WORKSHOP

The DEXMART project for advanced bimanual manipulation

# Grasping and control of multifingered hands


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Presenter

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# Introduction

Grasping and control of multifingered hands

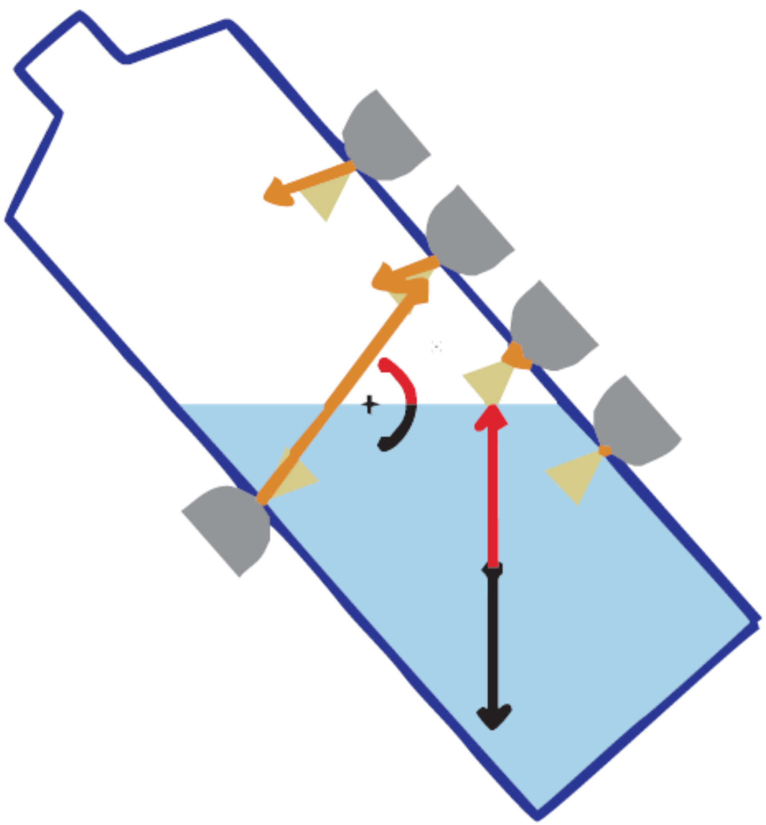
- **DEXterous and autonomous dual-arm/hand robotic manipulation with sMART sensory-motor skills: A bridge from natural to artificial cognition**
  - New robotic hand with tactile and force sensing capabilities
  - Advanced manipulation skills using also two hands
  - Mechanical design inspired to human hand

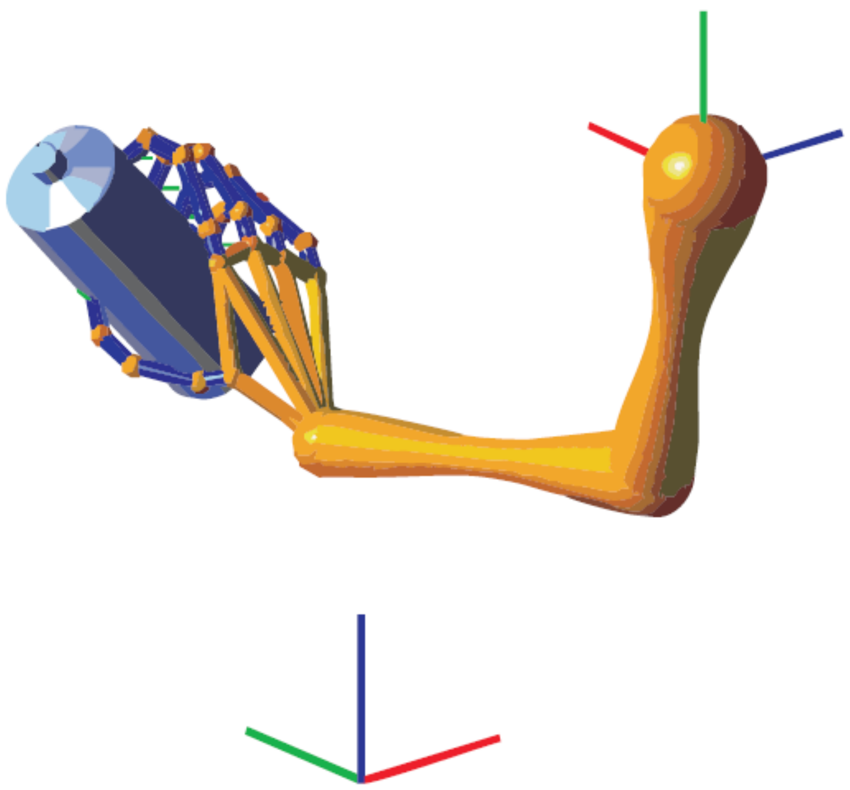
- **Three research topics**
  - Online computation of the optimal grasping forces able to cope with uncertainties/variations of the dynamic parameters of the object or external forces applied
  - Manipulation by exploiting the redundant kinematic DOFs of the system within a task-based control framework
  - Tacking advantage of anthropomorphism to control the robotic hand in a space of reduced dimension based on human hand synergies

# GFO

Grasping Force Optimization

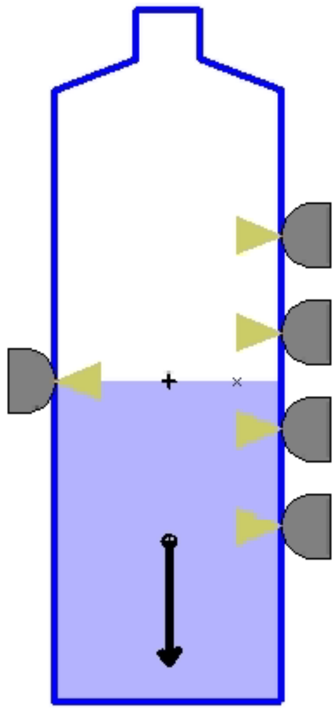
- **Grasping Force Optimization**
  - Computation of the optimal contact forces required to balance the external forces (object dynamics and forces acting on the object) while considering friction limits and joint torque limits on the basis of the sensed force

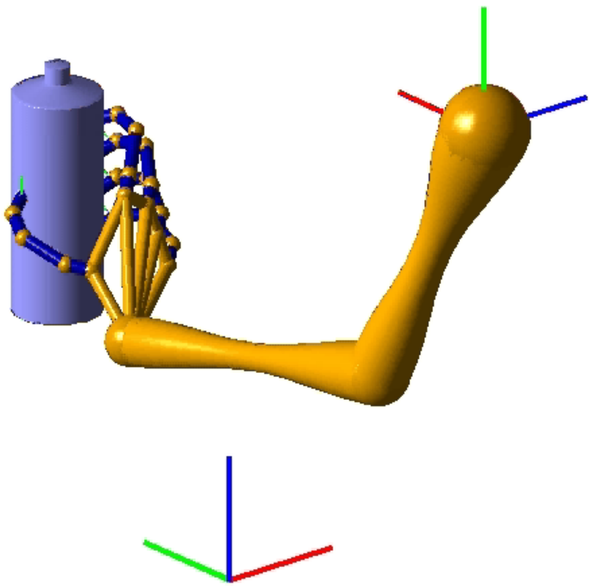




# Online!

## Grasping Force Optimization





# Progress wrt state of art

Grasping Force Optimization

## ① Nonlinear optimization problem

- Nonlinear programming not suitable for real-time applications!

## ② Formulation as **convex optimization problem** with **linear constraints**

- Gradient flow algorithms proposed for real-time applications

## ③ Friction cone constraints formulated as **LMIs**

- Interior point algorithm (small number of fingers)
- Joint torque limits considered as LMIs

## ④ Our solution

- Iterative algorithm based on a compact semi-definite matrix representation of the friction cone constraints
- Initial point self-evaluation
- Affine constraint matrix decomposed into two matrices of reduced dimension
- Dynamic selection of joint-torque constraints

# Constraints formulation/1

## Grasping Force Optimization

- **Grasp equilibrium equation**

$$\boldsymbol{h}_e = \boldsymbol{G}\boldsymbol{c}$$

- **Friction constraints**

$$\boldsymbol{F}(\boldsymbol{c}) = \mathrm{diag}\left(\boldsymbol{F}_1(\boldsymbol{c}_1), \ldots, \boldsymbol{F}_n(\boldsymbol{c}_n)\right) > 0$$

point contact with friction

$$\boldsymbol{F}_i(\boldsymbol{c}_i) = \begin{bmatrix} c_{i,z} + \frac{c_{i,x}}{\mu_i} & \frac{c_{i,y}}{\mu_i} \\ \frac{c_{i,y}}{\mu_i} & c_{i,z} - \frac{c_{i,x}}{\mu_i} \end{bmatrix}$$

soft finger contact

$$\boldsymbol{F}_i(\boldsymbol{c}_i) = \begin{bmatrix} c_{i,z} + \frac{c_{i,x}}{\sqrt{\mu_i}} & \frac{c_{i,y}}{\sqrt{\mu_i}} - j\frac{c_{i,t}}{\sqrt{\mu_{i,t}}} \\ \frac{c_{i,y}}{\sqrt{\mu_i}} + j\frac{c_{i,t}}{\sqrt{\mu_{i,t}}} & c_{i,z} - \frac{c_{i,x}}{\sqrt{\mu_i}} \end{bmatrix}$$

# Constraints formulation/2

Grasping Force Optimization

- **Residual joint torques at equilibrium**

$$\boldsymbol{\tau}_B = \begin{bmatrix} \boldsymbol{\tau}_{B,L} \\ \boldsymbol{\tau}_{B,H} \end{bmatrix} = \begin{bmatrix} \boldsymbol{J}^{\mathrm{T}}(\boldsymbol{q})\boldsymbol{c} - \boldsymbol{\tau}_L + \boldsymbol{\tau}_e \\ -\boldsymbol{J}^{\mathrm{T}}(\boldsymbol{q})\boldsymbol{c} + \boldsymbol{\tau}_H - \boldsymbol{\tau}_e \end{bmatrix}$$

- **Joint torque limits constraints**

$$\boldsymbol{T}(\boldsymbol{c}, \boldsymbol{q}, \boldsymbol{\tau}_e) = \mathrm{diag}\left(\boldsymbol{\tau}_B\right) > 0$$

# Compact constraints formulation

- **Friction and joint torque constraints**

$$\boldsymbol{P} = \operatorname{diag}(\boldsymbol{F}, \boldsymbol{T}) > 0$$

  - Subject to a set of equalities corresponding to the grasp equilibrium equation and to the joint torques equilibrium equation

$$\boldsymbol{A}\boldsymbol{\xi}(\boldsymbol{P}) = \boldsymbol{b}$$

$$\boldsymbol{\xi}(\boldsymbol{P}) = \left[\boldsymbol{c}(\boldsymbol{F})^{\mathrm{T}}, \boldsymbol{\tau}_B(\boldsymbol{T})^{\mathrm{T}}\right]^{\mathrm{T}}$$

# Formulation

## Grasping Force Optimization

- **Optimization problem corresponding to the minimization of the cost function**

$$\Phi(\boldsymbol{P}) = \mathrm{tr}\left(\boldsymbol{W}_p\boldsymbol{P} + \boldsymbol{W}_b\boldsymbol{P}^{-1}\right)$$

  - The first term weights the normal forces at each contact point, i.e. the pressure forces on the object
  - The second term represents a barrier function which goes to infinity when friction or torque limits are approached
- **The cost function has a unique minimum that can be computed using the linear constrained exponentially convergent gradient flow**

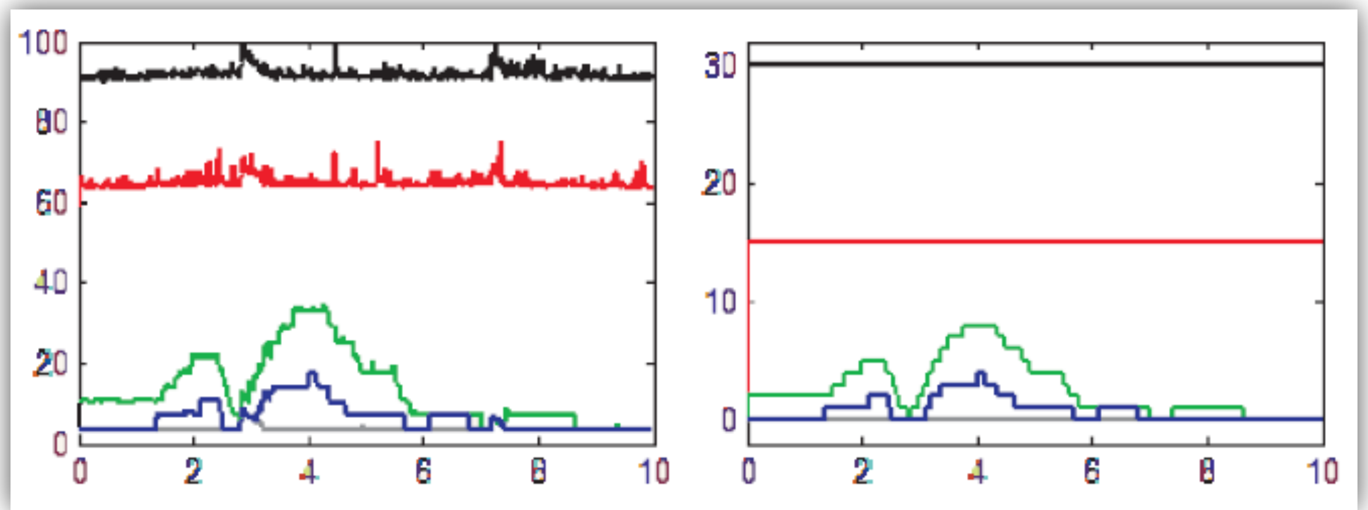
$$\xi(\dot{\boldsymbol{P}}) = \boldsymbol{Q}\xi(\boldsymbol{P}^{-1}\boldsymbol{W}_b\boldsymbol{P}^{-1} - \boldsymbol{W}_p) \qquad \boldsymbol{Q} = (\boldsymbol{I} - \boldsymbol{A}^{\dagger}\boldsymbol{A})$$

# Iterative solution

## Grasping Force Optimization

- **New iterative formulation of the discrete version of the gradient flow**
  - ✓ Affine constraint decomposition: inversion of two matrices of reduced dimension, one depending only on grasp configuration and the other only on hand configuration
  - ✓ Initial point self-evaluation: simplified method for initial point computation at each iteration
  - ✓ Dynamic selection of joint-torque constraints: constraints activated only when needed

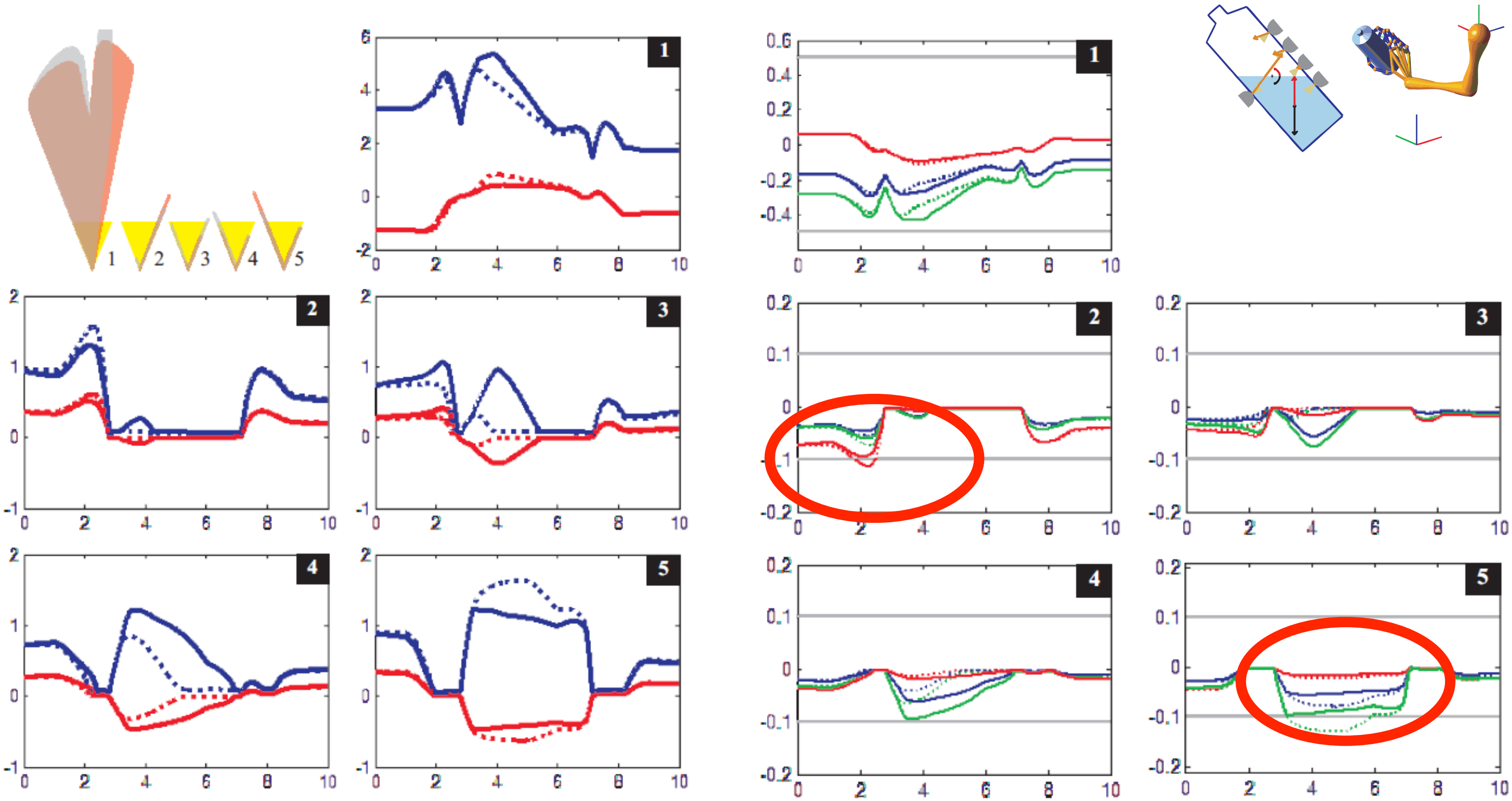
**normalized computational-time** **# of active joint constraints**



# Results

## Grasping Force Optimization

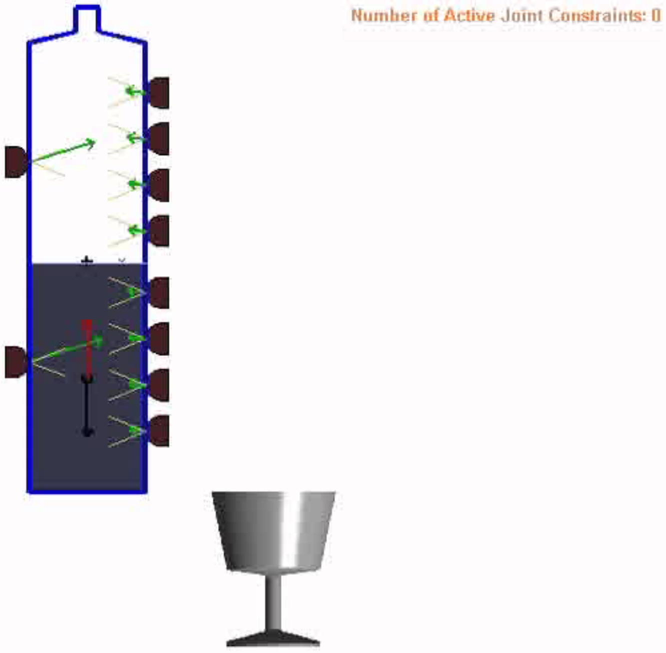
- **Frictional cones - Contact forces - Joint torque limits**



# Bi-manual task

## Grasping Force Optimization

- **Load sharing**



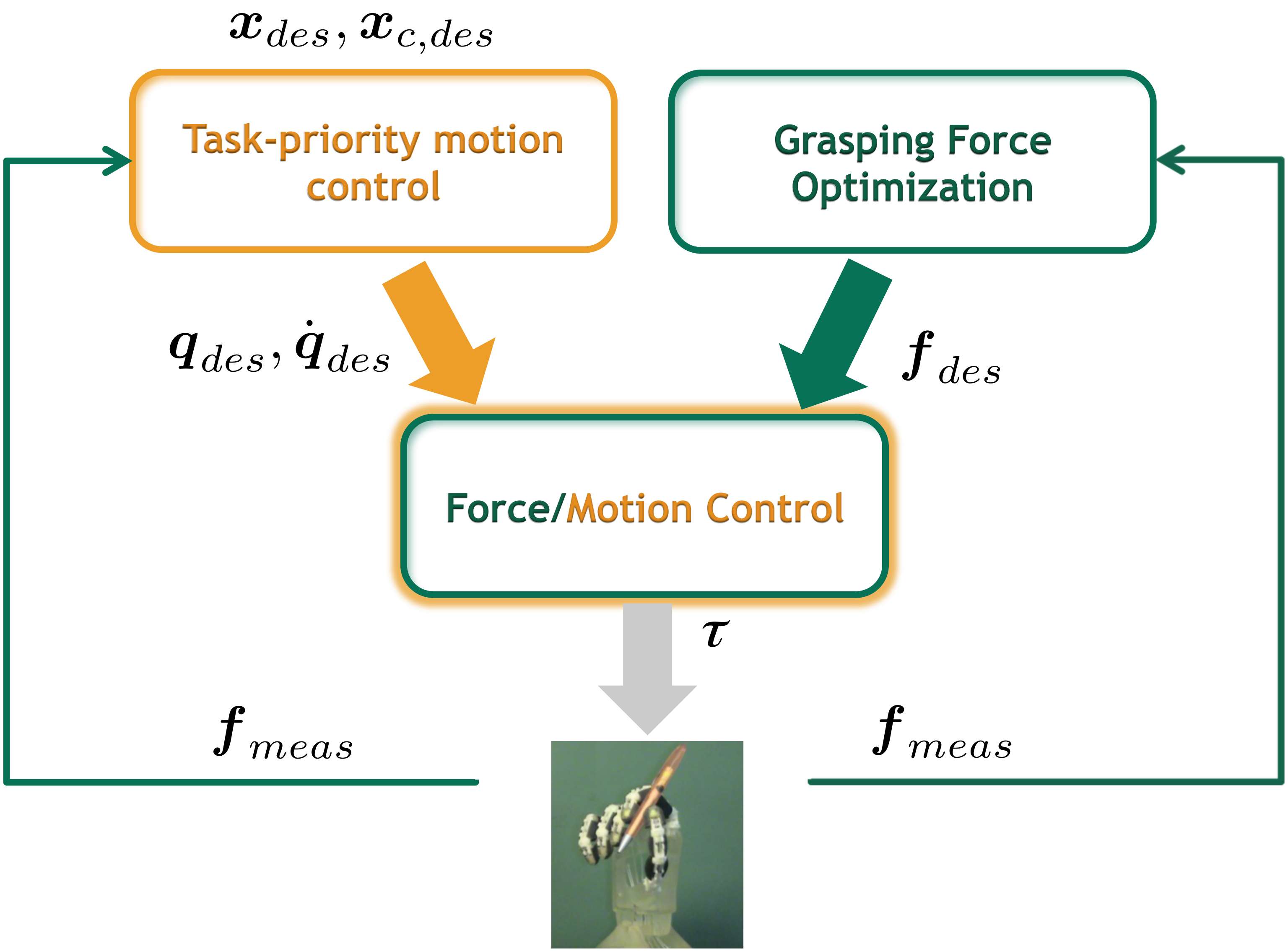
# Task-based approach

Grasp control exploiting redundancy

- **Manipulation as a complex task achieved by composing a suitable set of subtasks each involving a reduced number of DOFs**
- **Task-based approach to grasp and manipulation control**
  - Motion control conceived as a hierarchical composition of task objectives with a certain number of constraints
    - main task (desired object motion/contact point positions) + a certain number of sub-tasks (force closure, manipulation dexterity…) + constraints (joint limits, internal collisions…)
    - tasks are ordered in a dynamic stack and conflicts between tasks at different priority are avoided by projecting each task in the null space of the previous ones
  - Force control via impedance control or parallel force/position control

# Control structure

## Grasp control exploiting redundancy



# Redundancy resolution

## Grasp control exploiting redundancy

- The augmented projection method allows to fulfill multiple tasks with desired hierarchy

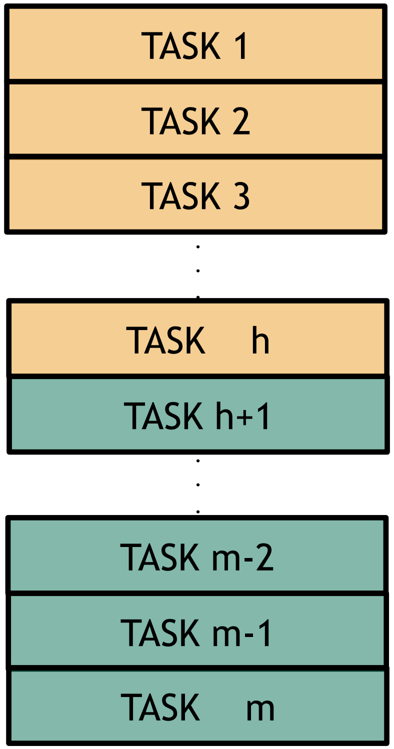
$$\dot{\tilde{q}} = \boxed{\tilde{J}^{\dagger}(\tilde{q}, \Delta l_d) G^{\mathrm{T}} (\tilde{v}_{o_d} + K_o \tilde{e}_o)}$$ primary task

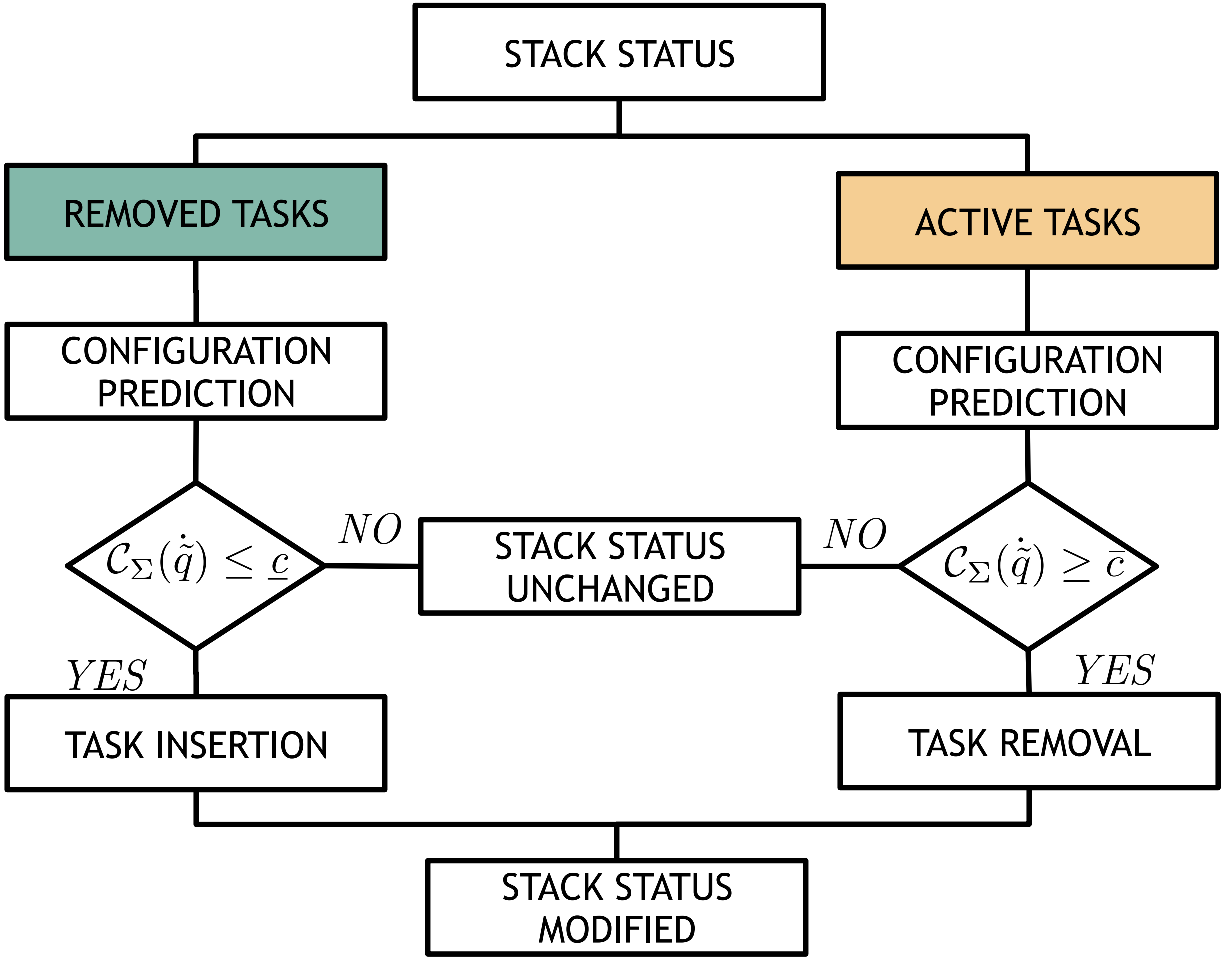
$$\boxed{+\sum_{h=1}^{m} \rho_{t_h} N(J_{t_h}^{A}) J_{t_h}^{\dagger} K_{t_h} e_{t_h}}$$ subtasks

$$\boxed{-k_{\nabla} N(J_{t_{m+1}}^{A}) \nabla_{\tilde{q}}^{T} \mathcal{C}_{\Sigma}}$$ constraints

- A subtask must be disabled if it comes close to violate a constraint

- **Task sequencing with smooth transitions**

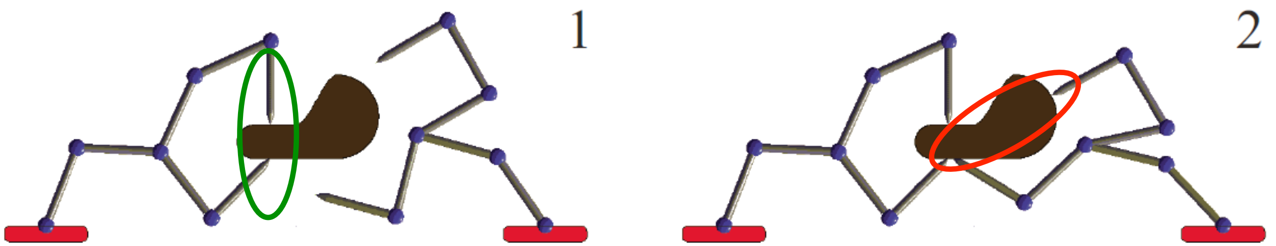


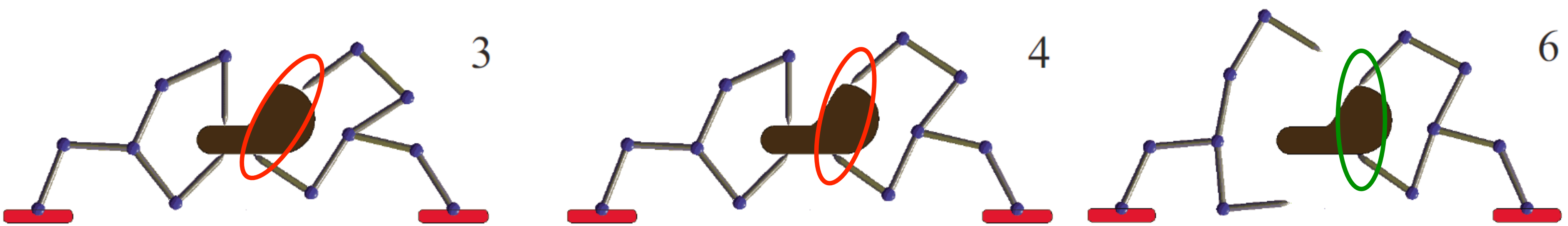



# Case study

## Grasp control exploiting redundancy

- Exchanging an object between left and right hand using thumb and index



# Subtasks and constraints

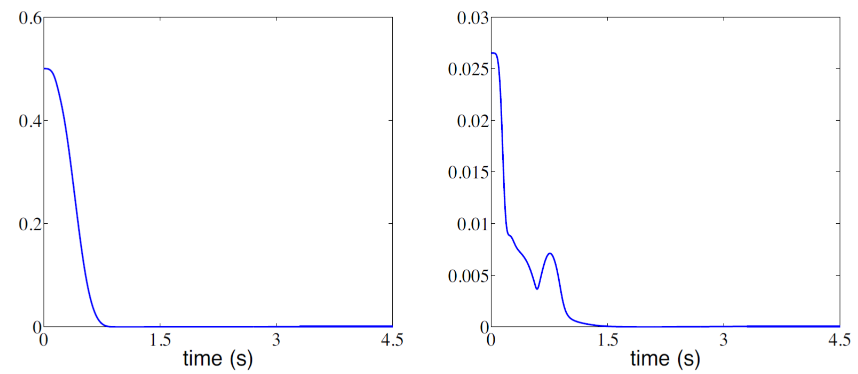
## Grasp control exploiting redundancy

- **Unit frictionless equilibrium (force closure)**

$$\varepsilon_f = \frac{1}{2}\boldsymbol{f}^T\boldsymbol{f}\,, \qquad \boldsymbol{f} = \sum_{i=1}^{4}\hat{\boldsymbol{n}}_i^o\,,$$

$$\varepsilon_m = \frac{1}{2}\boldsymbol{m}^T\boldsymbol{m}\,, \qquad \boldsymbol{m} = \sum_{i=1}^{4}\boldsymbol{c}_i^o \times \hat{\boldsymbol{n}}_i^o$$

force and moment residuals



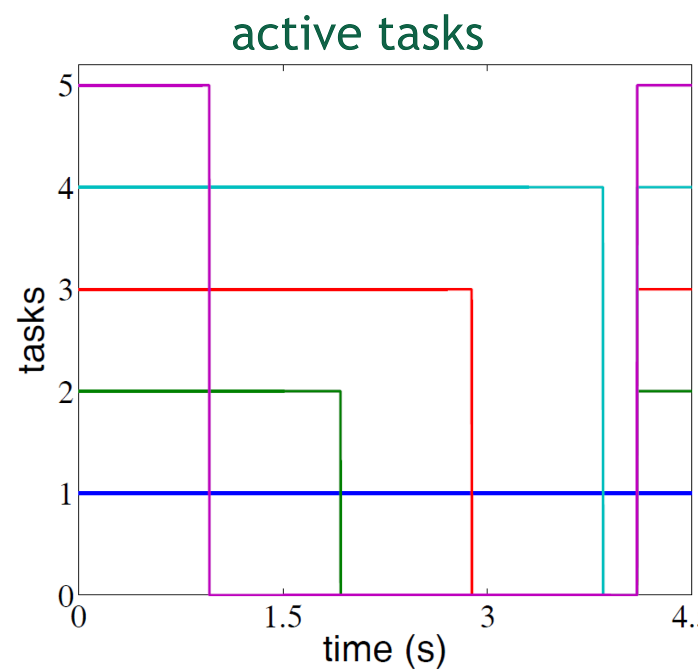

- **Manipulability**

$$w_i(\boldsymbol{q}_i) = \sqrt{det\left(\boldsymbol{J}_i(\boldsymbol{q}_i)\,\boldsymbol{J}_i^T(\boldsymbol{q}_i)\right)}$$

- **Distance of object from palms…**
- **Constraints**
  - Joint limits
  - Collisions avoidance

# Video

Grasp control exploiting redundancy

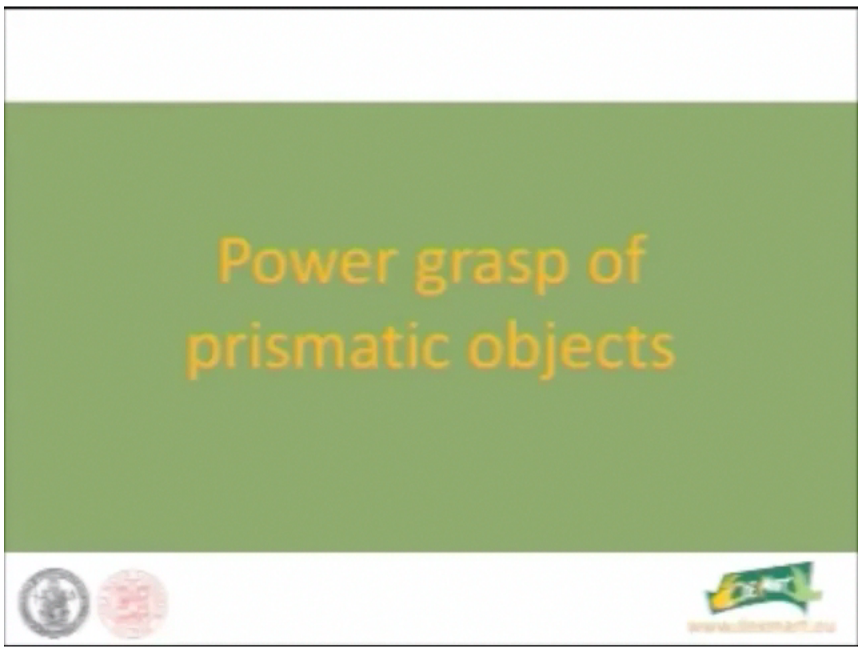



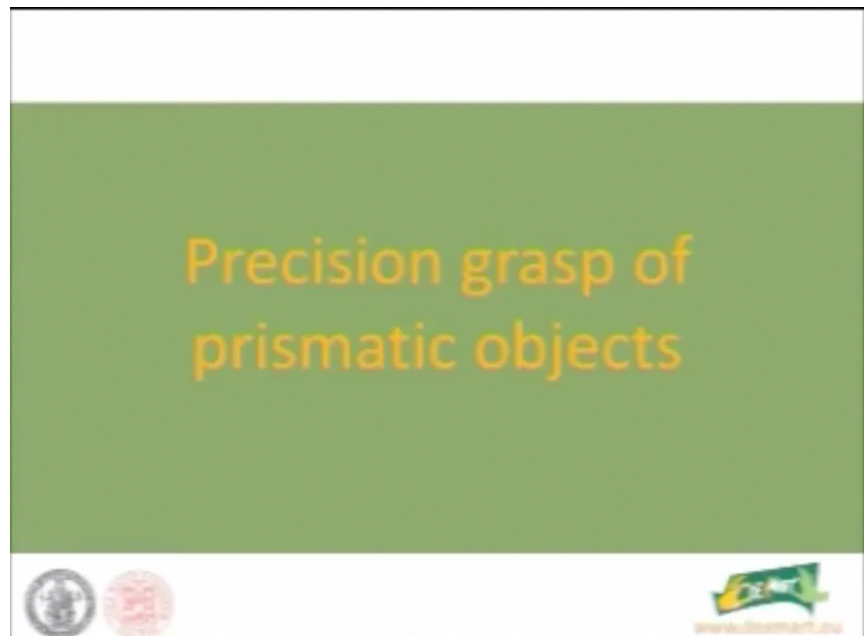

1. object pose
2. unit force residual
3. unit moment residual
4. manipulability
5. distance from palms

# Postural synergies

Grasp control using postural synergies

- **Motivation**
  - The behavior of the human hand during grasp is dominated by movements in a continuous configuration space of reduced dimension wrt hand DOFs
  - Tendon couplings and muscle activation patterns lead to coordination movements called postural synergies
- **Goal**
  - Controlling the DEXMART hand in a space of reduced dimension with respect to the number of DOFs (15)



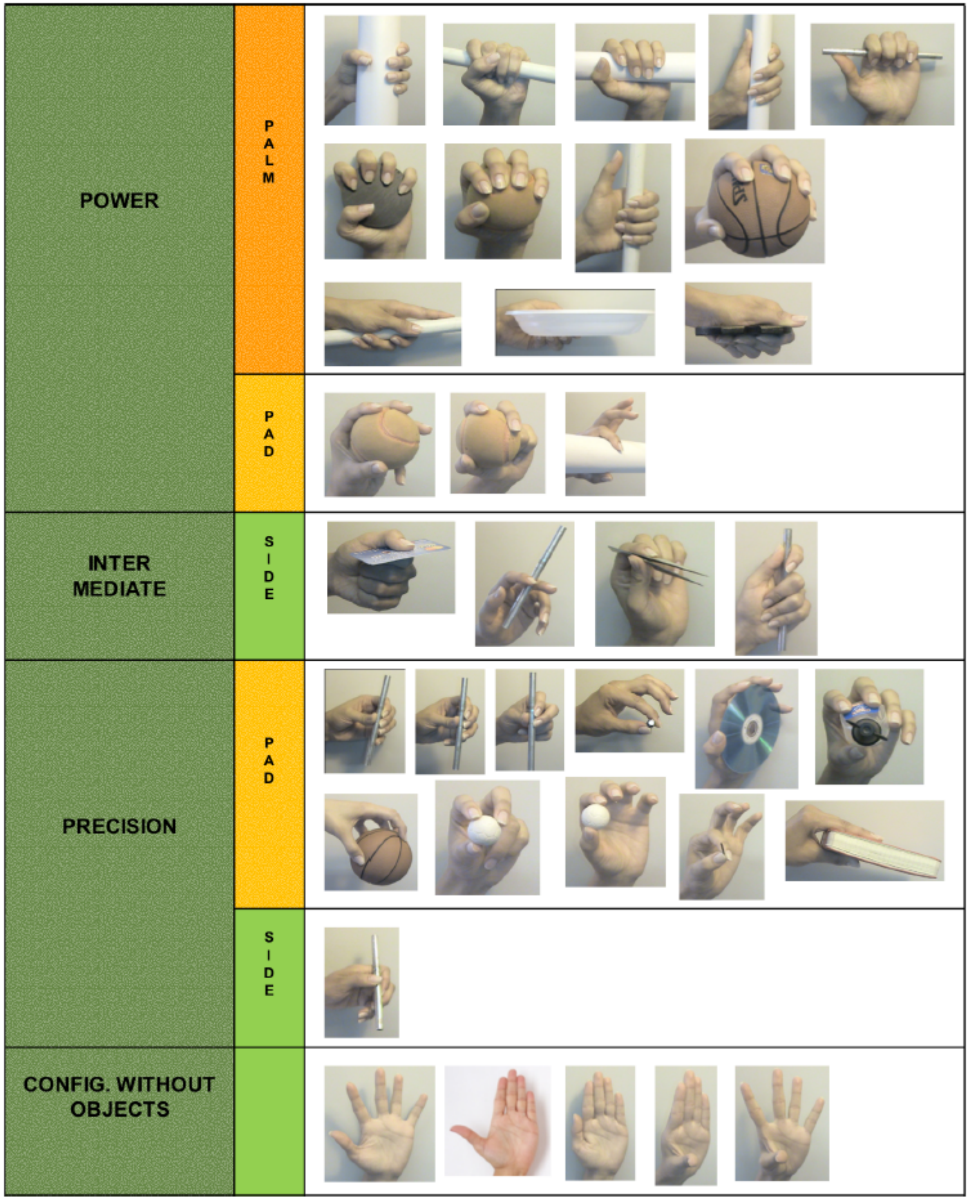
# Computing the synergies

Grasp control using postural synergies

- **36 hand configurations taken from a recent grasp taxonomy reproduced with DEXMART hand**
  - Principal Component Analysis performed on the joint measurements set
  - The first three principal components assumed as a basis of the hand configuration space (eigenpostures)

$$\hat{\boldsymbol{E}} = \begin{bmatrix} \boldsymbol{e}_1 & \boldsymbol{e}_2 & \boldsymbol{e}_3 \end{bmatrix}$$

  - The three first eigenpostures accounts for >96% of hand postures



# Reduced configuration space

Grasp control using postural synergies

- **Hand configuration** for the i-th grasp computed as

$$\hat{\boldsymbol{c}}^i = \bar{\boldsymbol{c}}_h + \hat{\boldsymbol{E}} \begin{bmatrix} \alpha_1^i \\ \alpha_2^i \\ \alpha_3^i \end{bmatrix}$$




  - The third synergy is mainly useful for precision grasps and intermediate side grasps

# Control using synergies

Grasp control using postural synergies

- Interpolation of the weight values in **three configurations**

zero offset

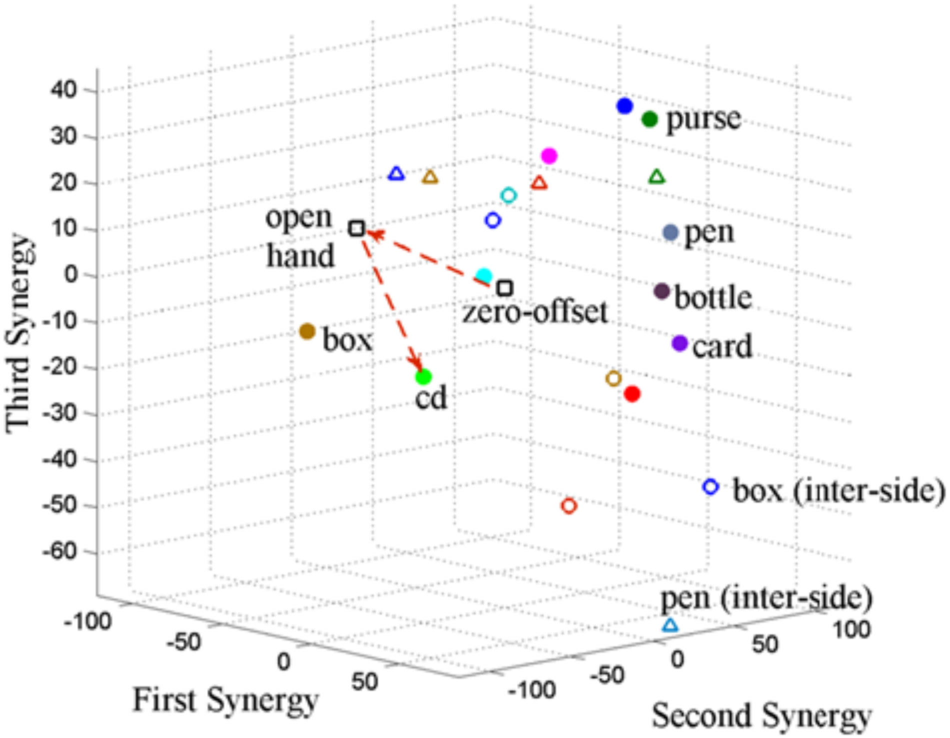
$$\bar{\boldsymbol{c}}_h \Longrightarrow \boldsymbol{\alpha} = \mathbf{0}$$

open hand

$$\hat{\boldsymbol{c}}_h^0 \Longrightarrow \boldsymbol{\alpha}^0 = \hat{\boldsymbol{E}}^\dagger(\boldsymbol{c}_h^0 - \bar{\boldsymbol{c}}_h)$$

desired grasp

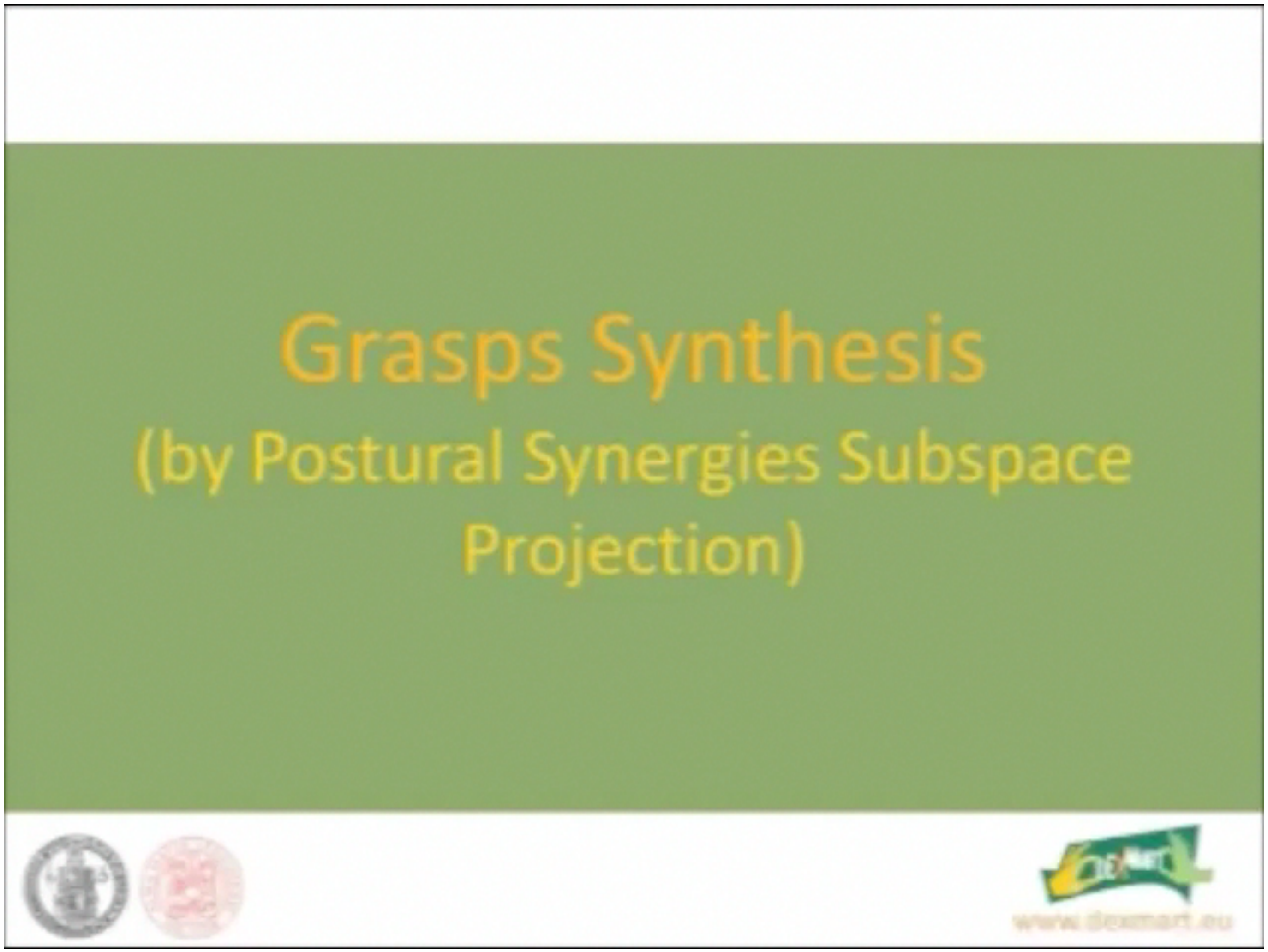
$$\hat{\boldsymbol{c}}_h^d \Longrightarrow \boldsymbol{\alpha}^d = \hat{\boldsymbol{E}}^\dagger(\boldsymbol{c}_h^d - \bar{\boldsymbol{c}}_h)$$



# Experiments

Grasp control using postural synergies

- **Grasp control using the first three synergies**



# Conclusion

Grasping and control of multifingered hands

- Three steps forward toward **grasping and control of multifingered robotic hands**
- Online grasping force optimization
  - V. Lippiello, B. Siciliano, L. Villani, "Online dextrous-hand grasping force optimization with dynamic torque constraints selection," *2011 IEEE International Conference on Robotics and Automation*, May 2011
- Grasp control exploiting redundancy
  - F. Caccavale, V. Lippiello, G. Muscio, F. Ruggiero, L. Villani, "Kinematic Control with Force Feedback for a Redundant Bimanual Manipulation System," *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, September 2011
- Grasp control based on synergies
  - F. Ficuciello, G. Palli, C. Melchiorri, B. Siciliano, "Experimental Evaluation of Postural Synergies During Reach to Grasp with the UB Hand IV," *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, September 2011

Thanks for your attention!