iCub
a shared platform for research in robotics & AI

Genoa
June 25, 2015

Giorgio Metta & the iCub team
Istituto Italiano di Tecnologia
ViaMorego, 30 - Genoa, Italy
we have a dream
the iCub

price: 250K€
30 iCub
distributed since 2008
about 3-4 iCub’s/year
why is the iCub special?

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

- **sensors**: human-like, e.g. no lasers
  - cameras, microphones, gyros, encoders, force, tactile…

- **electronics**: flexibility for research
  - custom electronics, small, programmable (DSPs)

- **reproducible platform**: community designed
  - reproducible & maintainable yet evolvable platform
  - large software repository (~2M lines of code)
why humanoids?

• scientific reasons
  – e.g. elephants don’t play chess

• natural human-robot interaction

• challenging mechatronics

• fun!
why open source?

- repeatable experiments
- benchmarking
- quality

this resonates with industry-grade R&D in robotics
open source

- Google
- Android
- Ubuntu
- Canonical, the Ubuntu Service Provider Company
- Alfresco
- Content Manager built on open source
- MySQL
- Oracle and MySQL
- Linux Foundation
- Red Hat

6/25/2015
series-elastic actuators

- C spring design
- 320Nm/rad stiffness

features:
- stiffness by design
- no preloading necessary (easy assembly)
- requires only 4 custom mechanical parts
- high resolution encoder for torque sensing
Yet Another Robot Platform

- YARP is an open-source (LGPL) middleware for humanoid robotics

- history
  - an MIT / Univ. of Genoa collaboration
  - born on Kismet, grew on COG, under QNX
  - with a major overhaul, now used by the iCub project

- C++ source code (some 400K lines)

- IPC & hardware interface

- portable across OSs and development platforms
exploit diversity: portability

• operating system portability:
  – Adaptive Communication Environment, C++ OS wrapper: e.g. threads, semaphores, sockets

• development environment portability:
  – CMake

• language portability:
  – via Swig: Java (Matlab), Perl, Python, C#
iCub sensors
torque control

\[ e = \tau - \tau_d \]

\[ \hat{\omega}_e = \begin{bmatrix} I & 0 \\ -\left[r_{se}\right]_x & I \end{bmatrix} \cdot (\omega_s - \omega_i) \]

\[ \hat{\tau}_e = J^T(q) \cdot \hat{\omega}_e \]

\[ e = \hat{\tau}_e - \tau_d \]

\[ u = k_p \cdot e + k_d \cdot \dot{e} + k_i \cdot \int e \]

\[ \tau_d = K \cdot (q - q_d) + D \cdot (\dot{q} - \dot{q}_d) \]
learning dynamics

- learning body dynamics
  - compute external forces
  - implement compliant control

- so far we did it starting from e.g. the cad models
  - but we’d like to avoid it
our method in 4 easy steps

• regularized least square
  \[ f(x) = w^T x \]
  \[ \min_w J = \frac{\lambda}{2} \|w\|^2 + \frac{1}{2} \|y - Xw\|^2 \]
  \[ w = \left( \lambda I + X^T X \right)^{-1} X^T y \]

• kernelized
  \[ f(x) = \sum_{i=1}^{m} c_i k(x, x_i) \]
  \[ c = (K + \lambda I)^{-1} y \]

• approximate kernel
  \[ k(x_i, x_j) = E \left[ \frac{1}{D} \sum_{d=1}^{D} z_{w_d}(x_i)^T z_{w_d}(x_j) \right] \]
  \[ z_w(x) = \begin{bmatrix} \cos(w^T x) & \sin(w^T x) \end{bmatrix} \]

• make it incremental
  \[ w = \left( \lambda I + \Phi^T \Phi \right)^{-1} \Phi^T y \]
  + Cholesky rank-1 update

6/25/2015
properties

- $O(1)$ update complexity w.r.t. # training samples
- exact batch solution after each update
- dimensionality of feature mapping trades computation for approximation accuracy
- $O(D^2)$ time and space complexity per update w.r.t. dimensionality of feature mapping
- easy to understand/implement (few lines of code)
- not exclusively for dynamics/robotics learning!
batch experiments

- 3 inverse dynamics datasets: Sarcos, Simulated Sarcos, Barrett [Nguyen-Tuong et al., 2009]
- approximately 15k training and 5k test samples
- comparison with LWPR, GPR, LGP, Kernel RR
- RFRR with 500, 1000, 2000 random features
- hyperparameter optimization by exploiting functional similarity with GPR (log marginal likelihood optimization)
datasets

Table 5.1: Datasets used for the batch dynamics experiments.

<table>
<thead>
<tr>
<th></th>
<th>#joints</th>
<th>output</th>
<th>#train</th>
<th>#test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated Sarcos</td>
<td>7 ( \tau \times 7 )</td>
<td>14904</td>
<td>5520</td>
<td></td>
</tr>
<tr>
<td>Sarcos</td>
<td>7 ( \tau \times 7 )</td>
<td>13922</td>
<td>5569</td>
<td></td>
</tr>
<tr>
<td>Barrett</td>
<td>7 ( \tau \times 7 )</td>
<td>13572</td>
<td>5000</td>
<td></td>
</tr>
</tbody>
</table>
incremental experiments

Table 5.2: Datasets used for the incremental dynamics experiments.

<table>
<thead>
<tr>
<th></th>
<th>#joints</th>
<th>output</th>
<th>#train</th>
<th>#test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sarcos</td>
<td>7</td>
<td>(\tau \times 7)</td>
<td>4449</td>
<td>44484</td>
</tr>
<tr>
<td>James</td>
<td>4</td>
<td>([F, \tau]_{x,y,z})</td>
<td>15000</td>
<td>195977</td>
</tr>
<tr>
<td>iCub</td>
<td>4</td>
<td>([F, \tau]_{x,y,z})</td>
<td>15000</td>
<td>72850</td>
</tr>
</tbody>
</table>
incremental experiments

(a) $\tau_1$

(b) $\tau_2$

(c) $\tau_3$

(d) $\tau_4$
temperature compensation

\[ \phi(x) = \frac{\sigma_f}{\sqrt{D}} \left[ \sin \left( \langle \omega_1^T, x \rangle \right), \cos \left( \langle \omega_1^T, x \rangle \right), \ldots, \sin \left( \langle \omega_D^T, x \rangle \right), \cos \left( \langle \omega_D^T, x \rangle \right), t \right]^T \]
summary

- Fast prediction and model update of RFRR
  - 200RF: 400μs
  - 500RF: 2ms
  - 1000RF: 7ms
- Non-stationary: thermal sensor drift in force components
- Rapid convergence of RFRR
- No further gain by using additional random features (problem specific)
experiments & model validation

static configuration:

an additional six axis F/T sensor is placed at the end effector to measures the external wrenches $w_e$

in this experiment we consider the following quantities:

- joint torques measured by the joint torque sensors: $t_j$
- joint torques computed from the arm F/T sensor: $t_{FT}$
- joint torques estimated through the additional F/T sensor located at the end effector: $t_e=J^Tw_e$
- joint torques predicted by the arm model (no external forces): $t_m$

---

### Table of Results

<table>
<thead>
<tr>
<th>Joint 0</th>
<th>Joint 1</th>
<th>Joint 2</th>
<th>Joint 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E(t_j-t_m)$</td>
<td>0.127 Nm</td>
<td>-0.049 Nm</td>
<td>-0.002 Nm</td>
</tr>
<tr>
<td>$\sigma(t_j-t_m)$</td>
<td>0.186 Nm</td>
<td>0.131 Nm</td>
<td>0.013 Nm</td>
</tr>
<tr>
<td>$E(t_j-(t_m+t_e))$</td>
<td>0.075 Nm</td>
<td>-0.098 Nm</td>
<td>-0.006 Nm</td>
</tr>
<tr>
<td>$\sigma(t_j-(t_m+t_e))$</td>
<td>0.191 Nm</td>
<td>0.173 Nm</td>
<td>0.020 Nm</td>
</tr>
</tbody>
</table>
the robot skin

ground plane: e.g. conductive fabric
parameters: mechanical properties, impedance, etc.

soft material: e.g. silicone
parameters: dielectric constant, mechanical stiffness, etc.

electrodes: etched on a flexible PCB
parameters: shape, folding, etc.
principle

lots of sensing points

structure of the skin
tests of various materials

![Graph showing various materials and their test results]

- Soma Foama Hard
- PDMS
- Soma Foama Soft
- Neoprene2mm
- SpongeRubberLycra
- NeopreneGrid2mm
- NeoGridNeobulkLycra
- NeoGridNeobulkLycra2
- Neoprene2mmLycra
- NeopreneGrid3mm
- Others (discarded)
latest implementation

advantages:
• good performance: gluing is made with industrial machines, no hysteresis due to glue
• production: automatic and reliable
• mounting and replacing is easy, easy ground connection
• protective layer can be of different materials → increase reliability
• customizations: surface can be printed

6/25/2015
skin calibration

performed manually by poking the robot with a tool

works iteratively with different datasets taken in different robot positions

12 sensors
14.5 x 13 mm

Fabric, conductive+protective
Plastic interface transforming to curved shape
Inner support for PCB
PCB
fingemail
CDC chip
Scenario 1. Balancing with multiple rigid contacts.

Scenario 2. Goal directed actions involving contacts.

Scenario 3. Learning non-rigid contacts.

Scenario 4. Human assistive contacts.
floating base robots

\[
\begin{bmatrix}
I_c^T & F \\
F & H
\end{bmatrix}
\begin{bmatrix}
b_a \\
b_\ddot{q}
\end{bmatrix}
+ \begin{bmatrix}
p^c \\
n
\end{bmatrix}
= \begin{bmatrix}
0 \\
\tau
\end{bmatrix}
+ \sum_{l \in L} \begin{bmatrix}
b_{X_l^*} \\
J_l^T
\end{bmatrix} f_l
\]

\(a_b\) spatial acceleration of the floating base
\(q\) joint positions
\(I_c\) composite rigid body inertia of the tree
\(p^c\) spatial bias force of the composite tree
\(\tau\) joint torques
\(f_l\) the external wrench acting on link \(l\)
\(H\) joint inertia matrix
\(n\) the bias torques
\(J_l\) the Jacobian for link \(l\)
NEW controller
point to point movements

Point-to-Point Movement

Target Point

x [m]  y [m]  z [m]

0.26  0.24  0.04

0.05  0.15  0.26

0.01  0.03  0.02

0.1  0.16  0.2

Target Point

look

inv kinematics

controller
\[
q_d = \arg\min_{q \in \mathbb{R}^n} (\|\alpha_d - K_d(q)\|_2^2 + \beta (q_{\text{res}} - q)^T W (q_{\text{res}} - q)) \\
\text{s.t. } \|x_d - K_x(q)\|_2^2 < \epsilon \\
q_L < q < q_U
\]

- quick convergence (<20ms)
- scalability
- singularities and joints bound handling
- tasks hierarchy
- complex constraints

\[
\begin{align*}
\min_{q, \dot{q}} & \frac{1}{2} ( (\dot{q} - \dot{q}_d)^T W_q (\dot{q} - \dot{q}_d) + (\dot{x} - \dot{x}_d)^T W_x (\dot{x} - \dot{x}_d) ) \\
\text{s.t. } & \dot{x} = J \dot{q}
\end{align*}
\]

- merges joint and Cartesian space trajectories

\[
\dot{q} = \dot{q}^d + W_q^{-1} J^T \left( W_x^{-1} + J W_q^{-1} J^T \right)^{-1} \left( \dot{x}^d - J \dot{q}^d \right)
\]
\[ f : \{q_{\text{arm}}, q_{\text{head}}\} \mapsto \mathcal{I} \]

\[ \mathcal{I} = \{u_{\text{left}}, v_{\text{left}}, u_{\text{right}}, v_{\text{right}}\} \in \mathbb{N}^4 \]

\[ q_{\text{arm}} \in \mathbb{R}^7 \quad q_{\text{head}} \in \mathbb{R}^6 \]
Please put those into the dishwashing machine.

Could you please help me with the TV set?

The iCub puts the plates into the dishwashing machine.

The iCub puts the plates into the dishwashing machine.
<table>
<thead>
<tr>
<th>actions</th>
<th>objects</th>
<th>tools</th>
</tr>
</thead>
<tbody>
<tr>
<td>learning actions</td>
<td>learning objects</td>
<td>learning tools</td>
</tr>
<tr>
<td>recognizing actions</td>
<td>recognizing objects</td>
<td>using tools</td>
</tr>
</tbody>
</table>
All Gestures You Can 2.0
A Memory Game

I. Gori, S.R. Fanello, F. Odone, G. Metta

iCub Facility
Istituto Italiano di Tecnologia
Department of Informatics Bioengineering Robotics and Systems Engineering
Università degli Studi di Genova

Ranked 2nd at Microsoft Kinect Demonstration Competition,
CVPR 2012 Providence, Rhode Island
Human Robot Interaction is a **new and natural** application for visual recognition. In robotics settings strong cues are often available, therefore object detectors can be avoided. Recognition as tool for complex tasks: grasp, manipulation, affordances, pose.


Operator: What is this?
dataset

Verbal (weak) Supervision

Human “Teacher”

Motion Detection

sprinkler
iCubWorld dataset (2.0)

- Growing dataset collecting images from a real robotic setting
- Provide the community with a tool for benchmarking visual recognition systems in robotics
- 28 Objects, 7 categories, 4 sessions of acquisition (four different days)
- 11Hz acquisition frequency.
- ~50K Images

methods

Mainstream Object Recognition Pipelines:

Convolutional Neural Networks:
methods

Mainstream Object Recognition Pipelines:

- **Image**
  - Sparse Coding [yang et al. ’09]
  - Learned on iCubWorld

Convolutional Neural Networks:

- **Image**
  - Overfeat [sermanet et al. ’14]
  - Learned on Imagenet
some questions

- **Scalability.** How do iCub recognition capability decrease as we add more objects to distinguish?
- Can we use assumptions on physical continuity to make recognition more stable?
- **Incremental Learning.** How does learning during multiple sessions affect the system recognition skills?
- **Generalization.** How well does the system recognize objects “seen” under different settings?
We started by addressing instance recognition.
performance wrt # of objects
exploiting continuity in time
Incremental learning

Cumulative learning on the 4 days of acquisition. Tested on:

- **Present**: test on current day
- **Causal**: test on current and past days
- **Future**: test on future days (current not included)
- **Independent**: train & test on current day only
what about a week?
... or a month?

??

accuracy (avg. over classes)

day

OF present
OF causal
OF future
OF Independent
Experiments on affordances

(a) Real Tools.

(b) Simulated Tools.

Detailed list of extracted features

- Based on convex hull
  - Depth of the 5 larger convexity defects
  - Histogram of bisector angles at convexity defects
  - Area of the convex hull
  - Solidity

- Based on thinning
  - Number of skeleton bifurcations to the left, right, under and above
  - Number of skeleton endings to the left, right, under and above the blob's center of mass

- Based on Moments
  - Normalized central moments

- Shape descriptors
  - Area, perimeter, compactness
  - Major principal axis (length), Minor principal axis (width)
  - Aspect ratio, Extension, Elongation, Rectangularity

- From the angle signature
  - Bending energy (sum of squares of the angle variation along the contour), divided by the number of points in the contour
  - Angle signature histogram

- Domain transformation from the distance to the centroid signature
  - Fourier coefficients
  - Wavelet coefficients

6/25/2015
Experiments on affordances
Experiments on affordances
Experiments on affordances

(a) Simulated data

(b) Robot data

<table>
<thead>
<tr>
<th>Environment</th>
<th>Goal Acc. (%)</th>
<th>Avg. Diff [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>86.51 %</td>
<td>0.064</td>
</tr>
<tr>
<td>Robot</td>
<td>86.11 %</td>
<td>0.056</td>
</tr>
</tbody>
</table>
Learning grasp dependent pull affordances of tools on the iCub Humanoid robot

Tanis Mar, Vadim Tikhanoff, Giorgio Metta, Lorenzo Natale
3D vision for grasping

Input  Segmentation  Disparity
force reconstruction
raw data

(a) One-dimensional force condition (Z axis)
GP approximation

(a) In the X axis direction
(b) In the Y axis direction
(c) In the Z axis direction
### TABLE I

**PERFORMANCE OF ALL MODELS AND CONDITIONS**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Model</th>
<th>$F_x$</th>
<th></th>
<th>$F_y$</th>
<th></th>
<th>$F_z$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RMSE</td>
<td>CC</td>
<td>AME (N)</td>
<td>RMSE</td>
<td>CC</td>
<td>AME (N)</td>
</tr>
<tr>
<td>One-dimensional force</td>
<td>Normal GP model</td>
<td>0.955</td>
<td>0.959</td>
<td>2.847</td>
<td>0.645</td>
<td>0.979</td>
<td>3.055</td>
</tr>
<tr>
<td>force condition</td>
<td>Proposed model</td>
<td>0.718</td>
<td>0.977</td>
<td>2.000</td>
<td>0.447</td>
<td>0.989</td>
<td>2.014</td>
</tr>
<tr>
<td></td>
<td>Markov order</td>
<td></td>
<td>$n = 6$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Three-dimensional force</td>
<td>Normal GP model</td>
<td>0.792</td>
<td>0.979</td>
<td>2.115</td>
<td>0.549</td>
<td>0.980</td>
<td>1.654</td>
</tr>
<tr>
<td>force condition</td>
<td>Proposed model</td>
<td>0.714</td>
<td>0.983</td>
<td>1.932</td>
<td>0.518</td>
<td>0.981</td>
<td>1.503</td>
</tr>
<tr>
<td></td>
<td>Markov order</td>
<td></td>
<td>$n = 5$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross learning condition</td>
<td>Normal GP model</td>
<td>1.664</td>
<td>0.870</td>
<td>4.218</td>
<td>1.505</td>
<td>0.877</td>
<td>2.813</td>
</tr>
<tr>
<td></td>
<td>Proposed model</td>
<td>1.472</td>
<td>0.901</td>
<td>3.210</td>
<td>1.530</td>
<td>0.873</td>
<td>2.740</td>
</tr>
<tr>
<td></td>
<td>Markov order</td>
<td></td>
<td>$n = 7$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
spinal reflexes

walking behavior: cat rehabilitated to walk after complete spinal cord transection

wiping reflex: an irritating stimulus elicits a wiping movement precisely directed at the stimulus location

visuo-tactile fusion
double touch

From two fixed-base chain to a single floating-base serial chain → 12 dof

\[ q^* = \arg \min_{q \in \mathbb{R}^n} (n_O \cdot y_{ee}) \]

\[ s.t. \begin{cases} \|K_x(q) - O\|^2 < \epsilon \\ q_l < q < q_u \end{cases} \]
<table>
<thead>
<tr>
<th>Type</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>
receptive fields

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

\[
\begin{aligned}
D &= sgn(\vec{d} \cdot \vec{z}) || \vec{d} || \\
TTC &= \frac{|| \vec{d} ||}{|| \vec{v} || \cdot \cos(\alpha)} \\
p(\mathbf{x}) &= \frac{1}{n} \sum_{i=1}^{n} \frac{1}{\sqrt{2\pi\sigma}} \exp \left( -\frac{(\mathbf{x}_i - \mathbf{x})^2}{2\sigma^2} \right) \\
\mathbf{x} : \{D, TTC\}
\end{aligned}
\]
single taxel model
no noise
noisy data
with double touch
visual tracker
external stimulation
2. Learning peripersonal space representation

distributed representation of nearby space through visuo-tactile associations
extending peripersonal space
Task:
Clear the table
what future?

Now

iCub2.0

iCub3.0

iCub new tech

The future?
Google Acquires Seven Robot Companies, Wants Big Role in Robotics

A few months ago, we heard rumors that Google was planning something big in robotics. We also heard that Andy Rubin, the engineer who spearheaded

Related Stories

Automaton

-related robotics blog, featuring photos, articles, and videos on robotics, artificial intelligence, and more.

Contact us: automaton@espressotech.com

Follow Automaton

Editor

Brian Gooch

New York, NY

Contributors

Jason Favela

Canada

Newsletter Sign Up

Sign up for the Automaton newsletter

Seiko Epson Shows Off Its DualArm Robot

The Economist

RISE OF THE

ROBOTS

A 14-PAGE SPECIAL REPORT

Marine Le Pen woes France

Obama v Obamacare

How to make a chromosome

Will Japanese women rebel?

Understanding the first world war

iit

ISTITUTO ITALIANO
DI TECNOLOGIA

6/25/2015 100
"How old are you?" she wanted to know.

"Thirty-two," I said.

"Then you don't remember a world without robots. There was a time when humanity faced the universe alone and without a friend. Now he has creatures to help him; stronger creatures than himself, more faithful, more useful, and absolutely devoted to him. Mankind is no longer alone. Have you ever thought of it that way?"
external funding

- RobotCub, grant FP6-004370, http://www.robotcub.org
- CHRIS, grant FP7-215805, http://www.chrisfp7.eu
- ITALK, grant FP7-214668, http://italkproject.org
- Robotdoc, grant FP7-ITN-235065 http://www.robotdoc.org
- Roboskin, grant FP7-231500 http://www.roboskin.eu
- eMorph, grant FP7-231467 http://www.emorph.eu
- Poeticom, grant FP7-215843 http://www.poeticom.eu

• more information: http://www.iCub.org

- Poeticom++, grant FP7-288382 http://www.poeticom.eu
- Xperience, grant FP7-270273 http://www.xperience.org
- EFAA, grant FP7-270490 http://efaa.upf.edu/
- Codyco, grant FP7-600716 http://www.codyco.eu
- Tacman, grant FP7-610967
- Wysiwyd, grant FP7-612139
- Walk-man, grant FP7-611832
- Koroibot, grant FP7-611909