Whole-body Compliant Dynamical Contacts for Humanoids: the CoDyCo project

(FP7 EU project No. 600716 / 2013-2017)

Vincent Padois, Maître de Conférences

vincent.padois@upmc.fr

Institut des Systèmes Intelligents et de Robotique
Sorbonne Universites - UPMC Univ Paris 06 - CNRS, UMR 7222

JNRH@IRCCyN - 08/06/2015

The CoDyCo Project : Motivations

The CoDyCo Project : Motivations

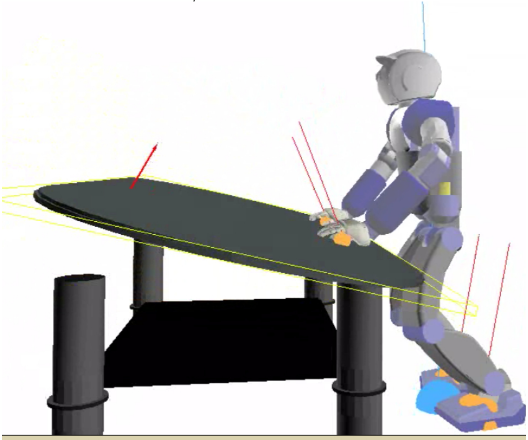
A long way to go ...

- Whole-body control with multiple contacts
- Unkwnon contact behaviour
- Under-actuated system with discrete contact changes
- Short-time decision making

The CoDyCo Project : Background work in whole-body control

"Classically" solved problem : given some operational tasks to achieve and some physical constraints to meet, compute the actuation torque every 1ms

- L. Sentis, J. Park and O. Khatib : Compliant Control of Multicontact and Center-of-Mass Behaviors in Humanoid Robots, IEEE TRO 2010



- Torque control
- Tasks hierarchy through null space projection
- Analytical resolution : constraints are treated as tasks
- Contacts location are unchanged
- Simulation

The CoDyCo Project : Background work in whole-body control

- L. Saab, O. Ramos, N. Mansard, P. Souères, J.Y. Fourquet : Dynamic Whole-Body Motion Generation Under Rigid Contacts and Other Unilateral Constraints, IEEE TRO 2013

  → torque control, tasks hierarchy through hierachy of QPs, numerical resolution (QP) : constraints are treated as constraints, position replay on the real robot

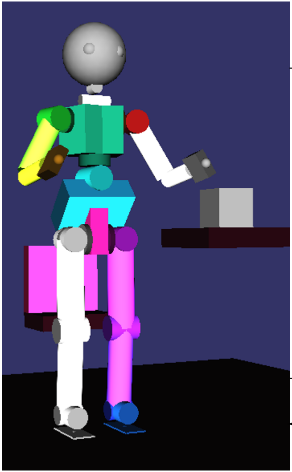
- A. Del Prete, F. Nori, G. Metta, L. Natale : Prioritized motion–force control of constrained fully-actuated robots :"Task Space Inverse Dynamics", RAS 2015

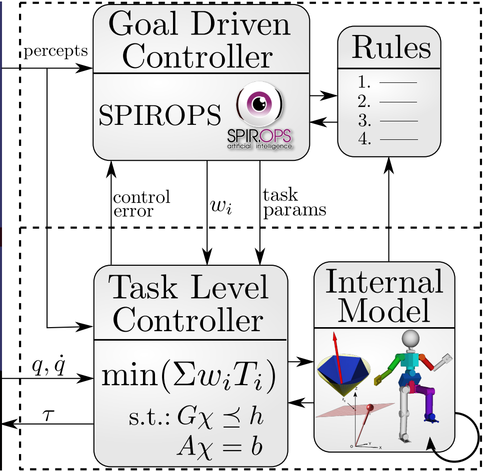
  → torque control, tasks hierarchy through null space projection, analytical resolution : inequality constraint are not dealt with, simulation

- J. Salini, V. Padois, P. Bidaud : Synthesis of Complex Humanoid Whole-Body Behavior : a Focus on Sequencing and Tasks Transitions, ICRA 2011

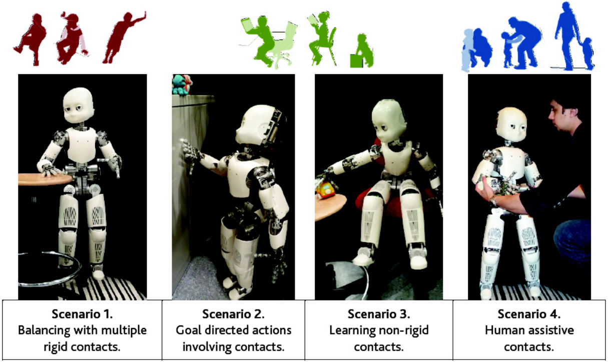
  → torque control, tasks hierarchy trough weightings, numerical resolution (QP) : constraints are treated as constraints, simulation

The CoDyCo Project : Background work in whole-body control



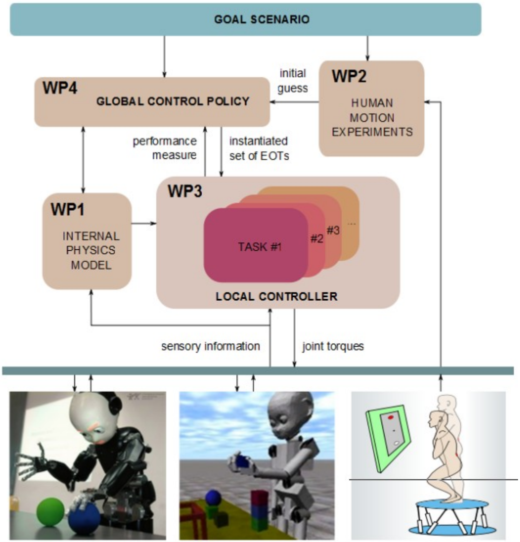


The CoDyCo Project : Objectives



- Whole-body dynamics computation with multiple external contacts
- Understanding human use of external contacts
- Whole body control and regulation of whole body compliance
- Machine learning for acquiring models of compliant contact with the environment
- "Real-world" validation with the iCub humanoid robot

The CoDyCo Project : Consortium and organization



Francesco Nori, WP5

Jan Peters, WP4

Jan Babic, WP2

Mike Mistry, WP1

Serena Ivaldi, WP4

Vincent Padois, WP3

Hardware and Software

The CoDyCo Project : Hardware and Software

The iCub

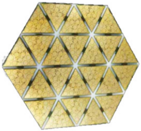
The **iCub** is the humanoid baby-robot designed as part of the **RobotCub** project

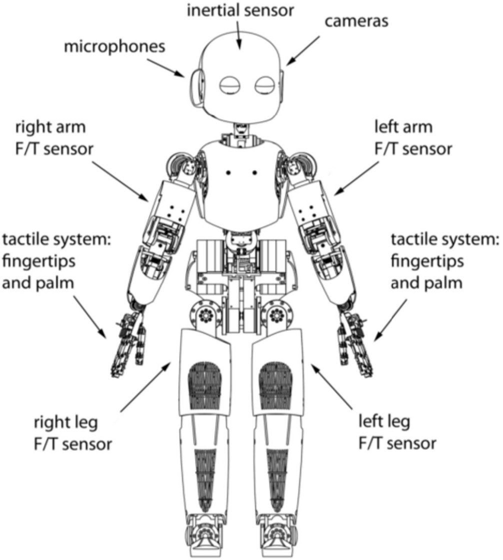
- The iCub is a full humanoid robot sized as a three and half year-old child
- The total height is 104cm
- It has 53 degrees of freedom, including articulated hands to be used for manipulation and gesturing
- The robot is LGPL/GPL/FDL: software, hardware, drawings, documentation, etc.

→ cf. http://www.icub.org

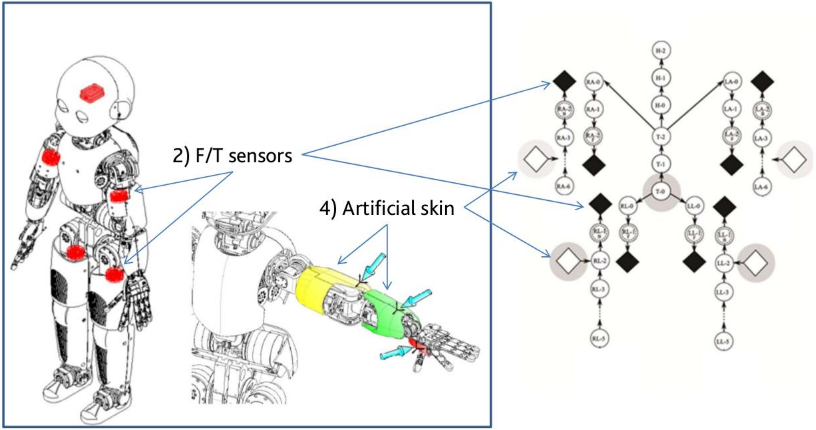
The CoDyCo Project : Hardware and Software

iCub sensors





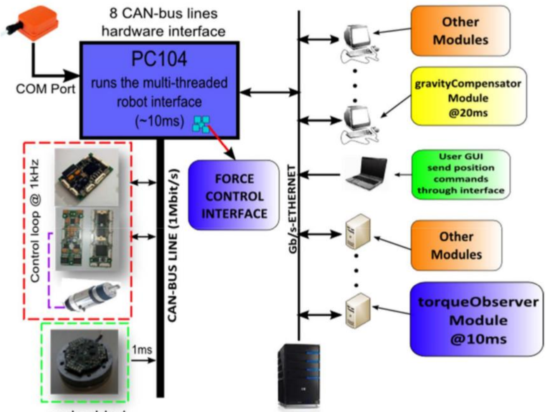
The CoDyCo Project : Hardware and Software



→ Joint torque estimation based on dynamics model and measurement through RNE calculation : iDyn++

The CoDyCo Project : Hardware and Software

Software and Hardware Architecture:



embedded
6 channels A/D
converter

F/T data, 3 d.o.f. orientation tracker measurements, joint position and derivatives, and motor commands are transmitted throug a Gb/s ethernet using YARP ports and interfaces.

Torque control:
Runs on motor control boards @ 1ms

$$u = k_{PID}\left(\tau_d - \tau\right) + \tau_{offset}$$

Impedance control:
Runs on motor control boards @ 1ms

$$\tau_d = k_p\left(q_d - q\right) - k_d\dot{q}$$

If velocities are commanded, the control strategy becomes:

$$\tau_d = k_p\left(\int \dot{q}_d - q\right) - k_d\dot{q}$$

torqueObserver Module:
Performs the estimation of joint torque exploiting F/T sensor's measurements and the dynamic model of the robot

gravityCompensator Module:
estimates gravitational torques on joints and send offset commands to the torque regulator

The CoDyCo Project : Hardware and Software

All software developed for the CoDyCo project, including modules for the control of balancing and reaching with multiple contacts, are available as open-source :
https://github.com/robotology/codyco-superbuild
Additional documentation is available via the icub wiki :
http://wiki.icub.org/codyco/dox/html/index.html

The `codyco-superbuild` meta repository aggregates the following projects :

- `idyntree` : YARP-based Floating Base Robot Dynamics Library
- `wholebodyinterface` : C++ Interfaces to sensor measurements, state estimations, kinematic/dynamic model and actuators for a floating base robot
- `yarp-wholebodyinterface` : Implementation of the wholeBodyInterface for YARP robots
- `WBI-Toolbox` : Simulink Toolbox for rapid prototyping of Whole Body Robot Controllers
- `codyco-modules` : YARP modules and controllers developed within the CoDyCo project
- ...

Tools for simulating humanoid robot dynamics : a survey based on user feedback
S. Ivaldi, J. Peters, V. Padois and F. Nori
Humanoids, 2014

Human studies

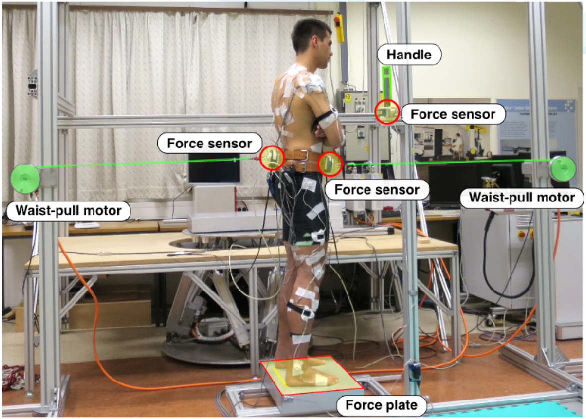
The CoDyCo Project : Human studies

Goal : Understanding and modelling human whole-body behaviours in physical interaction

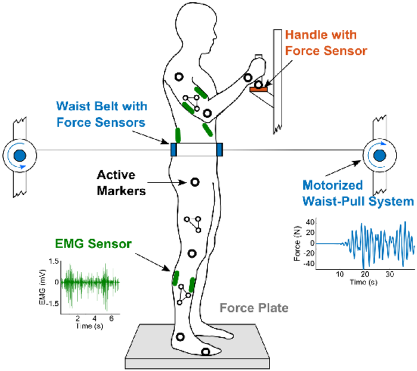
- Review of human postural control and whole body motion in contact with environment (cf. Deliverable 2.1)
- **Design of reduced models for human whole body motion in contact** [*Babic et al., Gaitt and Posture 2014*]
- **Strategies of dealing with uncertainties in contact**
- Human contact choice and learning through physical interaction

The CoDyCo Project : Human studies

Role of supportive hand contact and associated changes in postural responses during continuous perturbations of stance



Experimental setup



Light continuous perturbations – filtered white noise (0.25 Hz – 1 Hz)

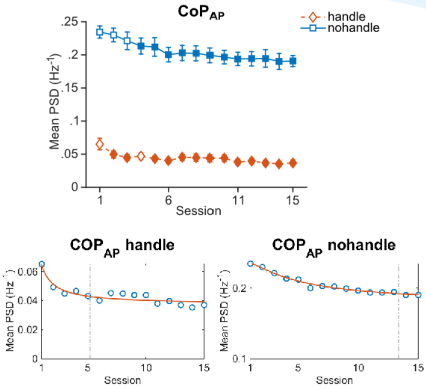
Whole body kinematics – 20 active markers

Muscle activity – EMG of arm, trunk, and leg muscles

Contact forces – force plate and force sensor in the handle

Analyses – Power Spectral Density (PSD)

Adaptation through time

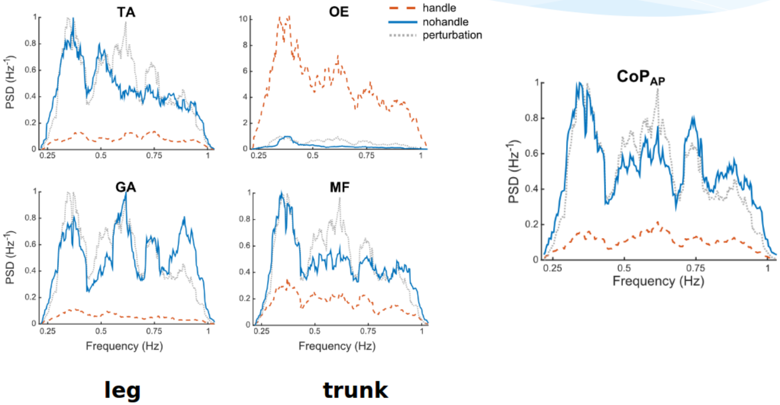


Larger COP motion in no handle condition

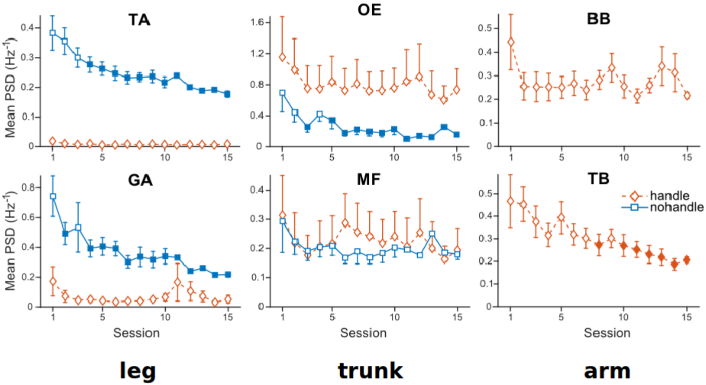
Adaptation happened in both conditions

Faster adaptation when using hand contact

Effect of perturbation on muscle activity



Adaptation of muscle activity through time



Are supportive hand contacts planned or reactive ?

- Reaching for a far target on the screen
- 20 subjects
- Trunk and arm kinematics – 17 active markers
- Contact forces – 2 force plates for GRF and table forces
- Analyses – novel environment, catch trials, aftereffects, correlation of motion of arms and trunk

The CoDyCo Project : Human studies

Whole-Body control

The CoDyCo Project : Whole-body control

Goal : Control and optimization of whole-body motion in contact

- **Formulate and solve the WB control problem**
- **Bootstrap with MPC** and Learning techniques
- Rigid and compliant cases [*Liu et al., submitted IROS 2015*]

The CoDyCo Project : Whole-body control

Generalized hierarchical controller [*Liu et al., Autonomous Robots 2015*]

$$\underset{\ddot{\boldsymbol{q}}',\chi}{\arg\min} \sum_{i=1}^{n_t} \left\| \boldsymbol{f}_i\left(\ddot{\boldsymbol{q}}'_i, \ddot{\xi}_i^d\right) \right\|^2 + \left\| \begin{bmatrix} \ddot{\boldsymbol{q}}' \\ \chi \end{bmatrix} \right\|_{Q_r}^2$$

subject to

$$J_c(\boldsymbol{q})^T \chi = M(\boldsymbol{q}) P \ddot{\boldsymbol{q}}' + \boldsymbol{n}(\boldsymbol{q}, \dot{\boldsymbol{q}})$$

$$G(\boldsymbol{q}, \dot{\boldsymbol{q}}) \begin{pmatrix} P\ddot{\boldsymbol{q}}' \\ \chi \end{pmatrix} \leq \boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}}),$$

with $\ddot{\boldsymbol{q}}' = \begin{bmatrix} \ddot{\boldsymbol{q}}'_1 \\ \vdots \\ \ddot{\boldsymbol{q}}'_{n_t} \end{bmatrix}$ and $P = [P_1(\alpha_1) \dots P_{n_t}(\alpha_{n_t})]$

Generalized projector : P_i

Overall joint space acceleration : $\ddot{\boldsymbol{q}} = \sum_{i=1}^{n_t} P_i(\alpha_i) \ddot{\boldsymbol{q}}'_i$

Features

- Optimization problem formulation
- Single LQ Program to solve
- Strict and soft priorities
- Smooth task evolution and transitions
- General approach (kinematics, statics, dynamics) ...
- ... for many types of robotic systems

Task hierarchy parameterization

Generalized projector

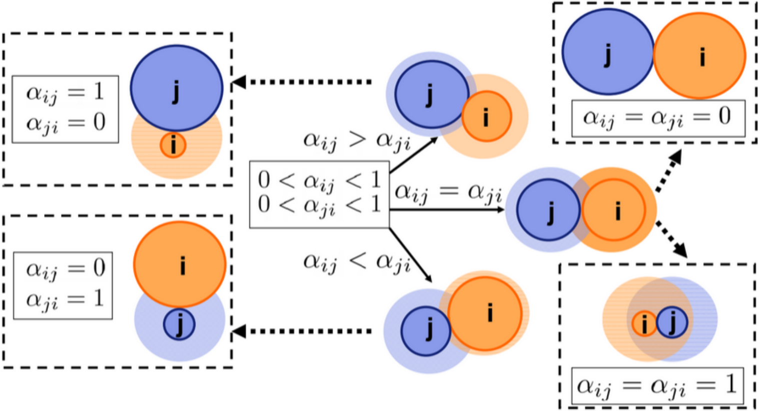
$$\mathbf{P}_i(\mathbf{A}_i) = \mathbf{I}_n - \mathbf{B}_i(\mathbf{J}_{s_i})^T \mathbf{A}^s_{i,r}(\mathbf{A}_i, o)\mathbf{B}_i(\mathbf{J}_{s_i})$$

Priority matrix

$$\mathbf{A}_i = \begin{bmatrix} \alpha_{i1} I_{m_1} & 0 & 0 & 0 & 0 \\ 0 & \ddots & 0 & 0 & 0 \\ 0 & 0 & \alpha_{ij} I_{m_j} & 0 & 0 \\ 0 & 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & 0 & \alpha_{in_t} I_{m_{n_t}} \end{bmatrix}$$

$$\alpha_{ij} \in [0, 1]$$

Task hierarchy parameterization

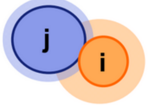


- Task activation $\alpha_{ii} = 1 \longrightarrow \alpha_{ii} = 0$
- Task deactivation $\alpha_{ii} = 0 \longrightarrow \alpha_{ii} = 1$

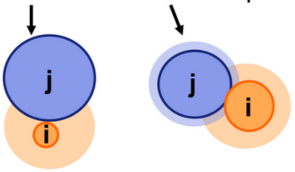
6

Characteristics of the generalized projector

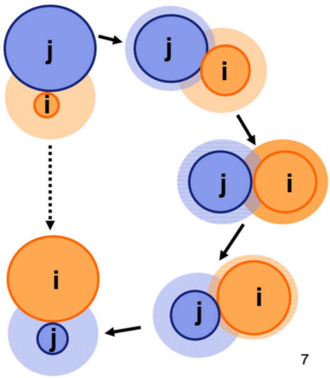
- Handle priority between each **pair of tasks**



- **Strict** and **non-strict** priority



- **Smoother** priority transition, task activation/deactivation

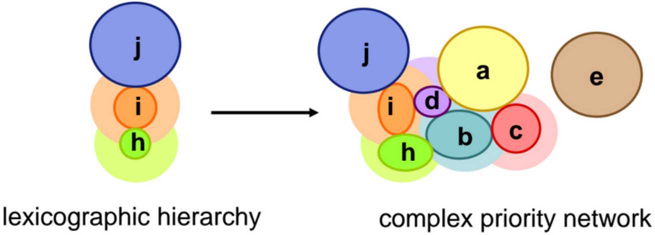


7

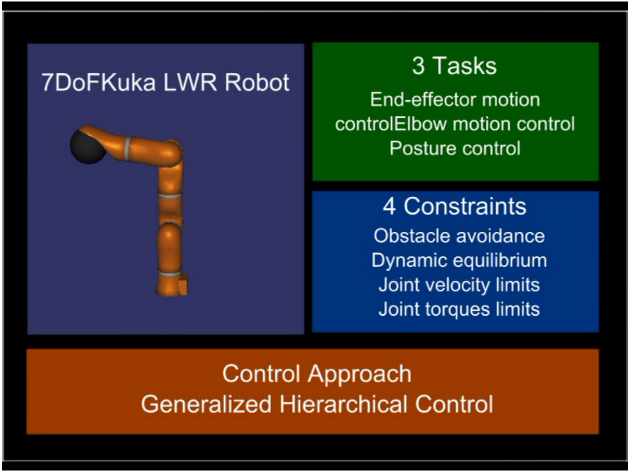
The CoDyCo Project : Whole-body control

Characteristics of the generalized projector

- Handle different types of **priority networks**



The CoDyCo Project : Whole-body control



TOWARDS MORE COMPLEX BEHAVIORS

- Generate increasingly complex motor abilities
  - **Anticipate** the effects of tasks
  - **Coordinate** tasks as a whole

$\rightarrow$ Model predictive control and distribution

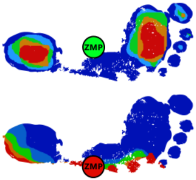
The CoDyCo Project : Whole-body control

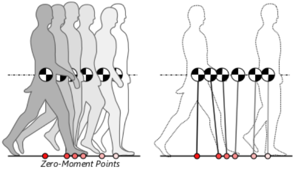
Model Predictive Control (MPC)

- **Optimal** control, receding horizon
- Requires a **model** of the process
  $x_{k+1} = f(x_k, u_k),\ y_{k+1} = g(x_{k+1})$

Control of biped postural balance [Wieber2006, Kanoun2009], [Herdt2010,Krause2012] based on the ZMP Preview Control [Kajita2003]

- robustness to disturbances
- regulation of the response
- constrained solutions



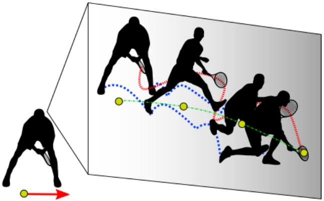


The CoDyCo Project : Whole-body control

Obstacle

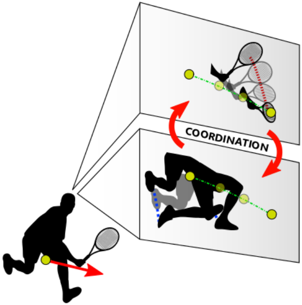
"Whole-body" MPC

- Dimension
  degrees of freedom $\times$ *horizon*
- Non-linearities

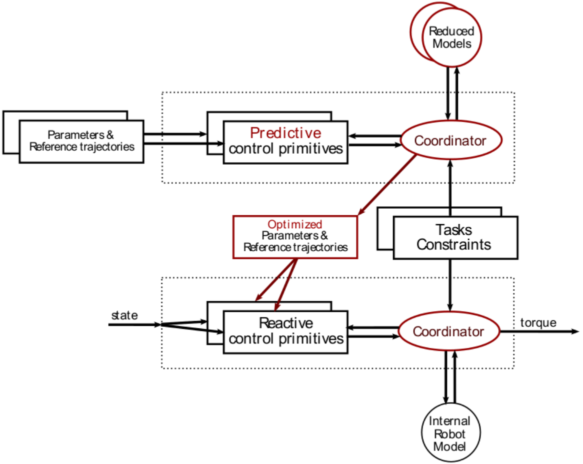


Distributed MPC (DMPC)

- Activity : global objective
- Sub-systems : **local** models & objectives

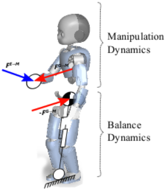


A MULTITASK PREDICTIVE CONTROL ARCHITECTURE

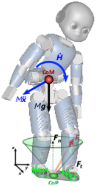


The CoDyCo Project : Whole-body control

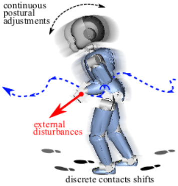
- Arbitrary decomposition and coupling
  - Task & Locomotion coordination



- Generic distribution : Distributed MPC
  - CoM dynamics coordination

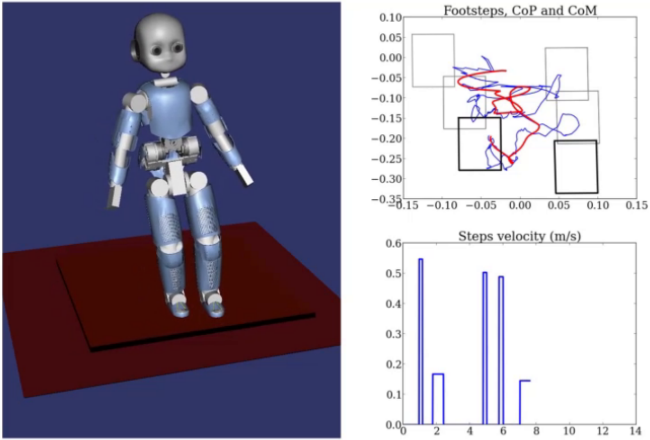


- Discrete nature of locomotion
  - Contact shifts & postural ajustments coordination



MPC for postural balancing under varying contact conditions [*Ibanez et al. IROS 2014*]

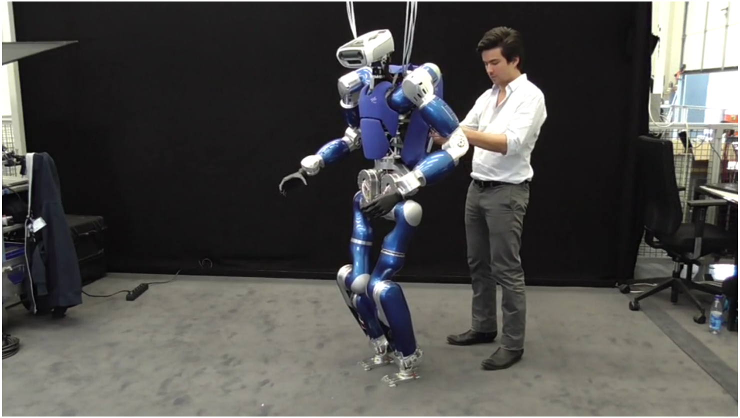
Aurelien Ibanez, Philippe Bidaud and Vincent Padois - Emergence of humanoid walking behaviors from Mixed-Integer Model Predictive Control



Submitted to 2014 IEEE/RSJ International Conference on Intelligent Robots and Systems on February 12. 2014

The CoDyCo Project : Whole-body control

MPC for postural balancing under varying contact conditions



→ From ZMP to 3-D conditions of stable balance criteria within MPC ... see Darwin Lau's presentation tomorrow

Learning

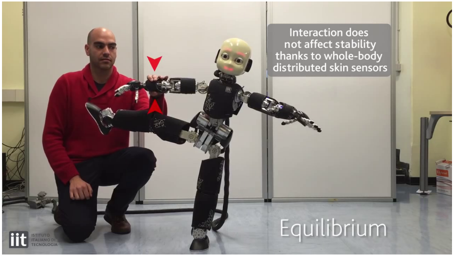
The CoDyCo Project : Learning

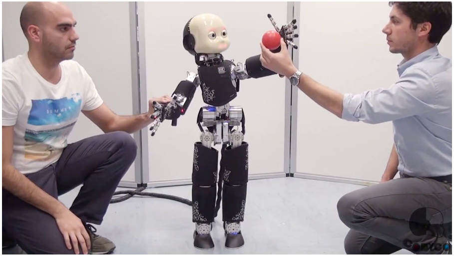
Goal : Adaptation, Generalization and Improvement of Compliant Control and Tasks with Contacts

- Improved Models from Real-Time Regression with Latent Contact Type Inference
- Inferring the Operational Space and Appropriate Controls with Multiple Contacts
- Generalizing and Improving Elementary Tasks with Contacts
- Learning the Prioritization of Tasks
  $\rightarrow$ see Ryan Lober's presentation tomorrow

iCub Demonstration

The CoDyCo Project : iCub Demonstration





For more, please visit : http://www.codyco.eu

Merci de votre attention

Whole-body Compliant Dynamical Contacts for Humanoids: the CoDyCo project

(FP7 EU project No. 600716 / 2013-2017)

Vincent Padois, Maître de Conférences

vincent.padois@upmc.fr

Institut des Systèmes Intelligents et de Robotique
Sorbonne Universites - UPMC Univ Paris 06 - CNRS, UMR 7222

JNRH@IRCCyN - 08/06/2015