Some perspectives in interactive Robotics

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Introduction - A bit of context

Observation

- Robotics is absent from many domains of human activities (industry, service)

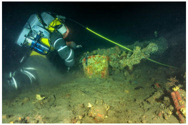
↪ Complexity of the activities and their related environments

A few industrial examples

- Construction, maintenance and dismantling of industrial products
- Flexible production lines, Construction and public works, production and transportation of energy, naval construction and aeronautics, off-shore activities...

??? →

Introduction - A bit of context

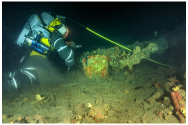
Limits of "classical" industrial Robotics

- No versatility: pre-defined trajectories
- Intrinsically dangerous: high structural stiffness, high gear ratios and inertia, non back-drivability
- Perception capabilities ≈ 0

Caracteristics of the potentially new application fields of Robotics

- Highly constrained and partially structured/known environments:
  - geometrically
  - mechanically
  - dynamically
- Multiple modes:
  - autonomous
  - teleoperated
  - collaborative
  - mixt
- Contacts are intrinsically present:
  - Under-actuated systems with non fixed base
  - Comanipulation
  - Task related mechanical actions applied to the environment

Introduction - A bit of context



What possibilities for the design of robots in this context ?

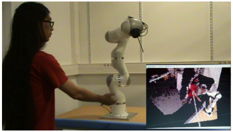
- Morphology and mechatronics properties
- Control laws
- Perception capabilities
- Control architectures

Design objectives ?

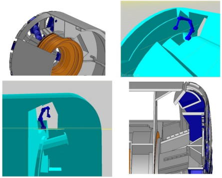
- Physical and cognitive ergonomy for the end users
- Safety wrt the environment
- Adaptation capabilities
- Performances

$\rightarrow$ **Complex problems!**

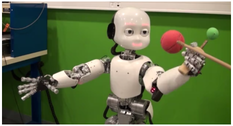
Scope of the presentation



Multi-tasks control under constraints



A few words about the automatic design of dedicated robotics architecture



A few words about learning and adaptation

Multi-tasks control under constraints

Considered System

$$M(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{n}(\boldsymbol{q}, \dot{\boldsymbol{q}}) + \epsilon(\boldsymbol{q}, \dot{\boldsymbol{q}}, \dots) = J_c(\boldsymbol{q})^T \boldsymbol{\chi}, \quad (1)$$

with $\boldsymbol{\chi} = \begin{bmatrix} \boldsymbol{w}_c^T & \boldsymbol{\tau}^T \end{bmatrix}^T$:

- actuation torque ($\boldsymbol{\tau} \in \mathbb{R}^{n_a}$)
- external wrenches ($\boldsymbol{w}_c = \begin{bmatrix} \boldsymbol{w}_{c,1}^T & \dots & \boldsymbol{w}_{c,n_c}^T \end{bmatrix}^T$)

Constraints

- physics: (1)
- actuation limits (max torque and speed);
- obstacles (joint limits, environment);
- contact wrenches (existence conditions, magnitude...).

$$G(\boldsymbol{q}, \dot{\boldsymbol{q}})\boldsymbol{\chi} \leq \boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}}). \quad (2)$$

Some prerequisites

- good knowledge of a realistic model of the system: modeling + identification + adaptation/learning
- perception and signal processing capabilities

Multi-tasks control under constraints

Task ?

- A function from the joint space to the operational space with characteristics:
  - a physical frame
  - a task parametrization $\boldsymbol{\xi}_i \in \mathbb{R}^{m_i}$
  - a forward model $\ddot{\boldsymbol{\xi}}_i = J_i(\boldsymbol{q})\ddot{\boldsymbol{q}} + \dot{J}_i(\boldsymbol{q}, \dot{\boldsymbol{q}})\dot{\boldsymbol{q}}$
  - a desired trajectory $\boldsymbol{\xi}_i^\star(t)$ obtained through
    - Global planning
    - On-line min-jerk like planning
    - Predictive control / Optimal control
    - Motion primitives learned by demonstration (e.g. DMPs)
    - CPGs (!)
    - ...
  - a local feedback controller (P(I)D with acceleration feedforward term) $\ddot{\boldsymbol{\xi}}_i^d = \ddot{\boldsymbol{\xi}}_i^\star + K_p\boldsymbol{e} + K_d\dot{\boldsymbol{e}}(+K_i\int \boldsymbol{e}dt)$
  - a level of hierarchical importance α_i with respect to other tasks

Multi-tasks control under constraints

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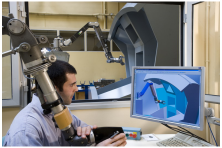
  - a level of hierarchical importance α_i with respect to other tasks

→ Find $\boldsymbol{\tau}$ at each control instant in order to maximize the task performance under constraints

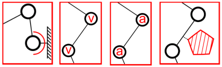
Multi-tasks control under constraints: the Telemach example

Objective: safe and reactive control law in a static environment



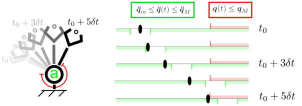
Reactive ?

- reactive $\neq$ planned movie
- Operational objectives are set in real-time
- Teleoperation, exteroceptive sensor-based control,...



Safe ?

- Robot related: joint position, velocity and torque limit
- Environment related: no collision



Guarantee the existence of a solution to the control problem $t \to \infty$

- Modify the constraints expression a priori
- Acceleration capabilities of the system in operational space (!)
- Check on-line the existence of an escape trajectory

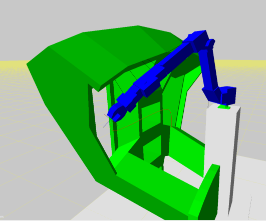
Multi-tasks control under constraints: the Telemach example

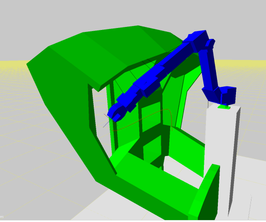
Constraints Compliant Control (CCC)

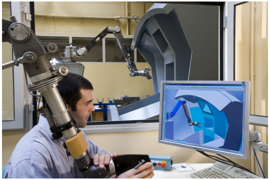
- 3-level hierarchical control law
  - Highest priority task: passive avoidance
  - Secondary task: task objective $\dot{\boldsymbol{\xi}}_O = J_O(\boldsymbol{q})\dot{\boldsymbol{q}}$
  - Smallest priority task: active avoidance
  - Tikhonov regularization of the Jacobian pseudoinverse
  - Heuristic iteration over the constraints to be avoided passively
- Hypothesis: constraints are compatible (a solution exists)
- $\dot{\boldsymbol{q}} = J_c^+ \, 0 + (J_O P_{J_c})^+ \dot{\boldsymbol{\xi}}_O^d + (J_{\bar{c}} P_{\begin{bmatrix} J_c \\ J_O \end{bmatrix}})^+ (\dot{\boldsymbol{\xi}}_{\bar{c}}^d - J_{\bar{c}} (J_O P_{J_c})^+ \dot{\boldsymbol{\xi}}_O^d)$

$\hookrightarrow$ **Under optimal LQP solution**

Some results







Multi-tasks control under constraints: workspace sharing

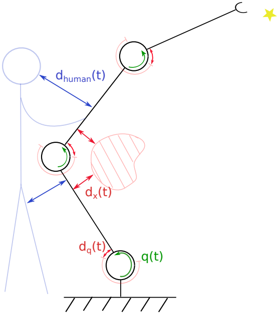
Objective: safe and reactive control law in a human/robot workspace sharing context

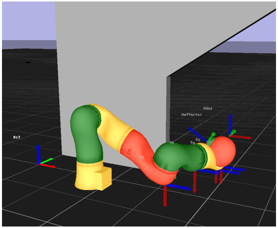
↪ Challenge 1 - Dynamic performance vs User safety

↪ Challenge 2 - Intuitive and continuous mode switching

! **Energetic approach**

- ↪ Classical obstacle avoidance (no contact) + ...
- ↪ ... monitored robot energy contact
- ↪ Considered energy for each segment: Σ_c (noo contact) + $\Sigma_{p,elastique}$ (contact)



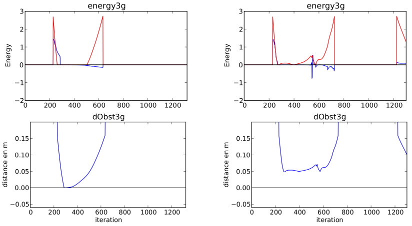


Multi-tasks control under constraints: workspace sharing

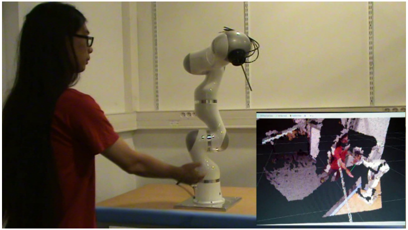
Control law

$$\min_{\chi,\ddot{q}} \frac{1}{2}\left(\beta\|\ddot{\boldsymbol{\xi}}^{d} - J\ddot{\boldsymbol{q}} + \dot{J}\dot{\boldsymbol{q}}\|^2 + \delta\|E_{i/j}\|^2\right)$$

$$\text{s.t.}\quad M(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{n}(\boldsymbol{q},\dot{\boldsymbol{q}}) = J_c(\boldsymbol{q})^T\chi$$
$$G(\boldsymbol{q},\dot{\boldsymbol{q}})\chi \leq \boldsymbol{h}(\boldsymbol{q},\dot{\boldsymbol{q}})$$
$$E_{i/j} \leq E^{j}_{limite}(d, d_{safe}, E_{safe}, d_{max}, k)$$

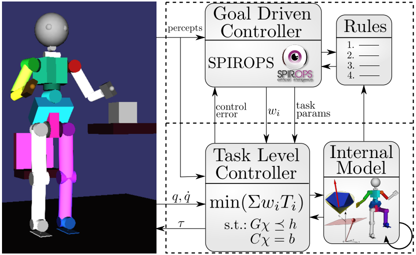


(a) Sans contrainte énergétique (b) Avec contrainte énergétique



Multi-tasks control under constraints: complex activities

Objective: complex activities through combination and sequencing of elementary tasks



Specificities

- Non strict task hierarchies (weighting strategy)
- Position, wrench or impedance takss
- Fuzzy decision making engine: tasks weights and activations
- Reactive approach but ...
- ... model predictive control to generate $\ddot{\xi}^d_{CdG}$
- Task transition mechanism

Limitations

- No strict hierarchies between tasks
- Reactive approach: no anticipation of disturbances related to task incompabilites at short term

Multi-tasks control under constraints: tasks hierarchies

Objective: Unique formalism to define both strict and soft tasks hierarchies and allowing to modify continously priority levels

- **Existing approaches**
  - Analytical → inequality constraints are problematic
  - Numerical (through opitmization, QP type)
  - In both case two paradigms: strict hierarchies (SoT) or soft hierarchies but no global approach

Soft hierarchies through weighting

$$\begin{cases} \min\limits_{\boldsymbol{w_1},\boldsymbol{w_2},\dot{\boldsymbol{q}}} & \frac{1}{2}[k_1\|\boldsymbol{w_1}\|^2 + k_2\|\boldsymbol{w_2}\|^2 + \varepsilon\|\dot{\boldsymbol{q}}\|^2] \\ \text{s.t} & \boldsymbol{w_1} = \dot{\boldsymbol{x}}_1 - \boldsymbol{J}_1\dot{\boldsymbol{q}} \\ & \boldsymbol{w_2} = \dot{\boldsymbol{x}}_2 - \boldsymbol{J}_2\dot{\boldsymbol{q}} \end{cases} \quad (3)$$

Strict hierachies

$$\begin{cases} \min\limits_{\boldsymbol{w_1},\dot{\boldsymbol{q}}} & \frac{1}{2}[\|\boldsymbol{w_1}\|^2 + \varepsilon\|\dot{\boldsymbol{q}}\|^2] \\ \text{s.t} & \boldsymbol{w_1} + \boldsymbol{J}_1\dot{\boldsymbol{q}} = \dot{\boldsymbol{x}}_1 \end{cases} \quad (4)$$

$$\begin{cases} \min\limits_{\boldsymbol{w_2},\dot{\boldsymbol{q}}} & \frac{1}{2}[\|\boldsymbol{w_2}\|^2 + \varepsilon\|\dot{\boldsymbol{q}}\|^2] \\ \text{s.t} & \boldsymbol{w_2} + \boldsymbol{J}_2\dot{\boldsymbol{q}} = \dot{\boldsymbol{x}}_2 \\ & |\dot{\boldsymbol{x}}_1 - \boldsymbol{J}_1\dot{\boldsymbol{q}}| \leq \boldsymbol{w}_1^* \end{cases} \quad (5)$$

Multi-tasks control under constraints: tasks hierarchies

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

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

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

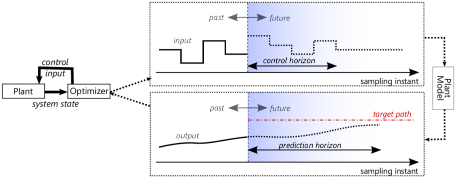
$$\text{with } \ddot{\boldsymbol{q}}' = \begin{bmatrix} \ddot{\boldsymbol{q}}'_1 \\ \vdots \\ \ddot{\boldsymbol{q}}'_{n_t} \end{bmatrix} \text{ and } P = [P_1(\alpha_1) \ldots P_{n_t}(\alpha_{n_t})].$$

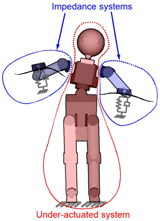
Specificites

- **Non** lexicographic notion of what priority is (no global order)
- By default, projection of task i in the kernel of others
- Continuous modification of the projector onto the kernel associated to task i: $i > j \leftrightarrow j > i$
- Implicit task insertion/deletion mechanism
- Continuous control approach

Multi-tasks control under constraints: tasks hierarchies

Objective: robustness of the solutions to the multi-tasks control under constraints problem





General principles

- Looking for an optimal control input horizon (sliding window)
- Use of a computationally inexpensive model of the system which dynamics has to be pre-visualized
- Locomotion: generation of reference trajectories for the center of mass position

Specificities

- Extension of the existing ZMP models to consider external disturbances
- Optimal horizon of control gains for the manipulation tasks (impedance adaptation)

Multi-tasks control under constraints: tasks hierarchies

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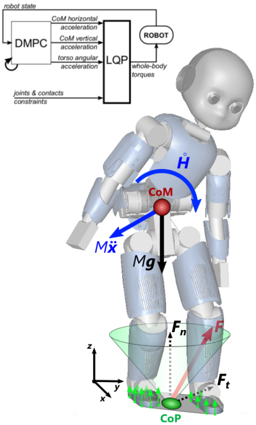
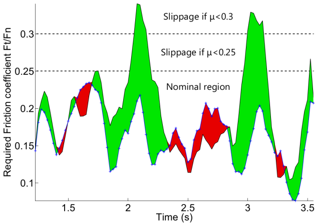
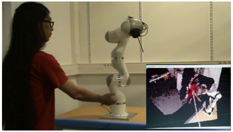


Specificities

- Distributed approach
- Optimal trade-off between several contradictory objectives for the center of mass
- Minimization of the tipping-over risk and optimization of the friction conditions
- Optimal horizon of horizontal and vertical center of mass acceleration and torso angular acceleration



Scope of the presentation



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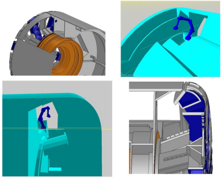
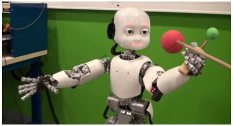


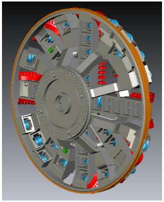
A few words about the automatic design of dedicated robotics architecture

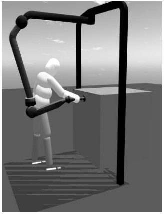


A few words about learning and adaptation

Automatic design of dedicated robots

Objective: Optimization of the morphology of a manipulator evolving in an highly cluttered environment





Observation

- No intuitive solution
- Combinatorics is high
- Classical design method are not adapted

↪ **MO optimization problem (MO)**

How to solve it ? . . . knowing that

- looking for an arrangement of bodies and joints
- Optimization criteria of very different nature / contradictory
- Evaluation of the solution wrt specific tasks ot be performed → simulations
- The structure of the space of solutions is unknown (local minima ...)
- Large optimization problem

↪ **Stochastic optimization using MO evolutionary algorithms**

Automatic design of dedicated robots

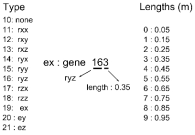
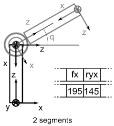


Fig. 3. Genotype table

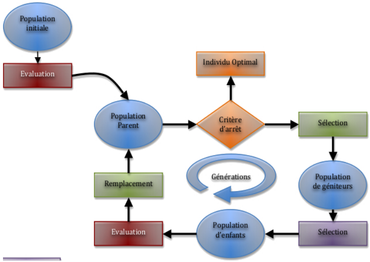


How to represent a robot

- Genotype: each gene codes for a body and the following joint
- The value of the gene accounts for the type of joint and the length of the associated body

Optimization criteria

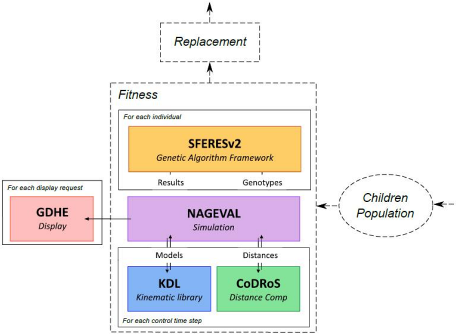
- ↘ complexity of the solution (nb. of DoFs, total length...)
- ↗ tasks performances
- ↗ ergonomy



General principle of genetic algorithms

- Initial candidate robots population
- Evaluation of the population
- Selection of the individuals of the next generation: performance and diversity
- Genetic operations (mutation, crossing,...) on the population
- Update of the population

Automatic design of dedicated robots

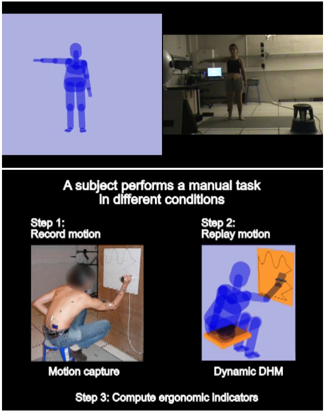


Telemach example

- NSGA2 algorithm in the Sferes *framework* (by S. Doncieux et JB. Mouret, ISIR)
- Kinematic evaluation of robots
- Trajectory tracking using of "typical" trajectories using the CCC

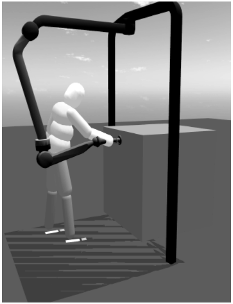
Automatic design of dedicated robots

Objective: Definition of quantitative ergonomy and performance indicators for the design of a cobot



Approach

- Mocap and indicators synthesis
- Cobots architectures are evaluated through simulation



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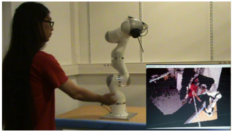

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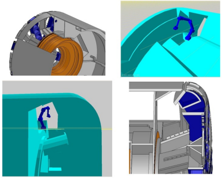

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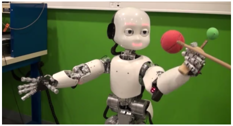
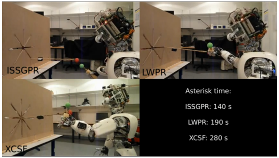


A few words about learning and adaptation

A few words about learning and adaptation

Objective: learning and adaptation of the models and optimal policies required for the control of robots



Problem

- Infinity of possibilities of the world
- Need of adaptation in unknown contexts
- Computationally efficient and incremental acquisition of optimal motor abilities

Some on-going work

- Visuo-motor Jacobian incremental learning
- Socially guided exploration for learning in high dimension spaces
- Bridging the gap between optimal control and policy learning through reinforcement learning
- Learning globally stable controllers based on demonstrated trajectories
- Context and objective based MPC parameters tuning through evolutionary exploration (with C. Santos, S. Doncieux and José Pontes)

Conclusions

- Manipulation in constrained environment is a complex problem !
- It requires scientific contributions in several domains
  - design
  - control
  - learning and adaptation
  - ...
- From a control perspective, advanced model-based control algorithms exist in order to
  - combine tasks
  - under constraints
  - in an optimal fashion (MPC)
- ... but they require
  - realistic models of the robot and its environment: identification, learning and adaptation
  - perception capabilities

Collaborations (academia and industry)

Chaire de Robotique d'Intervention RTE/UPMC - 2011–2016

Projet ANR TELEMACH - 2008–2010

Projet FUI ROMEO2 - 2013–2017

Projet TELEMACH, ROMEO2, Simulateur physique xde @CEA

Projet ANR Equipex robotex
Réseau "Robotique Humanoïde et Interactions Naturelles"

Projet PESSOA – 2014
avec l'Université de Minho

Projet européen CODYCO - STREP FP7-ICT-2011.2.1 - 2013–2017
porté par l'Institut Italien de Technologie + University of Birmingham + TU Darmstadt + Institut Jožef Stefan + UPMC

Projet ANR MACSi - 2010–2013
porté par l'UPMC + INRIA Bordeaux + ENSTA + Gostai

ISIR People involved

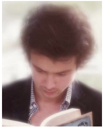

P. Bidaud


S. Doncieux


A. Droniou


S. Hak


G. Hamon


A. Ibanez

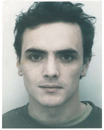

S. Ivaldi


M. Liu


P. Maurice


J. Pontes


S. Rubrecht


C. Salaün


J. Salini


A. Seeleuthner


O. Sigaud


Y. Tan

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Thank you for your attention.
Questions ?