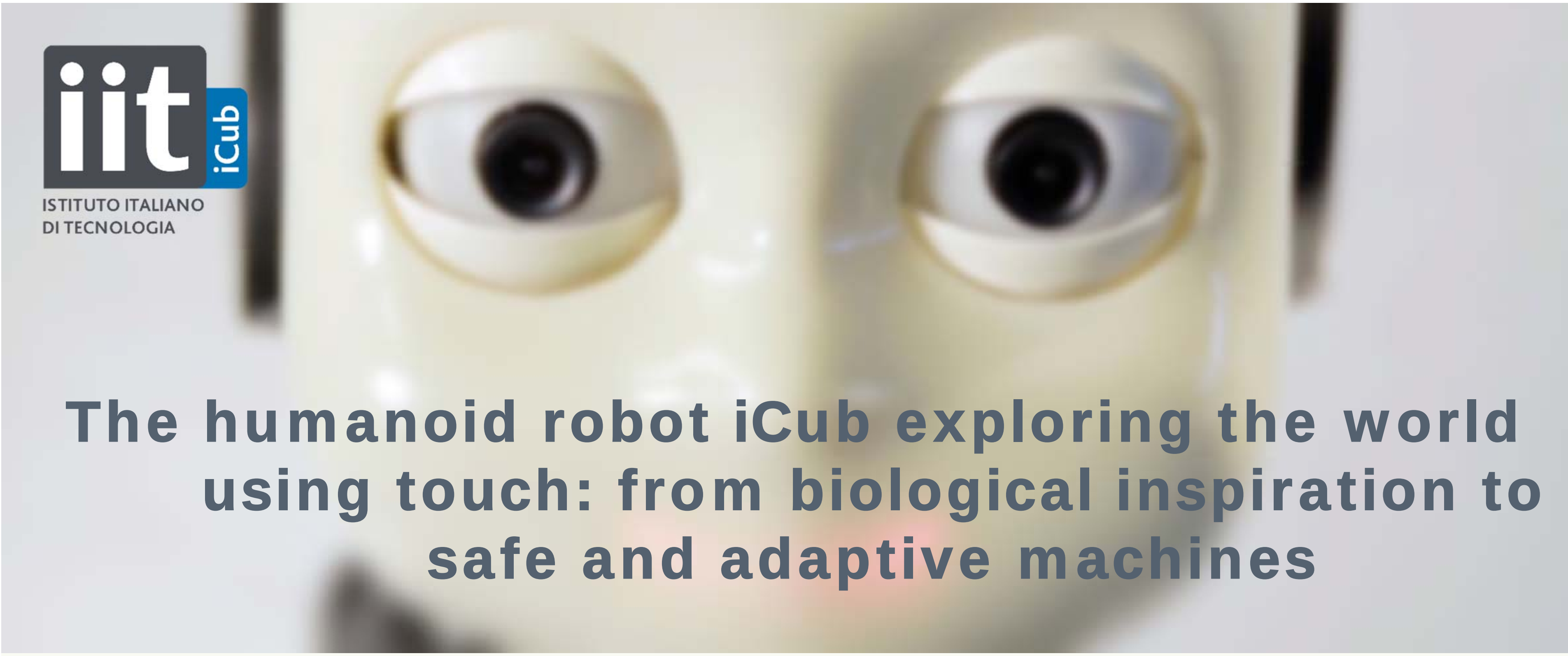


The humanoid robot iCub exploring the world using touch: from biological inspiration to safe and adaptive machines

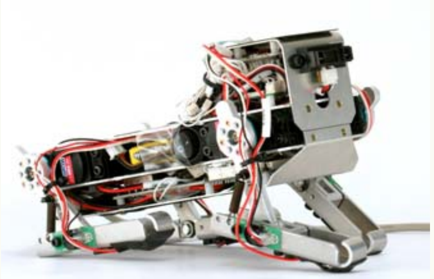
Matěj Hoffmann
iCub Facility, Italian Institute of Technology
matej.hoffmann@iit.it
https://sites.google.com/site/matejhof

About myself

- 2000-2006 Mgr. in Computer Science, Theoretical Computer Science, AI
  Faculty of Mathematics and Physics, Prague
  - MSc. thesis with Ivan M. Havel

- 2006-2012 PhD studies, then
  Senior Research Associate at Artificial Intelligence Lab, University of Zurich
  - PhD thesis: From locomotion to cognition: Bridging the gap between reactive and cognitive behavior in a quadruped robot

  Supervisor: Rolf Pfeifer



2012 – 2013 Swiss National Science Foundation Prospective Researcher Fellow

2014 – 2016 Marie Curie Experienced Researcher F.

iCub Facility, Italian Institute of Technology, Genoa

project: iCub body schema

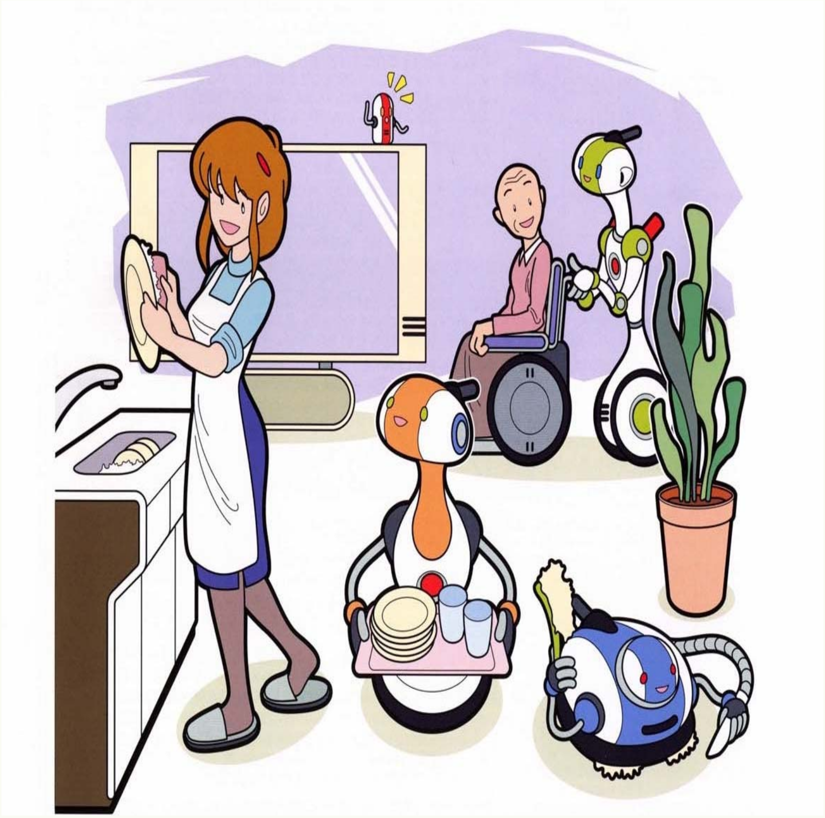
scientist in charge:

Giorgio Metta

Outline

1. Why humanoids and the iCub
2. Body representations on the iCub
   - Models of development and mechanisms of human/monkey body representations
   - Applications: self-calibration
3. The space around the body (peripersonal space) and safe human-robot interaction
4. Future work and conclusion

We have a dream…

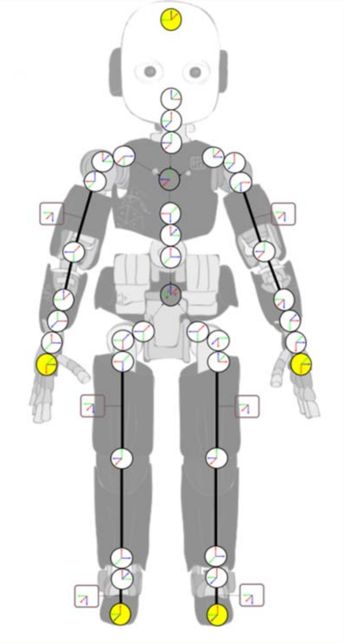


Why humanoids?

- Similarity to humans brings a number of advantages:
  - General:
    - functioning in an environment that has been tailored to humans
    - natural human-robot interaction
  - Scientific:
    - Similarity to humans make them an ideal tool to model human cognition.
    - Complex platforms with rich motor and sensory apparatus open up countless research topics.
  - Educational:
    - Perfect for basic and advanced robotics courses (kinematics, dynamics, vision, …).
  - Bonus:
    - anthropomorphic appearance -> attractive for public and media

iCub platform

- Size of a 4 year old child
- Motor / proprioception (joint angles)
  - 53 DOF
- Tactile information
  - cca 4000 pressure-sensitive tactile elements (taxels) on the whole body
- Vision
  - 2 standard cameras in biomimetic DOF setup (pan, tilt, vergence)
- Force/torque sensors
- Inertial sensors
- Microphones…

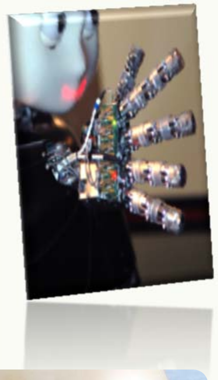


the iCub

30 iCubs distributed since 2008
about 3-4 iCubs/year

open hardware

why is the iCub special?



- hands: design started from the hands
  - 5 fingers, 9 degrees of freedom, 19 joints

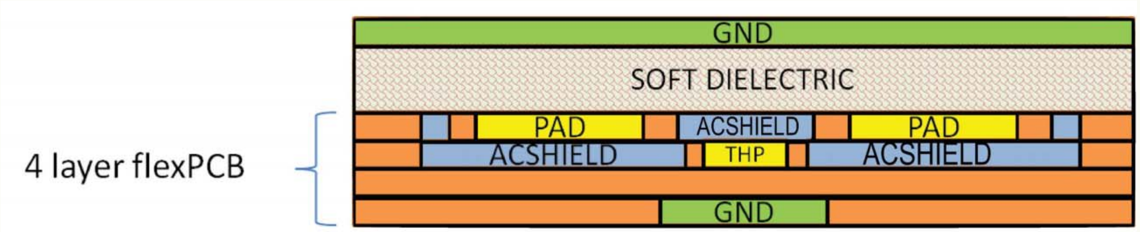
- sensors: human-like, e.g. no lasers
  - cameras, microphones, gyros, encoders, force, tactile…
- de facto standard platform in cognitive robotics
- OS independent – communication through YARP middleware
- large **open source** software repository (~2M lines of code)

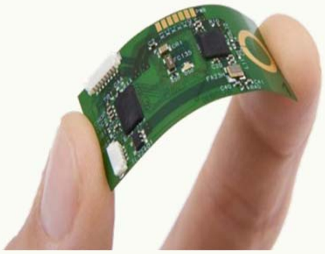
~10 years of research and software development

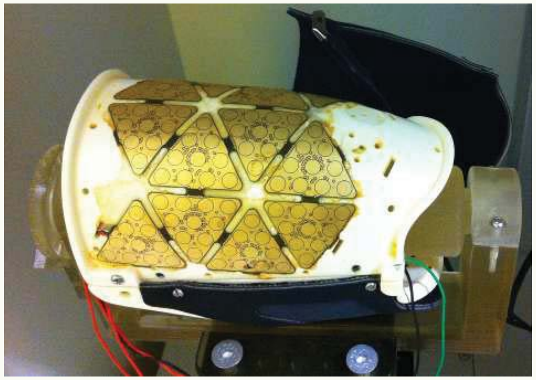
⇒ Countless modules implementing state-of-the-art algorithms automatically available

- Kinematics & dynamics
  - Forward and inverse kinematics
    - Cartesian controller for reaching
  - Position, velocity, or torque control + stiff or compliant interaction mode.
  - Whole-body dynamics, balancing, etc.
- Visual perception, object recognition and tracking …

The capacitive robot skin





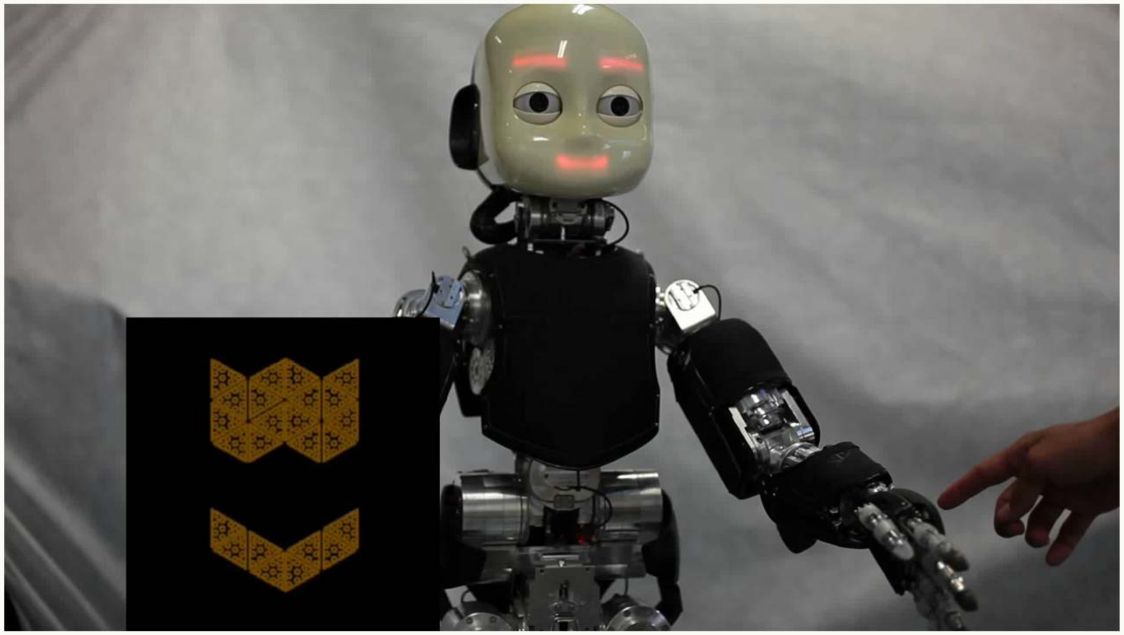


Maiolino, P.; Maggiali, M.; Cannata, G.; Metta, G. & Natale, L. (2013), 'A flexible and robust large scale capacitive tactile system for robots', *Sensors Journal, IEEE* ***13(10), 3910--3917.***

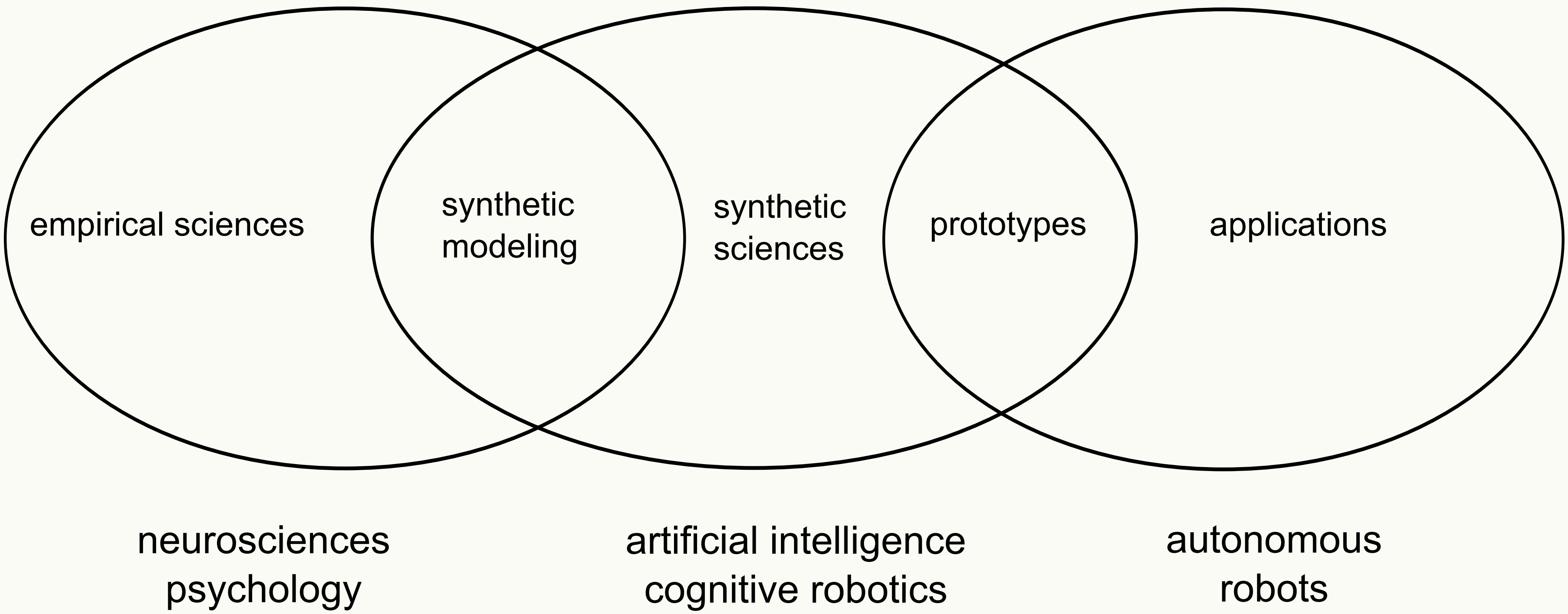
Outline

1. Why humanoids and the iCub
2. Body representations on the iCub
   - Models of development and mechanisms of human/monkey body representations
   - Applications: self-calibration
3. The space around the body (peripersonal space) and safe human-robot interaction
4. Future work and conclusion

My current project: motivation



Synthetic methodology



E.g., Pfeifer, R. & Bongard, J. C. (2007), *How the body shapes the way we think: a new view of intelligence, MIT Press.*

Body representations in primates

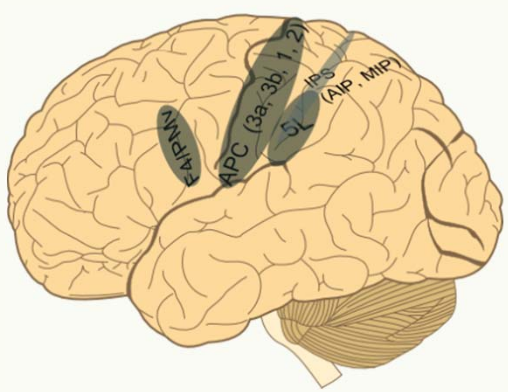
- Many different concepts proposed – e.g.:
  - **Body schema** - "sensorimotor representation for action"
    - The neural representation of the body [Head & Holmes, 1911]
    - "implicit knowledge structure that encodes the body's form, the constraints on how the body's parts can be configured, and the consequences of this configuration on touch, vision, and movement." *[Graziano & Botvinick, 2002]*
  - **Body image** – "for perception"
    - **body structural description** [Schwoebel & Coslett 2005]
    - **body semantics** [Schwoebel & Coslett 2005]
  - **Hierarchies – primary somatosensory repr., body form repr., postural repr.** [Medina & Coslett 2010]
  - …

fixed

plastic

centralized

distributed



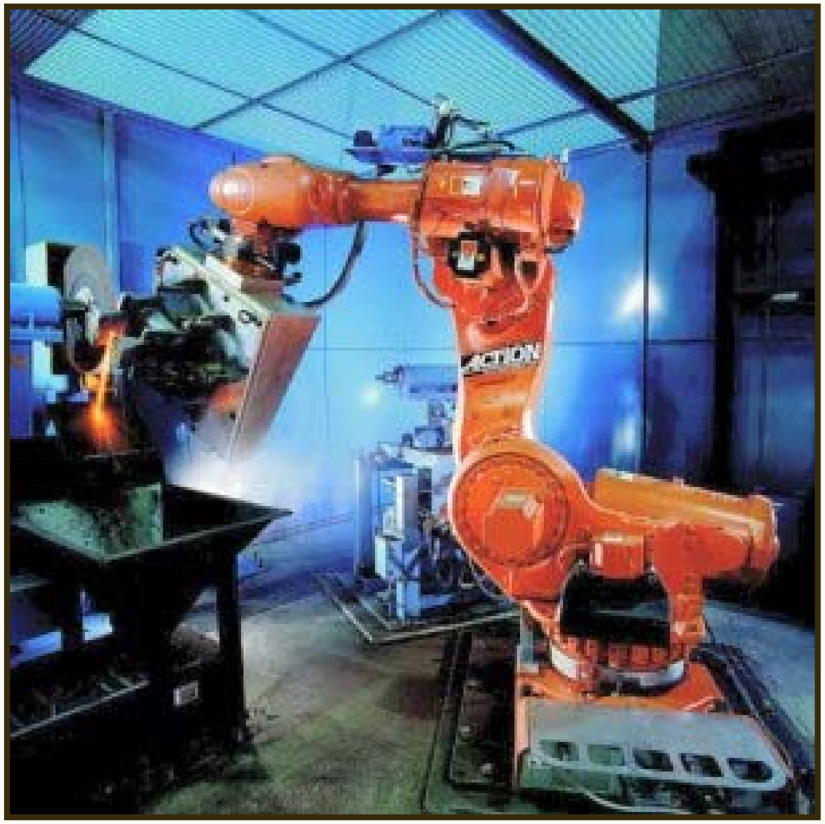
implicit

explicit

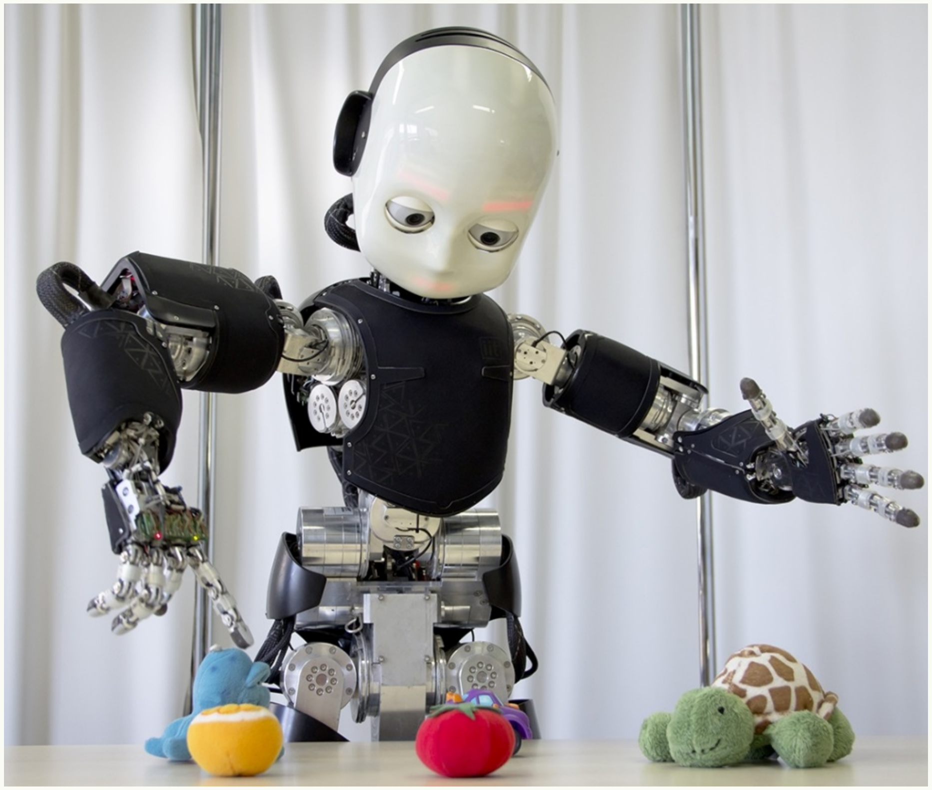
multimodal

amodal or unimodal

Body representations in robots



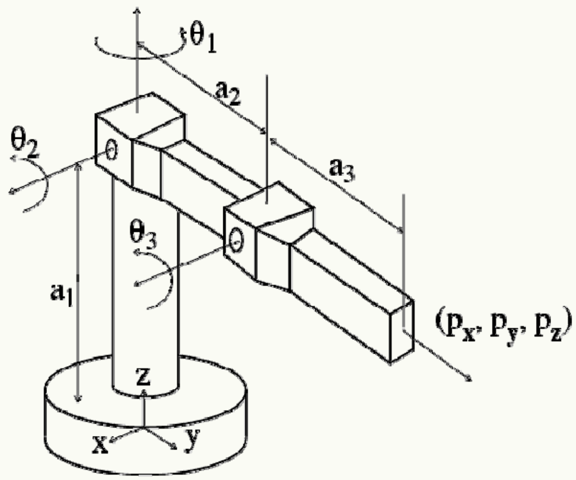
industrial robots



humanoid robots

Standard body representations

e.g., forward kinematics



Allows the end of the robot to be located in space relative to the base of the robot. The calculations are done to convert joint coordinates (joint angles) to cartesian coordinates.

$$p_x = \cos\theta_1 \, (a_3 \cos(\theta_2 + \theta_3) + a_2 \cos\theta_2)$$

$$p_y = \sin\theta_1 \, (a_3 \cos(\theta_2 + \theta_3) + a_2 \cos\theta_2)$$

$$p_z = a_3 \sin(\theta_2 + \theta_3) + a_2 \sin\theta_2 + a_1$$

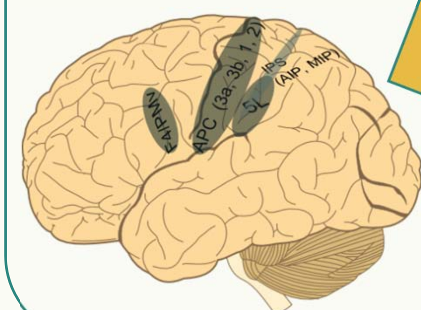
fixed

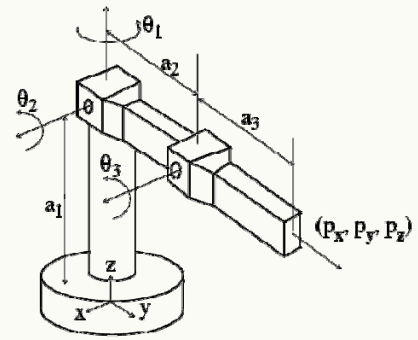
plastic

centralized

distributed

1. Modeling mechanisms of biological body representations





$$p_x = \cos\theta_1 \,(a_3 \cos(\theta_2 + \theta_3) + a_2 \cos\theta_2)$$
$$p_y = \sin\theta_1 \,(a_3 \cos(\theta_2 + \theta_3) + a_2 \cos\theta_2)$$
$$p_z = a_3 \sin(\theta_2 + \theta_3) + a_2 \sin\theta_2 + a_1$$

2. Better performance of robots – autonomy, robustness, safety

implicit

explicit

multimodal

amodal or unimodal

Behavioral studies functional body knowledge

Removal of vibrating target from body surface

- Transversal and longitudinal studies, infants 3-18 months
- Cross-lab team
  - Jeffrey J. Lockman, Tulane University, US
  - Kevin O’Regan, Jacqueline Fagard, Eszter Szomogyi, CNRS, Paris
  - Tobias Heed, Uni Hamburg
  - Matěj Hoffmann, IIT Genova

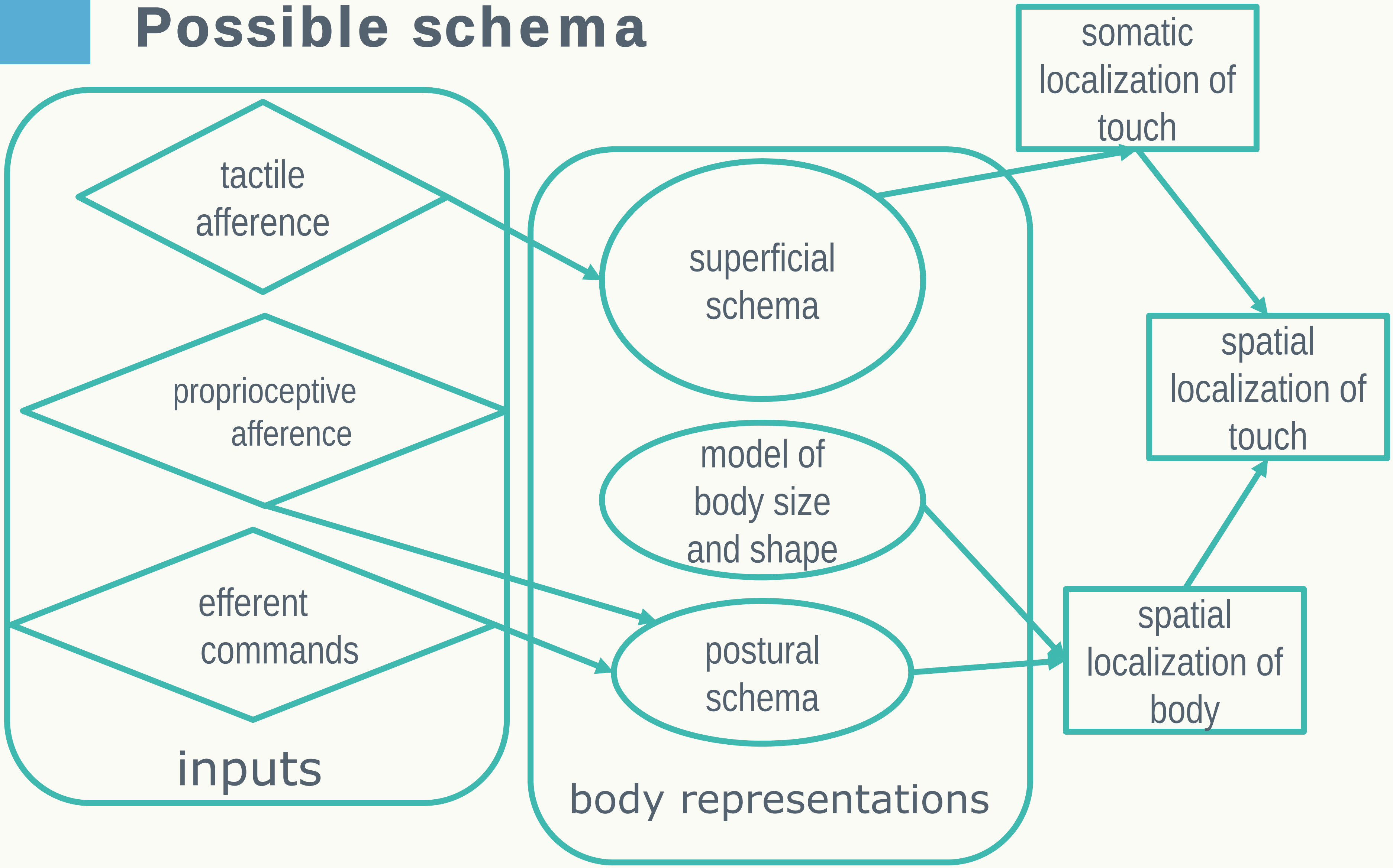
Development of “functional” body rep.

6 months, 19 days

8 months, 26 days

- How did this change occur? Hypothesis: through experience with self-touch
  - “infants engage in exploration of their own body as it moves and acts in the environment. They babble and touch their own body, attracted and actively involved in investigating the rich intermodal redundancies, temporal contingencies, and spatial congruence of self-perception'' Rochat 1998
- Mechanism?

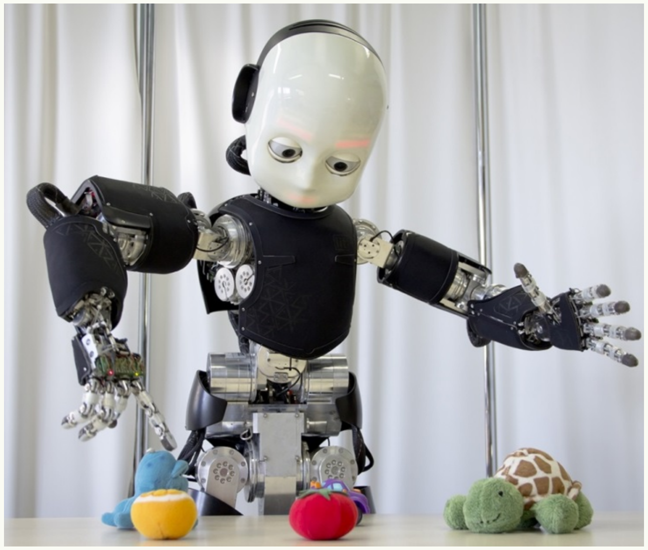
Possible schema



After Longo, M.; Azanon, E. & Haggard, P. (2010), 'More than skin deep: Body representation beyond primary somatosensory cortex', Neuropsychologia 48, 655--668.

The need for models of body representations

- Body schema etc. are concepts / umbrellas…
- The field is rich in experimental observations, but weak in mechanisms…
- => need for computational models
- The models need to be **embodied.**
- Humanoid robots come to the rescue!

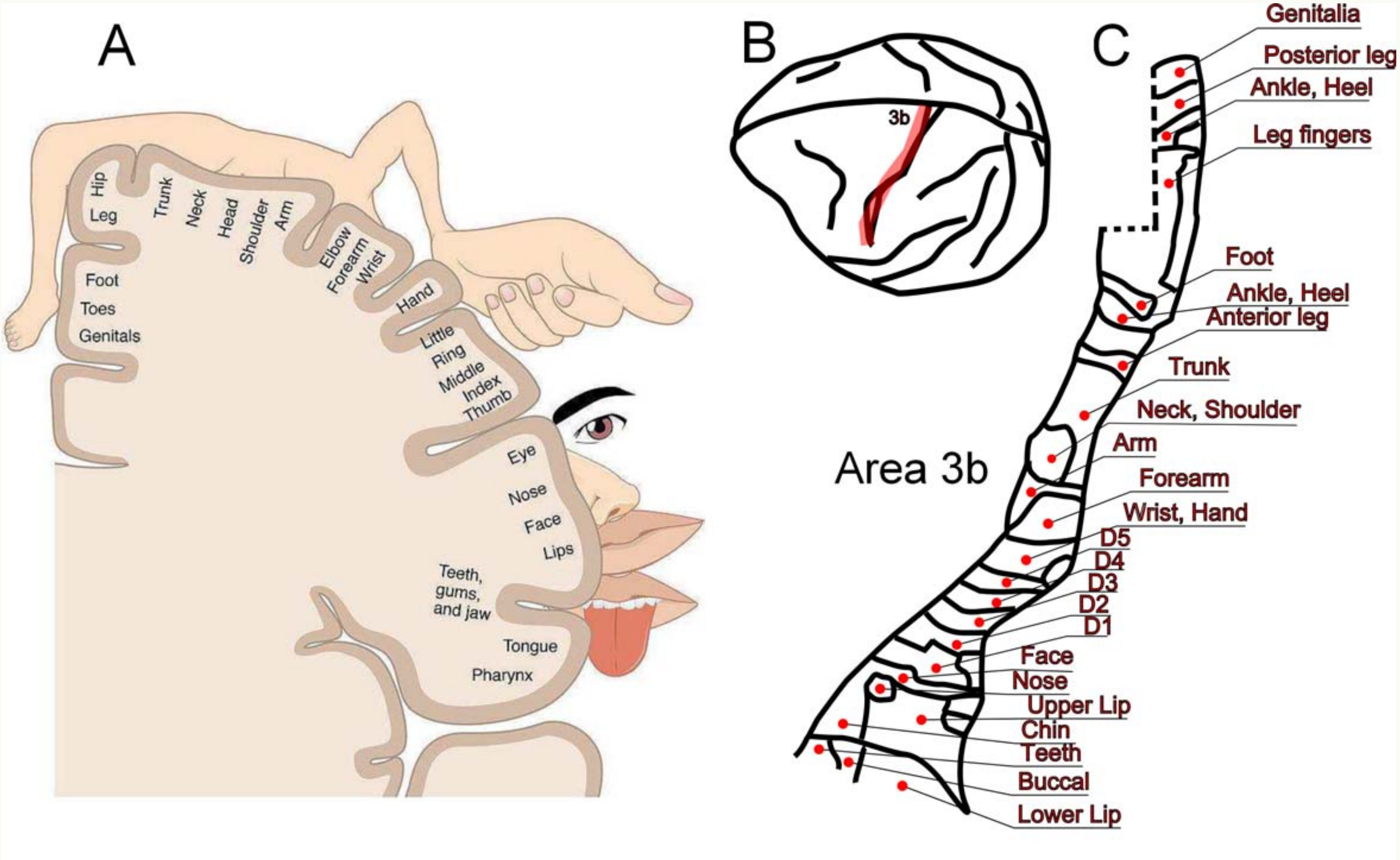


Modeling of putative brain mechanisms

- Start from bottom-up: connecting self-organizing maps of different modalities
- 4 sub-projects

1. Primary representation of tactile space – “iCub tactile homunculus” – with Zdeněk Straka et al.
2. Primary representation of proprioceptive space – N. Bednárová, Bc. thesis, FEL ČVUT Praha, 2015
3. Tactile and proprioceptive space together – Leyla Metohajrová, running Bc. thesis, collaboration with Igor Farkaš, U. Komenského, Bratislava
    - Learning from double touch; Goal: Being able to execute movement toward stimulated body part (~ buzzer removal)
4. Autonomous body exploration – Martin Varga, running MSc. thesis, in collaboration with Igor Farkaš, Pierre-Yves Oudeyer & Clement Moulin-Frier

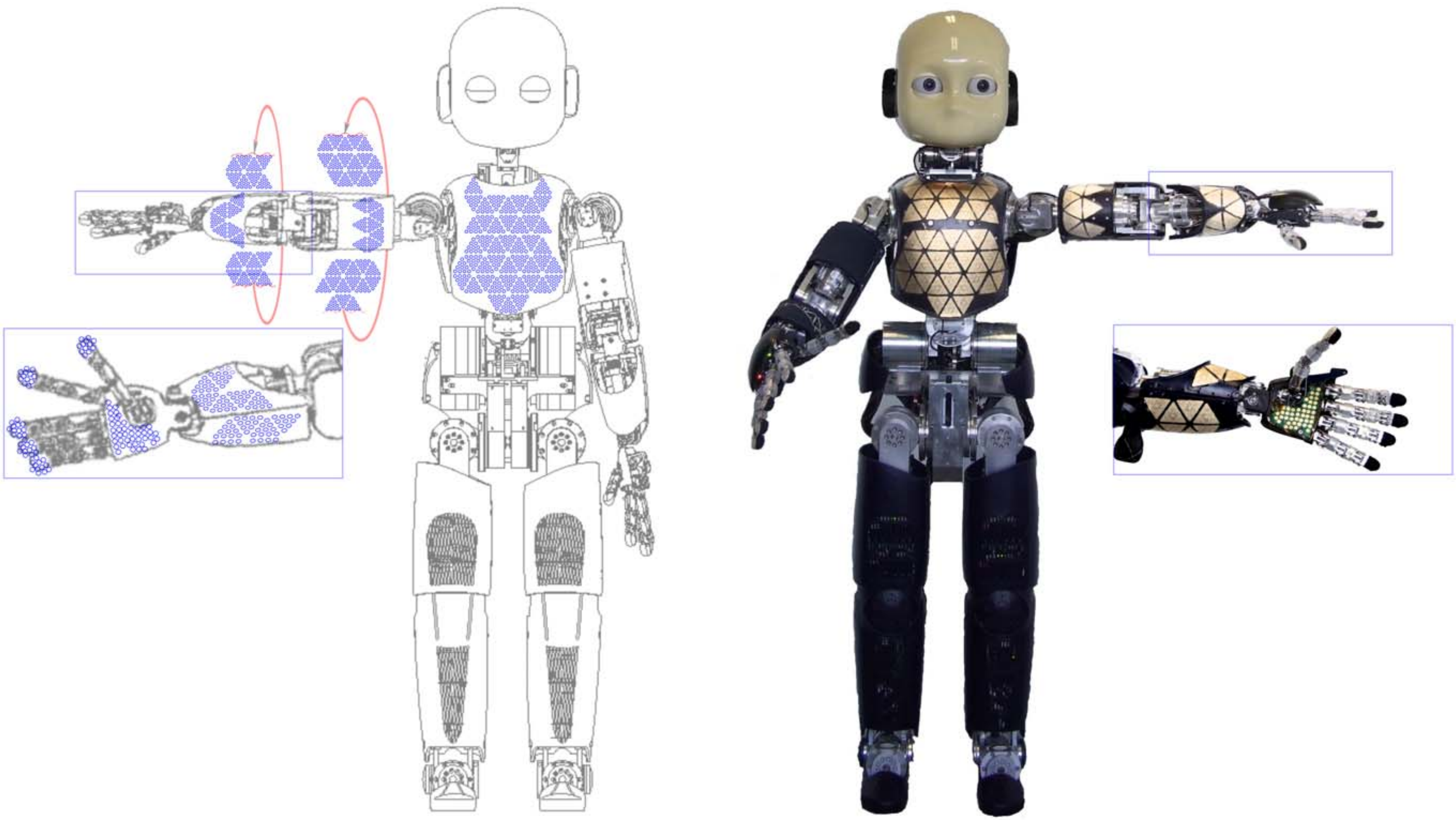
“Somatosensory homunculus”

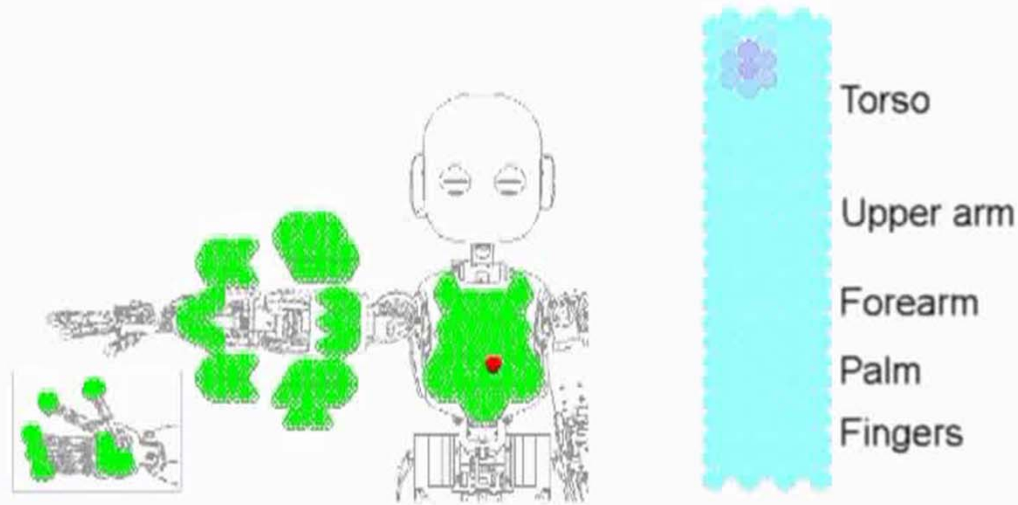


(A) Penfield W., Rasmussen T.: The cerebral cortex of man; a clinical study of localization of function, 1950. (pic from OpenStax College, download for free at http://cnx.org/contents/29cade27-ba23-4f4a-8cbd-128e72420f31@5}

(B,C) Organization of the representations of body surface in area 3b of the cynomolgus macaque. (after Nelson 1980)

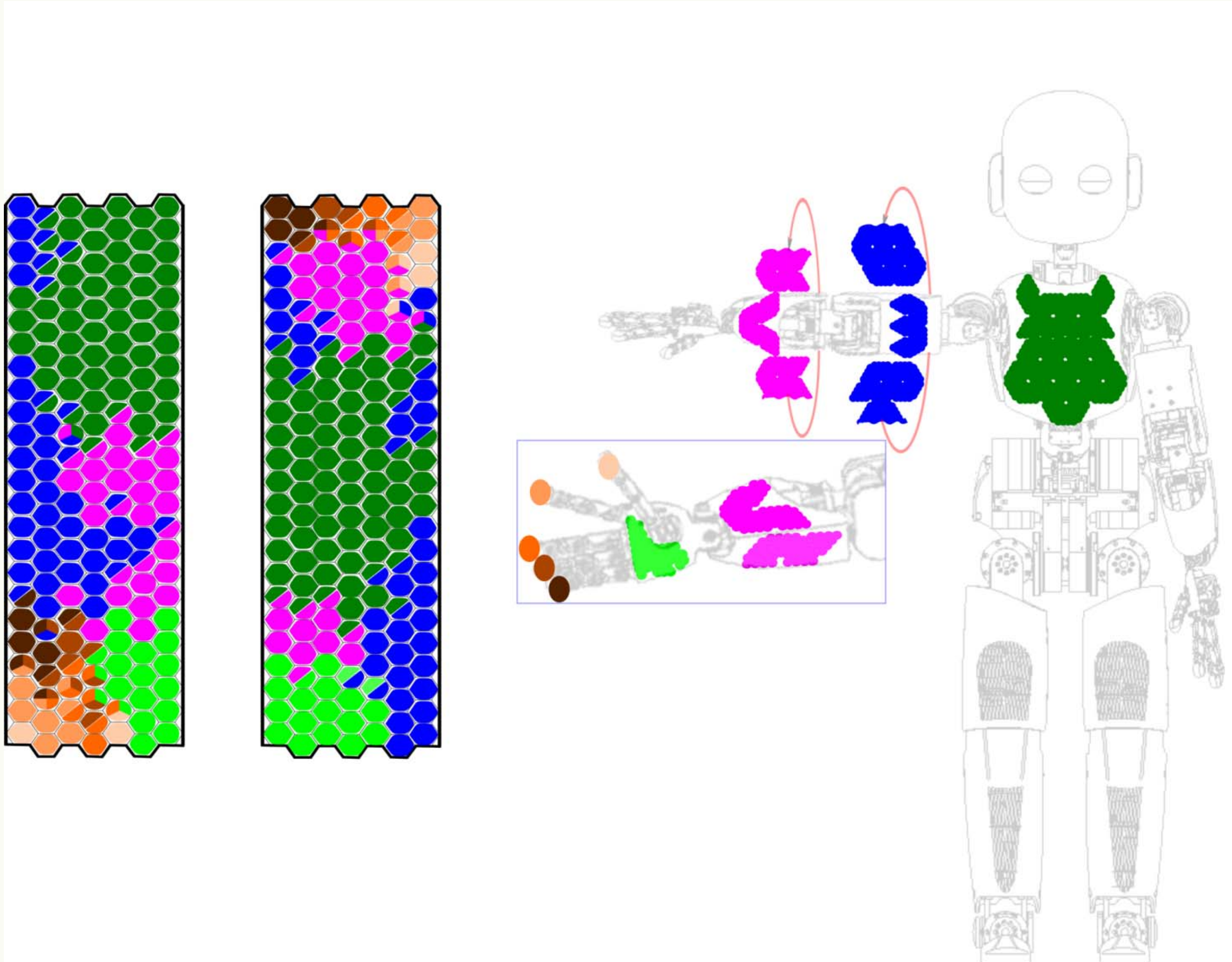
Project 1: iCub tactile homunculus - learning from skin stimulation



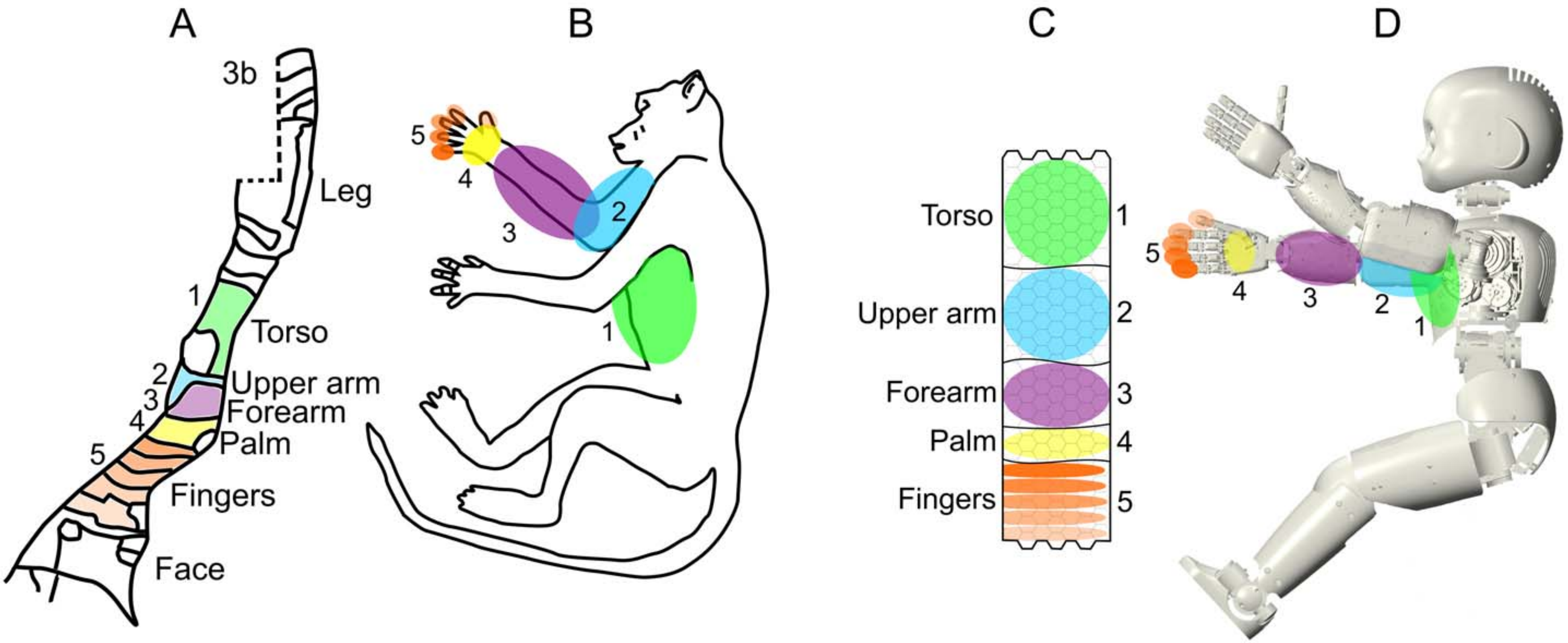


Z. Straka, Bc. thesis, CTU Prague, 2014.
Hoffmann, M.; Straka, Z.; Vavrecka, M.; Farkas, I. & Metta, G.: 'The iCub somatosensory homunculus: Learning of artificial skin representation in a humanoid robot motivated by the primary somatosensory cortex'. [under review]

Learning with standard SOM

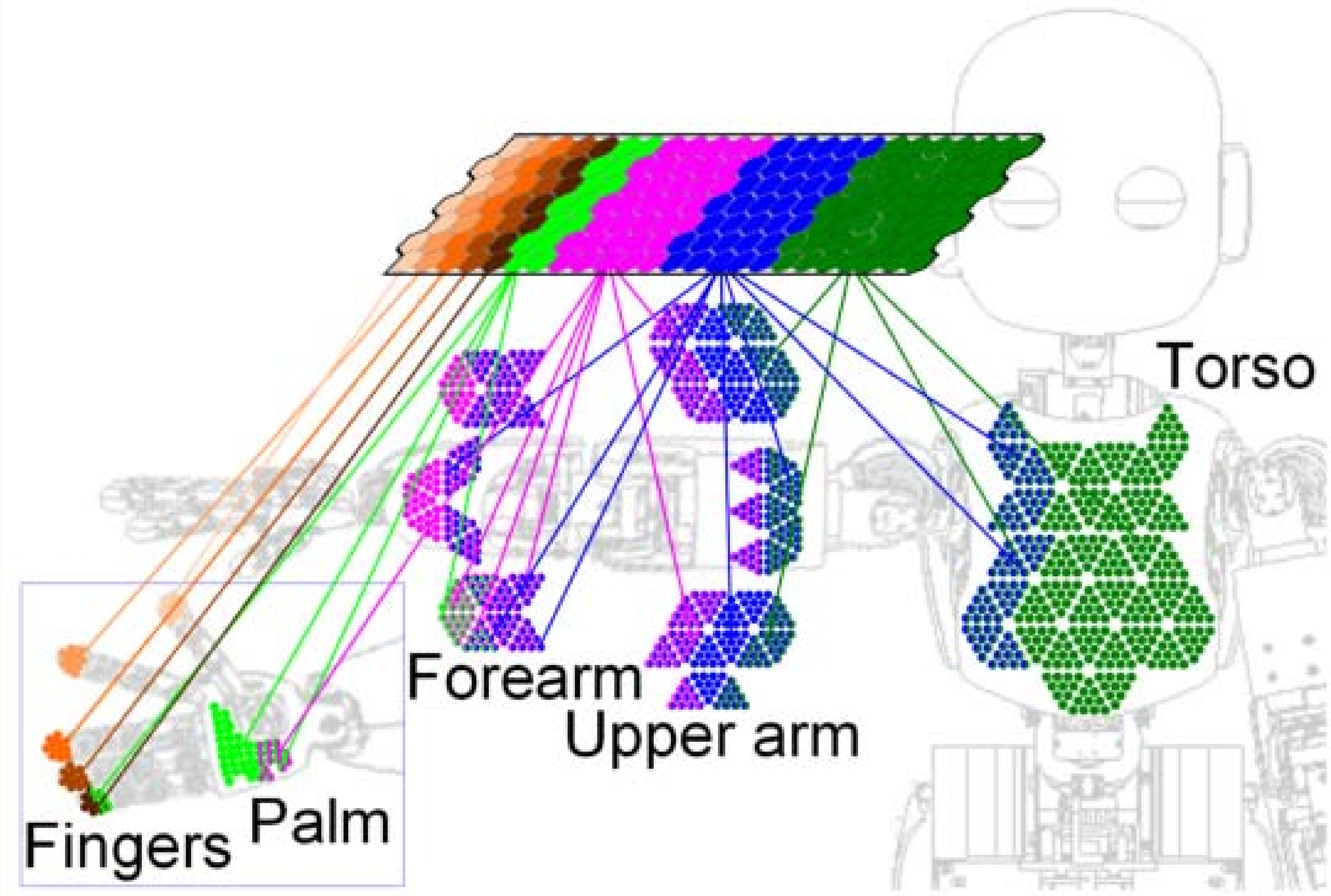


How to achieve layout similar to primate 3b?



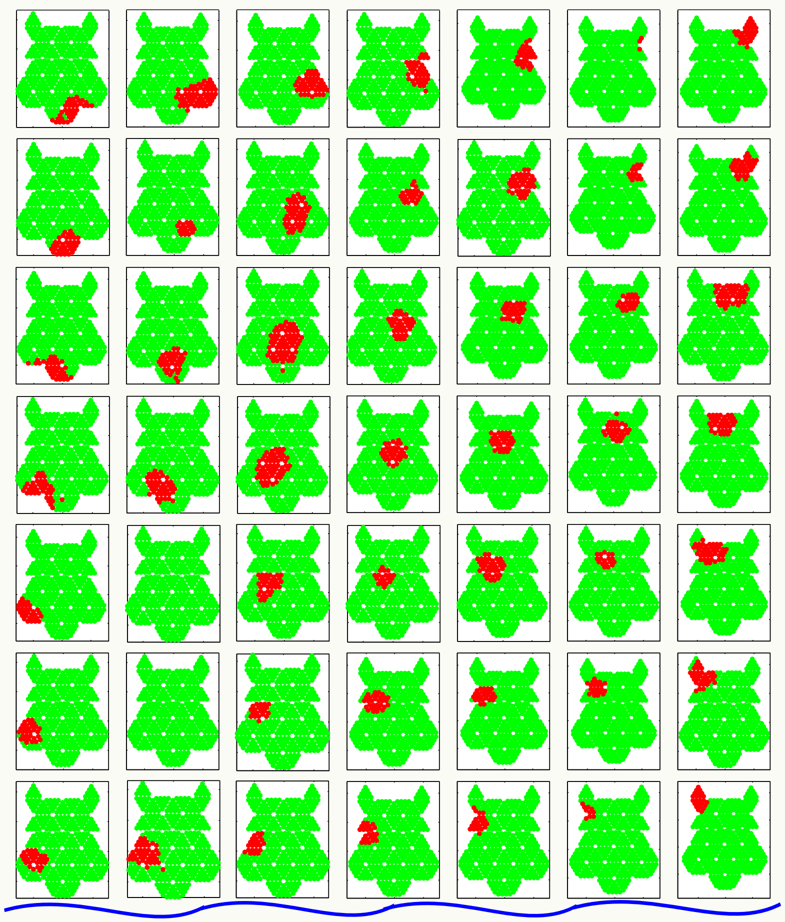
Sequence of body parts ensured through additional constraints – maximum receptive field size setting.

Maximum receptive field size setting

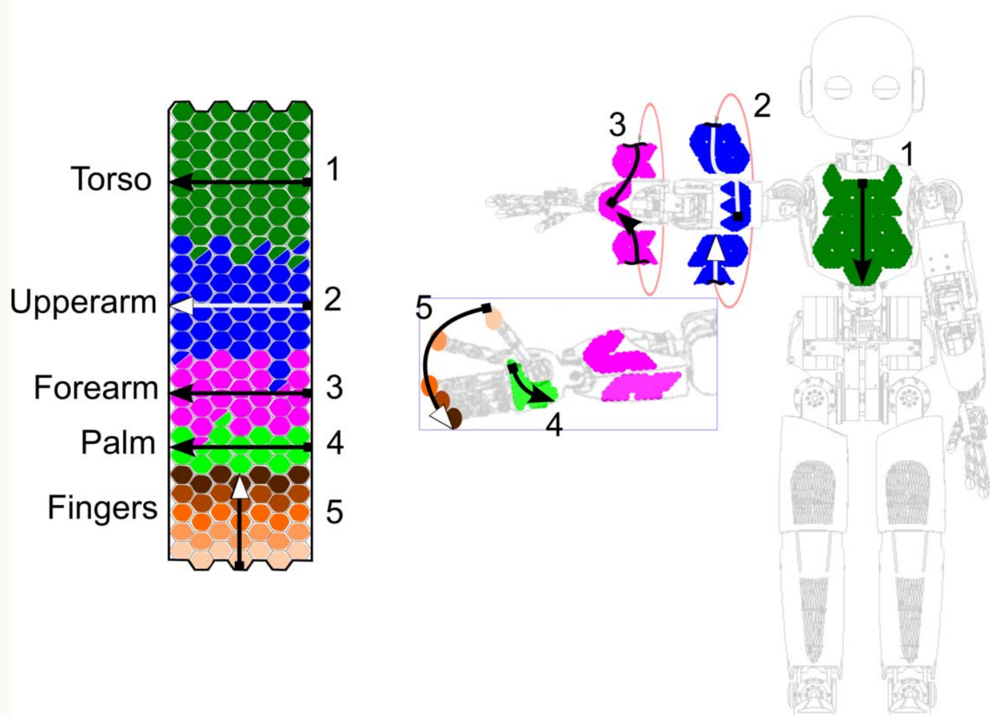


Learned SOM with maximum RF setting

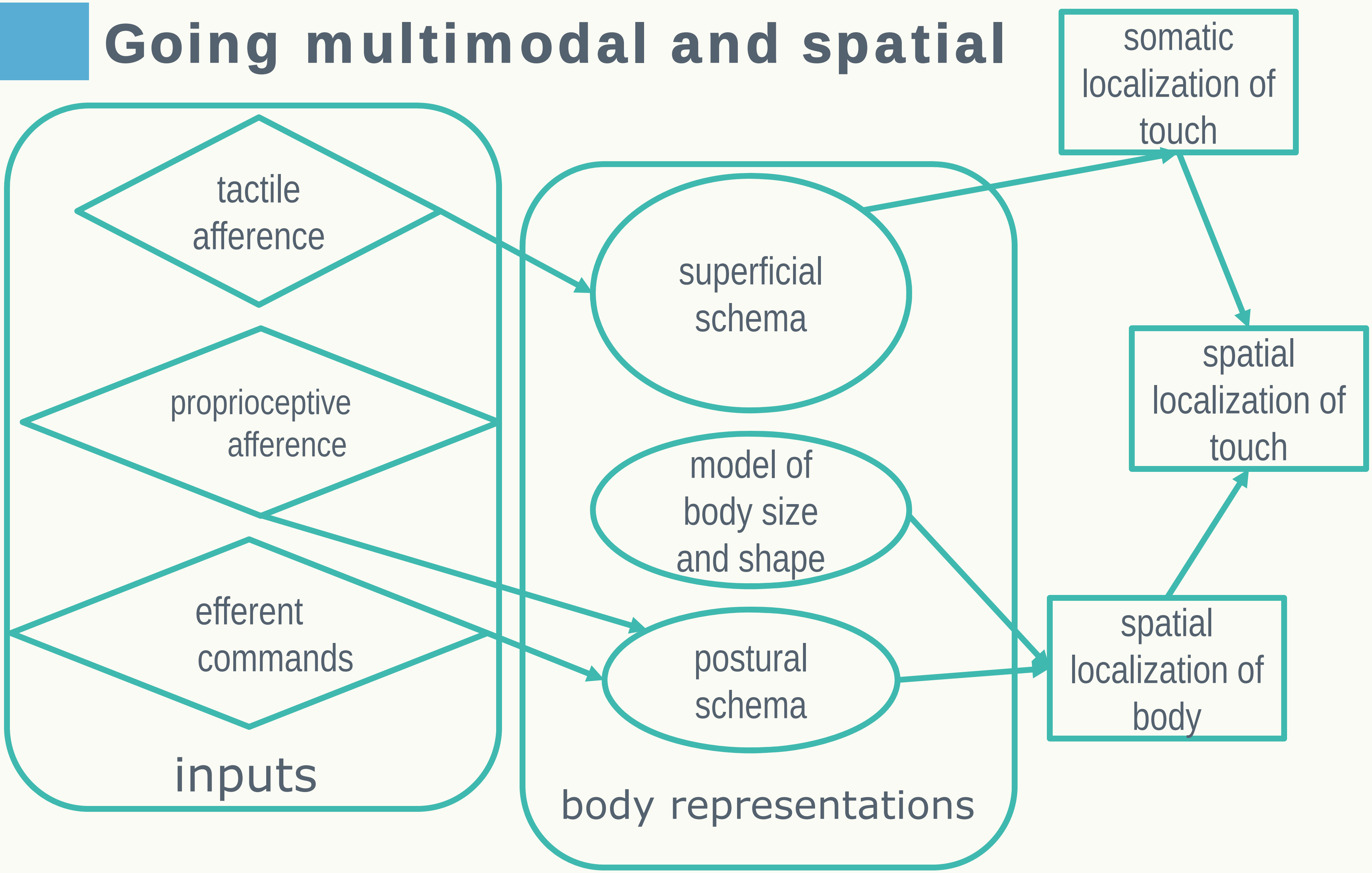
RFs of neurons representing torso



repr. of indiv. skin parts on final map

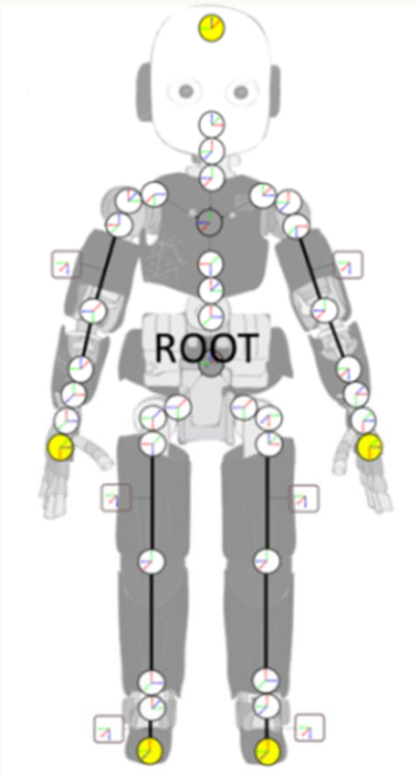


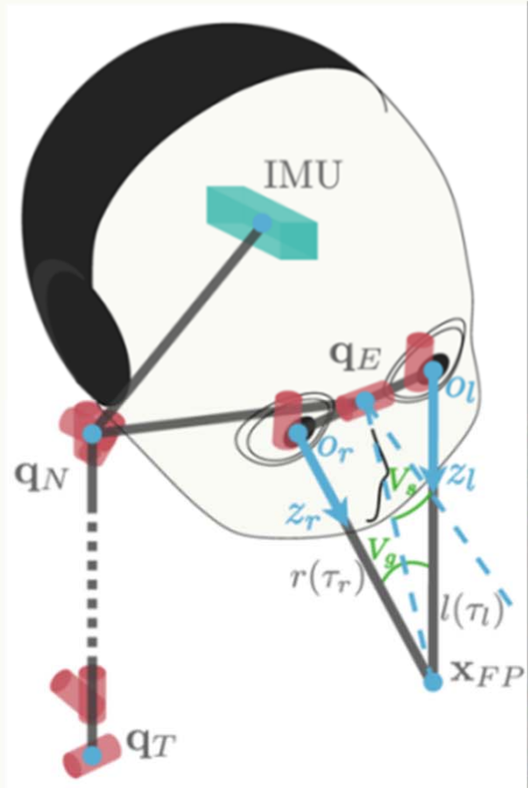
Going multimodal and spatial

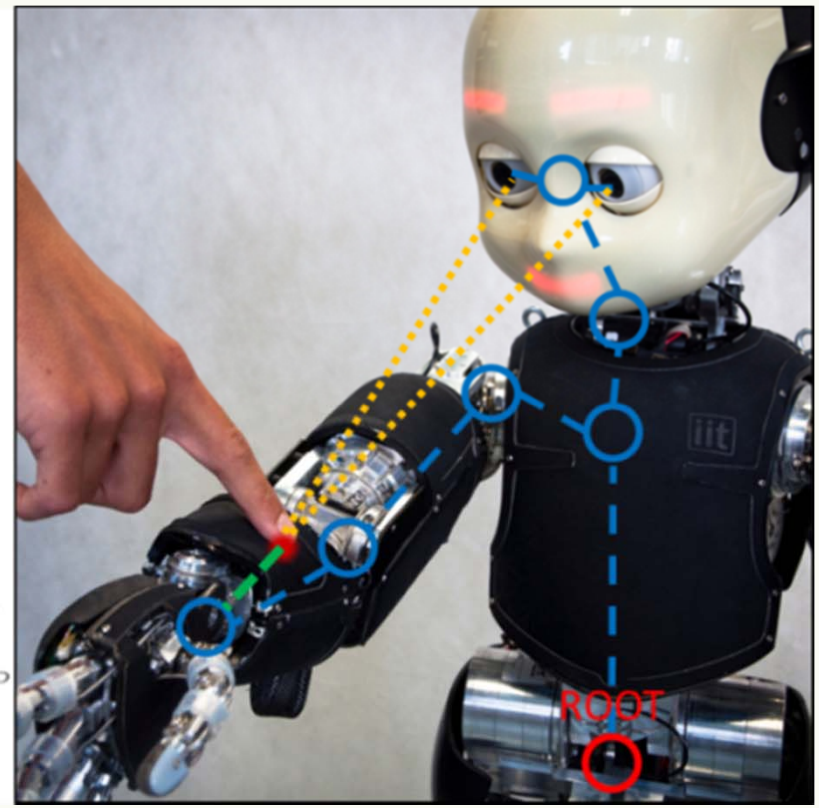


After Longo, M.; Azanon, E. & Haggard, P. (2010), 'More than skin deep: Body representation beyond primary somatosensory cortex', Neuropsychologia 48, 655--668.

Spatial localization of touch

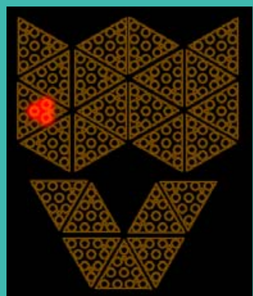






Learning spatial representation of the body from self-touch experience

Inputs

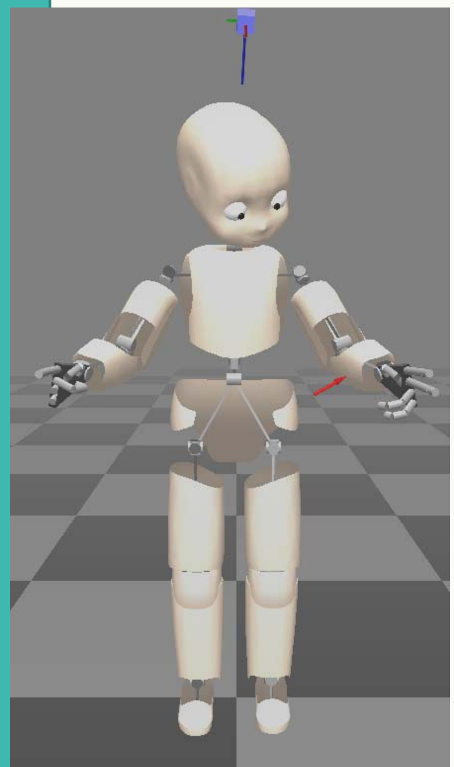


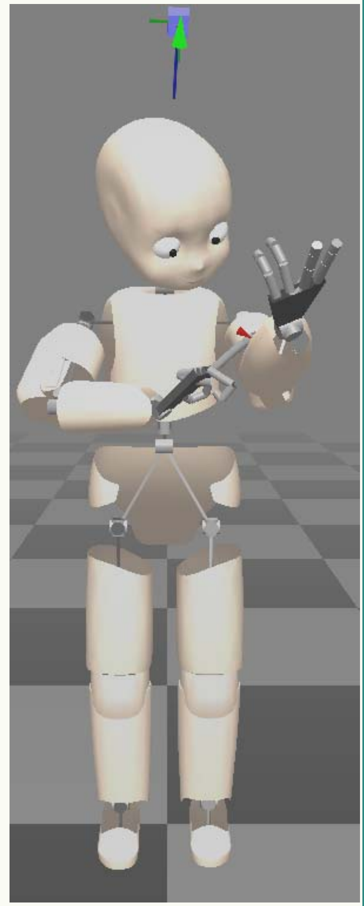
Tactile - Skin

$\theta_1 = (\theta_1,\ldots,\theta_n)$

Proprioception – joint angles

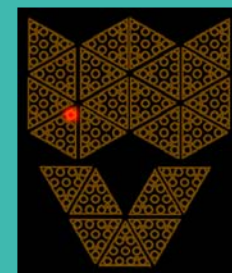
Vision - cameras

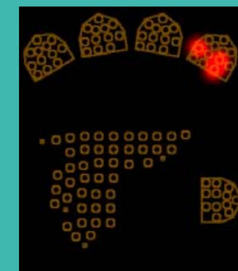




- External touch vs. double touch

Inputs

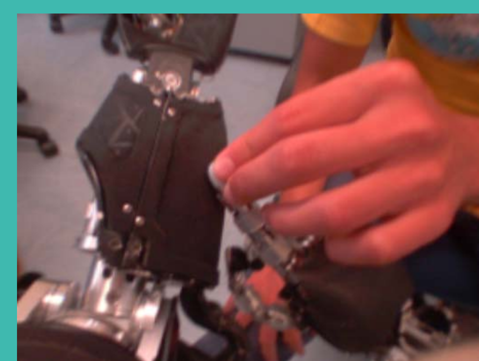




Tactile - Skin

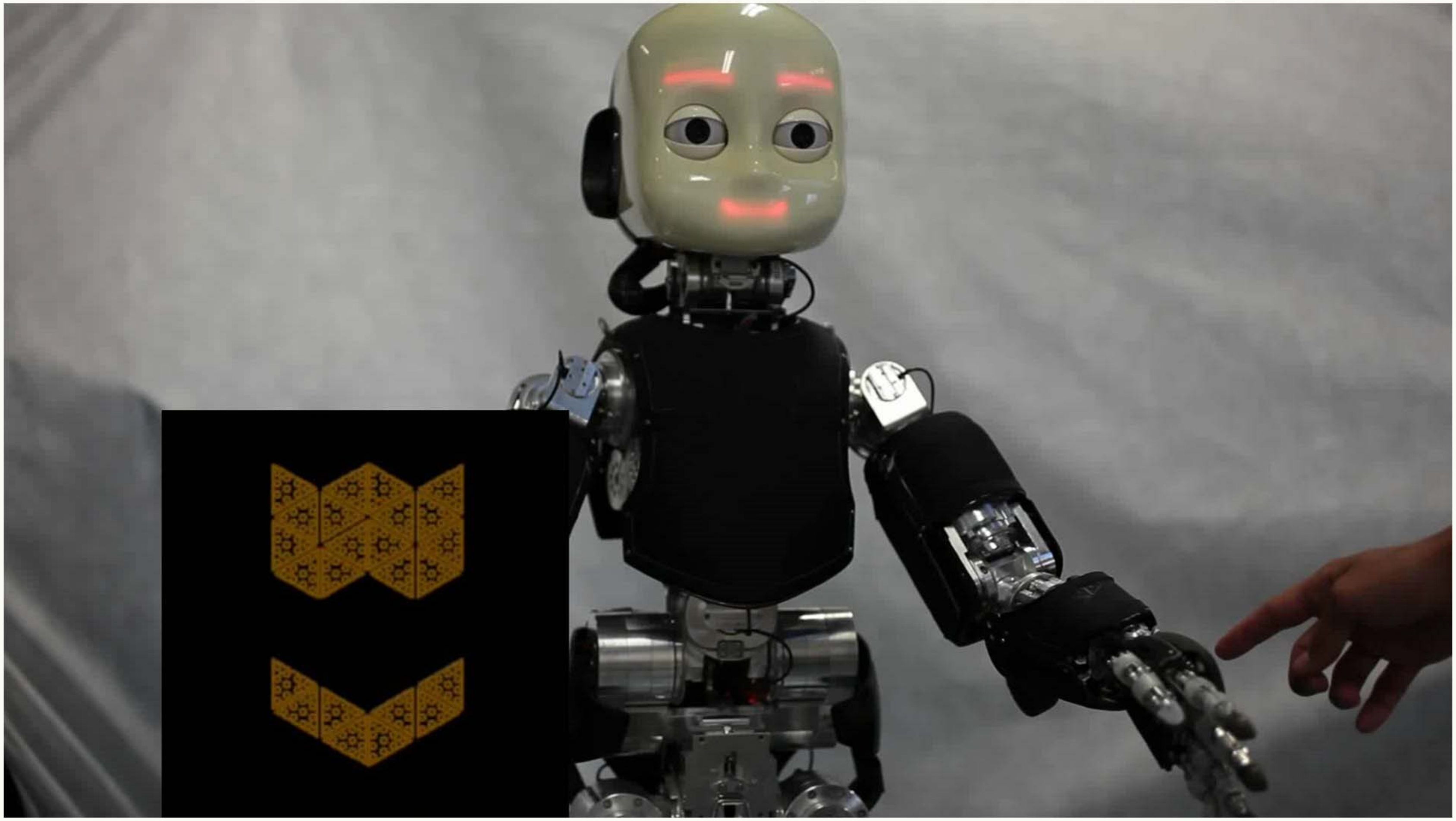
$\theta_2 = (\theta_1,\ldots,\theta_n)$

Proprioception – joint angles

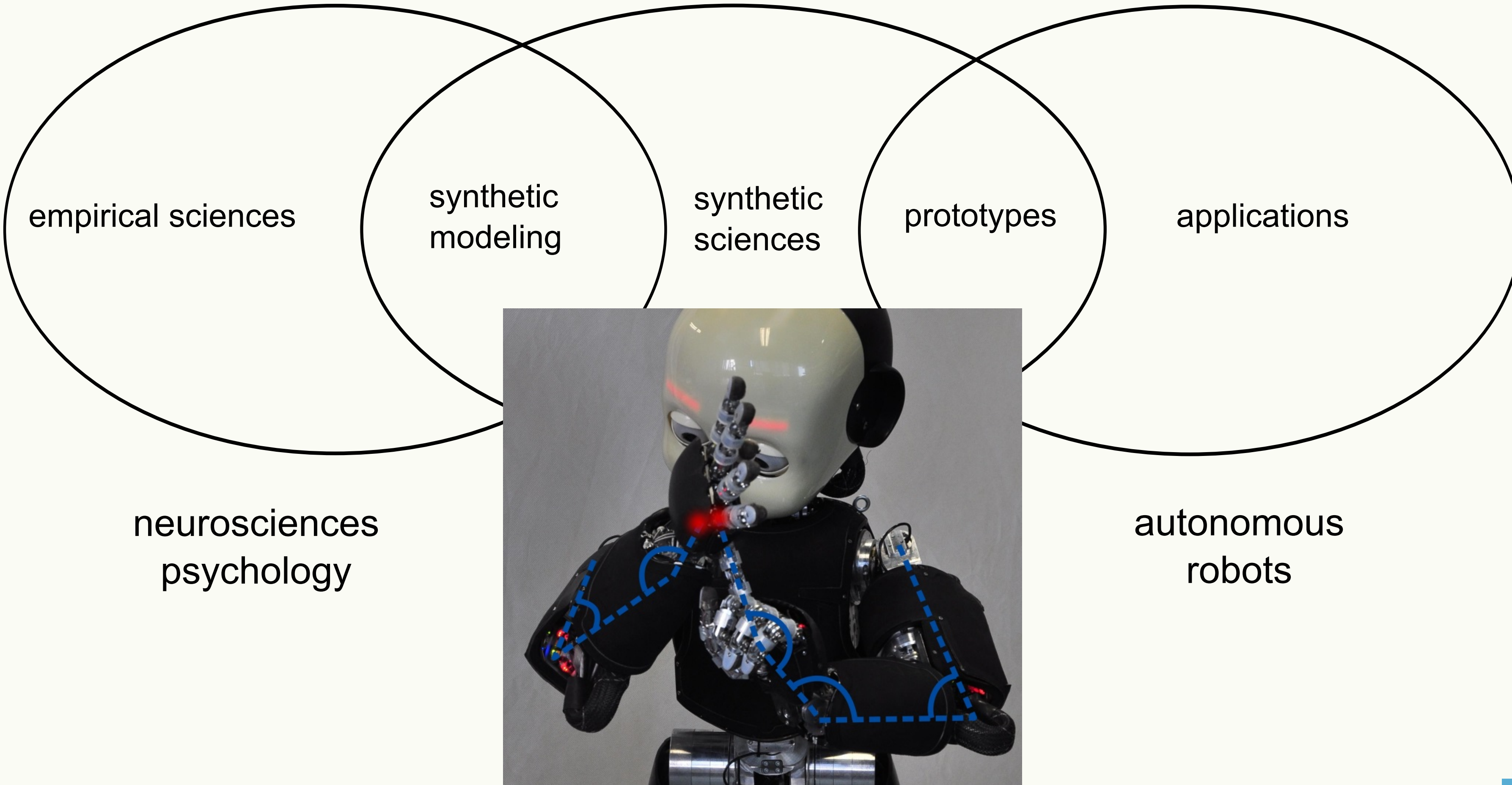


Vision - cameras

Double touch in the robot



Synthetic methodology

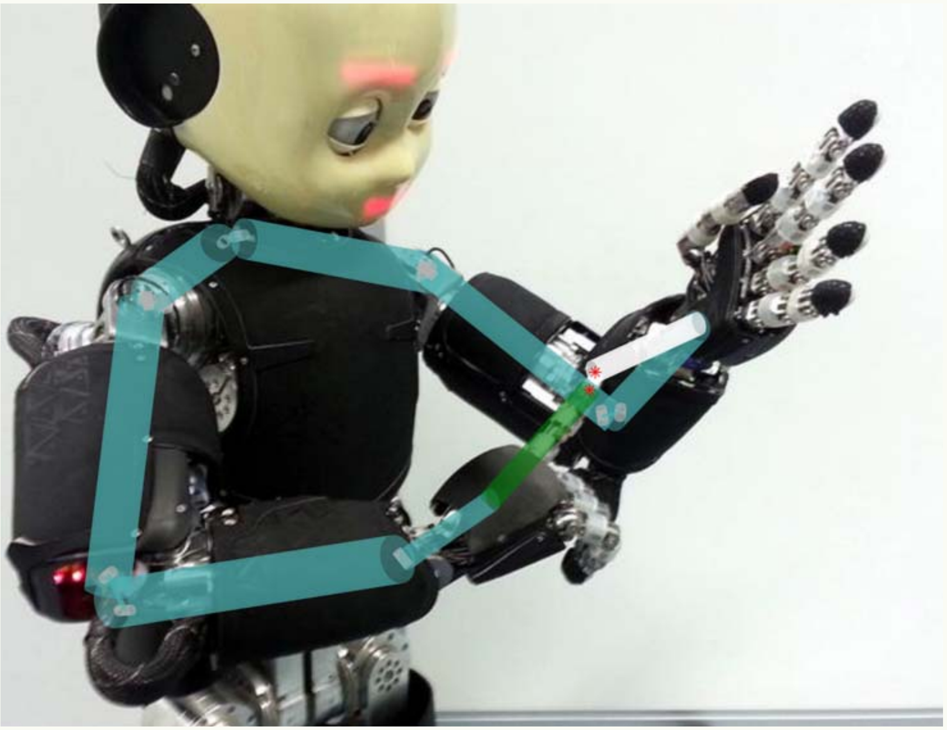


Outline

1. Why humanoids and the iCub
2. Body representations on the iCub
   – Models of development and mechanisms of human/monkey body representations
   – Applications: self-calibration
3. The space around the body (peripersonal space) and safe human-robot interaction
4. Future work and conclusion

Double touch as a self-calibration tool

- Closing the kinematic loop by touching own body.



Roncone, A.; Hoffmann, M.; Pattacini, U. & Metta, G. (2014), Automatic kinematic chain calibration using artificial skin: self-touch in the iCub humanoid robot, *in* 'Proc. IEEE Int. Conf. Robotics and Automation (ICRA)'.

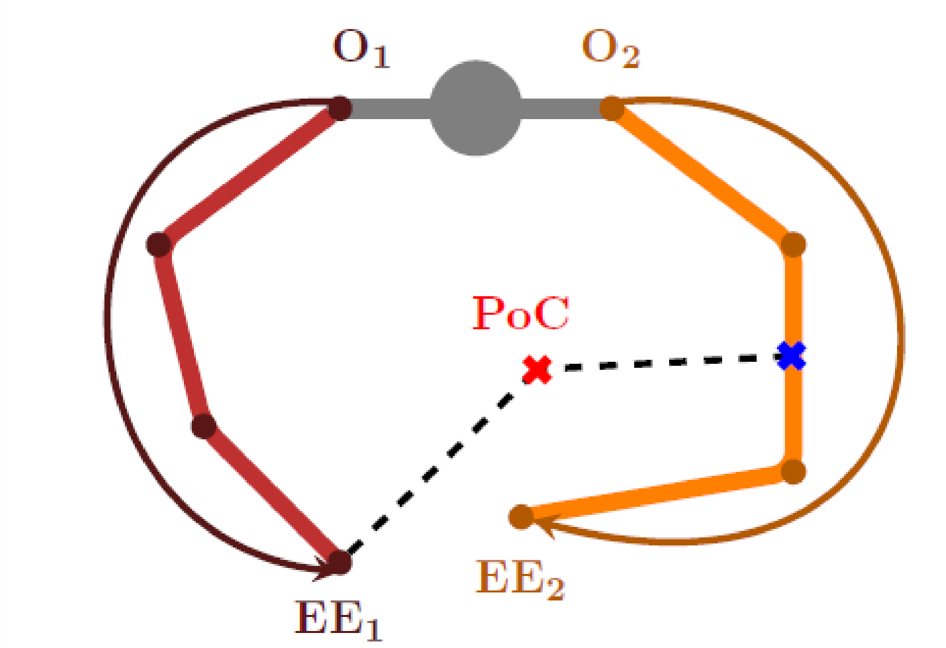
Making the robot touch its own body

Two fixed-base kinematic chains, with

- origins O_1 and O_2 (shoulders of iCub)
- end-effectors EE_1 and EE_2 (palms of the robot)
- blue cross – point to be touched
- PoC – final, *unknown*, point of contact in operational space

Problems:

- Limited nr. DOF for the task
- Finding PoC
- Undesired self-collisions at other points



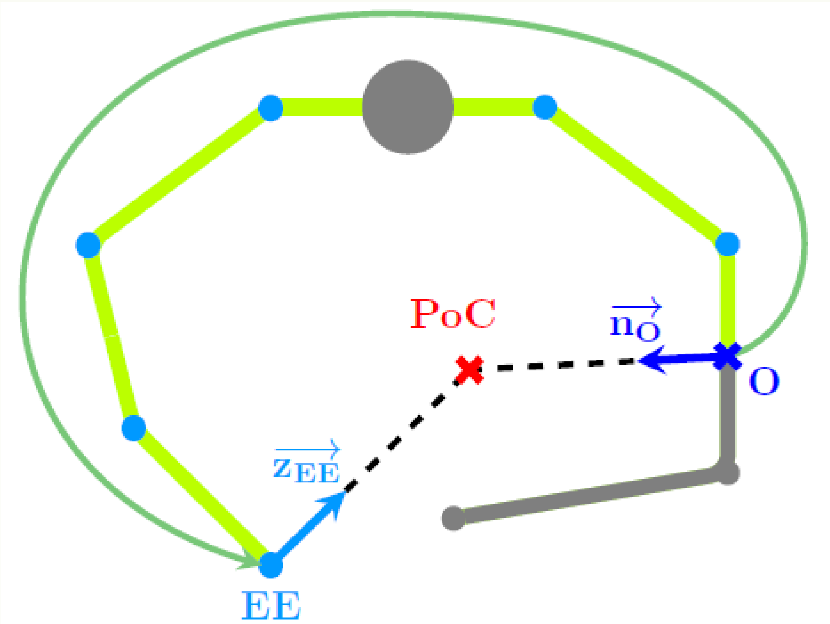
Reformulation of the kinematic chain

-> single floating-base serial chain with origin *O* in the point to be touched

- half of the kinematic chain needs to be "reversed" – traversed upside down

Advantages:

- Final PoC defined *implicitly* (base is floating)
- More DOF available (+2x3 shoulder joints)

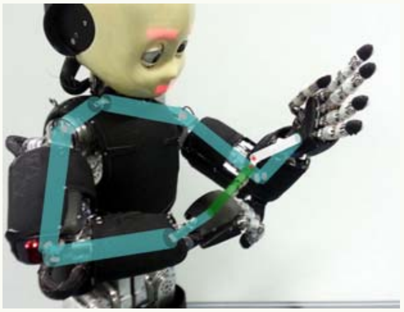


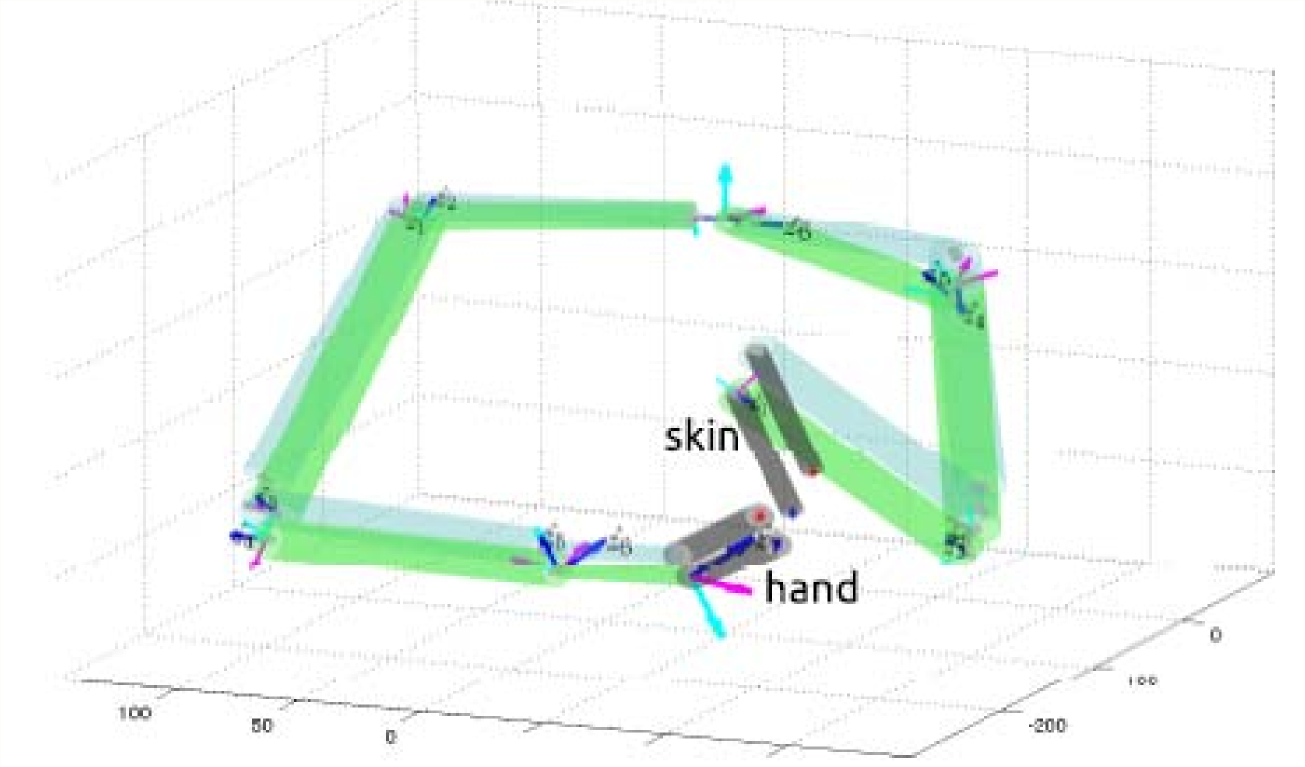
Self-calibration optimization problem formulation

Optimizing the parameter vector:
$\phi_i = a_i$, d_i , α_i, o_i with $i \in [1, n]$,

- where *a, d, α,* and *o* are the Denavit-Hartenberg parameters
- in our case i=12, i.e. 12 DOF (5 on the «touched» and 7 on «touching» arm)

Optimization problem formulation (2)





Optimization problem formulation (3)

$$\Phi^* = arg\min_{\Phi} \sum_{m=1}^{M} \|\mathbf{p}_s - \mathbf{p}_e(\Phi, \theta_m)\|$$

- Minimizing total position error, where
  - θ_m are joint angles of m-th sample as read from joint encoders
  - p_e is the estimated position as a function of joint angles and current param. values
  - p_s of the end-effector as measured from the skin
- Optimizer: IpOpt

A. Wächter and L. T. Biegler, "On the implementation of an interiorpoint filter line-search algorithm for large-scale nonlinear programming," *Mathematical programming*, vol. 106, no. 1, pp. 25–57, 2006.

Results

Error at end-effector

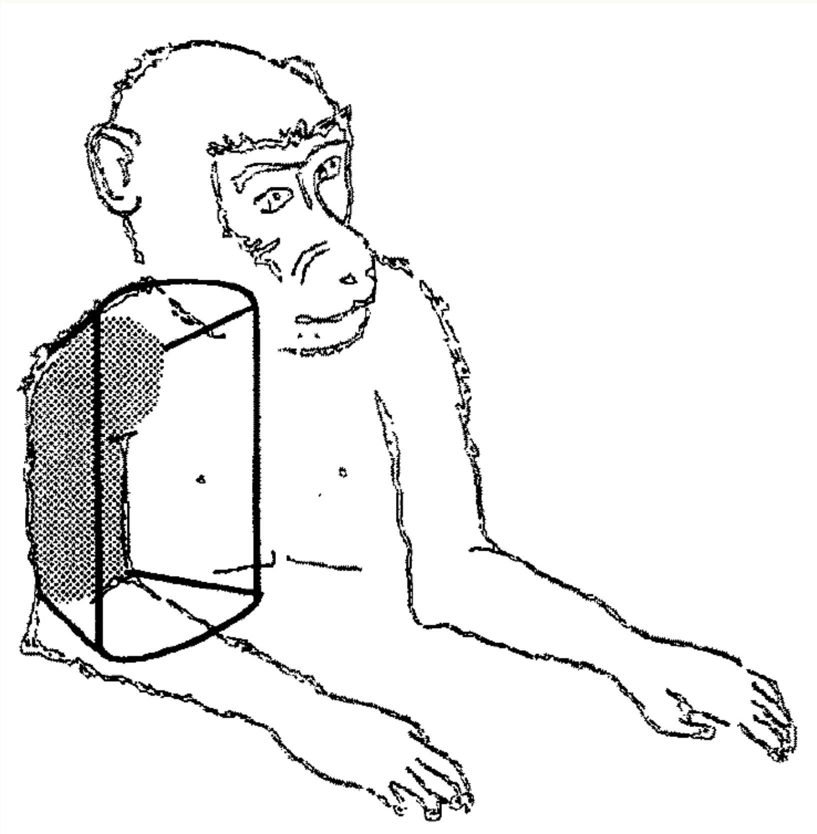
	Initial (m)	**Optimized (m)**
Exp 1	0.0226	0.0208
Exp 2 (10% noise)	0.0819 ± 0.0299	0.0377 ± 0.0139
Exp 3 (30% noise)	0.1919 ± 0.0301	0.0664 ± 0.0175

- Future work:
  - Data collection – tactile servoing
  - Multiple kinematic chain closures – e.g. touch legs
  - Close another loop by looking at touched point and calibrate also
    - Head and eye kinematics
    - Extrinsic camera parameters

Outline

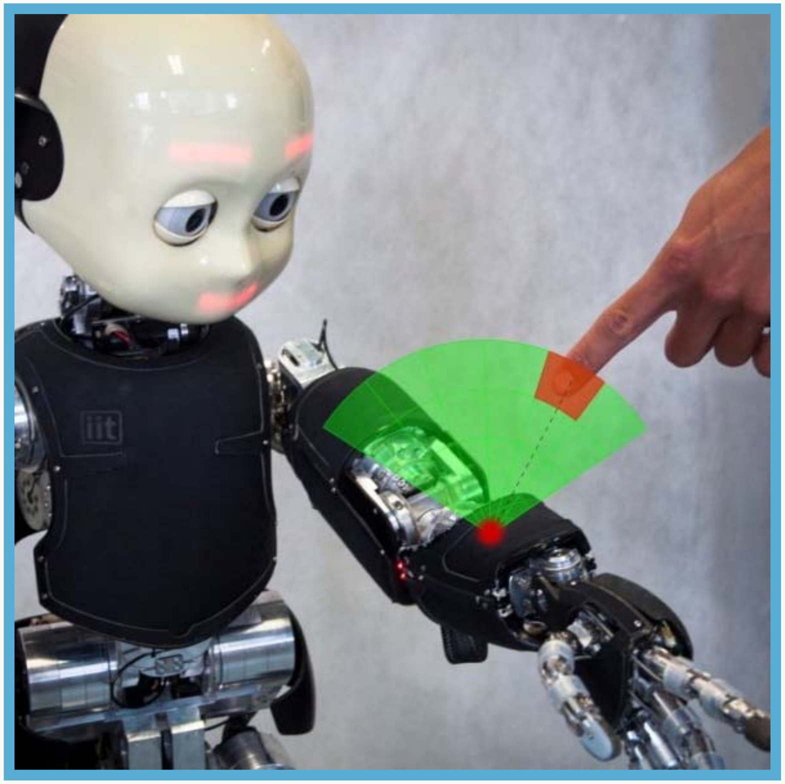
1. Why humanoids and the iCub
2. Body representations on the iCub
   - Models of development and mechanisms of human/monkey body representations
   - Applications: self-calibration
3. The space around the body (peripersonal space) and safe human-robot interaction
4. Future work and conclusion

Representation of space around the body (peripersonal space)



L. Fogassi, V. Gallese, L. Fadiga, G. Luppino, M. Matelli and G. Rizzolatti, "Coding of peripersonal space in inferior premotor cortex (area F4)," *Journal of Neurophysiology,* vol. 76, no. 1, pp. 141-157, 1996.

Peripersonal space in iCub



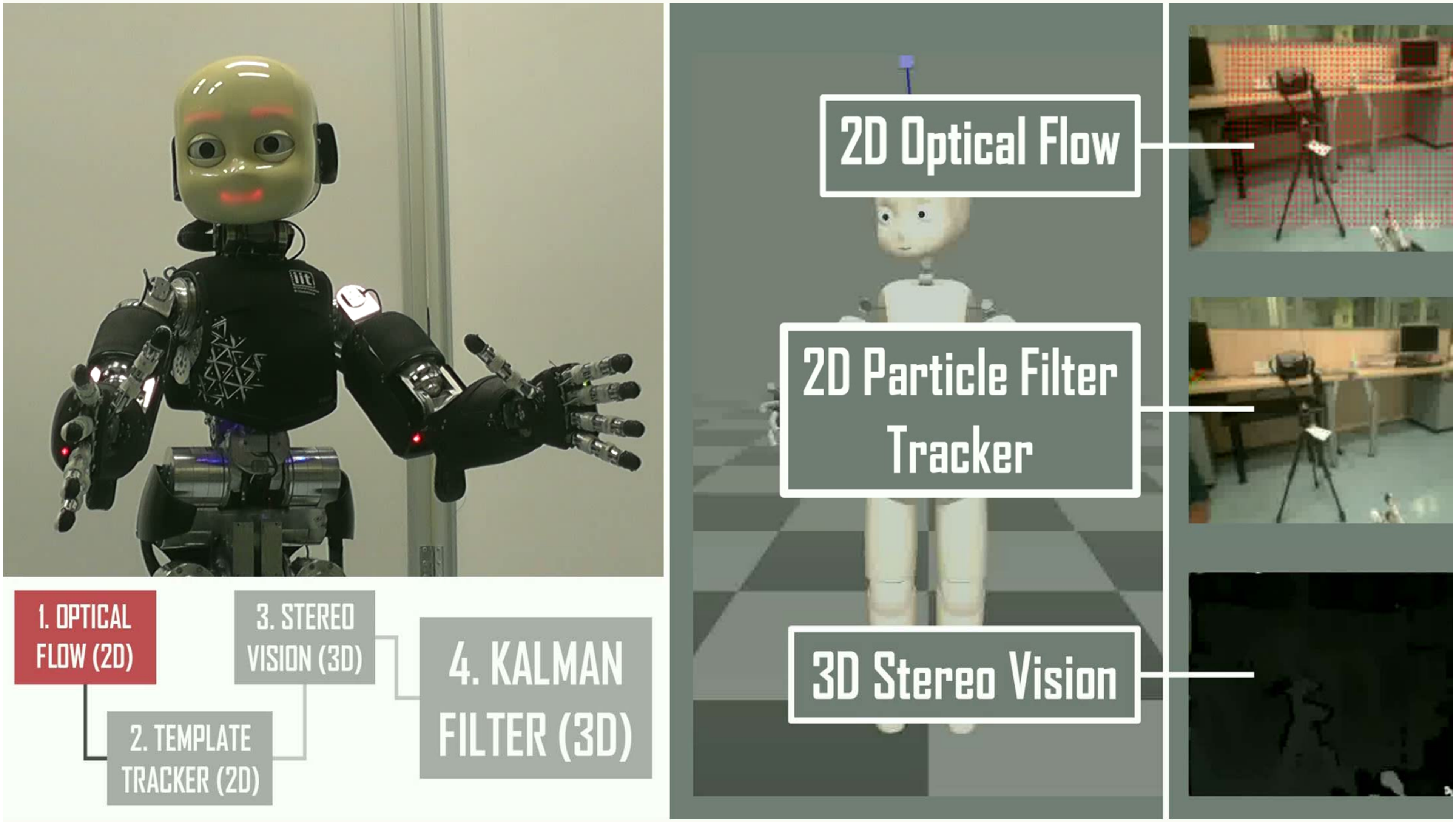
DISTRIBUTED REPRESENTATION of nearby space

Each taxel possesses a **SPATIAL RECEPTIVE FIELD** growing out from it

each taxel learns a **PROBABILITY** of **BEING TOUCHED**

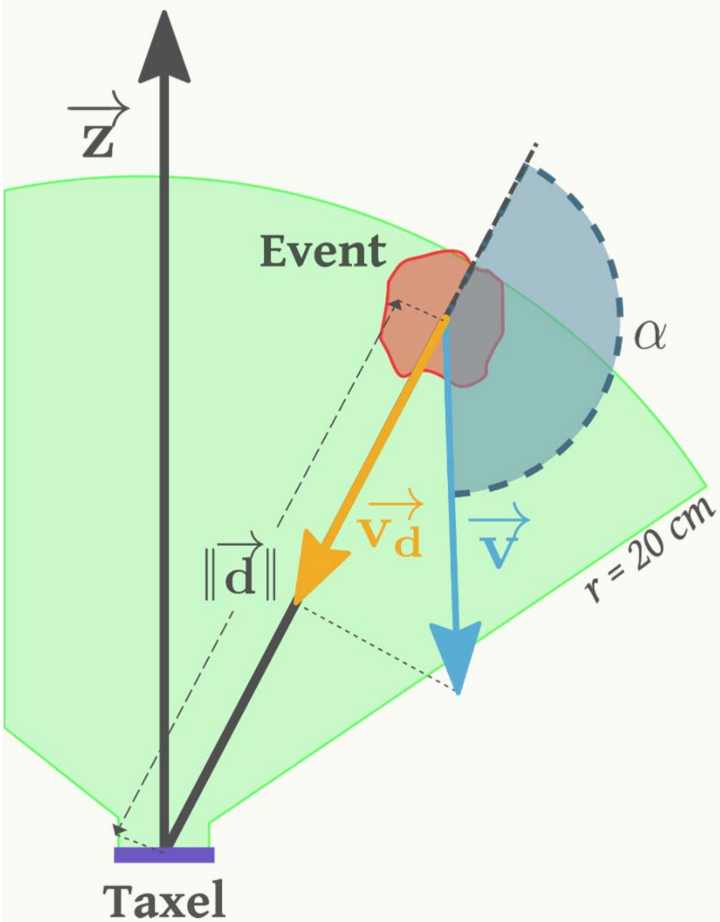
Roncone, A.; Hoffmann, M.; Pattacini, U. & Metta, G. (2015), Learning peripersonal space representation through artificial skin for avoidance and reaching with whole body surface, *in 'Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on', pp. 3366-3373.*

Video Time



1. OPTICAL FLOW (2D)
2. TEMPLATE TRACKER (2D)
3. STEREO VISION (3D)
4. KALMAN FILTER (3D)
iit
2D Optical Flow
2D Particle Filter Tracker
3D Stereo Vision

Representation of space around the body



for any input event, its **DISTANCE** and **VELOCITY** wrt the taxel is recorded in a 3 seconds buffer

Two key variables:

Distance [D]

Time to Contact [TTC]

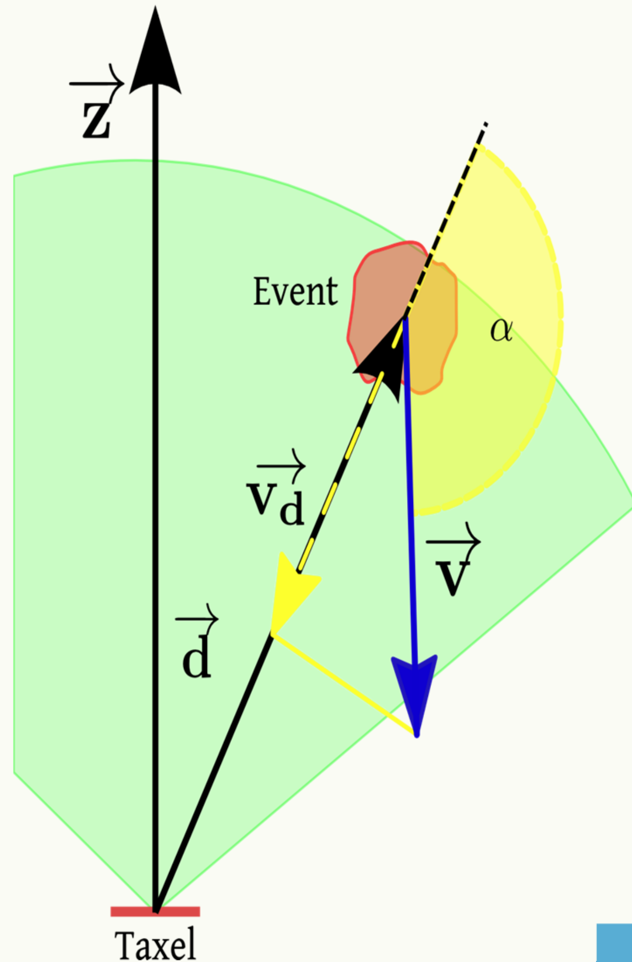
Roncone, A.; Hoffmann, M.; Pattacini, U.; Fadiga, L. & Metta, G. (), 'Peripersonal space and margin of safety around the body: learning tactile-visual associations in a humanoid robot with artificial skin'. [under review]

Receptive fields

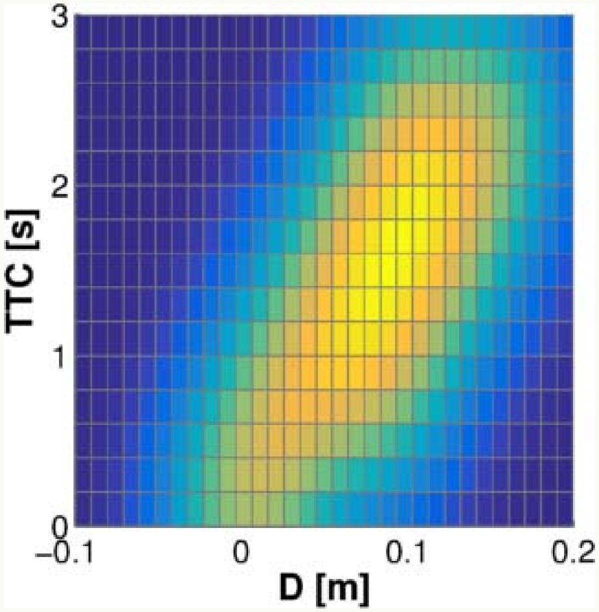
Receptive field: a cone that extends up to 0.2m and angle of 40°

$$\mathbf{D} = sgn(\vec{\mathbf{d}} \cdot \vec{\mathbf{z}})||\vec{\mathbf{d}}||$$

$$\mathbf{TTC} = \frac{||\vec{\mathbf{d}}||}{||\vec{\mathbf{v}}|| \cdot cos(\alpha)}$$



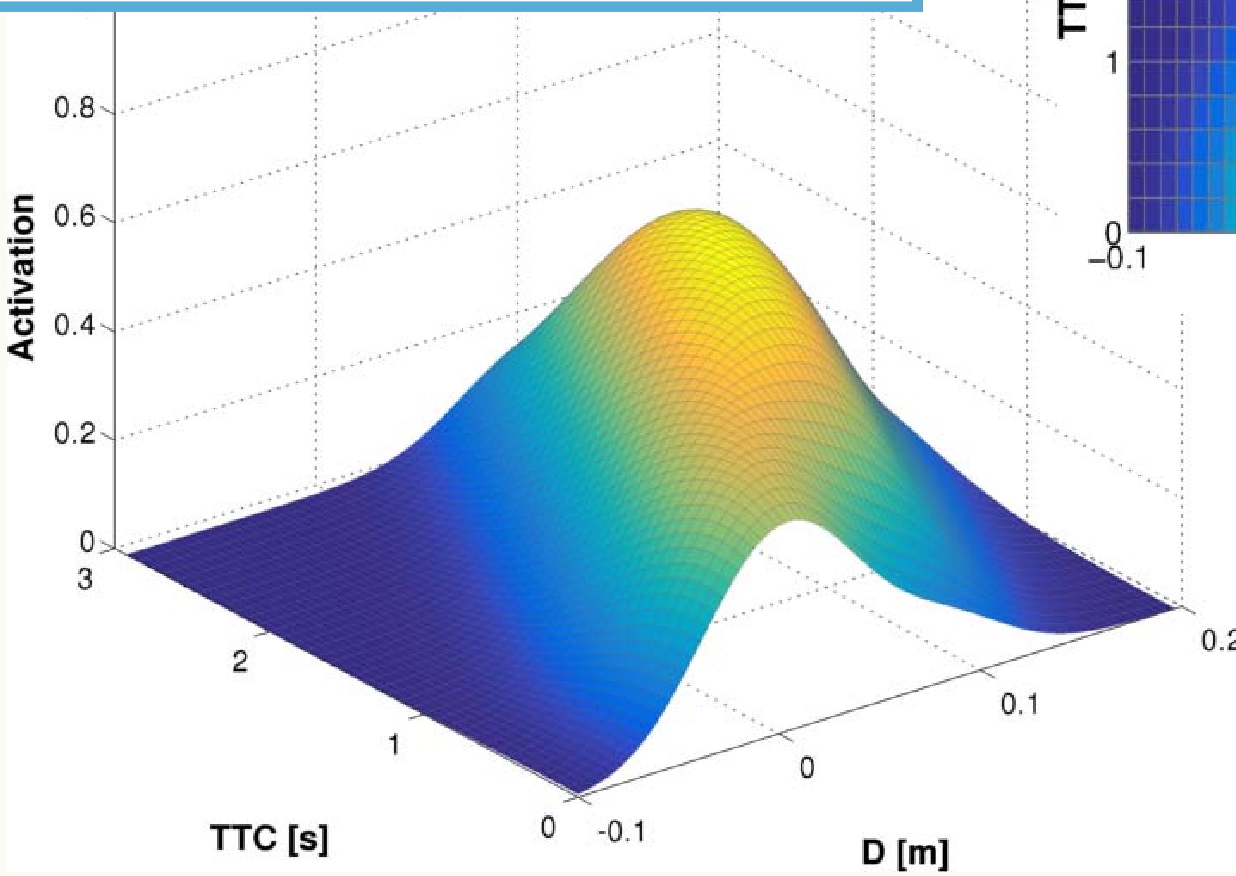
Representation of space around the body

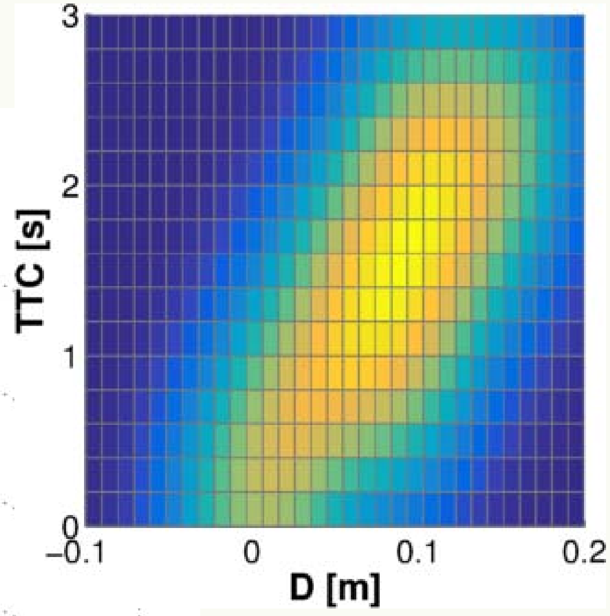


$$P(D, TTC) \approx f(D, TTC) = \frac{n_{positive}(D, TTC)}{n_{negative}(D, TTC)}$$

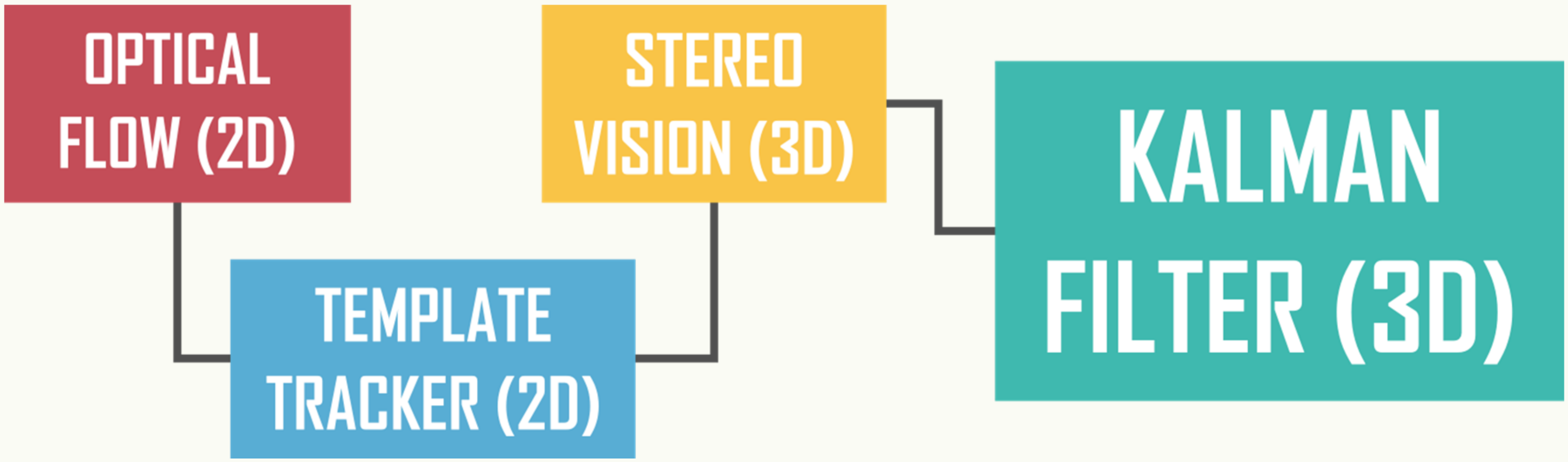
Representation of space around the body

$$p(x) = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{\sqrt{2\pi}\sigma}\exp\left(-\frac{(x_i - x)^2}{2\sigma^2}\right)$$





3D Tracking of «arbitrary» objects

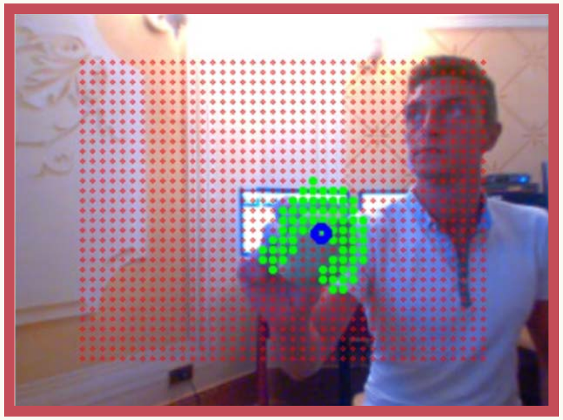


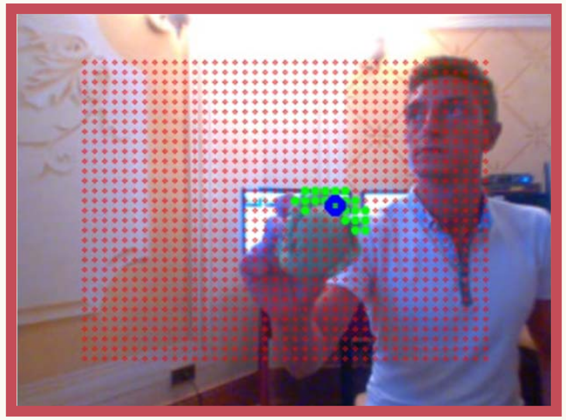
2D Optical Flow
[Ciliberto et al. 2011]

3D Stereo Vision
[Fanello et al. 2014]

2D Particle Filter
[Tikhanoff et al. 2013]

Kalman Filter
for robust 3D tracking



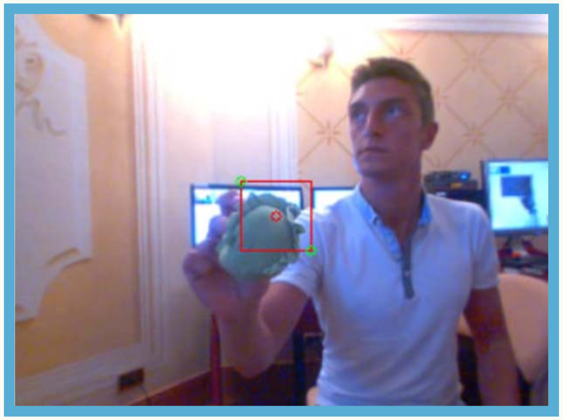


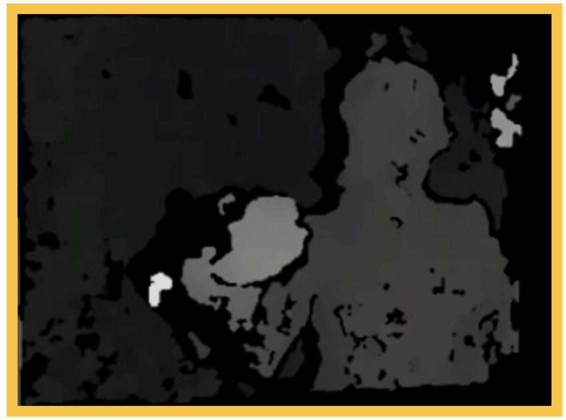
OPTICAL FLOW (2D)

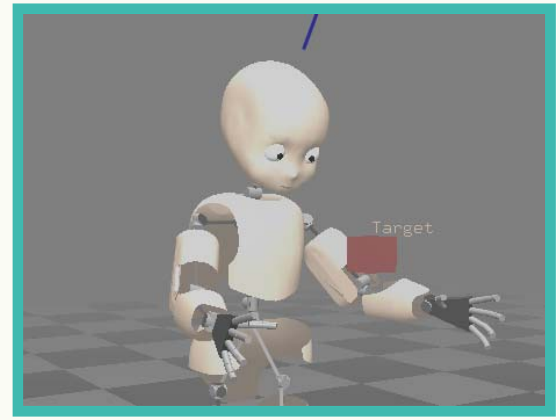
TEMPLATE TRACKER (2D)

STEREO VISION (3D)

KALMAN FILTER (3D)







OPTICAL FLOW (2D)

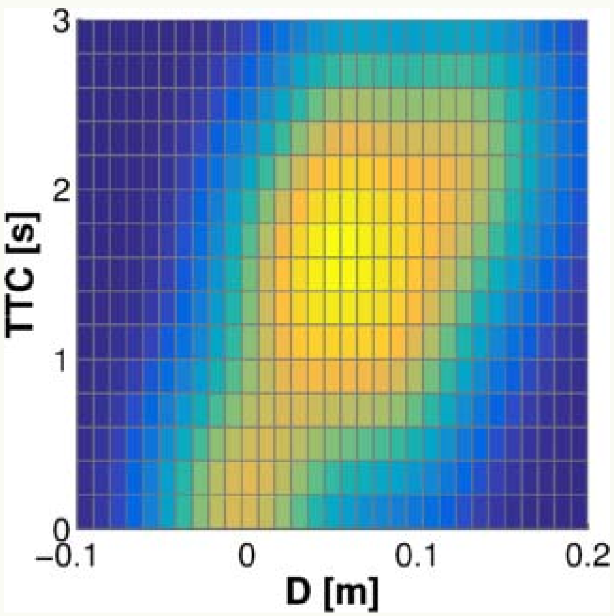
TEMPLATE TRACKER (2D)

STEREO VISION (3D)

KALMAN FILTER (3D)

Learned representation compensates for errors

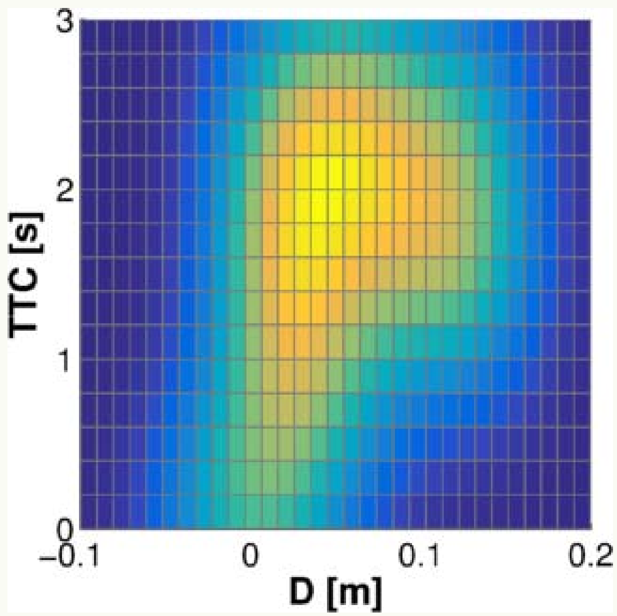
Left Forearm [int]



53 iterations

627 samples

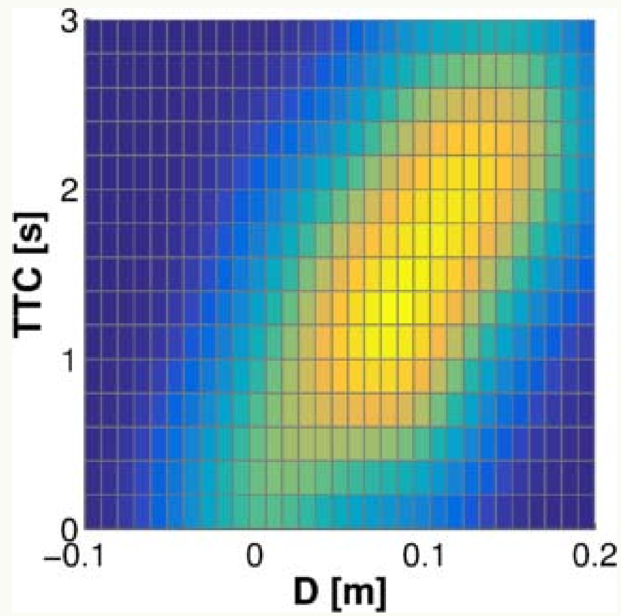
Left Forearm [ext]



34 iterations

451 samples

Right Hand



77 iterations

944 samples

Avoidance and Catching Controller

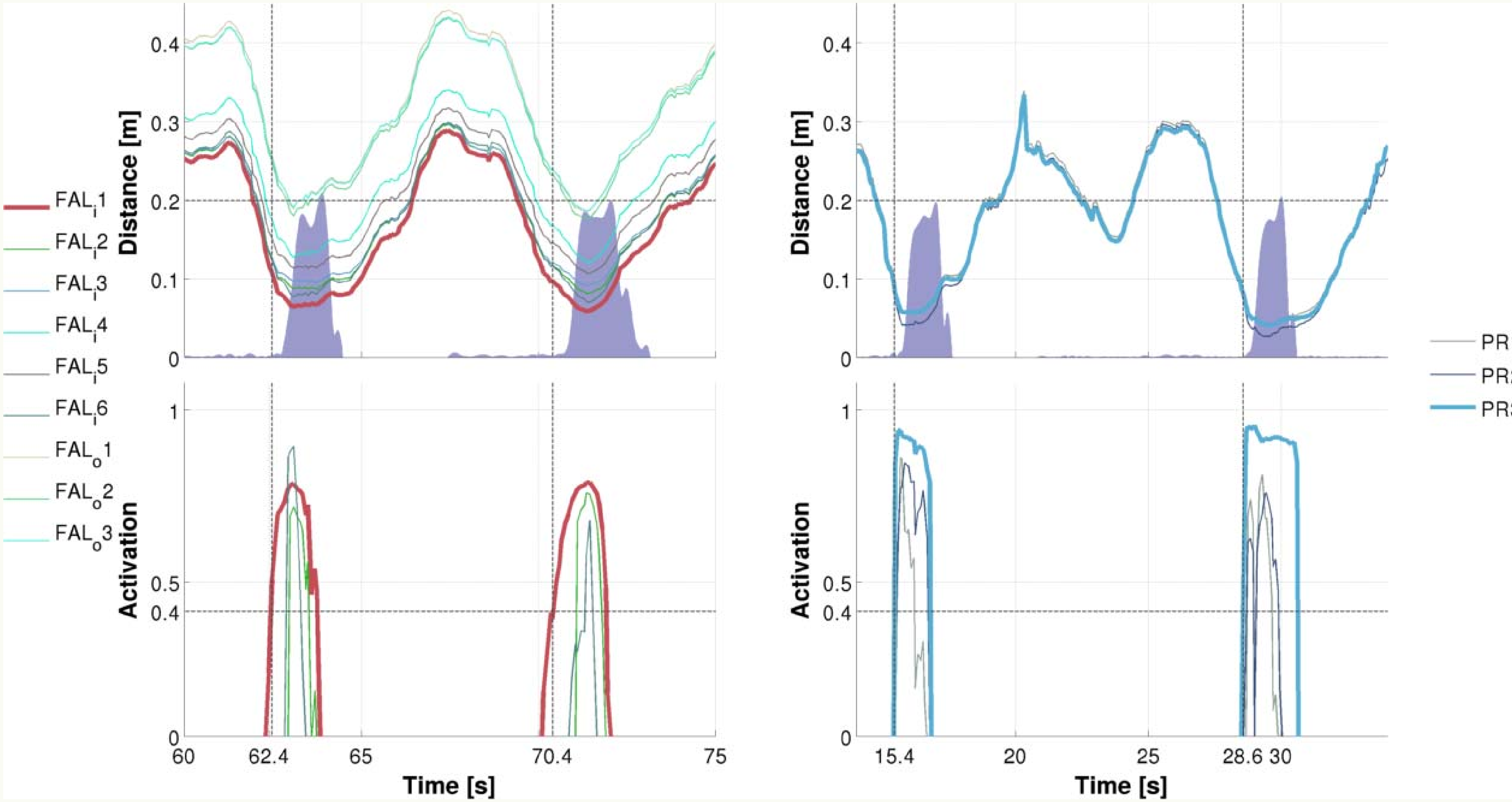
Distributed control

(i.e. avoidance and catching with any body part)

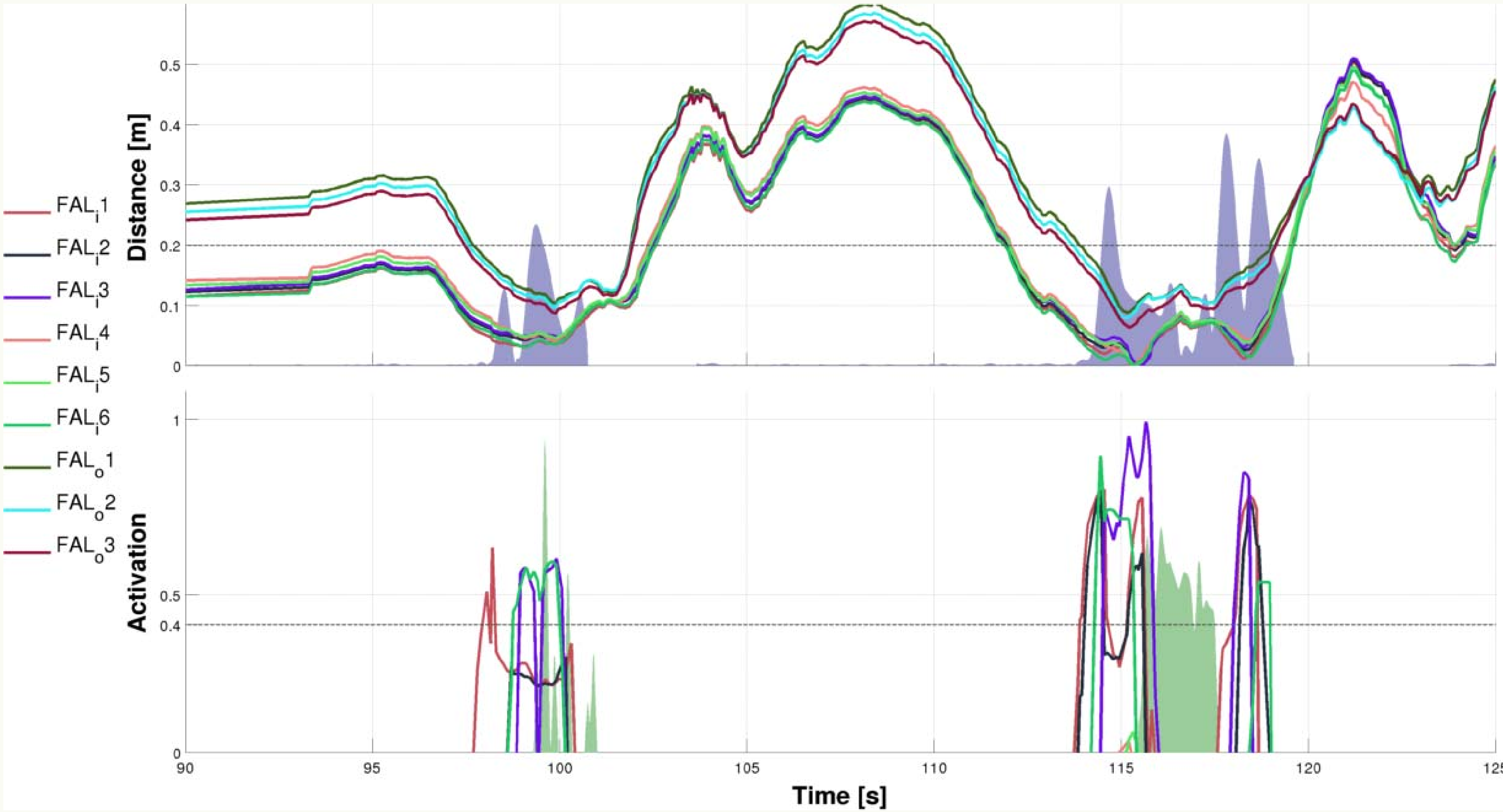
$$\mathbf{P}(t) = \frac{1}{k}\sum_{i=1}^{k}\left[a_i(t)\cdot \mathbf{p}_i(t)\right]$$

$$\mathbf{N}(t) = \frac{1}{k}\sum_{i=1}^{k}\left[a_i(t)\cdot \mathbf{n}_i(t)\right]$$

Avoidance Experiments .



Catching Experiments



Outline

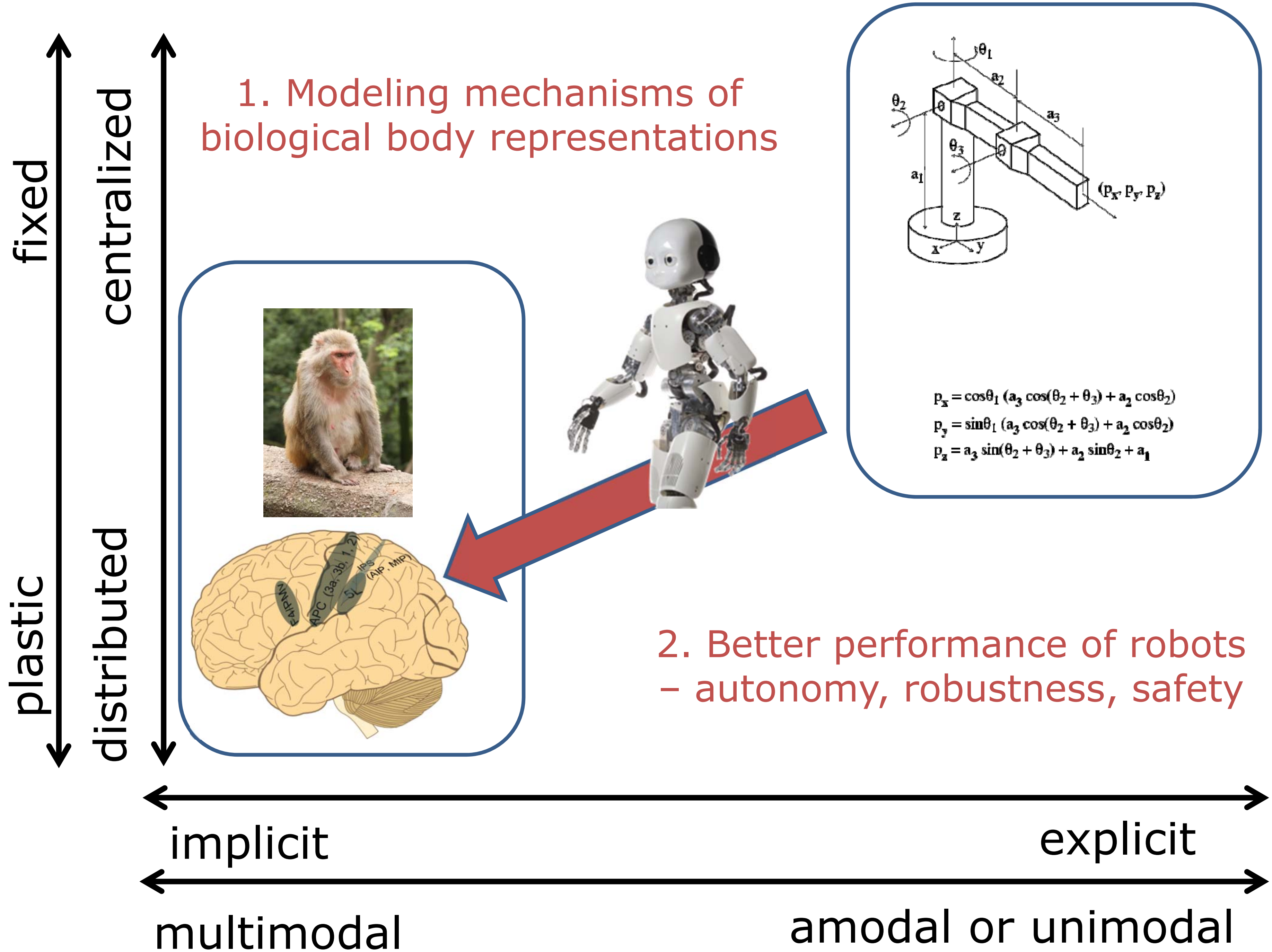
1. Why humanoids and the iCub
2. Body representations on the iCub
   - Models of development and mechanisms of human/monkey body representations
   - Applications: self-calibration
3. The space around the body – peripersonal space
4. Future work and conclusion

Safe and natural man-machine interaction

- Reaching while keeping a safety margin to obstacles and humans – taking the whole body into account
  - Reaching task integrating reactive collision avoidance
  - Using the distributed visuo-tactile representation – repulsive vectors

Conclusion

- To understand body representations
  - Individual modalities or capacities cannot be studied in isolation.
  - Whole sensorimotor loops need to be considered.
- Robots – a powerful modeling substrate.
  - Key physical properties (spatial characteristics) + sensorimotor capacities available
  - Robot model ensures that theory is explicit, detailed, consistent and complete (Pezzulo et al. 2011)
- Key application areas
  - Automatic robot self-calibration
  - Robots with whole-body awareness


fixed
plastic
centralized
distributed
1. Modeling mechanisms of
biological body representations
2. Better performance of robots
– autonomy, robustness, safety
implicit
explicit
multimodal
amodal or unimodal
$p_x = \cos\theta_1 (a_3 \cos(\theta_2 + \theta_3) + a_2 \cos\theta_2)$
$p_y = \sin\theta_1 (a_3 \cos(\theta_2 + \theta_3) + a_2 \cos\theta_2)$
$p_z = a_3 \sin(\theta_2 + \theta_3) + a_2 \sin\theta_2 + a_1$

Thank you!

- Thanks in particular to
  - Alessandro Roncone, Ugo Pattacini, Giorgio Metta – IIT Genova, Italy
  - Jeffrey J. Lockman – Tulane Uni, USA
  - Zdeněk Straka, Naďa Bednárová, Michal Vavrečka – Czech Technical University, Prague
  - Igor Farkaš – Comenius University, Bratislava
  - Tobias Heed – Uni Hamburg, Germany
- Funding: Marie Curie Intra-European Fellowship

  (iCub Body Schema 625727; FP7-PEOPLE-2013-IEF)

Matěj Hoffmann

iCub Facility

Italian Institute of Technology

matej.hoffmann@iit.it

https://sites.google.com/site/matejhof