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

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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
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
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My current project: motivation
Synthetic methodology

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]
  • …
Implicit vs. explicit, distributed vs. centralized, plastic vs. fixed, multimodal vs. amodal or unimodal.
Body representations in robots

industrial robots

humanoid robots
Standard body representations

e.g., forward kinematics

\[ \begin{align*}
    p_x &= \cos\theta_1 (a_3 \cos(\theta_2 + \theta_3) + a_2 \cos\theta_2) \\
    p_y &= \sin\theta_1 (a_3 \cos(\theta_2 + \theta_3) + a_2 \cos\theta_2) \\
    p_z &= a_3 \sin(\theta_2 + \theta_3) + a_2 \sin\theta_2 + a_1
\end{align*} \]

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.
1. Modeling mechanisms of biological body representations

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


   - Learning from double touch; Goal: Being able to execute movement toward stimulated body part (~ buzzer removal)

“Somatosensory homunculus”


(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
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

inputs
- tactile afference
- proprioceptive afference
- efferent commands

body representations
- superficial schema
- model of body size and shape
- postural schema

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

- Empirical sciences
- Synthetic modeling
- Synthetic sciences
- Prototypes
- Applications

- Neurosciences
- Psychology
- Autonomous robots
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Double touch as a self-calibration tool

• Closing the kinematic loop by touching own body.


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: 
\( \phi_i = a_i, d_i, a_i, o_i \) with \( i \in [1, n] \),
- where \( a, d, a, \) 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)

\[ \Phi^* = \arg\min_{\Phi} \sum_{m=1}^{M} \| p_s - p_e(\Phi, \theta_m) \| \]

- Minimizing total position error, where
  - \( \theta_m \) 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

Results

Error at end-effector

<table>
<thead>
<tr>
<th></th>
<th>Initial (m)</th>
<th>Optimized (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp 1</td>
<td>0.0226</td>
<td>0.0208</td>
</tr>
<tr>
<td>Exp 2 (10% noise)</td>
<td>0.0819 ± 0.0299</td>
<td>0.0377 ± 0.0139</td>
</tr>
<tr>
<td>Exp 3 (30% noise)</td>
<td>0.1919 ± 0.0301</td>
<td>0.0664 ± 0.0175</td>
</tr>
</tbody>
</table>

- 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
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Representation of space around the body (peripersonal space)

DISTRIBUTED REPRESENTATION of nearby space

Each taxel possesses a SPATIAL RECEPTIVE FIELD growing out from it

each taxel learns a PROBABILITY of BEING TOUCHED

Video Time

1. Optical Flow (2D)
2. Template Tracker (2D)
3. Stereo Vision (3D)
4. Kalman Filter (3D)

- 2D Optical Flow
- 2D Particle Filter Tracker
- 3D Stereo Vision
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°

\[ D = \text{sgn}(\vec{d} \cdot \vec{z}) \| \vec{d} \| \]

\[ \text{TTC} = \frac{\| \vec{d} \|}{\| \vec{v} \| \cdot \cos(\alpha)} \]
Representation of space around the body

\[ P(D, \text{TTC}) \approx f(D, \text{TTC}) = \frac{n_{\text{positive}}(D, \text{TTC})}{n_{\text{negative}}(D, \text{TTC})} \]
Representation of space around the body

\[ p(\mathbf{x}) = \frac{1}{n} \sum_{i=1}^{n} \frac{1}{\sqrt{2\pi\sigma}} \exp \left( -\frac{(x_i - x)^2}{2\sigma^2} \right) \]
3D Tracking of «arbitrary» objects

- **Optical Flow (2D)**
- **Stereo Vision (3D)**
- **Template Tracker (2D)**
- **Kalman Filter (3D)**

**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
Learned representation compensates for errors

Left Forearm [int]  Left Forearm [ext]  Right Hand

53 iterations  34 iterations  77 iterations
627 samples  451 samples  944 samples
Avoidance and Catching Controller

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

\[
P(t) = \frac{1}{k} \sum_{i=1}^{k} [a_i(t) \cdot p_i(t)]
\]

\[
N(t) = \frac{1}{k} \sum_{i=1}^{k} [a_i(t) \cdot n_i(t)]
\]
Avoidance Experiments
Catching Experiments
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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
1. Modeling mechanisms of biological body representations

2. Better performance of robots – autonomy, robustness, safety
Thank you!

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