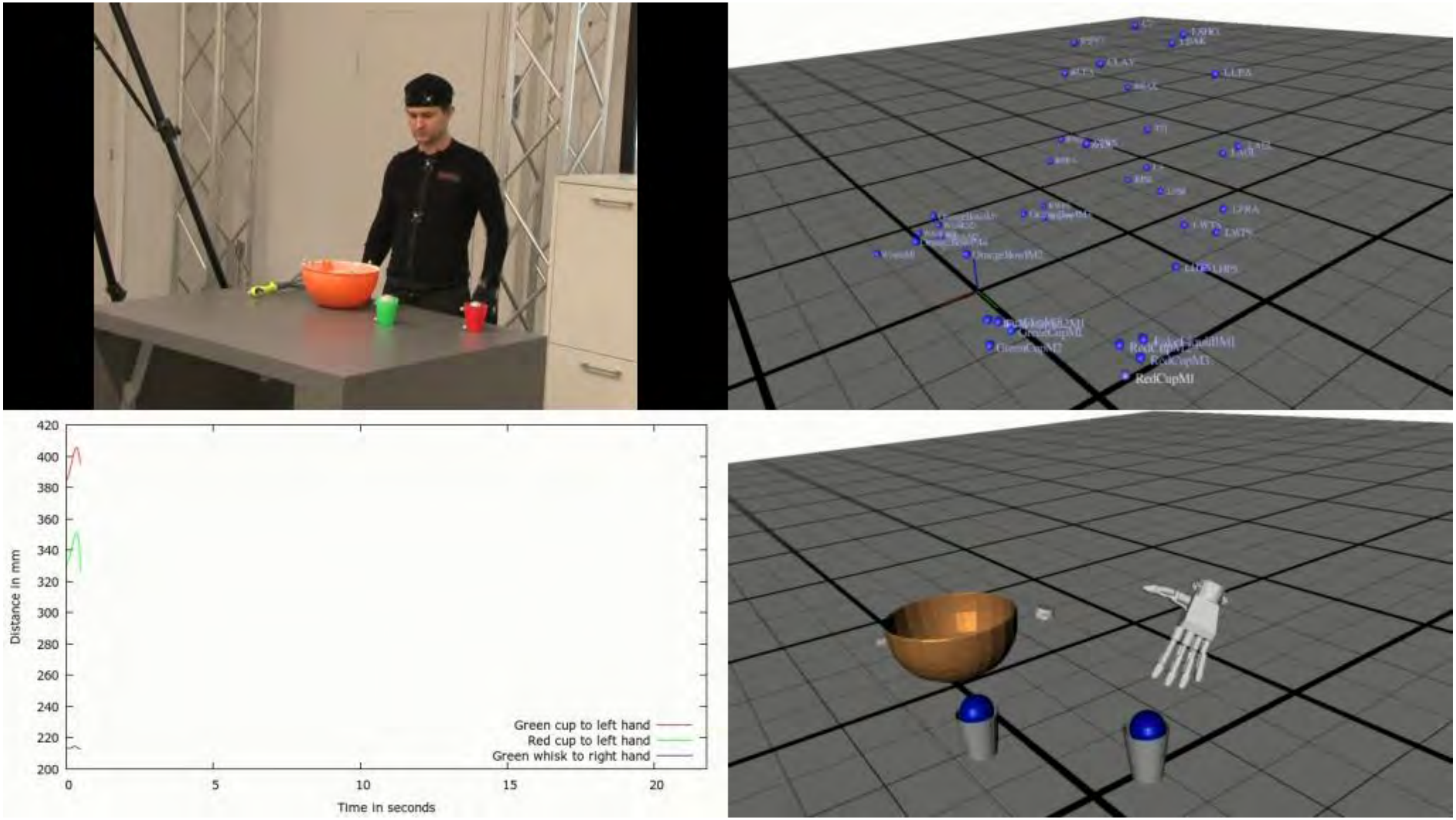
- **Hierarchical action segmentation** which considers motion and relevant objects
  - Semantic segmentation based on object-hand and object-object relation
  - Motion segmentation based on trajectory characteristics (motion dynamics)



Hierarchical Segmentation

No contact	Cup in left hand			No contact
Grasp	Lift	Pour	Place	Retreat

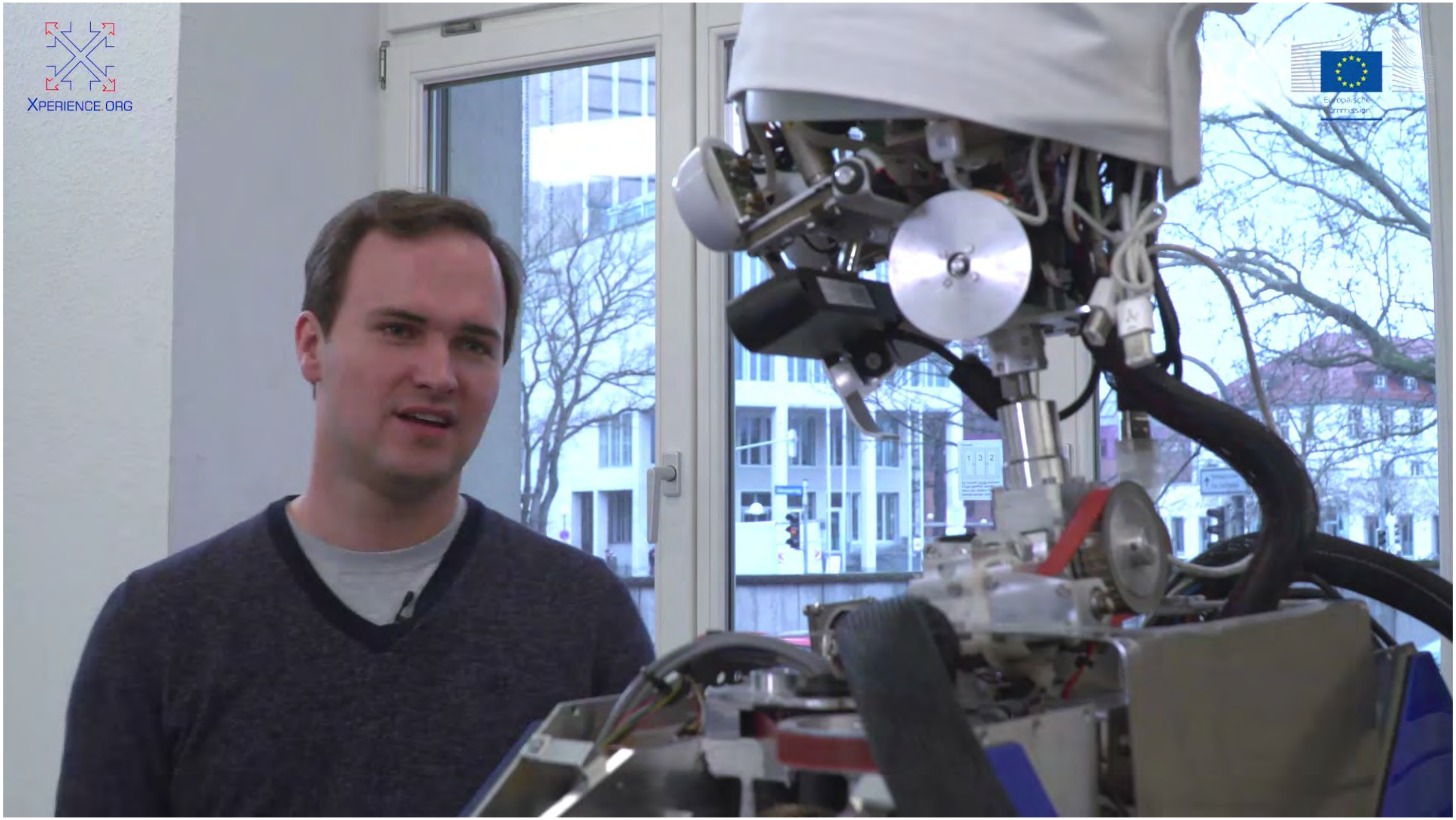
Hierarchical action segmentation



Learning from observation – prepare the dough

Integrating language, planning and execution with OACs

… dinner for two people …

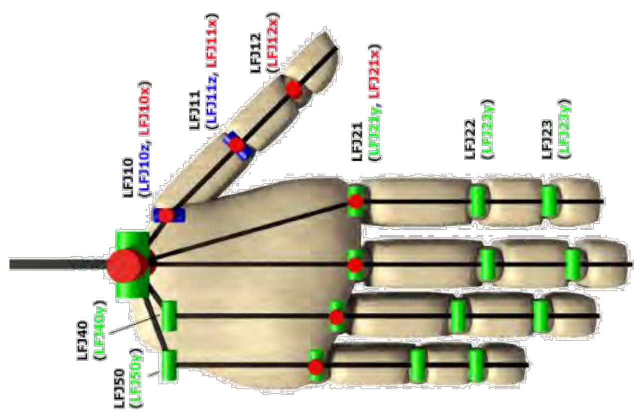


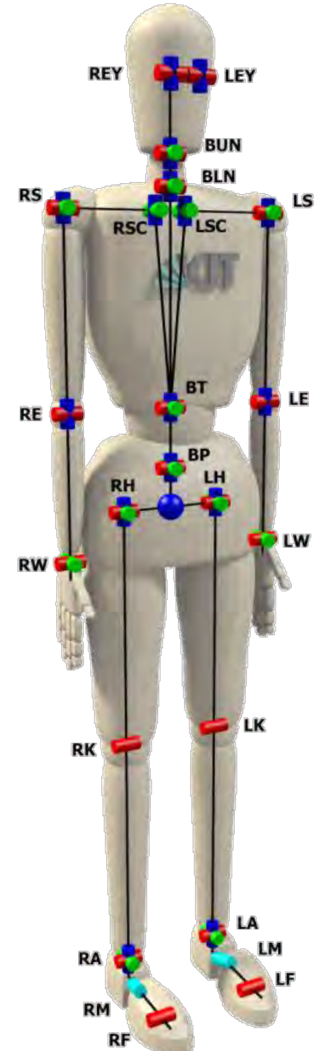
KIT whole-body human motion database

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

The Master Motor Map (MMM)

- **Reference model of the human body**
  - Kinematics and dynamics model
    - Joint Limits
    - Center of Mass
    - Mass percentage of total weight
    - Inertia Tensor
  - Kinematics/Dynamics properties scalable regarding subject height and weight
  - **Subject-specific** parameters
  - Currently: 104 DoF

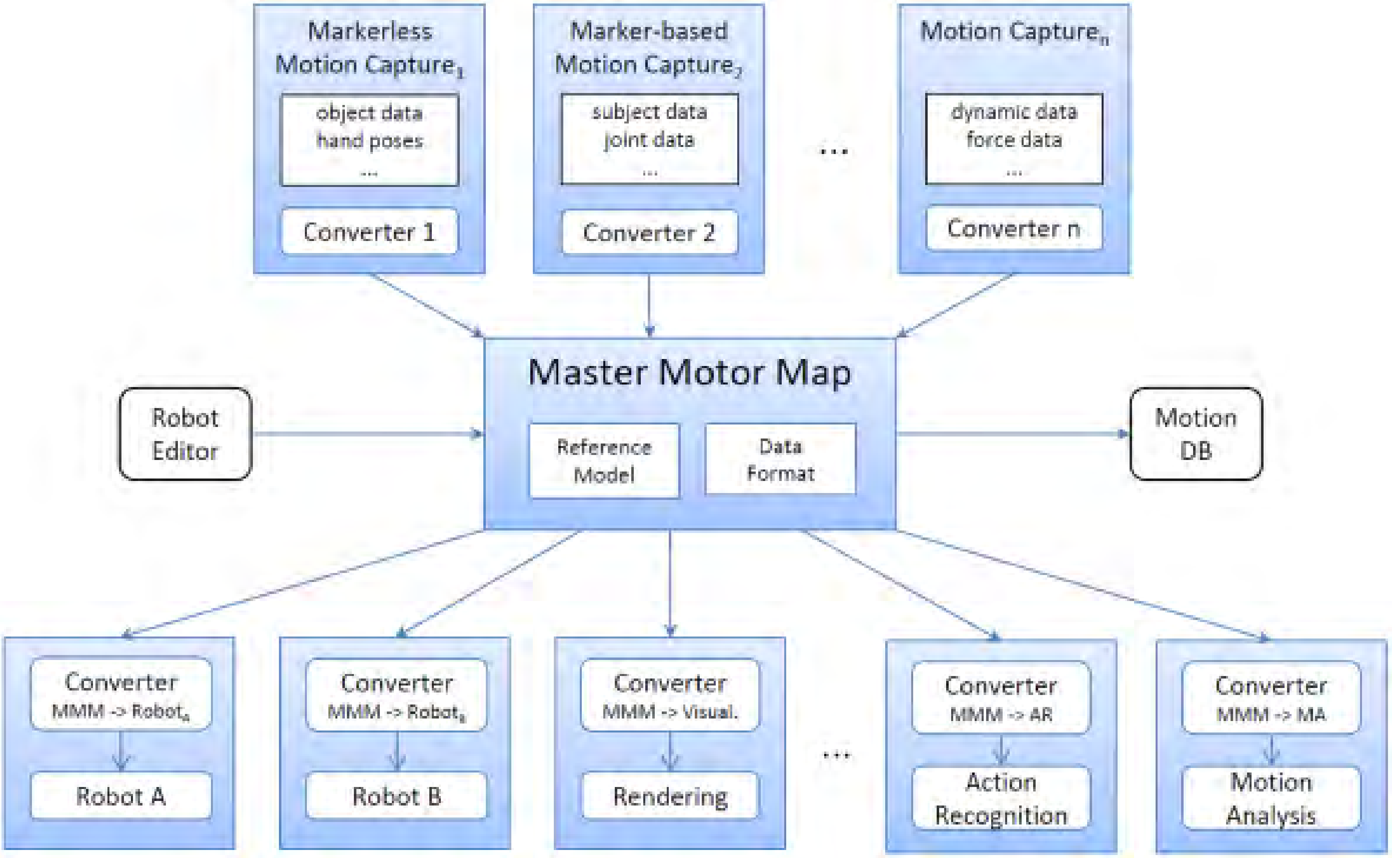




T-RO 2016

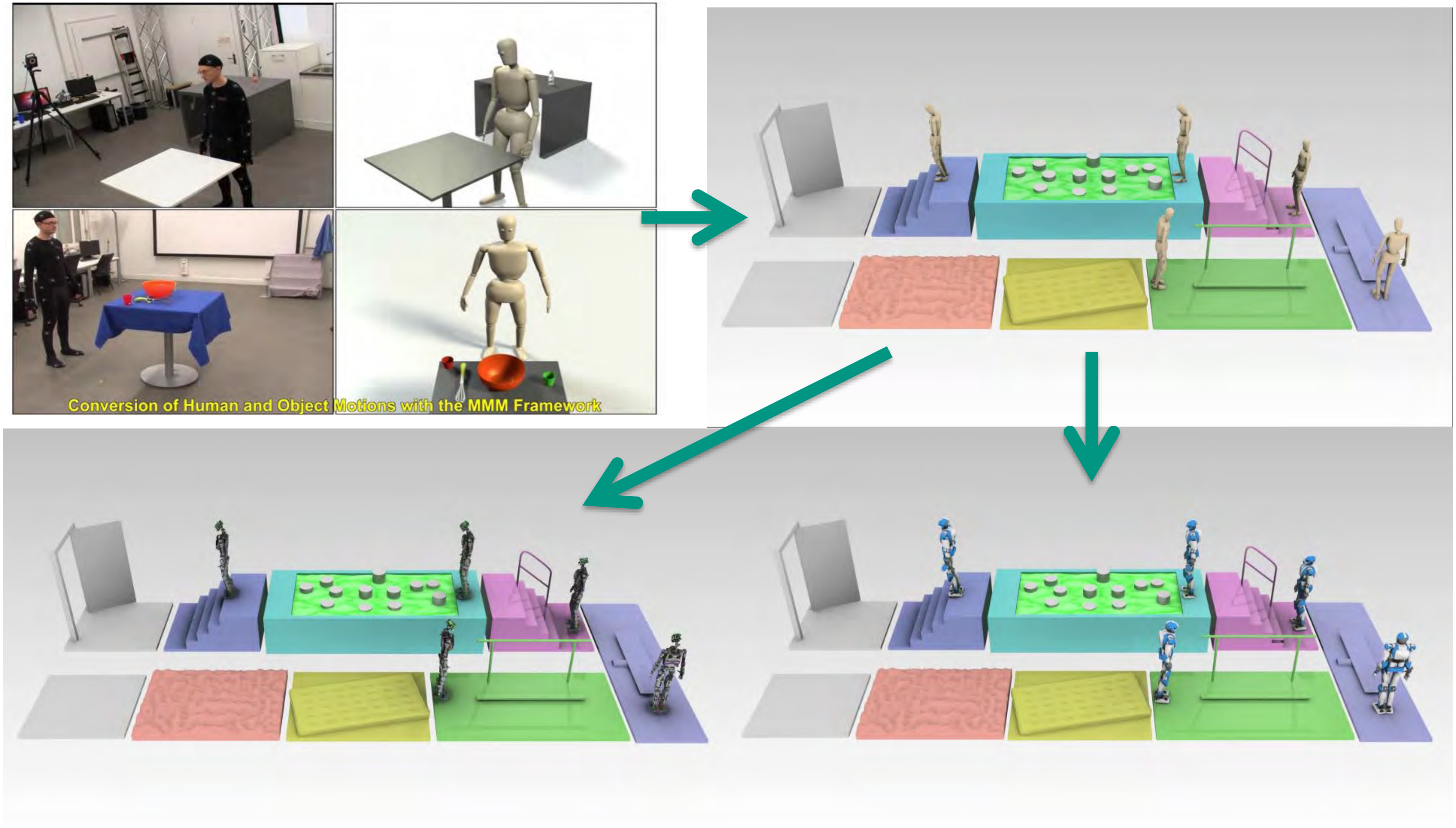
The Master Motor Map (MMM)

- **Unifying framework** for capturing, representation, visualization and whole body human motion and mapping/converting to different embodiments



T-RO 2016

The KIT whole-body human motion database

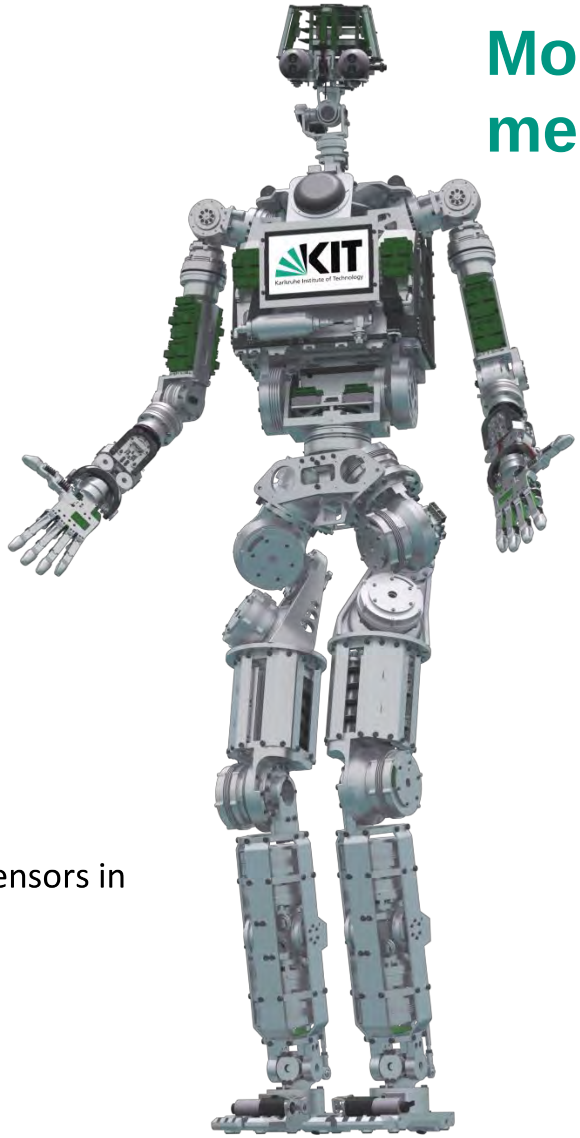


ARMAR-IV: Mechano-Informatics

- 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

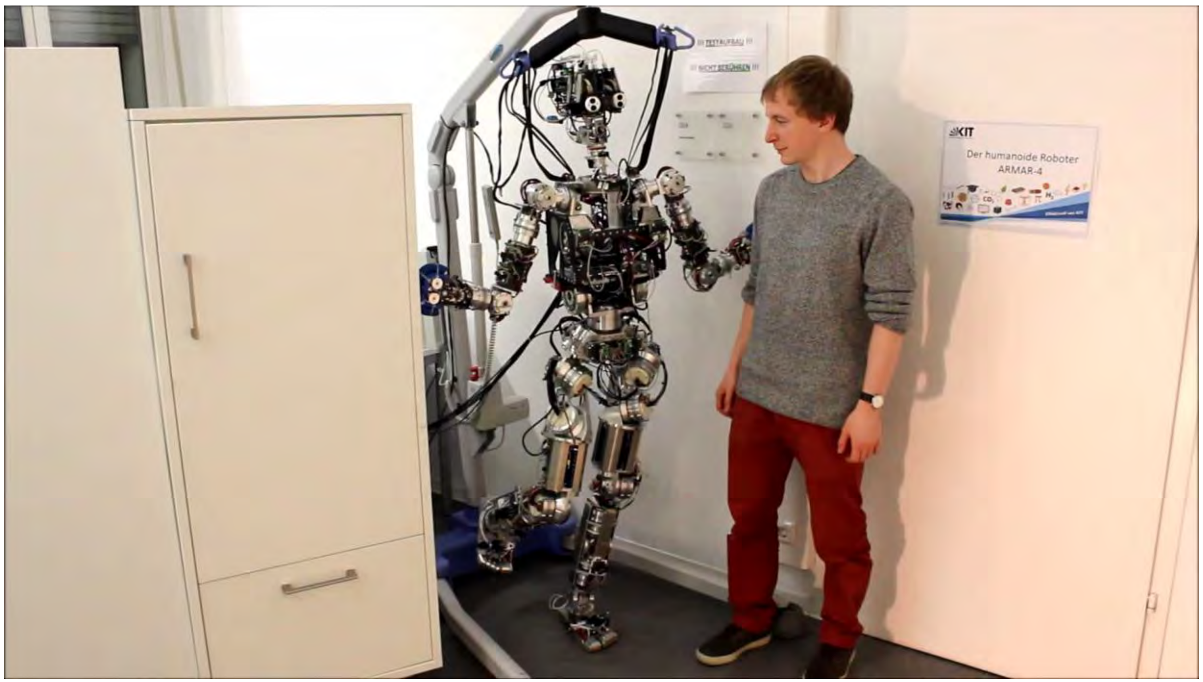
made@KIT

70 kg

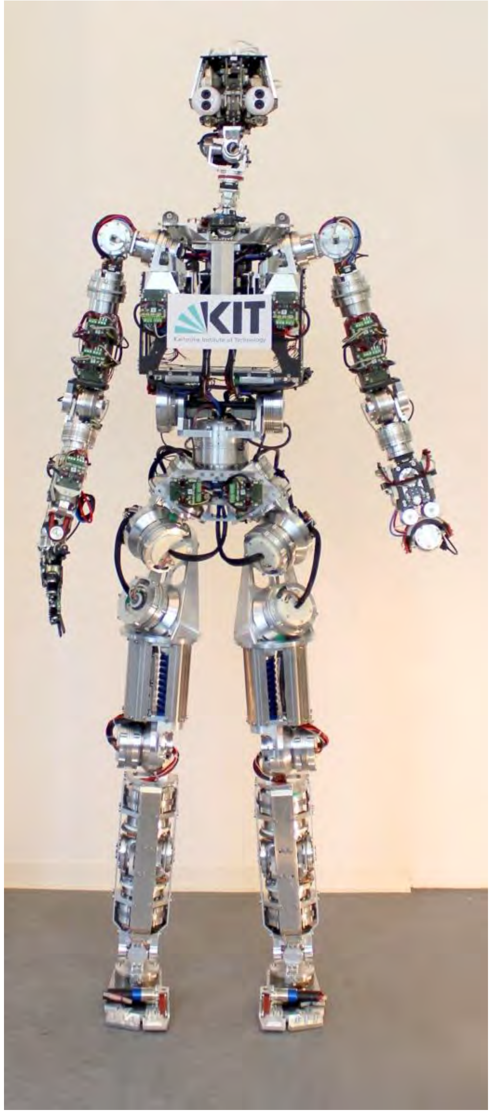
170 cm

… balancing, fall prevention, push recovery …

- 63 DOF
- Torque-controlled!



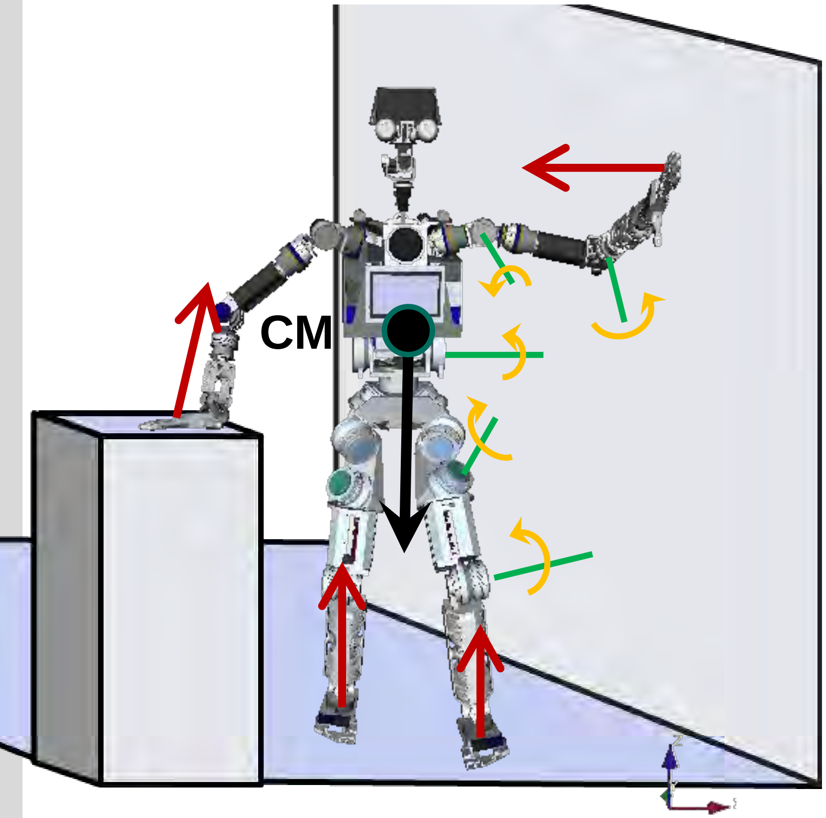
Multi-contact active compliance balancing controller

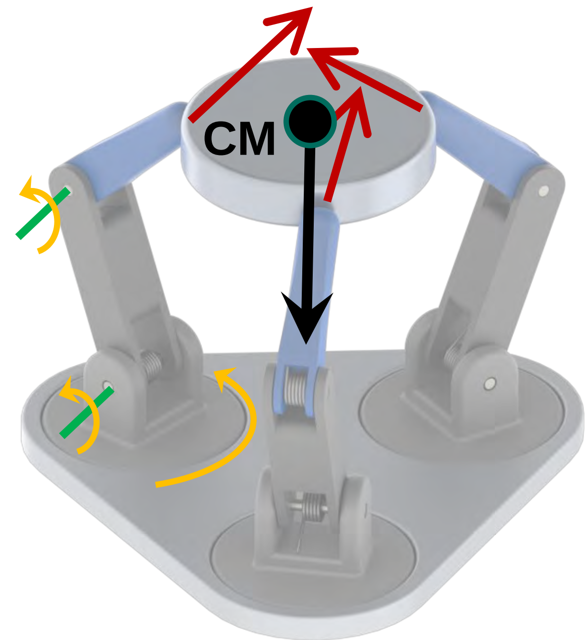


mocap data → MMM → robot model → real robot

The duality of grasping and balancing

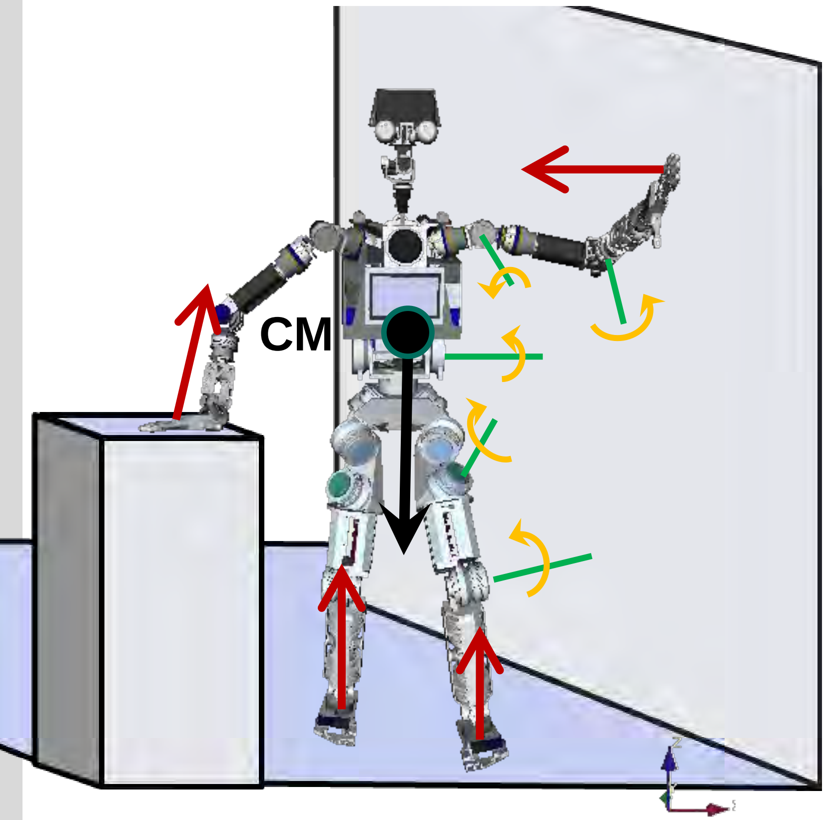
Equilibrium is reached by balancing similar sets of forces





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

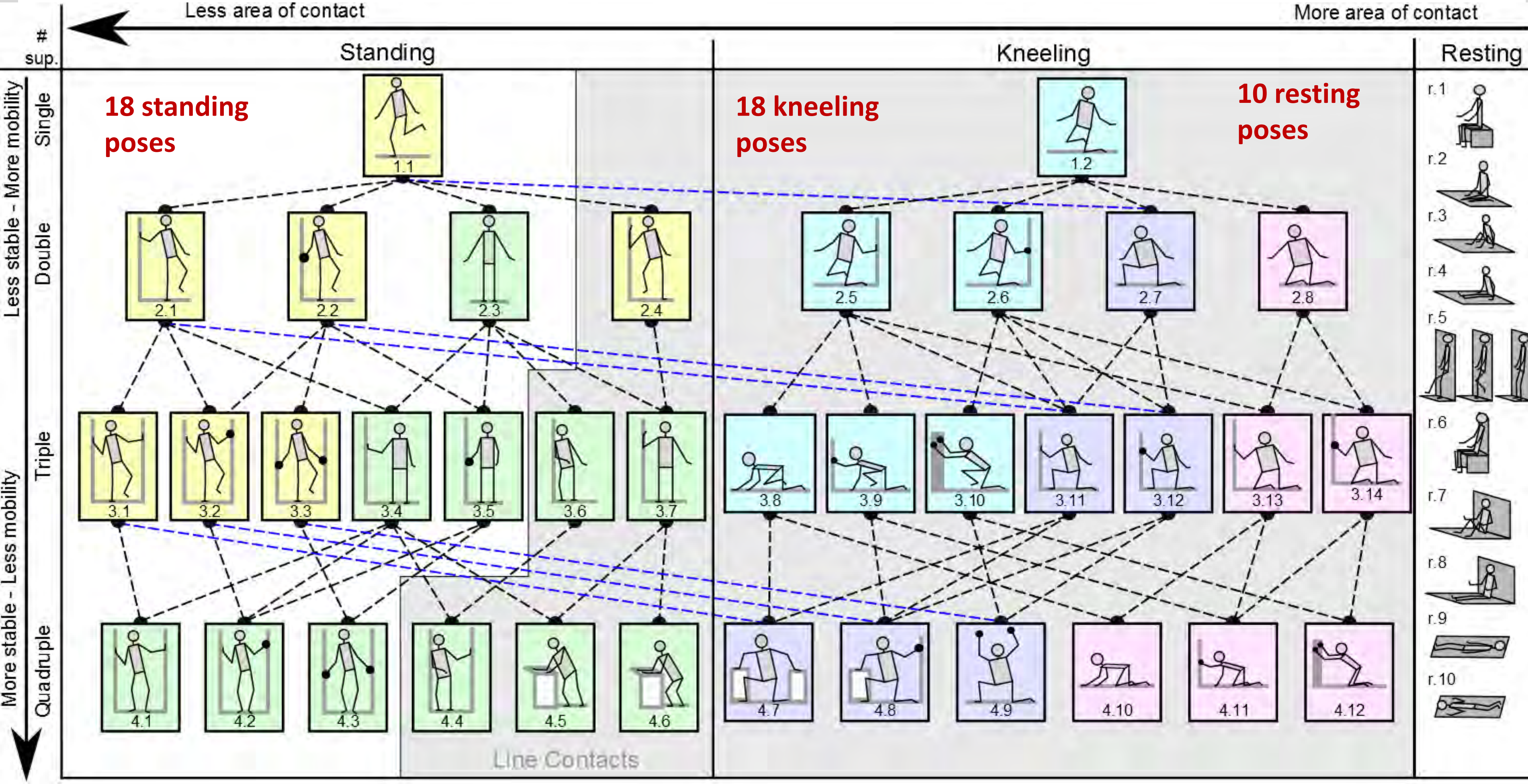
On the Duality of grasping and balancing

- 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

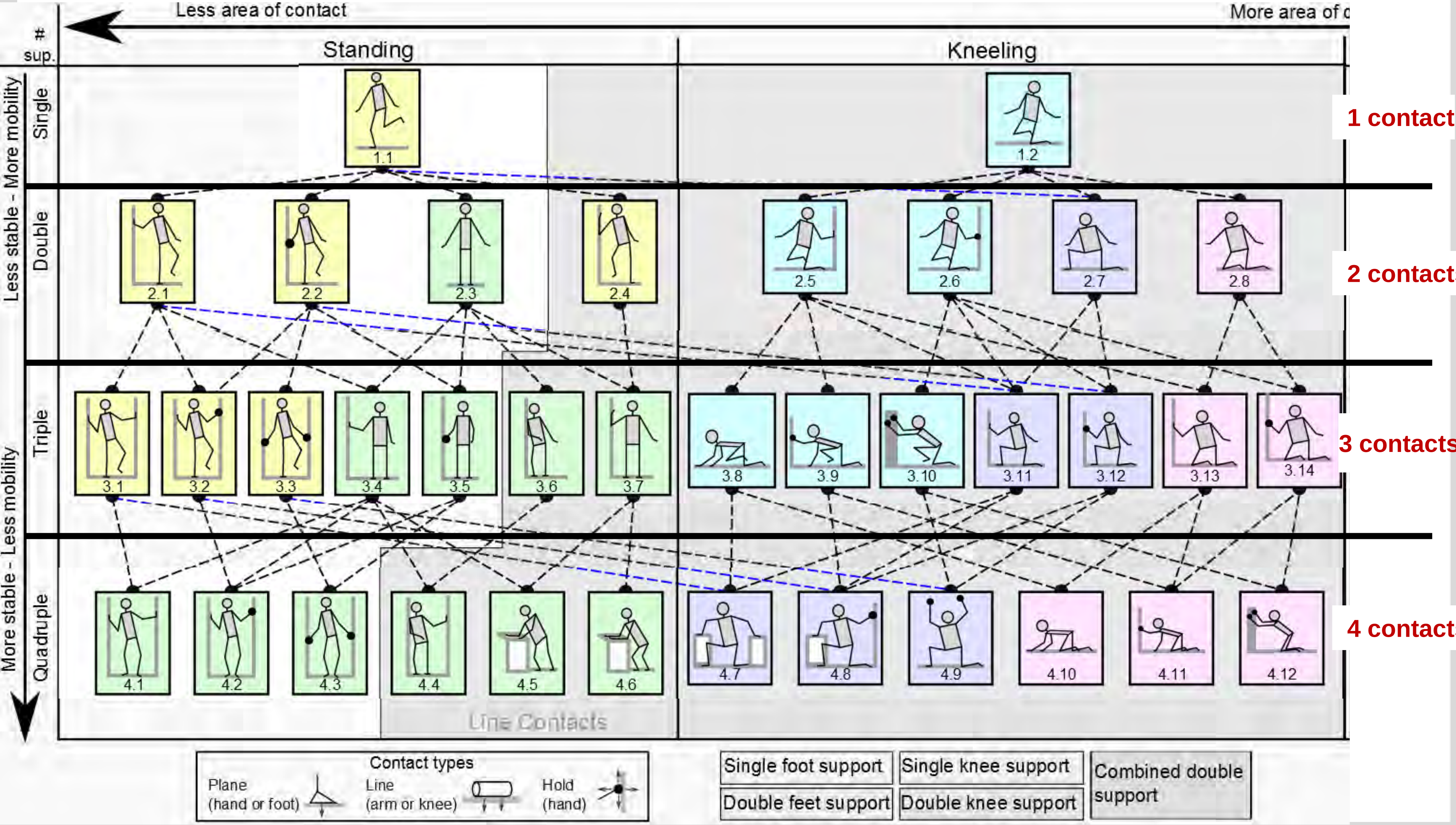
Taxonomy of whole-body poses



Total: 46 classes

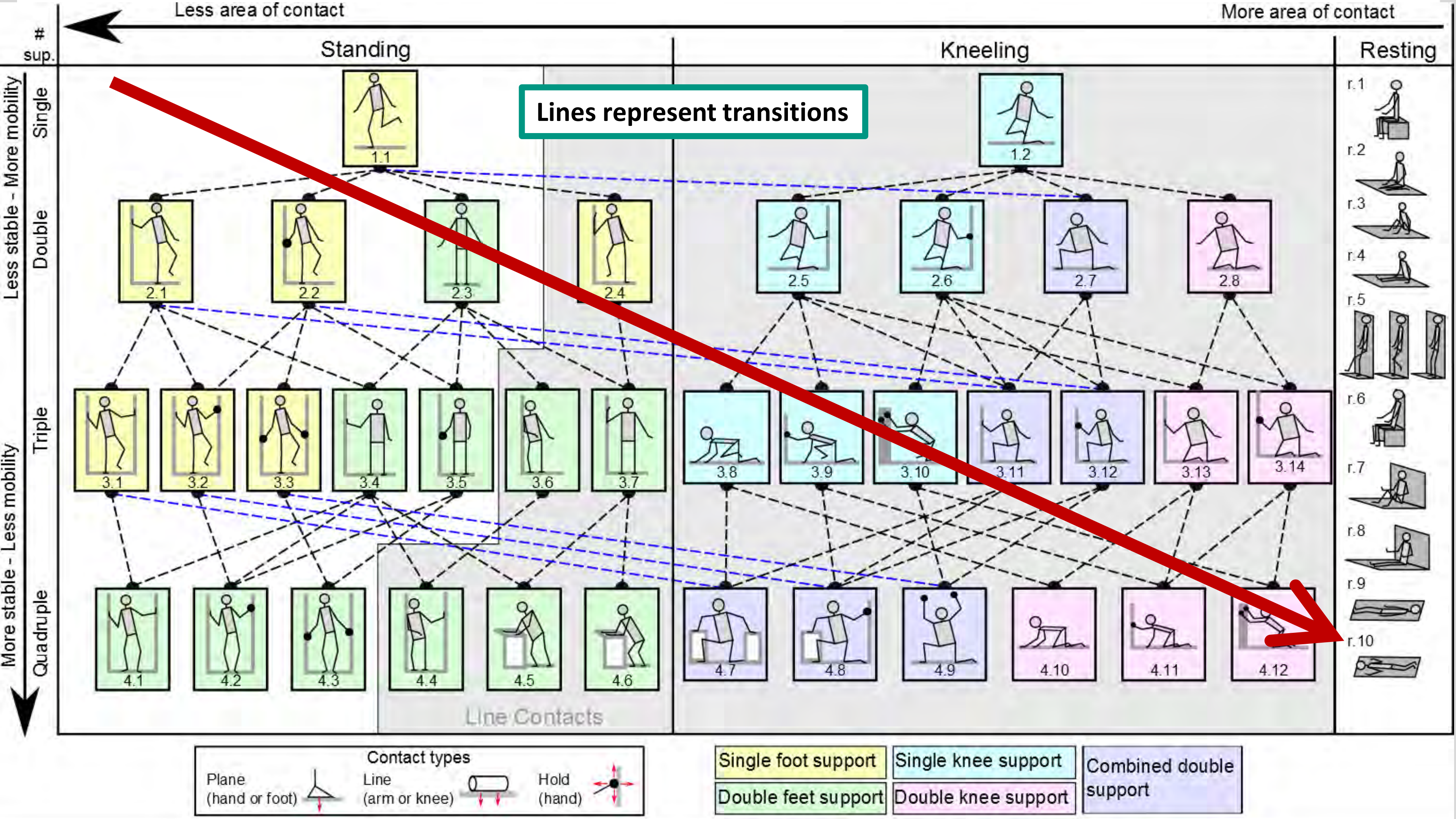
Borras and Asfour, IROS 2015

Taxonomy of whole-body poses



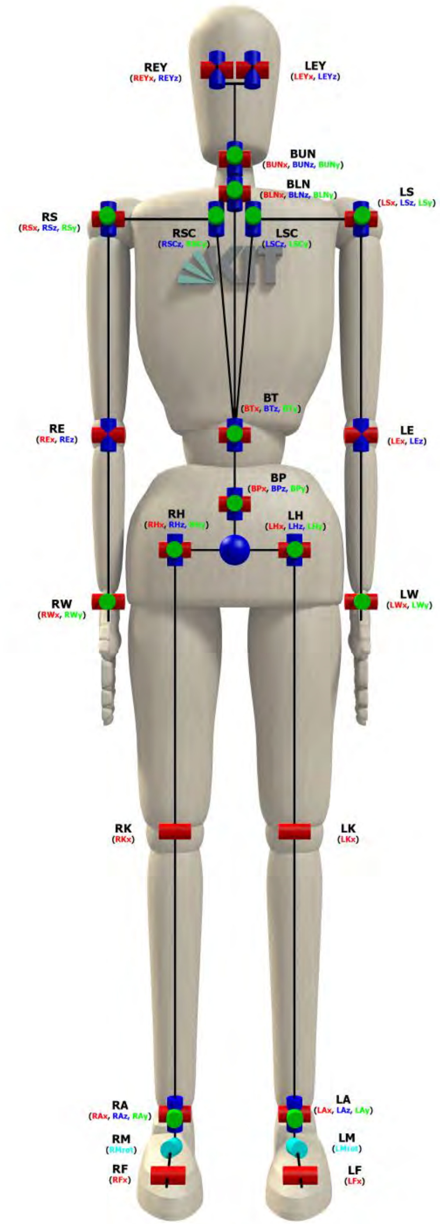
Borras and Asfour, IROS 2015

Taxonomy of whole-body poses



Validation of the taxonomy

- Analyses of different human loco-manipulation tasks with supports
- 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

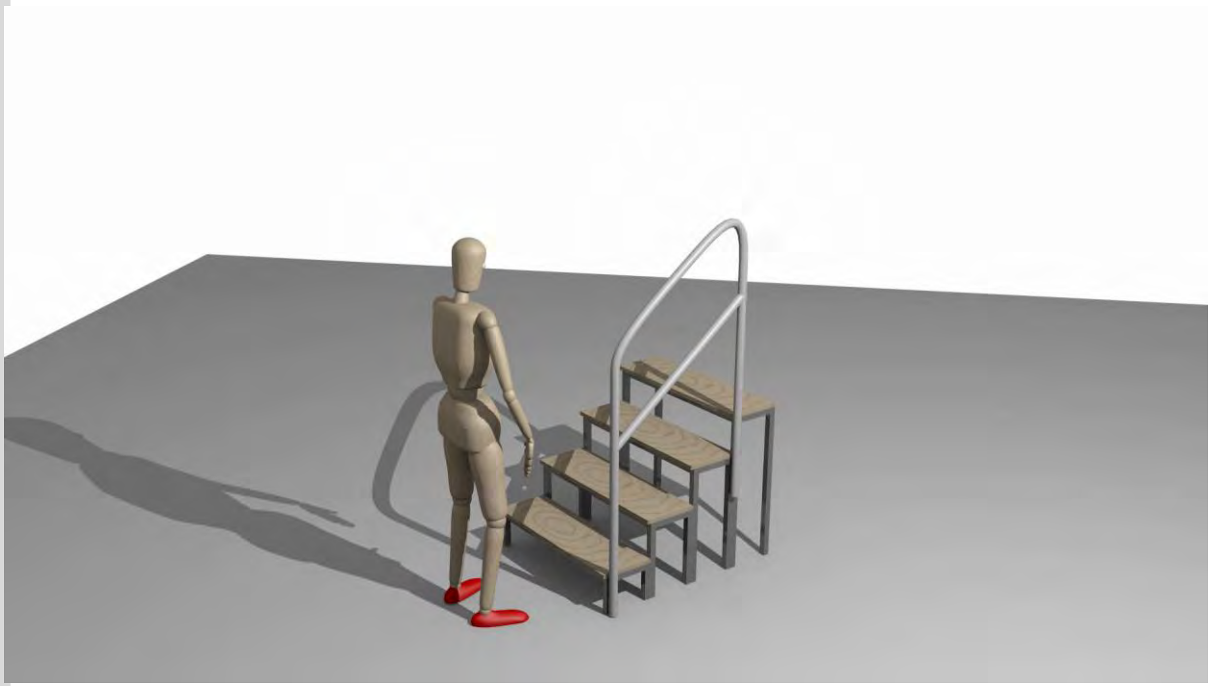


Analysis of pose transitions

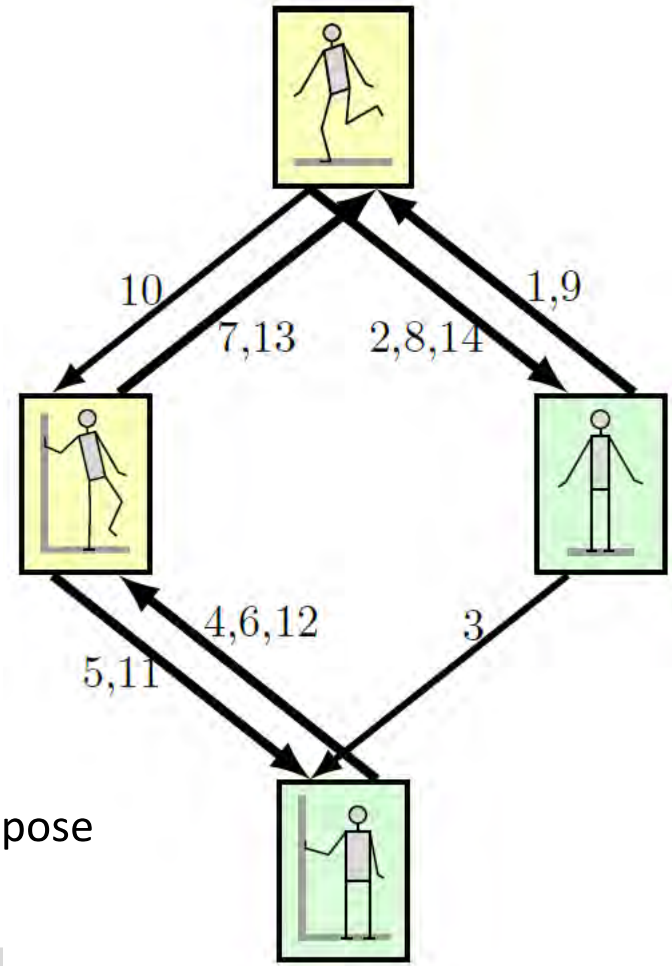
Karlsruhe Institute of Technology

Going upstairs with a handle

Detection of support contacts highlighted in red

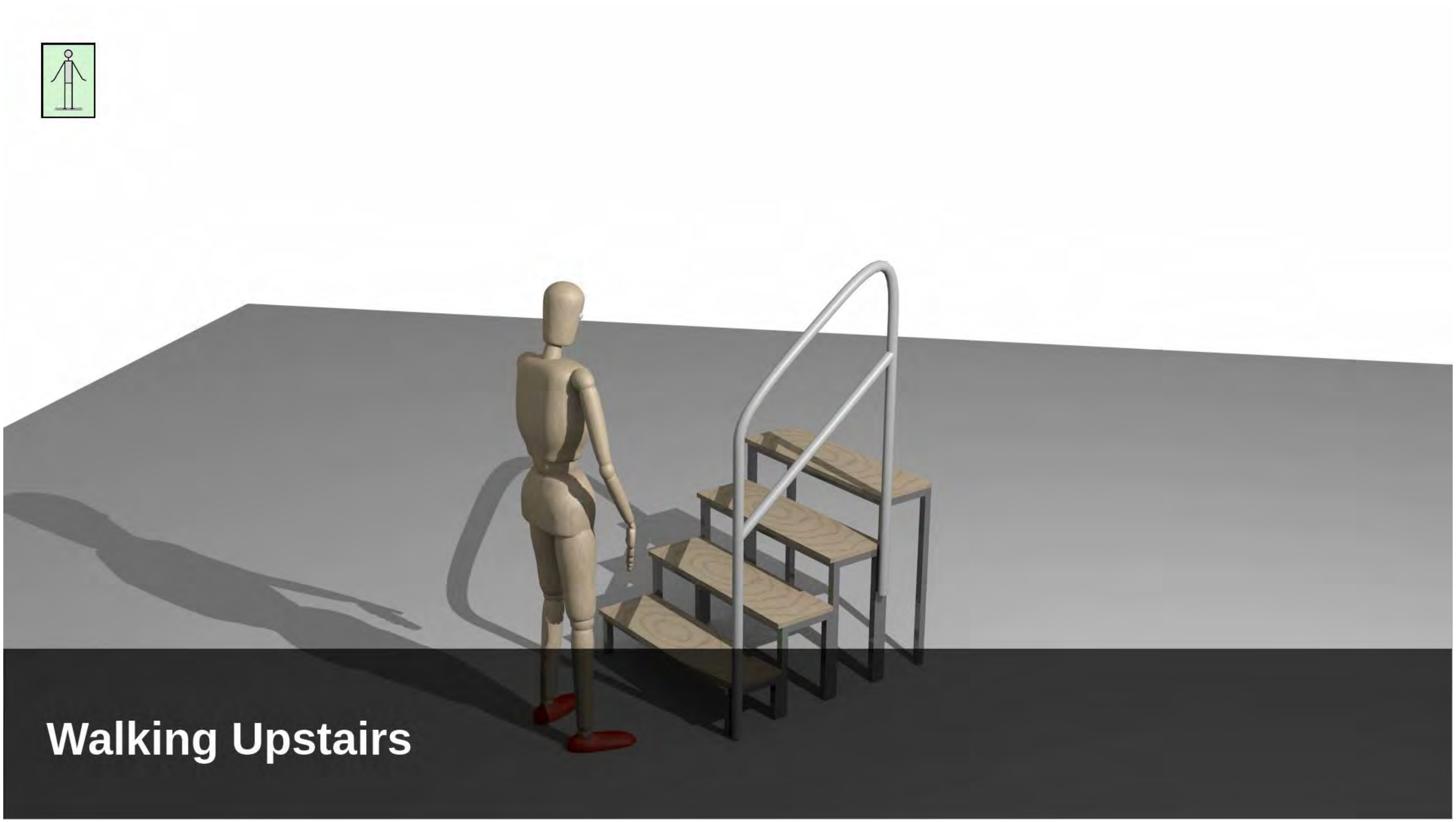


Generated graph of transitions:

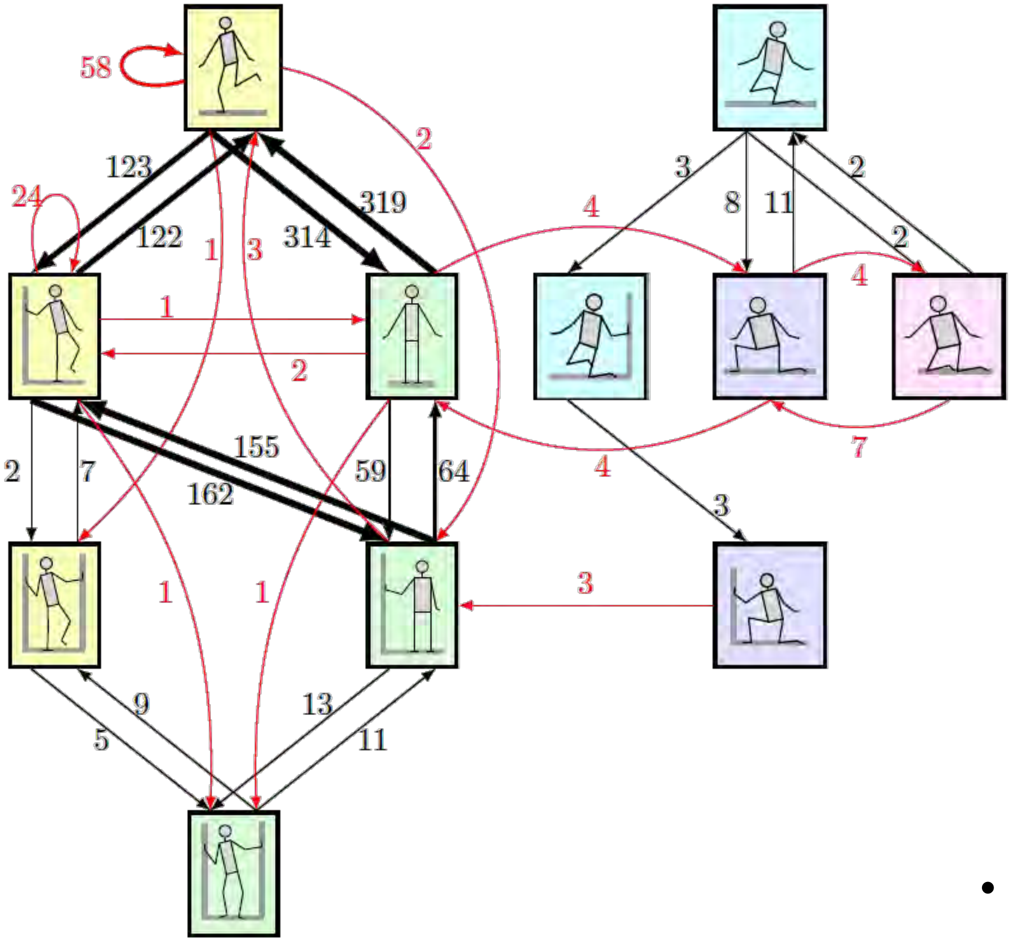


Subject swings left leg with a *right foot – right hand* support pose

Analysis of whole-body loco-manipulation tasks



Data-driven validation of the taxonomy

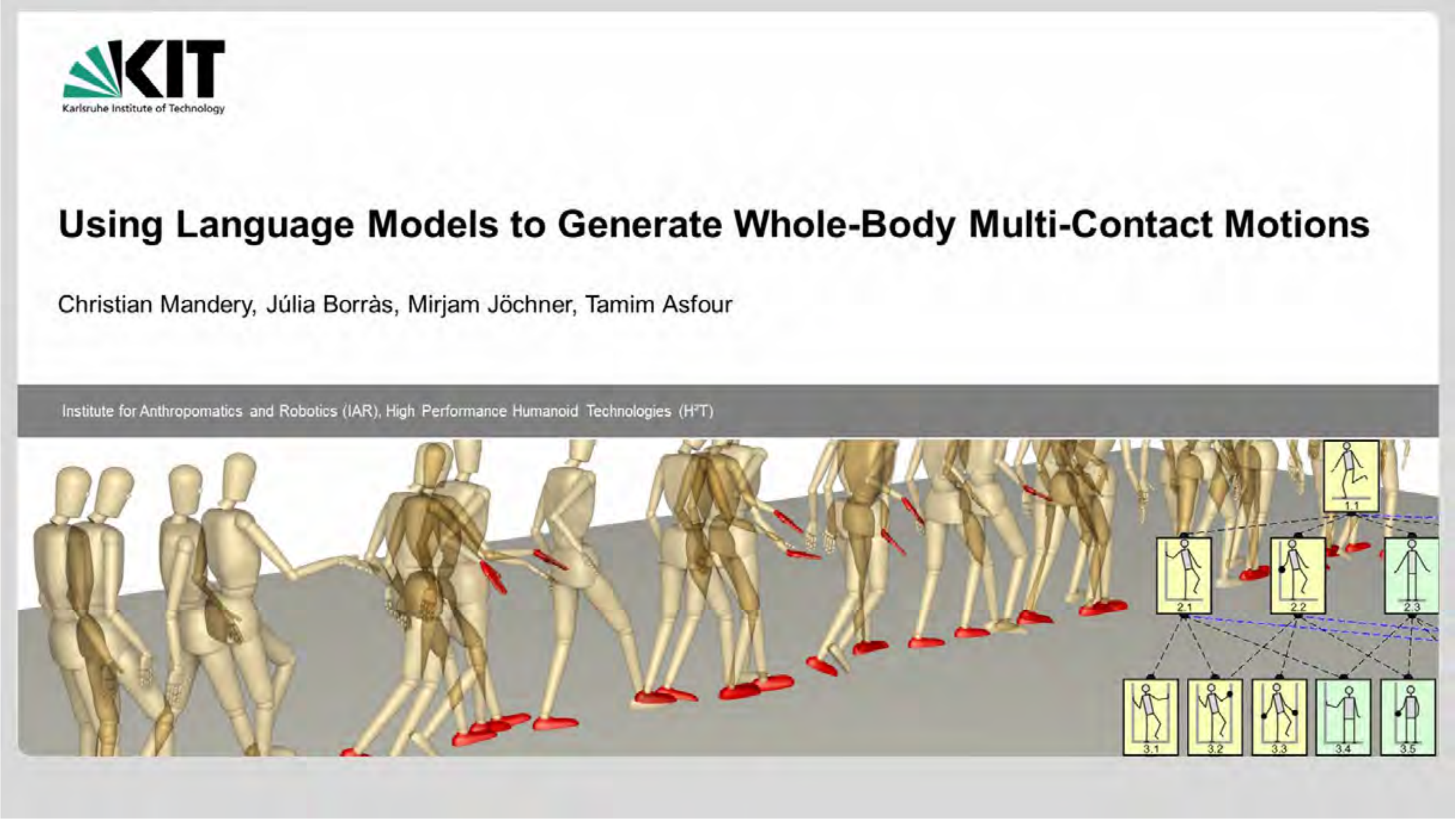


- Total of **121** motions processed
  - **Locomotion**
    - Upstairs/downstairs with handle
    - Walk with handle
    - Walk avoiding obstacles using hand supports
  - **Loco-manipulation**
    - Lean to reach/place/wipe
    - Bimanual pick and place of big objects
  - **Balancing**
    - push recovery
    - 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

IROS 2016



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/

The ArmarX Software

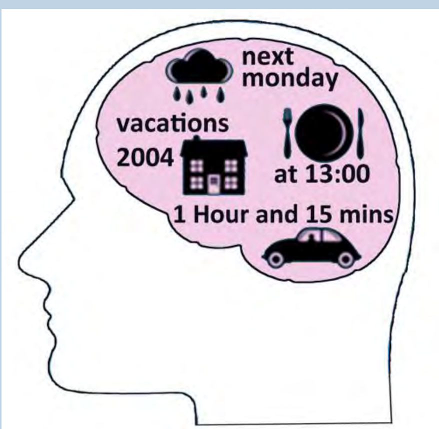
- Event-driven component-based robot software development environment
- Open Source robot software development environment
- Code and documentation
  - Source code: https://gitlab.com/ArmarX
  - Documentation: https://armarx.humanoids.kit.edu

Time

Time is vital

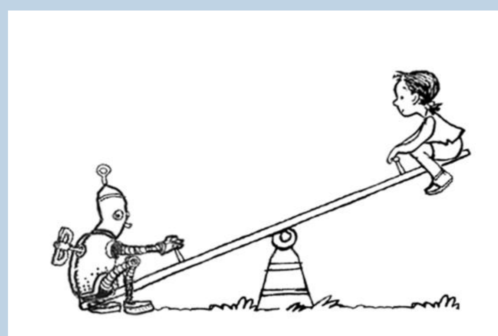
Knowing

- 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

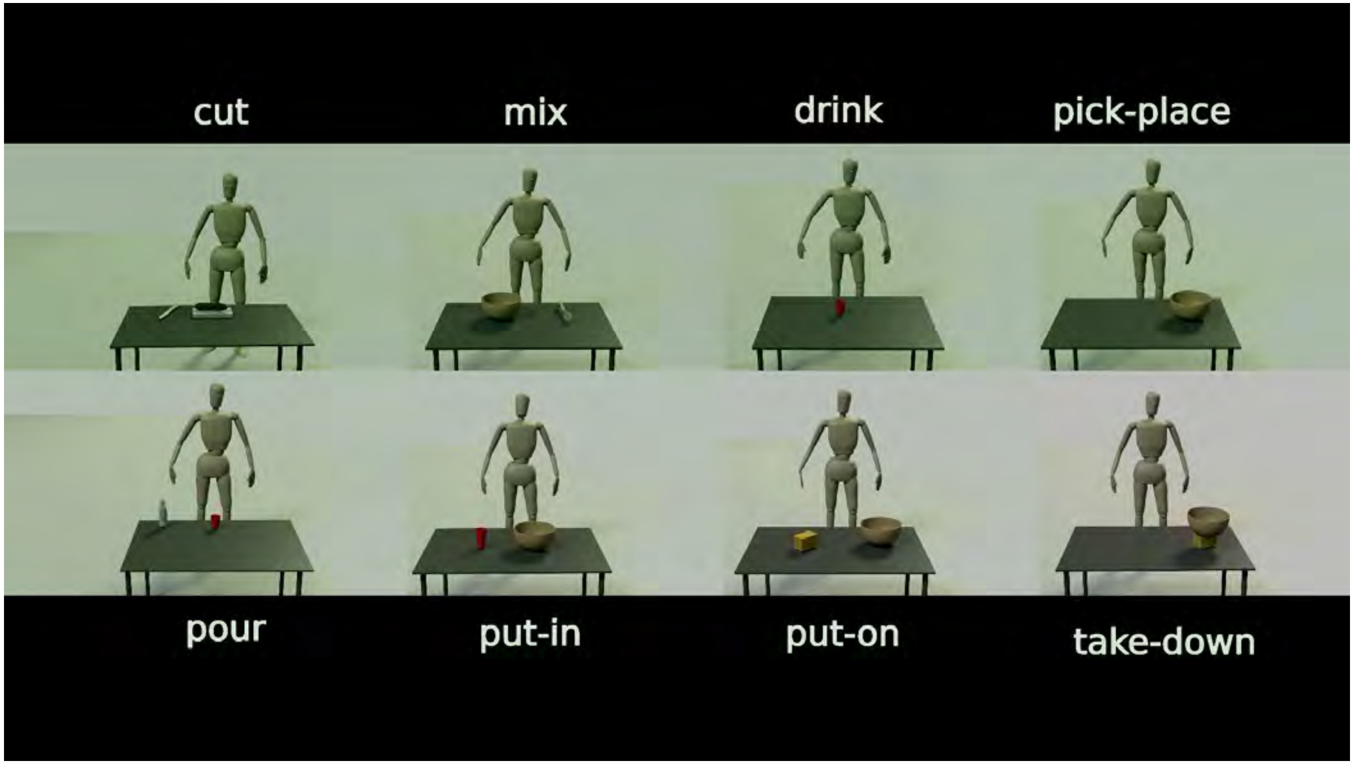
- Self identity over time
- Low level consciousness: perceive internal, environment changes
- High-level consciousness: link self to historical times

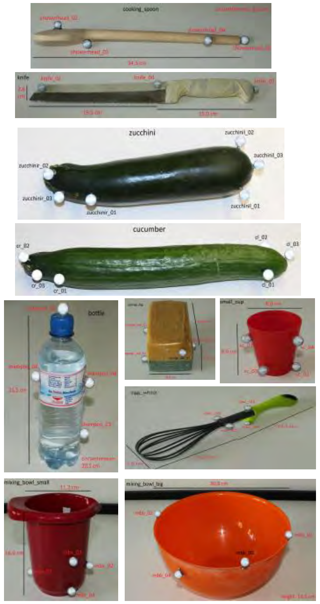
Time in Robotics

Past	Present	Future
• Experience	• Current world state	• Prediction

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

KIT Manipulation Action Dataset





10 Different Objects

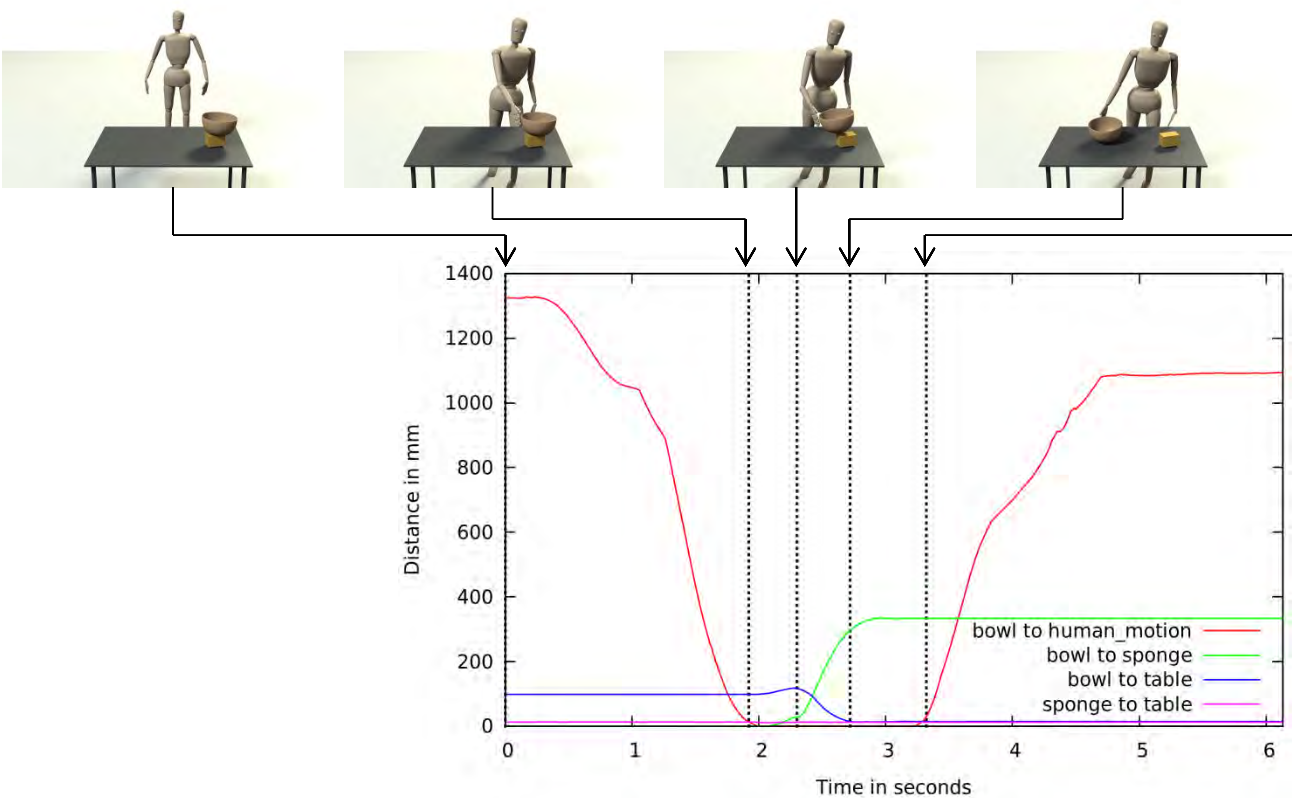
- In total 70 demonstrations of 8 different manipulation actions

Level I : Semantic Segmentation

Hierarchical Segmentation

Hand-Object Relation: No Contact | Bowl in hand | No Contact

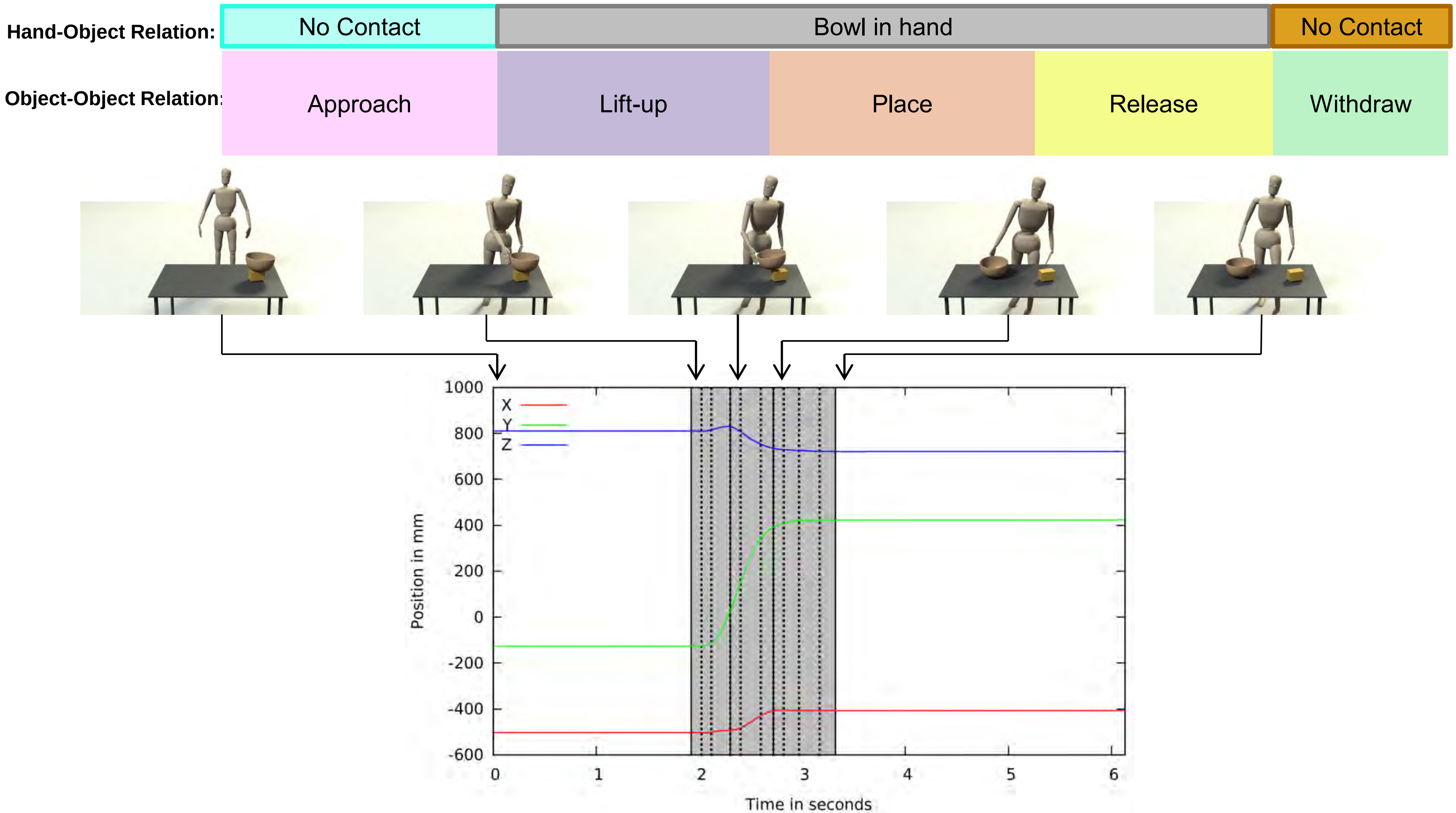
Object-Object Relation: Approach | Lift-up | Place | Release | Withdraw



Semantic Distance Profile

Level II : Motion Segmentation

Hierarchical Segmentation



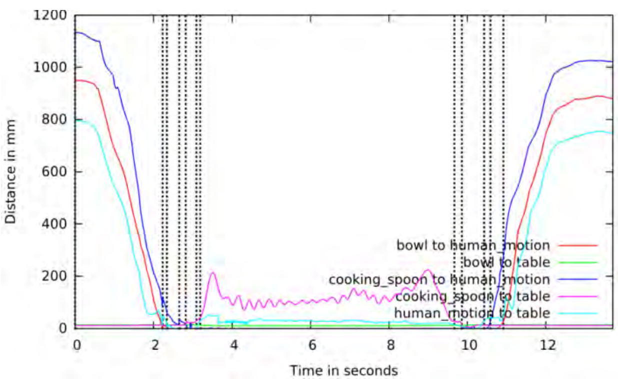
Trajectory of the Bowl

Semantic Action Similarity

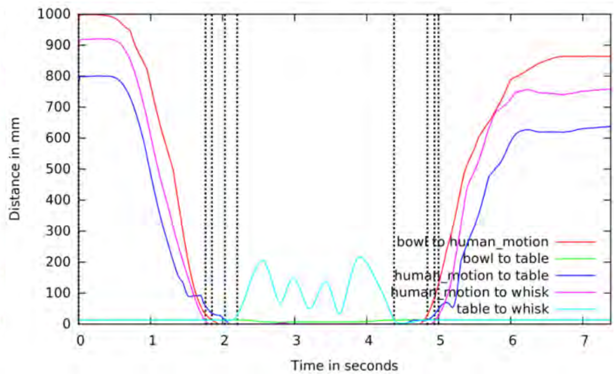
Human Demonstration:
Mixing with a *spoon*

Human Demonstration:
Mixing with a *whisk*

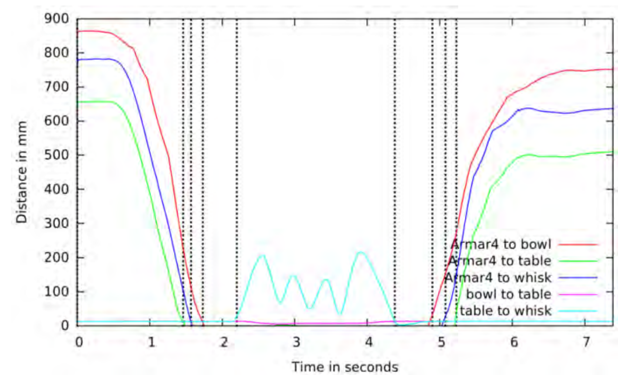
ARMAR-4 Imitation:
Mixing with a *whisk*



Result of hierarchical segmentation



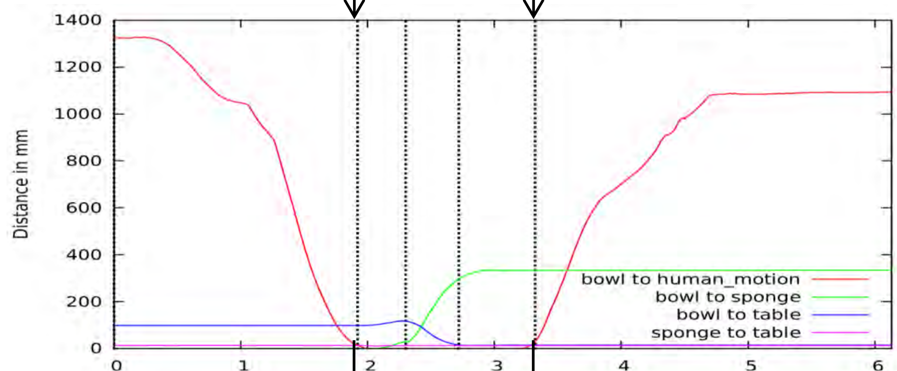
Result of hierarchical segmentation



Result of hierarchical segmentation

Perception of Time: Put-on Action

No Contact	Bowl in hand	No Contact



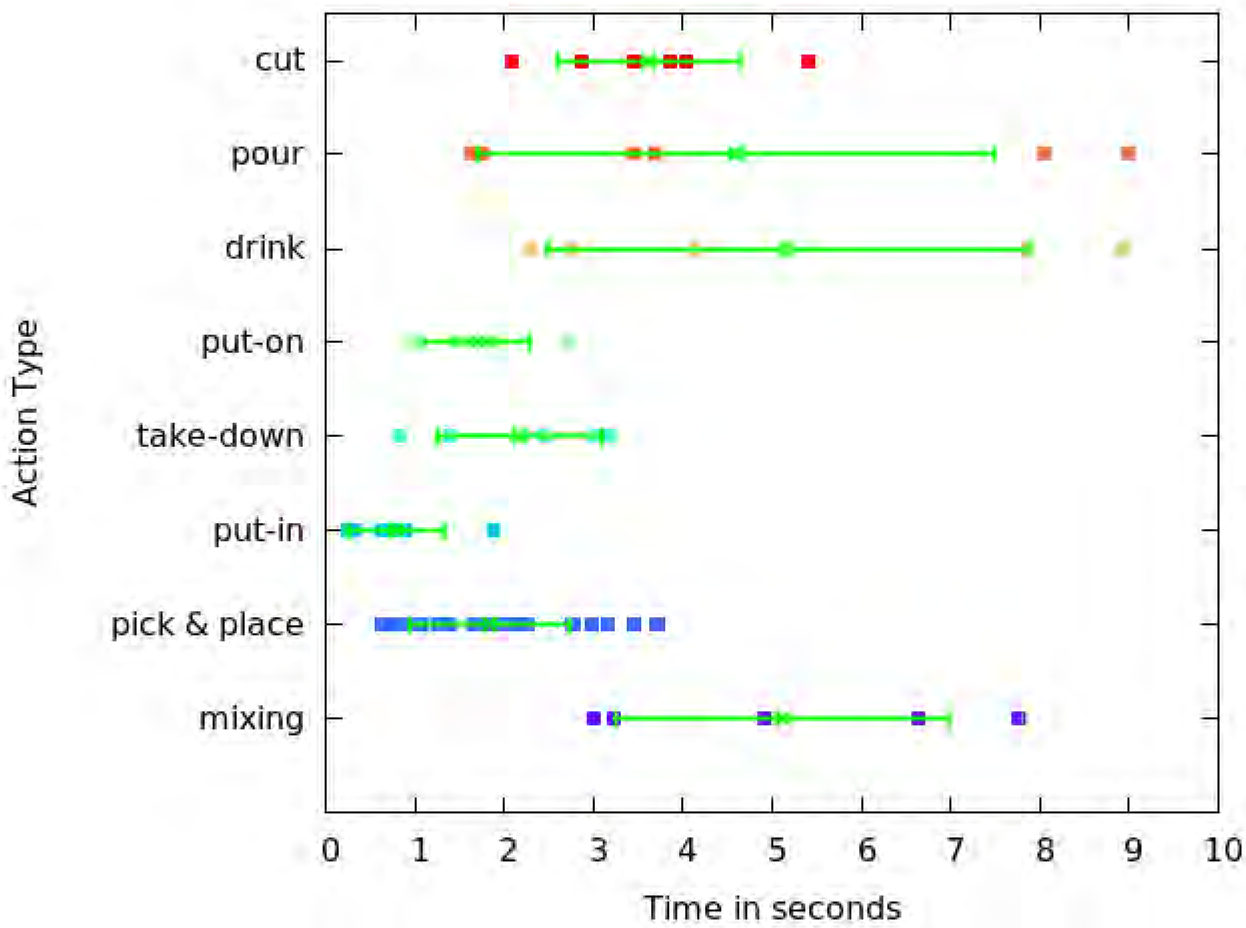
Put-on Action

							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

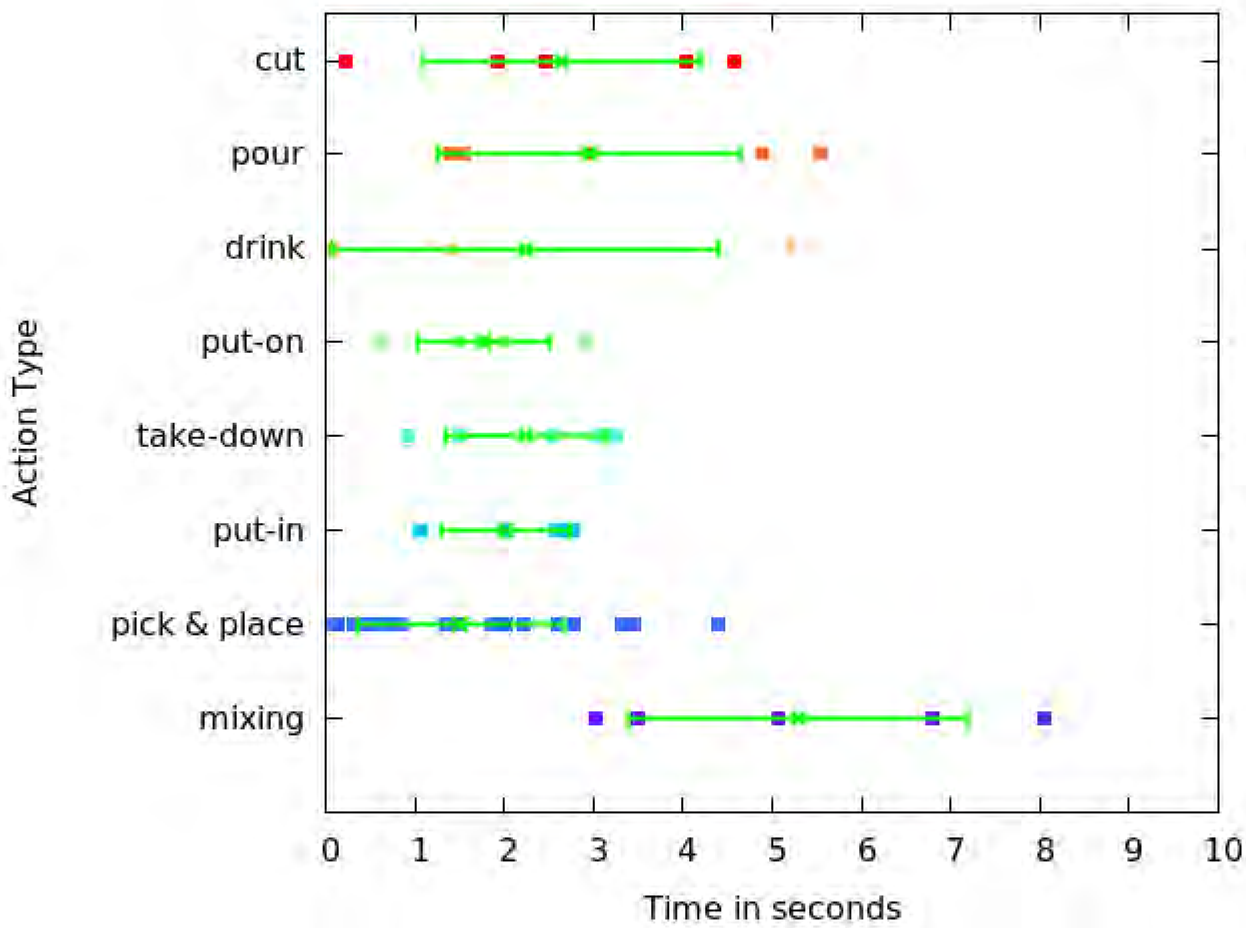
Δt

Mean : 2.1 sec Std: 0.9

Perception of Time: Human Demonstration

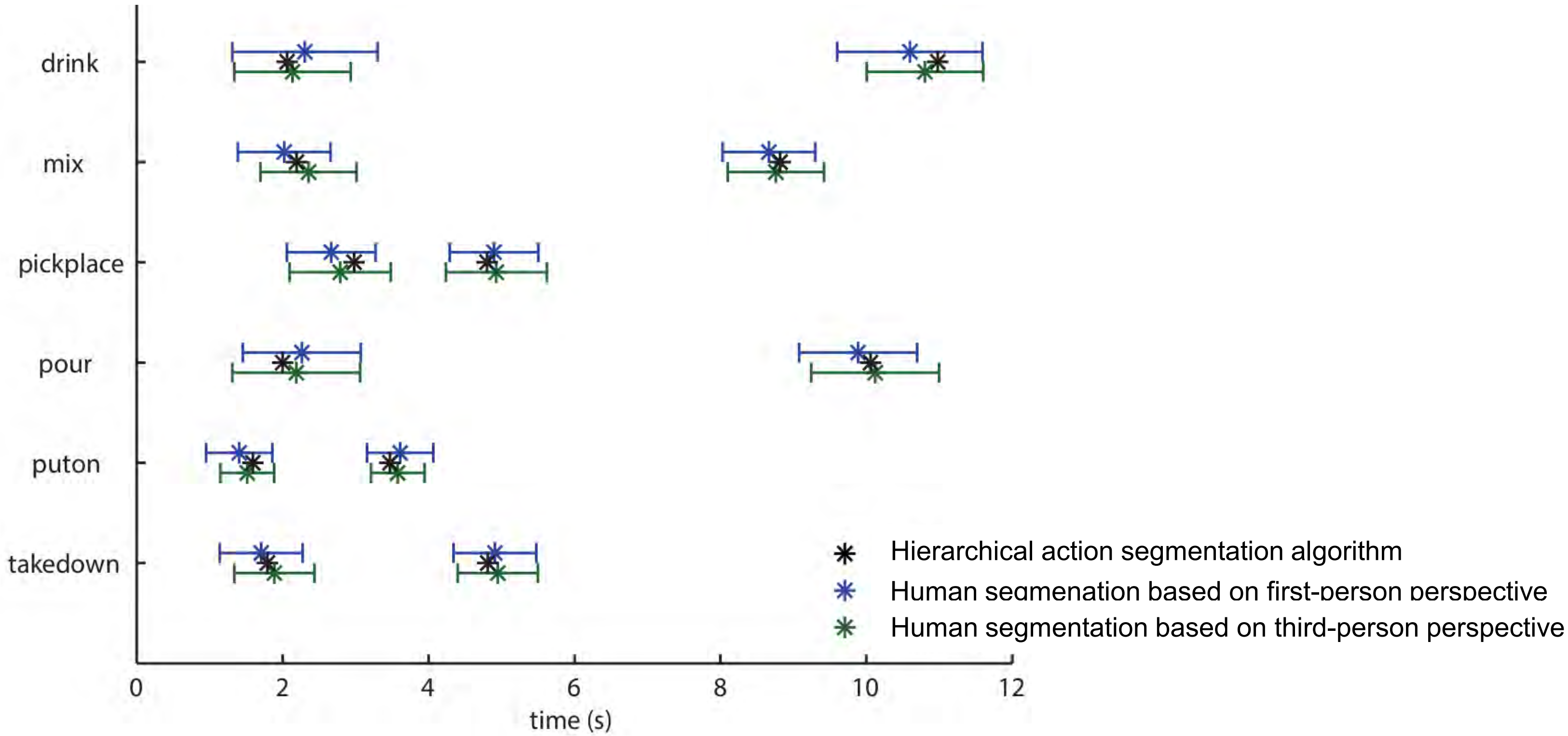


Perception of Time: ARMAR-4 Imitation



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)



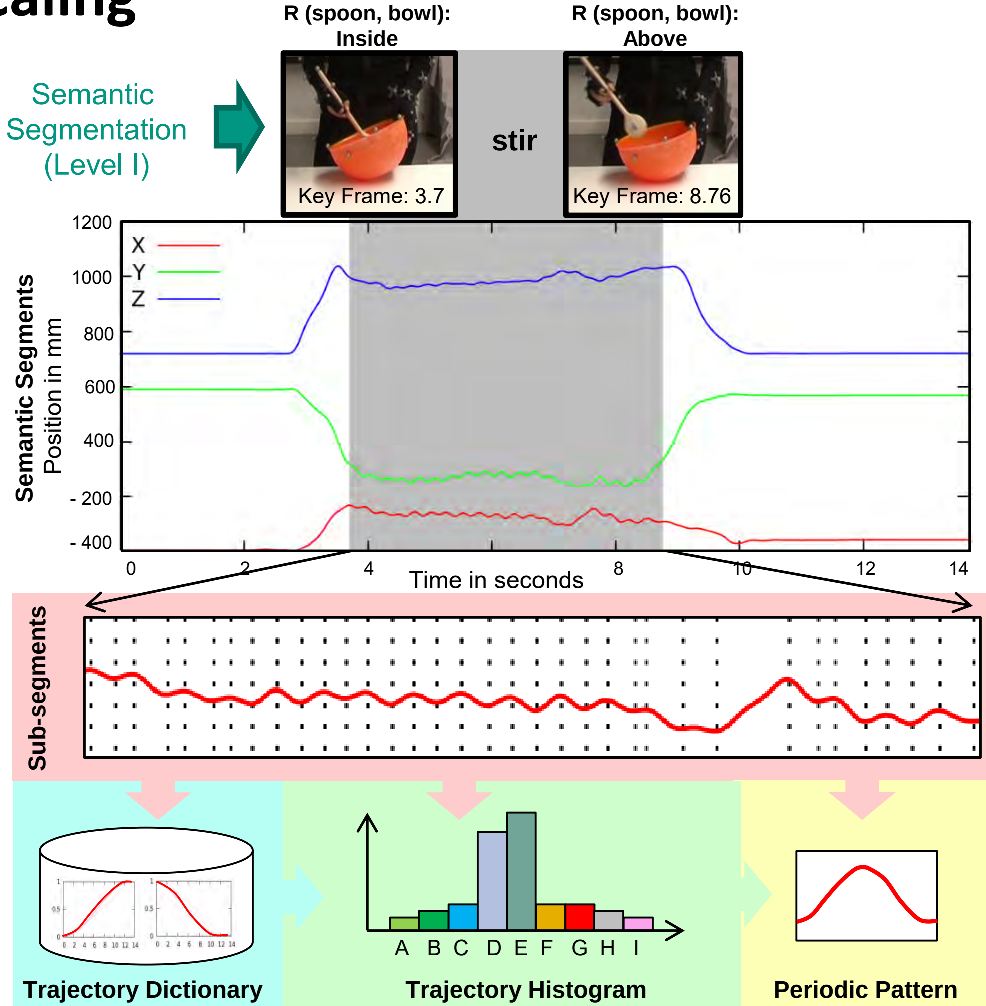
Schlichting al. "Temporal Context Influences the Perceived Duration of Everyday Actions", Under Review

Temporal Scaling

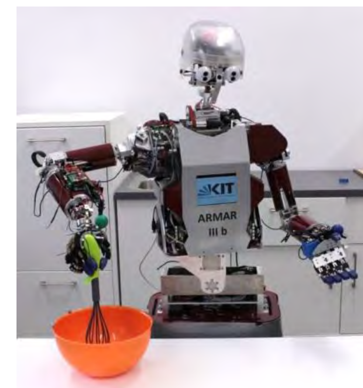
Human Demonstration

Semantic Segmentation (Level I)

Motion Segmentation (Level II)



Based on the Dynamic Time Warping Distance Measure

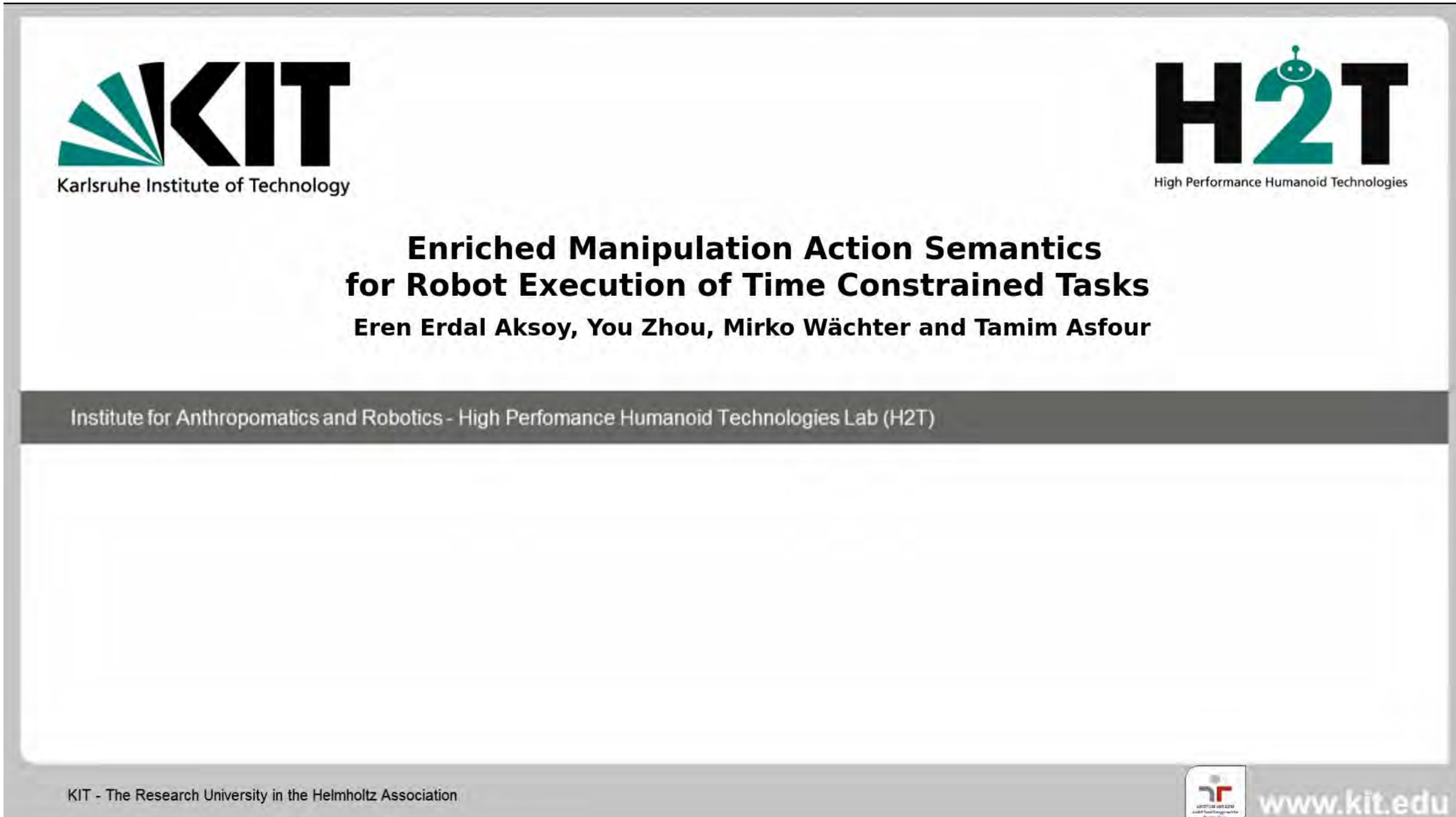


Robot execution at different temporal scales

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



Recent trends in robotics

- AI & robotics
  - Machine learning, Cloud robotics
- Intuitive robot programming
  - Learning from human observation
- Commercial investments in robotics
  - Google, Amazon, Qualcomm, Toyota, Honda, …
- New international key players
  - China, South Korea, Switzerland, United Arab Emirates, …
- Reduction in hardware costs
  - Affordable robot hardware
- Applications
  - In-home services, 3C market, agriculture, next generation production (robot as co-worker, mobile manufacturing machines, …)

Breakthroughs in robotics since ~2000 – my view

- Progress driven by
  - **„Cool“ new hardware**
    - Robot mechatronics:
      DLR/KUKA LWR, NAO, iCub, UR, 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)

Karlsruhe Institute of Technology

Thanks for your attention