CODYCO Whole-body Compliant Dynamical Contacts in Cognitive Humanoids

Whole-body Compliant Dynamical Contacts in Cognitive Humanoids

proj. no. 600716

WP5: Systems Integration, Standardization and Evaluation on the iCub robot

WP leader: IIT

Fondazione Istituto Italiano di Tecnologia.

Robotics, Brain and Cognitive sciences Department.

Work package goals

Scenario 2: iCub posture control while performing goal directed actions.

Milestone 2: validation scenario, balancing on feet while performing goal directed actions.

Scenario 2.
Goal directed actions involving contacts.

Implementation

* Implementation 1 (upper body goal directed action): whole-body torque-controlled balancing while gazing and reaching.

* Implementation 2 (lower body goal directed action): whole-body torque controlled stepping.

Scenario 2.
Goal directed actions involving contacts.

SEVENTH FRAMEWORK PROGRAMME

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Addressed challenges

- Dealing with incompatible postural/ Cartesian tasks coordination (hierarchic control: WP3).
- Simultaneous accurate torque (postural) and position (Cartesian) control (dynamic identification: WP1 and WP4).
- Real-time constraints: 30Hz visual control loop and 100Hz on posture.
- Implementation on different robots (iCubParis01 v1.5 and iCubParis02 v2.0).

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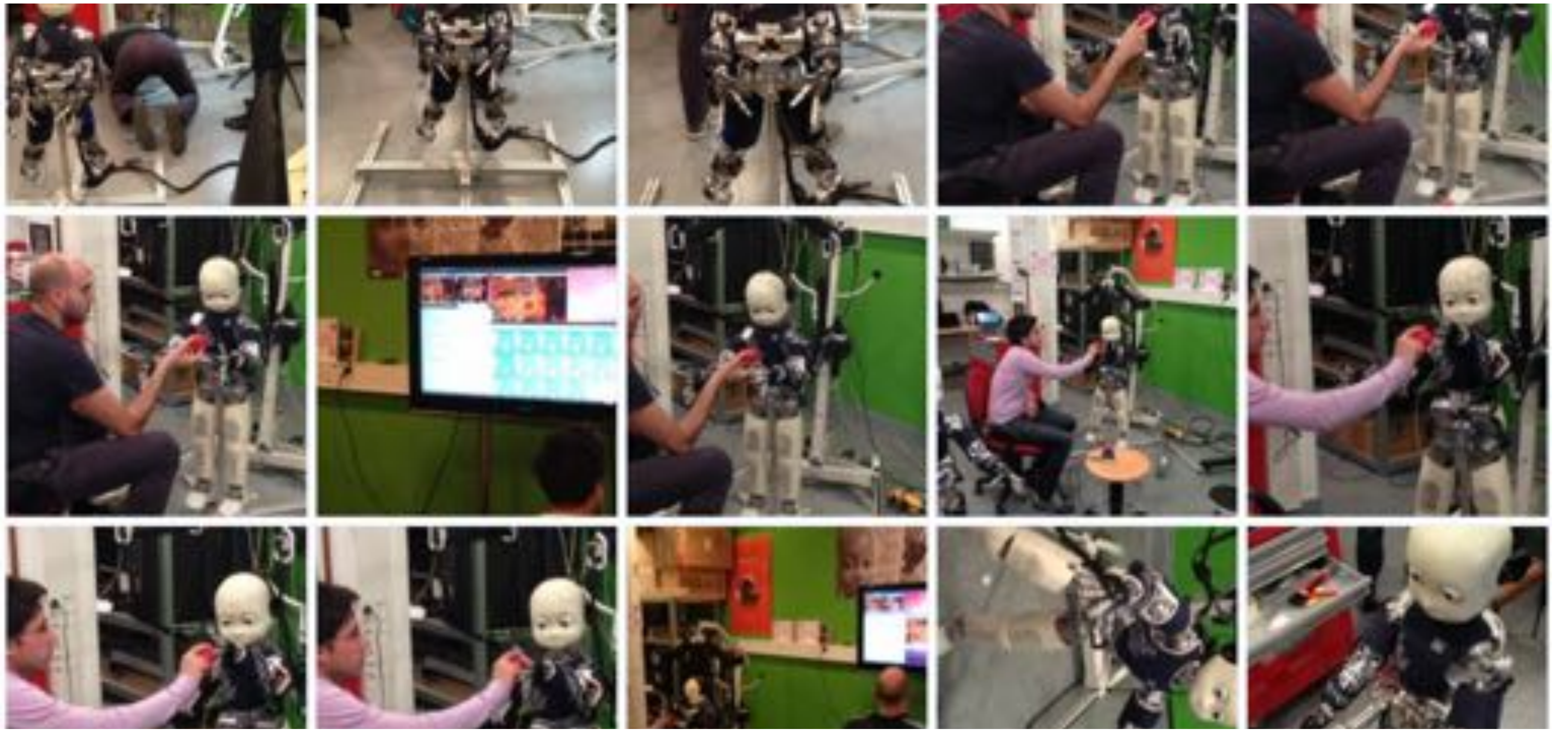
Integration @ ISIR

Integration @ ISIR



Integration @ ISIR

Integration @ ISIR

Outline

* T5.2 Scenario 2: iCub posture control while performing goal directed actions.
  - Integration of the iCub gaze, arm and foot Cartesian controller (Y2).
  - Enhanced whole-body control (Y1+).
  - Enhanced whole-body modeling (Y2).
  - Implementation on the real robot:
    - Validation scenario video.

SEVENTH FRAMEWORK PROGRAMME

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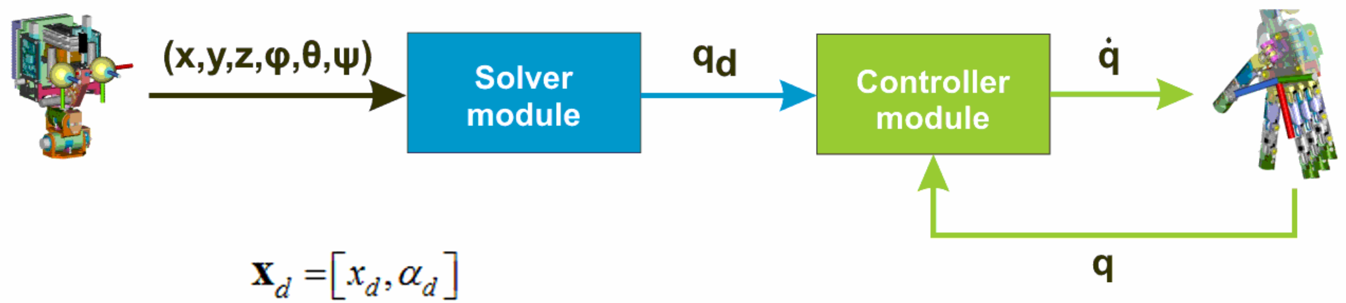
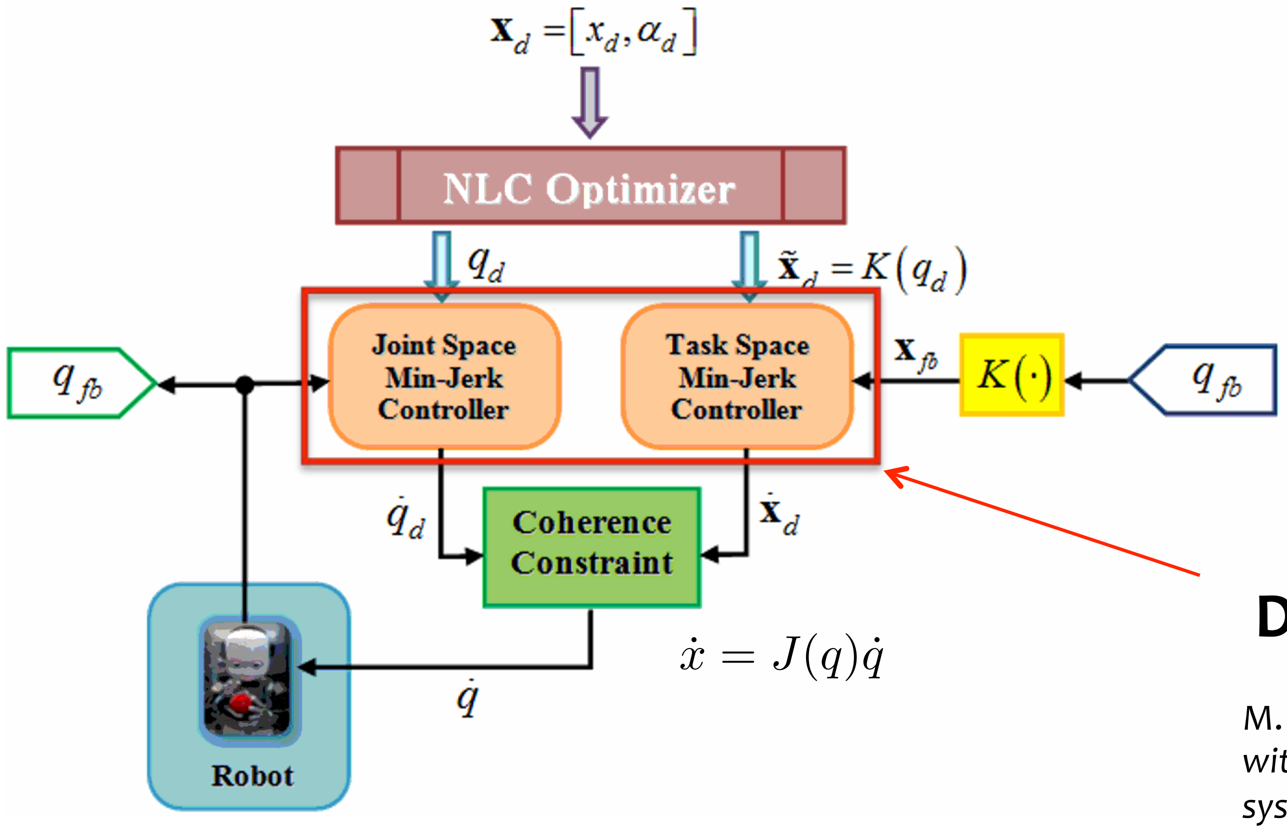
Cartesian Controller Structure



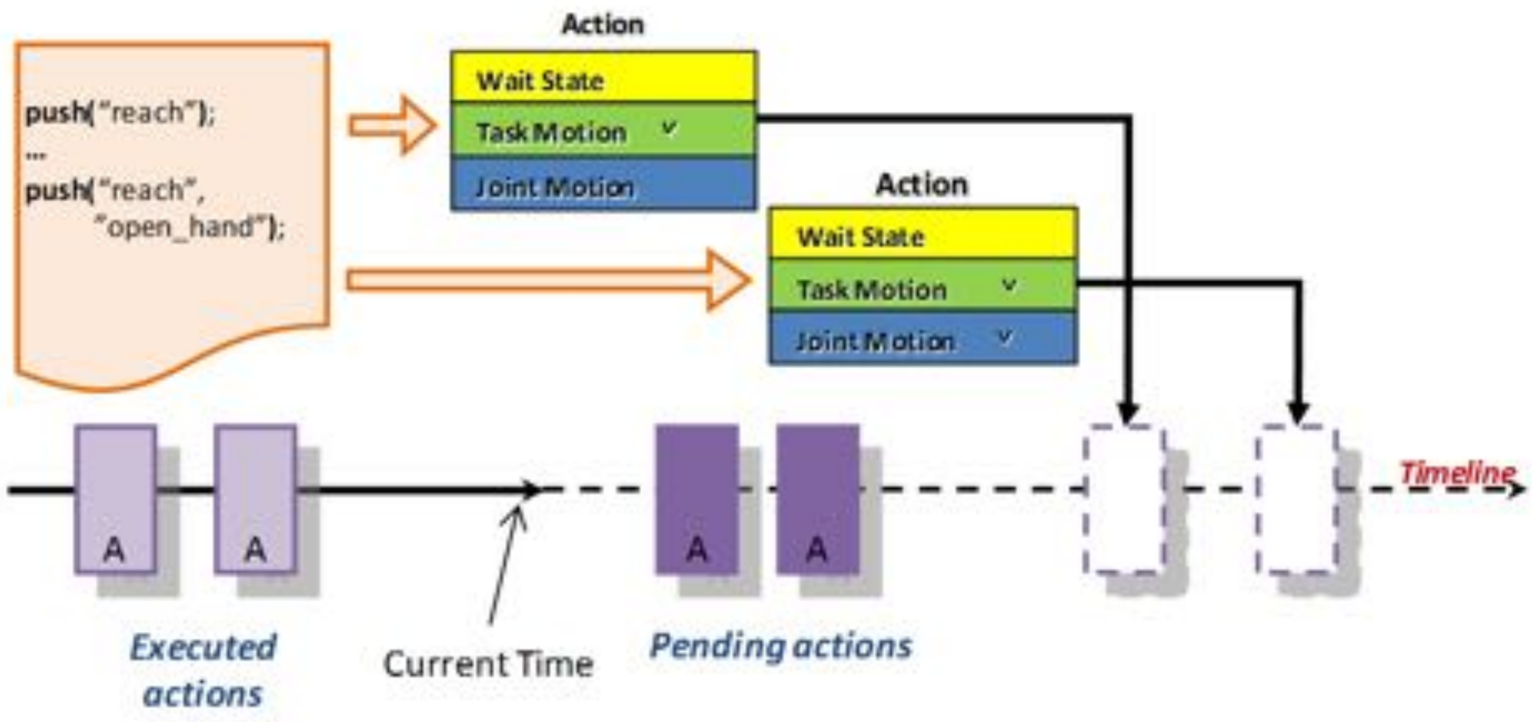


Multi Referential Dynamical Systems

M. Hersch, A.G. Billard, "*Reaching with multi-referential dynamical systems*", Springer-Verlag.

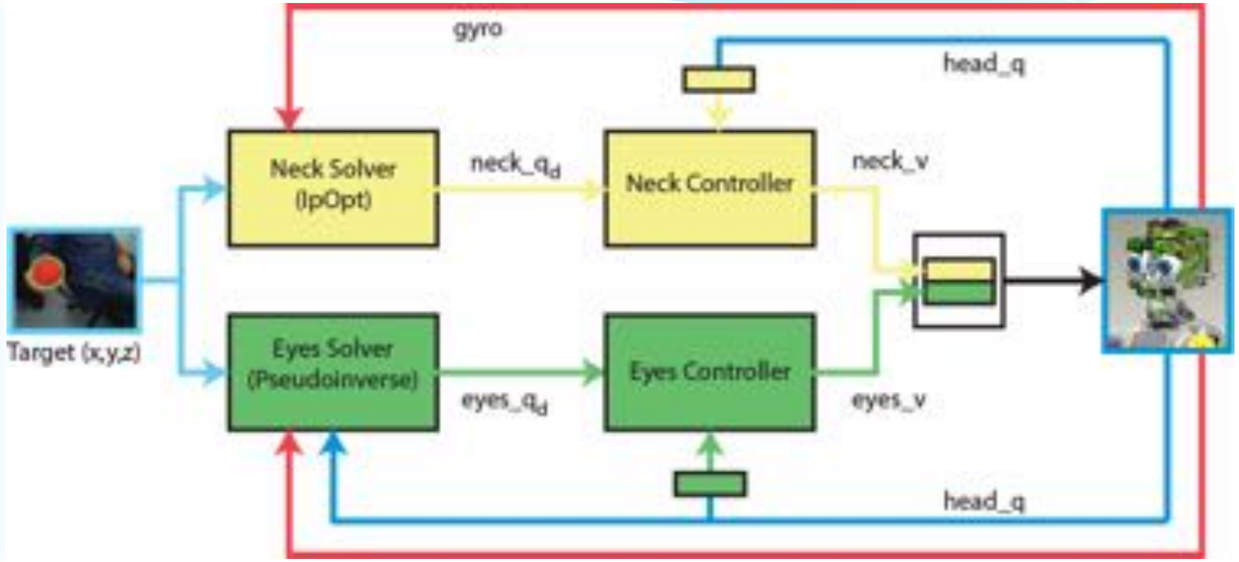
Motor primitives

3. Open-source library for **Motor Primitives**



4. Easy integration with low-level **wholeBodyControl**

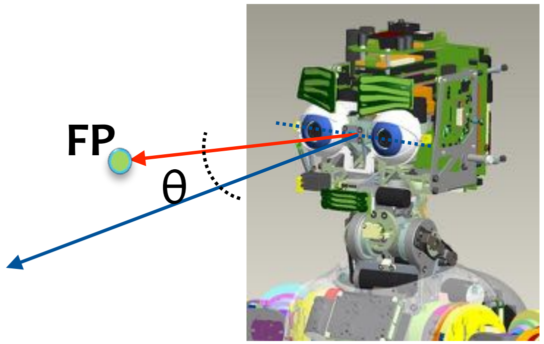
The gaze controller



Yet another Cartesian Controller: **<u>reuse ideas</u>** …

Then, apply easy transformations from Cartesian to …

1. Egocentric angular space
2. Image planes (mono and stereo)



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SEVENTH FRAMEWORK PROGRAMME

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Task Space Inverse Dynamics (TSID)

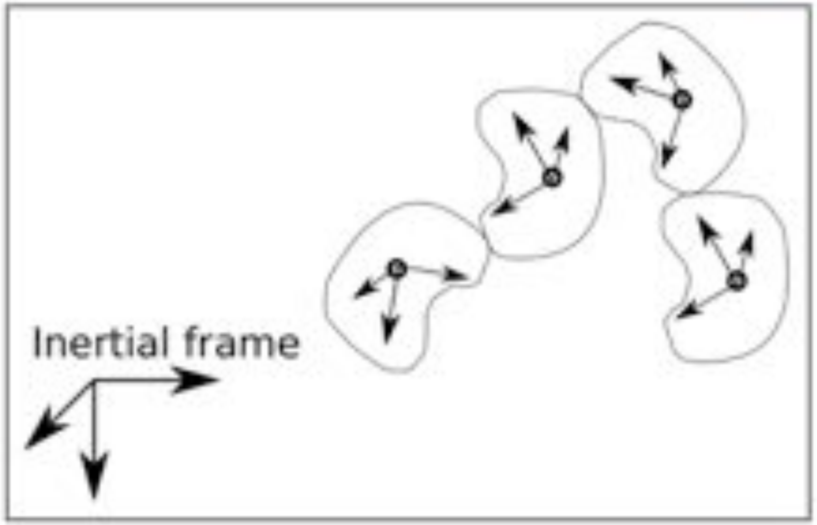
A framework for **prioritized** control of **positions** and **forces**

$$M(q)\dot{v} + C(q,v)v + g(q) - J^T F_{ext} = \begin{pmatrix} 0_6 \\ \tau \end{pmatrix}$$

SEVENTH FRAMEWORK PROGRAMME

Balancing

General definitions of the centroidal momentum



Centroidal Momentum

$$H := \sum_{i=0}^{n} I_i \nu_i$$

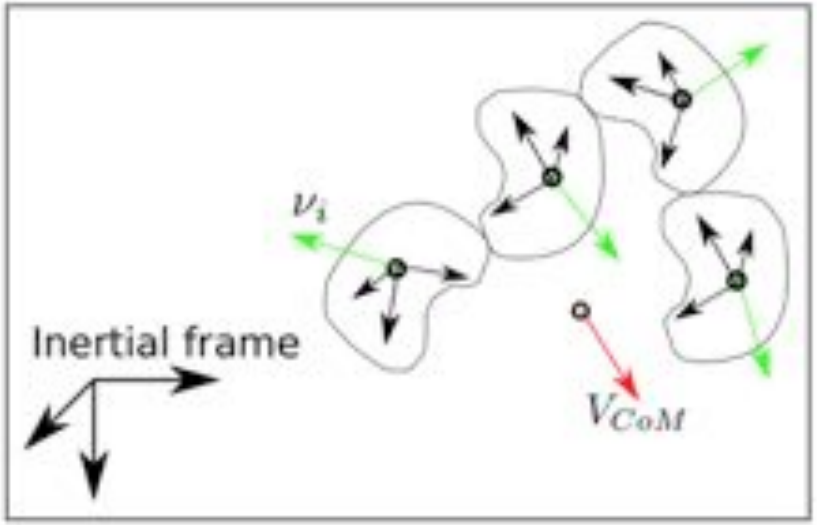
- ν_i twist of the *ith* body
- I_i : spatial inertia of the *ith* body

H is a coordinate-free (in the sense of Plucker) quantity

Balancing

T5.2

Centroidal momentum at the center of mass with inertial orientation



Centroidal Momentum

$$H_{CoM} := \begin{pmatrix} m_{tot} V_{CoM} \\ f(q, \dot{q}) \end{pmatrix}$$

- m_{tot}: total mass of the robot, q: joints' positions
- V_{CoM} : velocity of the center of mass

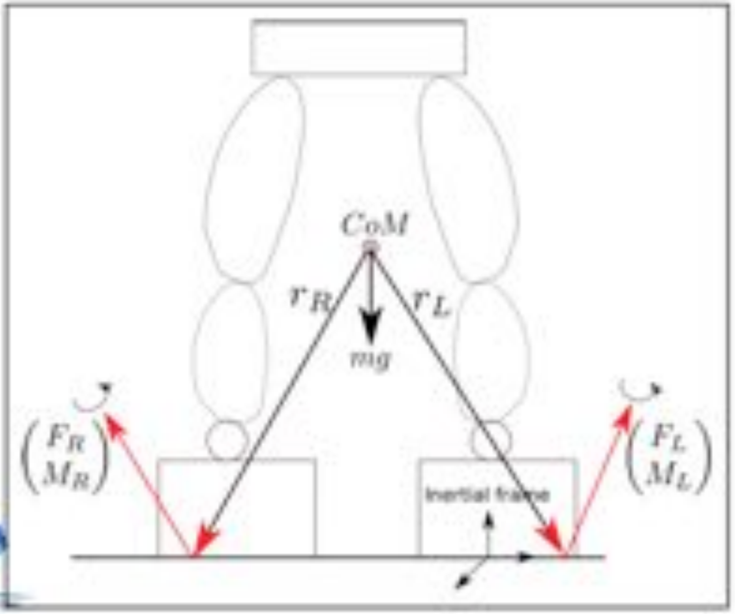
$$\frac{d}{dt} H_{CoM} = f_{Ext}^{CoM}$$

Balancing

Control strategy when balancing on two feet

$$\dot{H}_{CoM} = \text{grav} + A(q)F_{ext}$$

$$M(q)\dot{v} + C(q,v)v + g(q) - J^T F_{ext} = \begin{pmatrix} 0_6 \\ \tau \end{pmatrix}$$



$$A(q) = \begin{pmatrix} I_3 & 0_3 & I_3 & 0_3 \\ r_L\times & I_3 & r_R\times & I_3 \end{pmatrix}$$

$$F_{ext} = \begin{pmatrix} F_L \\ M_L \\ F_R \\ M_R \end{pmatrix}$$

Balancing

Control strategy when balancing on two feet

T5.2

$$\dot{H}_{CoM} = \text{grav} + A(q)F_{ext}$$

$$M(q)\dot{v} + C(q,v)v + g(q) - J^T F_{ext} = \begin{pmatrix} 0_6 \\ \tau \end{pmatrix}$$

Constraints on feet

$$J(q) := \begin{pmatrix} J_L \\ J_R \end{pmatrix}$$

$$J(q)\dot{v} + \dot{J}(q)v = 0$$

Find τ such that

(1) equilibrium is maintained

(2) $x = x_d$ goal directed task

Balancing

Control strategy when balancing on two feet

$$\dot{H}_{CoM} = \text{grav} + A(q)F_{ext}$$

$$M(q)\dot{v} + C(q,v)v + g(q) - J^T F_{ext} = \begin{pmatrix} 0_6 \\ \tau \end{pmatrix}$$

Constraints on feet

$$J(q) := \begin{pmatrix} J_L \\ J_R \end{pmatrix}$$

$$J(q)\dot{v} + \dot{J}(q)v = 0$$

Find τ such that

(1) $\dot{H}_{CoM} = \dot{H}^d_{CoM}, F^d_{Ext} \in FC$

(2) $q \approxeq q_d$ s.t. $x(q_d) = x_d$

Balancing

T5.2

Control strategy when balancing on two feet

$$\tau = \tau_f(F_{ext}^d) + N\tau_0$$

τ_0 is chosen as a proportional feedback (impedance behaviour around q_d) plus gravity and external force compensation:

$$\tau_0 = g(q) + K_p(q - q_d) + J^\top F_{ext}^d$$

q_d, the postural configuration, is chosen to coincide with the solution of the Cartesian controller to perform goal directed actions with the hands and/or feet.

Balancing

T5.2

Control strategy when balancing on two feet

$$H_{CoM} = \begin{pmatrix} mV_{CoM} \\ H_\omega \end{pmatrix} \Rightarrow \dot{H}_{CoM} = \begin{pmatrix} m\dot{V}_{CoM} \\ \dot{H}_\omega \end{pmatrix} = \text{grav} + A(q)F_{ext}$$

We choose F^d_{Ext} such that

$$\dot{H}_{CoM} = \dot{H}^d_{CoM} = \text{grav} + A(q)F^d_{ext}$$

We choose $\dot{H}^d_{CoM}$ such that

$$x_{CoM} \to x^d_{CoM} \quad H_\omega \to 0$$

A choice for F^d_{Ext} is

$$F^d_{ext} = A^\dagger(\dot{H}^d_{CoM} - \text{grav})$$

Pseudo-inverse suggests that there might be some null space to exploit (internal torques).

Balancing

T5.2

Control strategy when balancing on two feet

$$H_{CoM} = \begin{pmatrix} mV_{CoM} \\ H_\omega \end{pmatrix} \Rightarrow \dot{H}_{CoM} = \begin{pmatrix} m\dot{V}_{CoM} \\ \dot{H}_\omega \end{pmatrix} = \text{grav} + A(q)F_{ext}$$

A better choice for F^d_{Ext} is

$$F^d_{ext} = A^\dagger(\dot{H}^d_{CoM} - \text{grav}) + N_A F_0$$

Then, the torques are

$$\tau = \tau_f(F_0) + N\tau_0(F_0)$$

$$\tau_c = \arg\min_{F_0} |\tau(F_0)|$$

$$\text{s.t. } F^d_{ext}(F_0) \in FC$$

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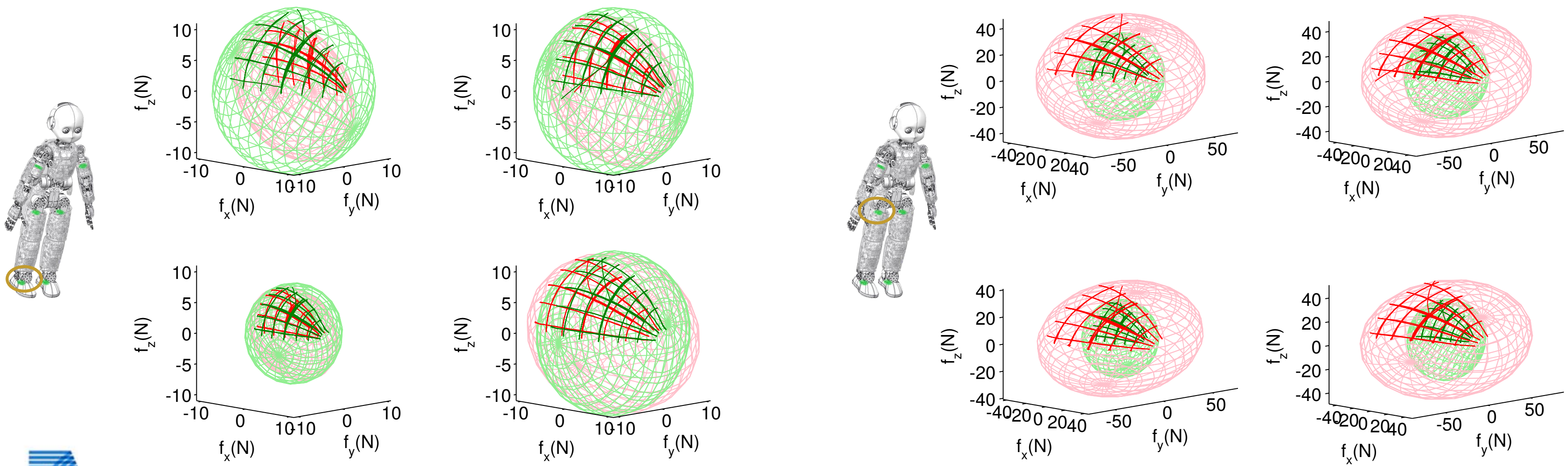
Force/torque sensor calibration: experimental results

* **Result 3:** after calibration on a training set, calibrated force and torques lie on a sphere (test set).



Open-source code: https://github.com/robotology-playground/insitu-ft-calibration

S. Traversaro et al. (*ICRA 2015*)

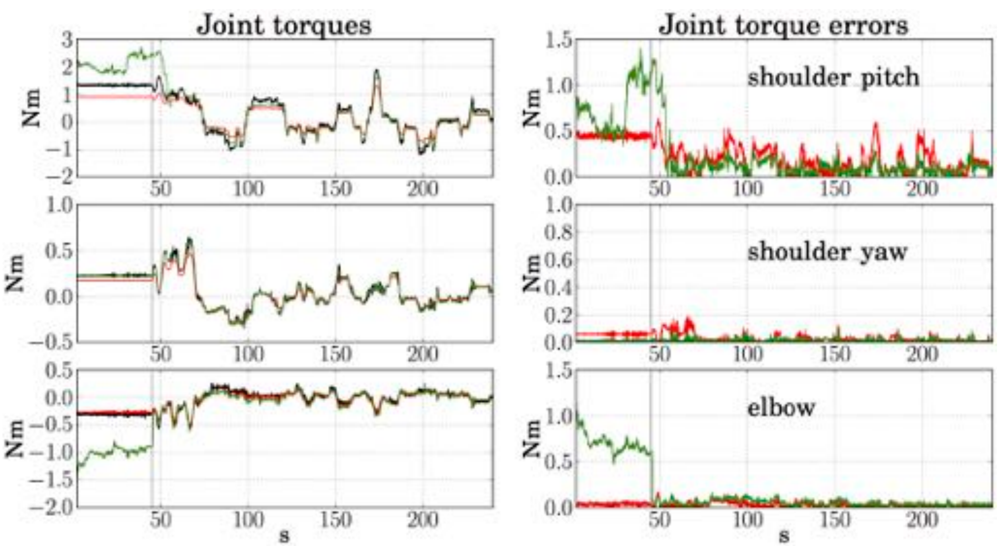
Identification with force@base

Proposition (Ayusawa et al., 2013)

The indefinable parameters subspace associated to joint torque measurements is a subspace of the one associated to base force measurements. In other terms, the parameters estimated with base forces can be used to predict joint torques.

Proposition (Traversaro et al., 2015)

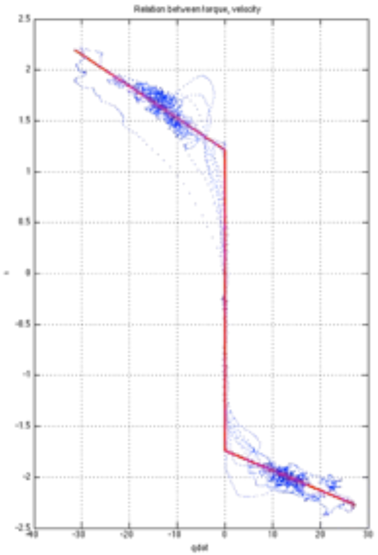
The indefinable parameters subspace associated with different choices of the base link coincides with the subspace associated to a specific choice of the base link. In other terms, the parameters estimated with base forces can be used to predict joint torques and external-forces.

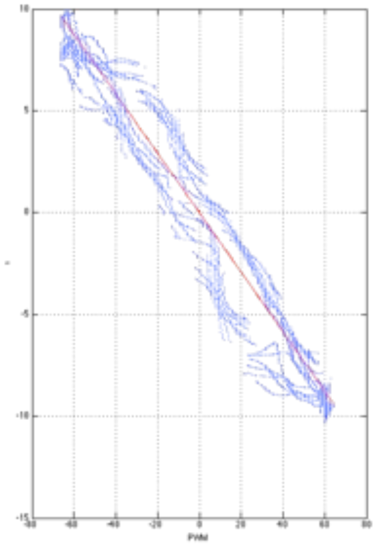


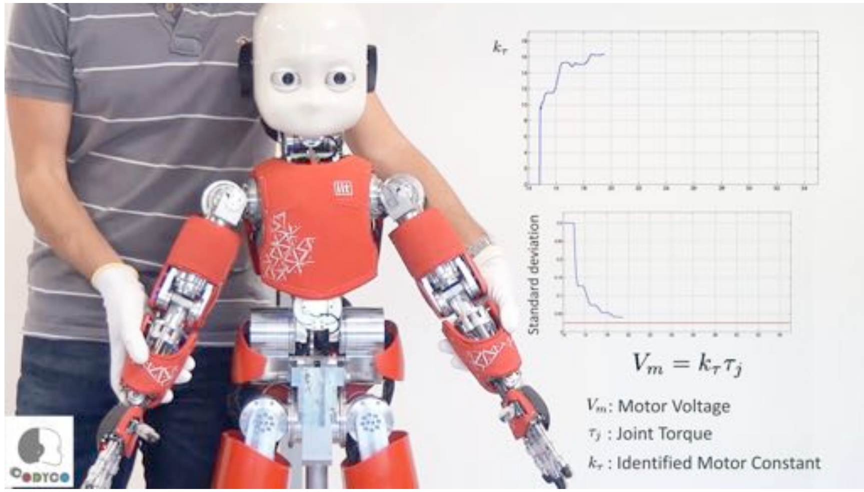
Open-source code:
https://github.com/robotology-playground/idyntree
S. Traversaro et al. *(ICRA 2015)*

Motor transfer function identification

$$V_i = k_t \tau_i + (k_{vp} s(\dot{\theta}_i) + k_{vn} s(-\dot{\theta}_i))\dot{\theta}_i + (k_{cp} s(\dot{\theta}_i) + k_{cn} s(-\dot{\theta}_i))\mathrm{sign}(\dot{\theta}_i),$$

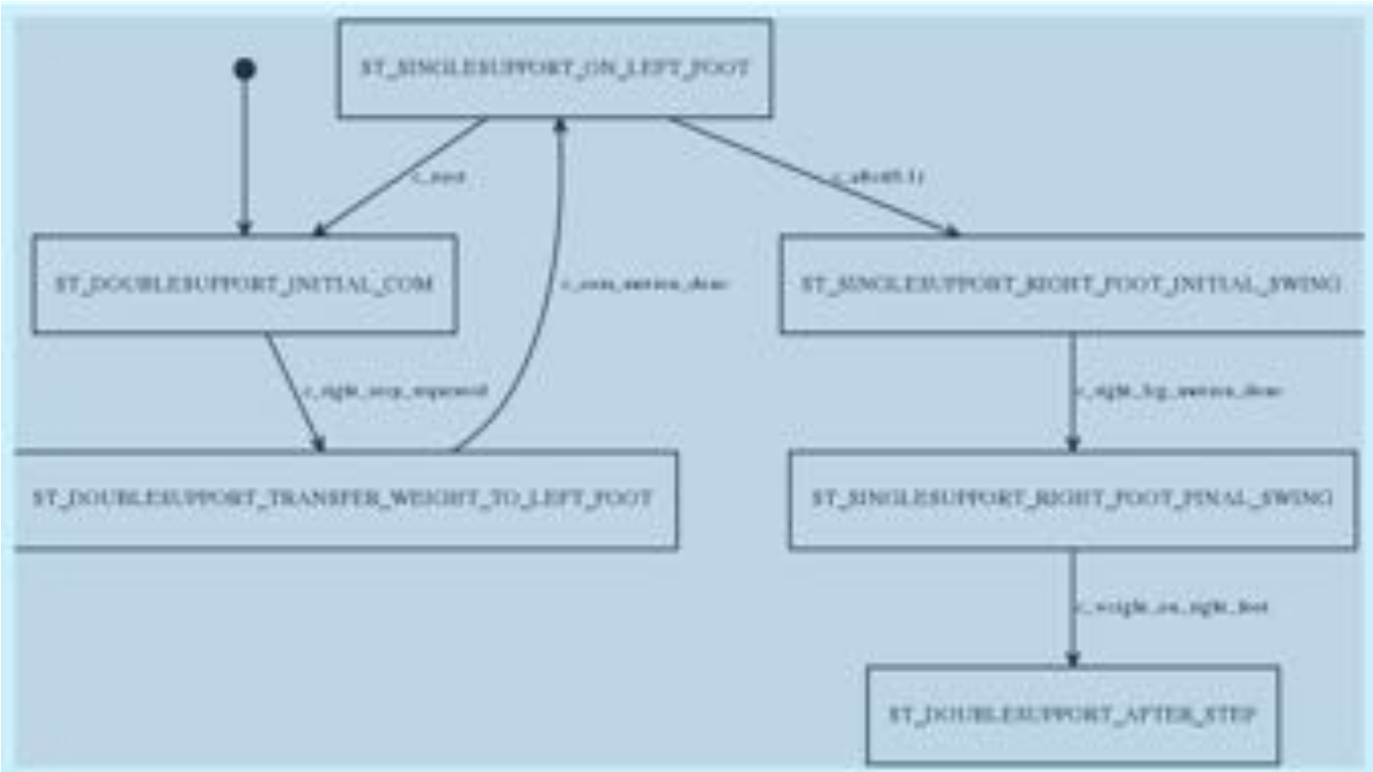






Fundamental identification procedure to match the model VS real gap.
https://github.com/robotology/codyco-modules/tree/master/src/modules/motorFrictionIdentification

Task sequencing



rFSM

YARP

Constraints on feet

$$J(q) := \begin{pmatrix} J_L \\ J_R \end{pmatrix} \quad \rightarrow \quad J(q) := \begin{pmatrix} I_n \alpha_l(t) & 0_n \\ 0_n & I_n \alpha_r(t) \end{pmatrix} \begin{pmatrix} J_L \\ J_R \end{pmatrix}$$

Based on the concept of generalized inverses (Adi Ben-Israel). See also the work by V. Padois in Orocos-KDL: **KDL::ChainIkSolverVel_wdls**

The controller: trajectory generation

MJ closed-loop:

$$\begin{bmatrix}\dot{x}\\ \ddot{x}\\ \dddot{x}\end{bmatrix}=\begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ -\frac{60}{(T-t)^3} & -\frac{36}{(T-t)^2} & -\frac{9}{T-t}\end{bmatrix}\begin{bmatrix}x\\ \dot{x}\\ \ddot{x}\end{bmatrix}+\begin{bmatrix}0\\ 0\\ \frac{60}{(T-t)^3}\end{bmatrix}x_d$$

$$x(t)=\left(C_1+C_2t+C_3t^2\right)\cdot\exp(\lambda\cdot t)+x_d$$

$$\lambda^*=\arg\min_{\lambda\in\mathbb{R}}\left(\int_0^\infty \dddot{x}^2(\tau)\,d\tau\right)\quad \text{s.t.}\ \begin{cases}\lambda<0\\ x(1)\geq 1-\varepsilon\end{cases}$$

LTI min-jerk approximation:

$$\begin{bmatrix}\dot{x}\\ \ddot{x}\\ \dddot{x}\end{bmatrix}=\underbrace{\begin{bmatrix}0 & 1 & 0\\ 0 & 0 & 1\\ \frac{a(\lambda)}{T^3} & \frac{b(\lambda)}{T^2} & \frac{c(\lambda)}{T}\end{bmatrix}}_{A}\begin{bmatrix}x\\ \dot{x}\\ \ddot{x}\end{bmatrix}+\underbrace{\begin{bmatrix}0\\ 0\\ -\frac{a(\lambda)}{T^3}\end{bmatrix}}_{B}x_d$$

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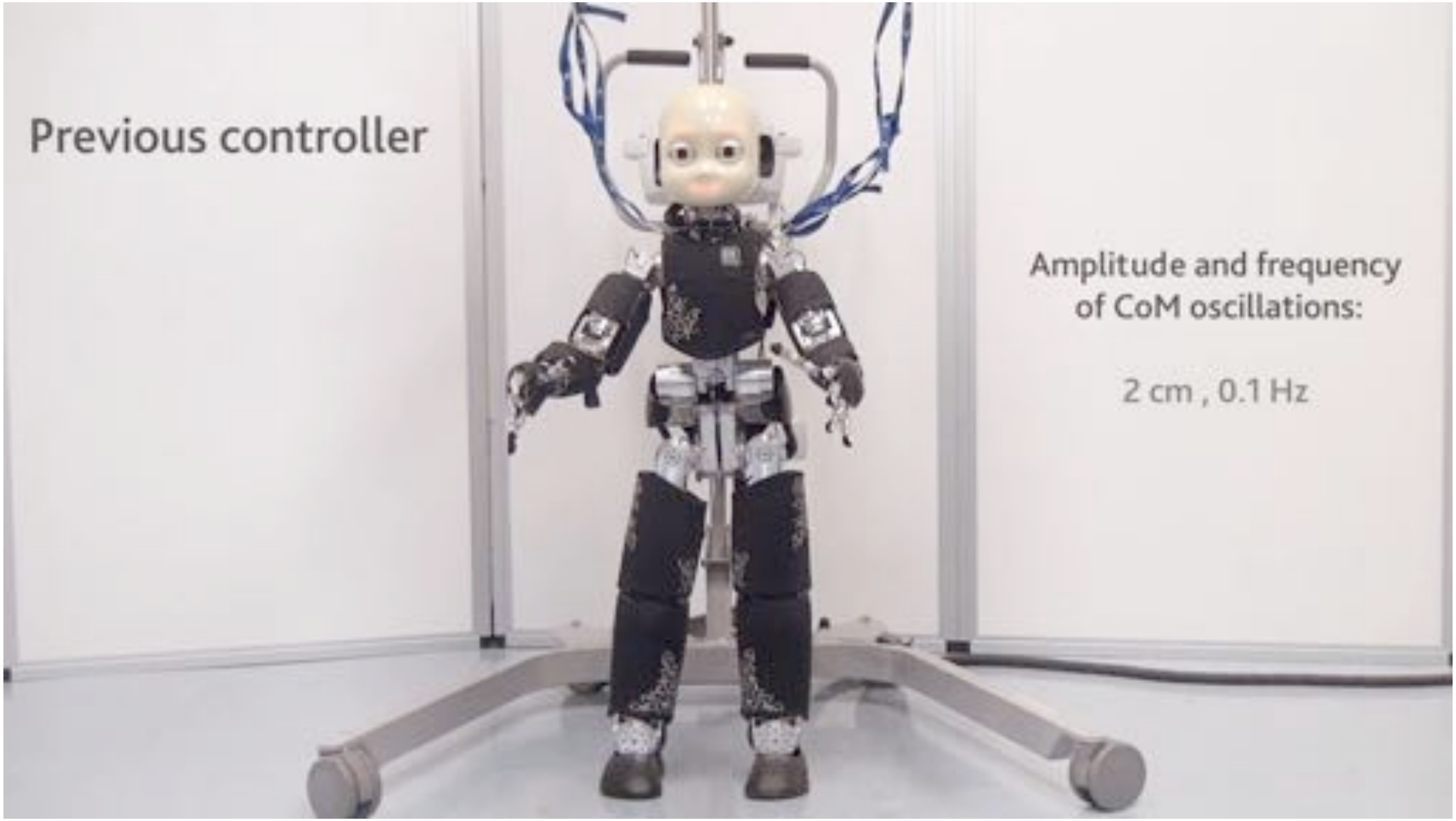
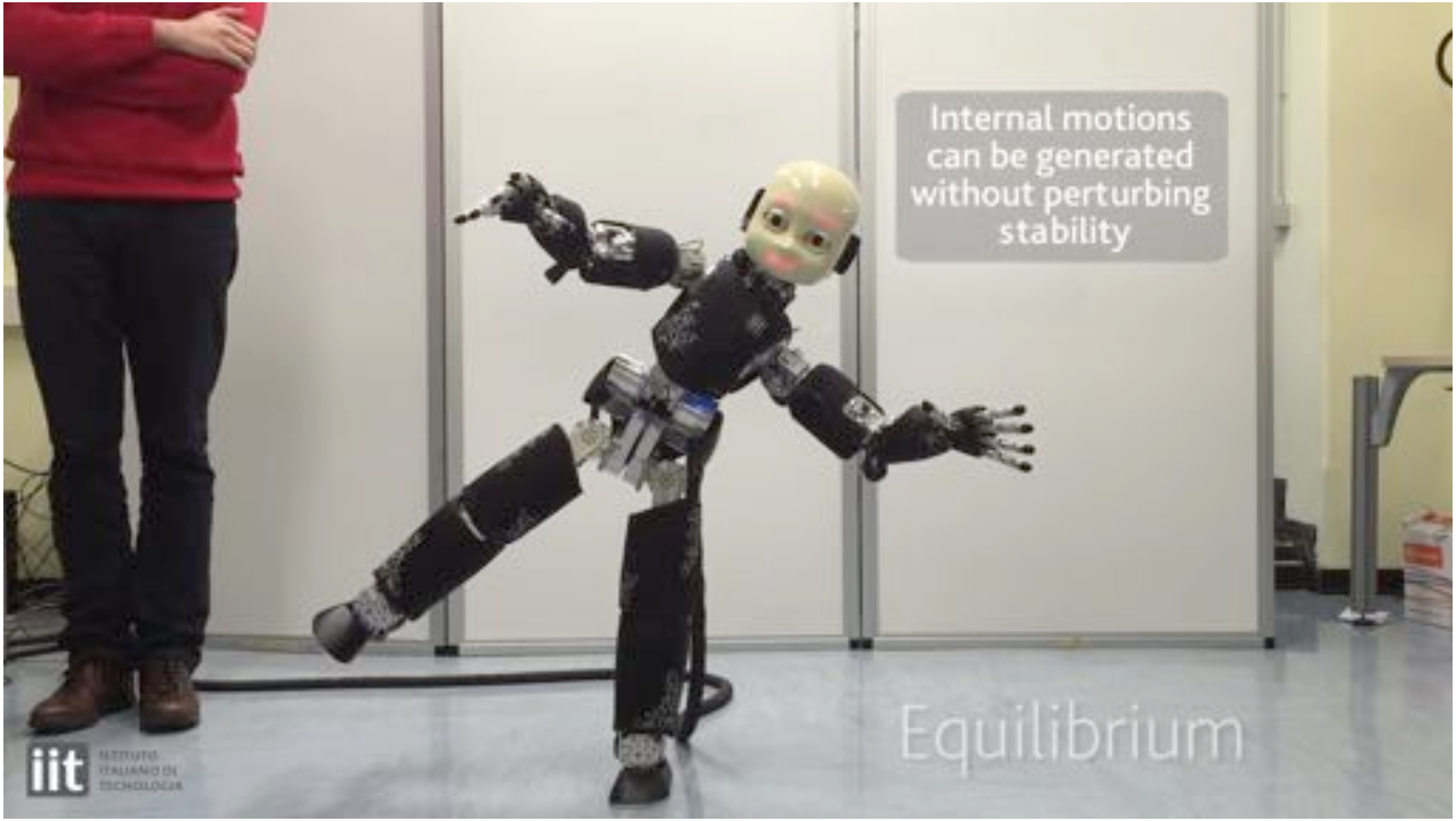
Internal torque minimization



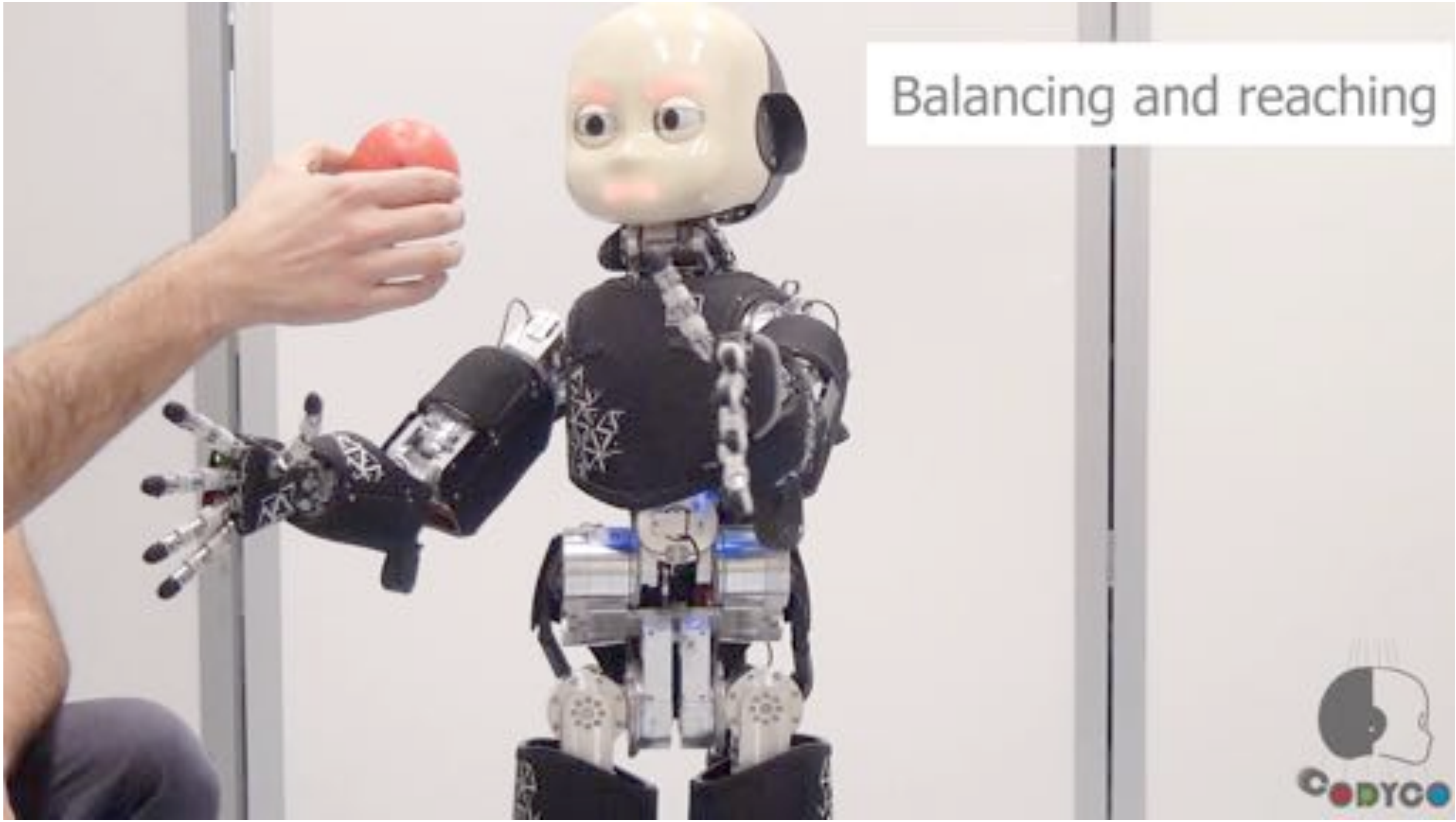
Single support balancing

T5.2



Goal directed balancing

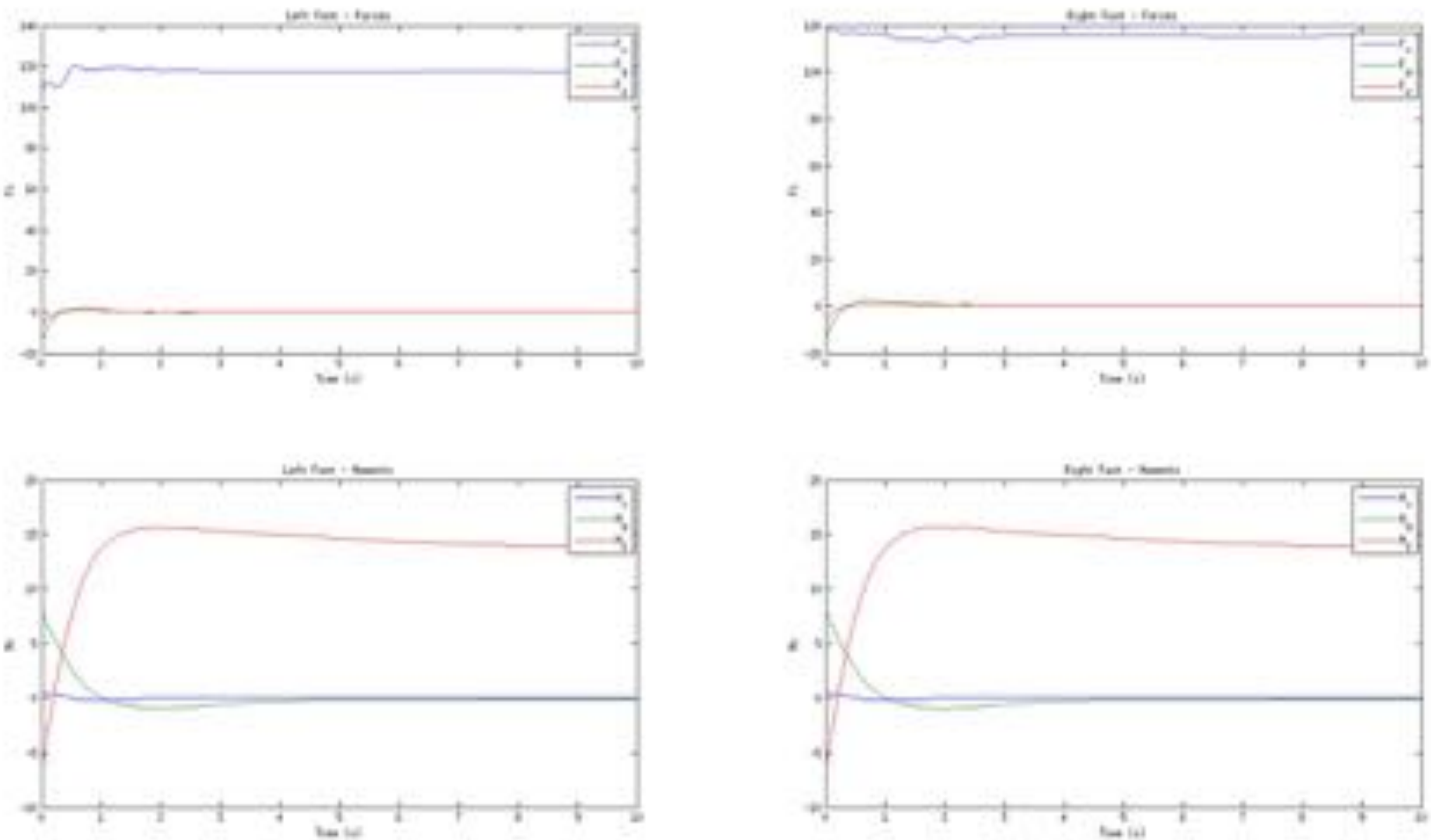
T5.2



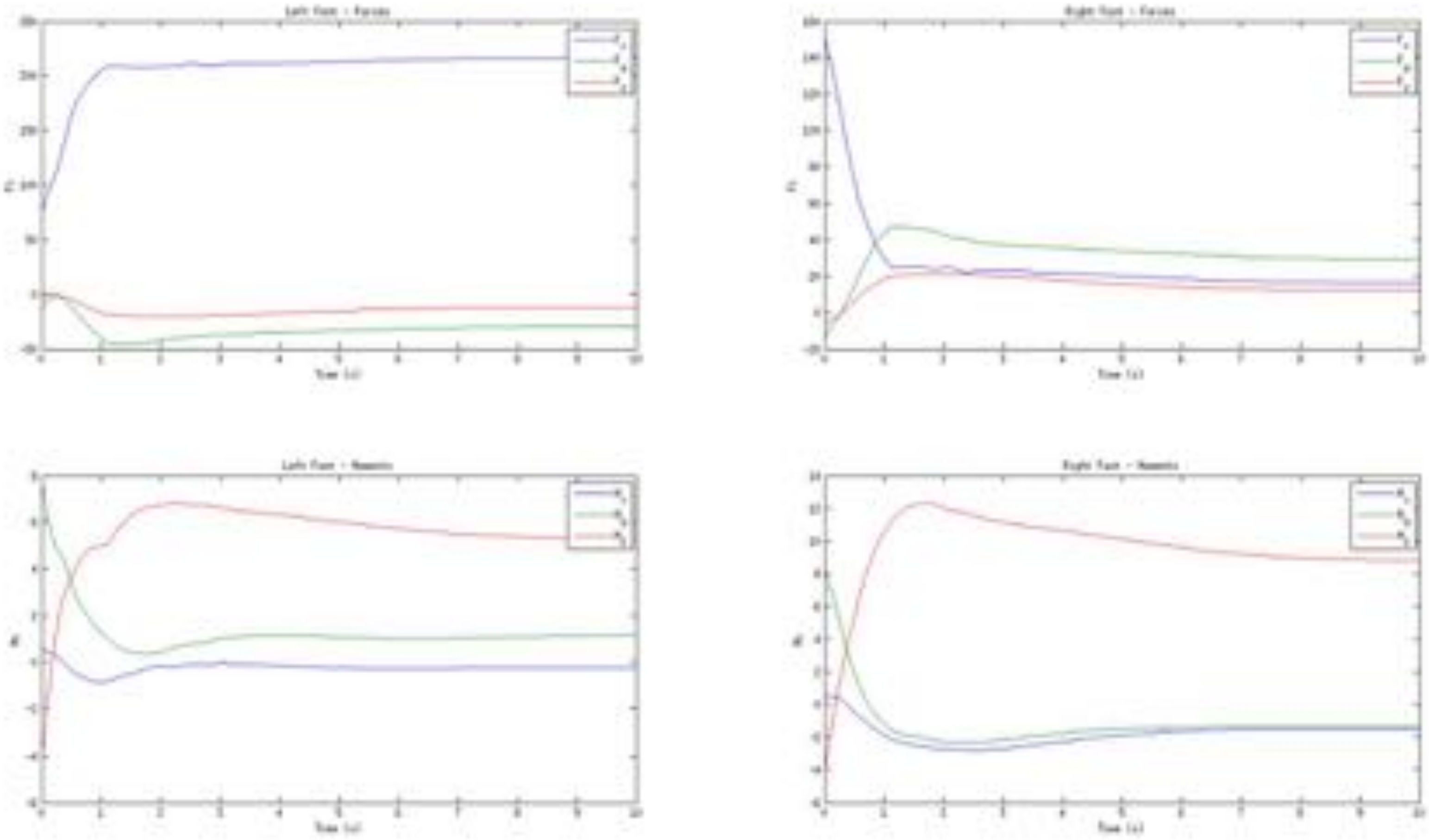
Conclusions

* Extensions of the first year scenario include:
  - Dealing with incompatible postural/Cartesian tasks coordination.
  - Simultaneous accurate torque (postural) and position (Cartesian) control.
  - Force/torque sensor calibration.
  - System identification.
  - Motor transfer function identification.
  - Implementation on other two iCub versions (v1.5/v2.0)

Internal torques: no minimization



Internal torques: minimization



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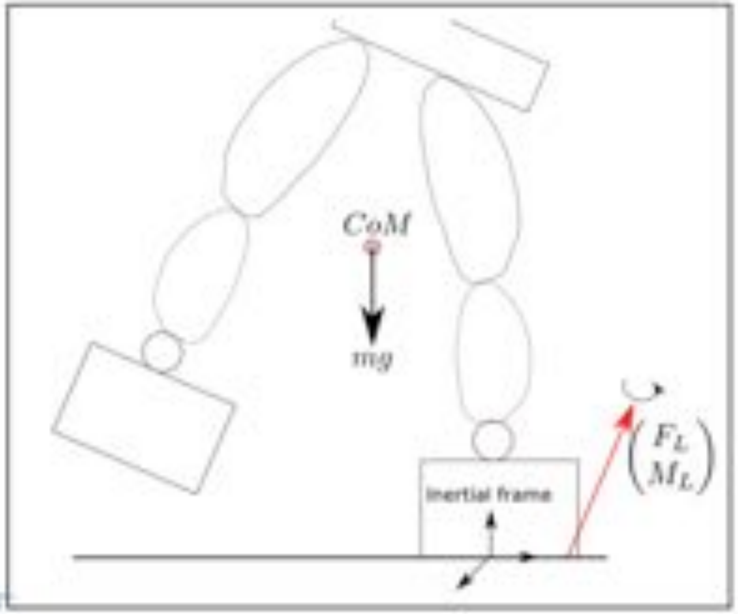

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$$F_{ext} = \begin{pmatrix} F_L \\ M_L \end{pmatrix}$$