



Grasping and Control of Multi-fingered Hands

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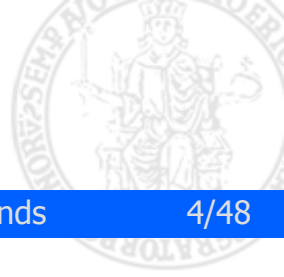


- Introduction
- Visual grasp of unknown objects
- Grasping force optimization
- Grasp control exploiting redundancy
- Grasp control using postural synergies
- Conclusion

- 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**
- Four research topics
 - Method for **fast visual grasp of unknown objects** with a multi-fingered hand, composed of object surface reconstruction algorithm and local grasp planner
 - 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
 - Taking advantage of anthropomorphism to control the robotic hand in a space of reduced dimension based on **human hand synergies**



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- **Visual grasp of unknown objects**
- Grasping force optimization
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- Visual grasp of unknown objects

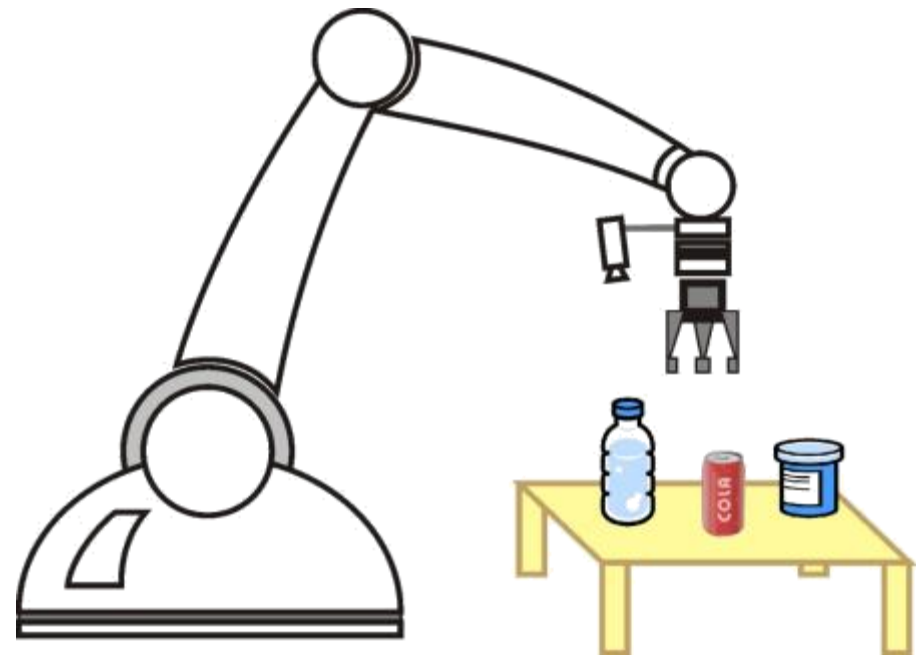
- An **object model reconstruction algorithm** is required
- Main required characteristics:
 - The algorithm must be **fast**
 - High accuracy is not required

and ...

- The reconstruction process should be suitable for **grasping**



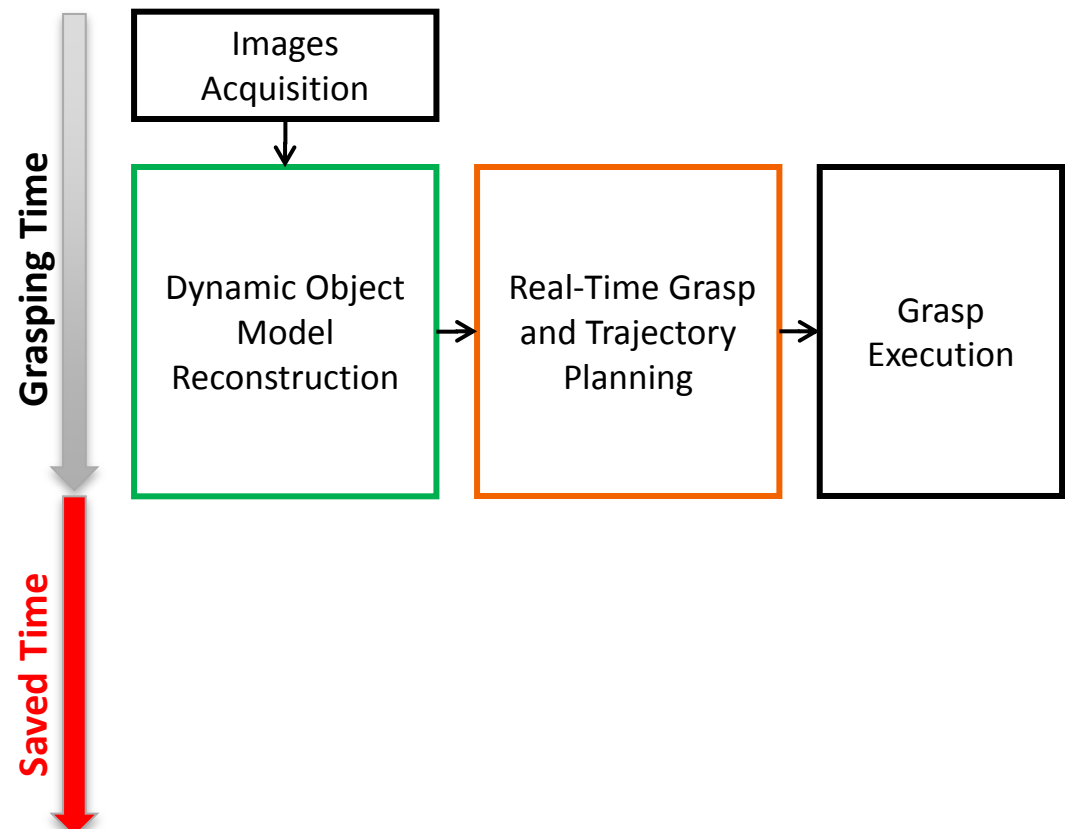
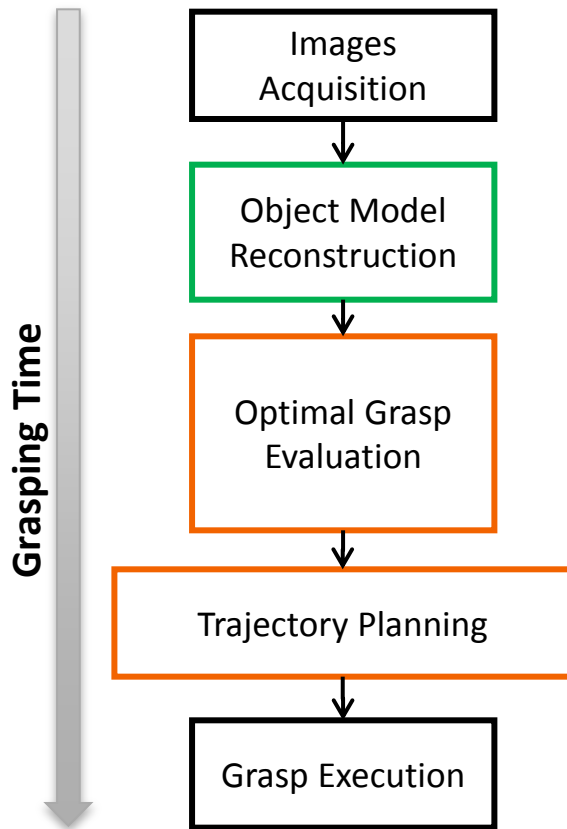
it becomes an **active component** of the grasp process



- Visual grasp of unknown objects

classical **serial** approach

proposed **parallel** approach





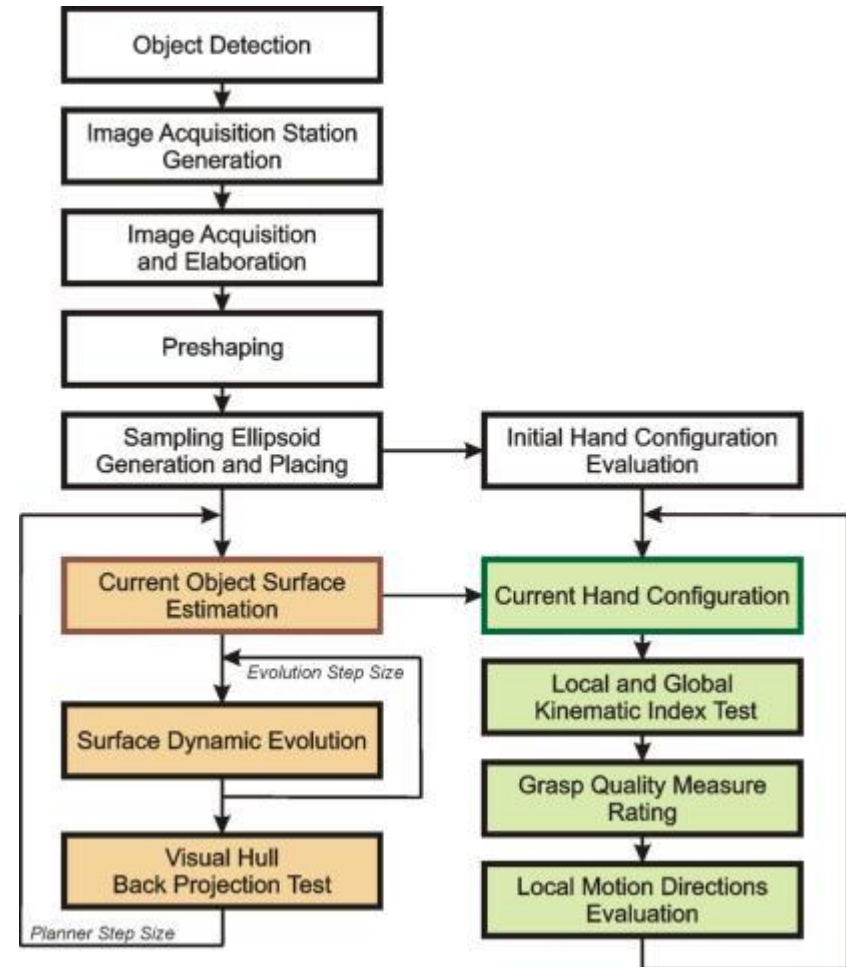
■ Assumptions

- An **eye-in-hand camera configuration** is considered
- **Multi-fingered hand**
- The observed object is
 - a **rigid body fixed** in the space
 - from a **topology** point of view, an **orientable** surface with **genus 0**
 - **distinguishable** with respect to the background and other objects

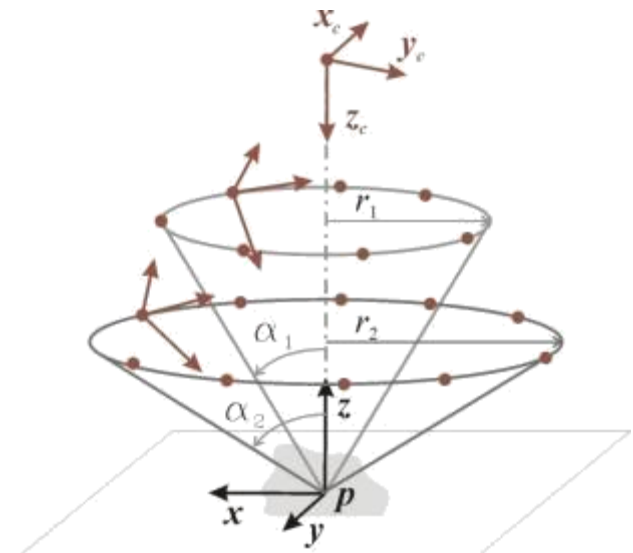
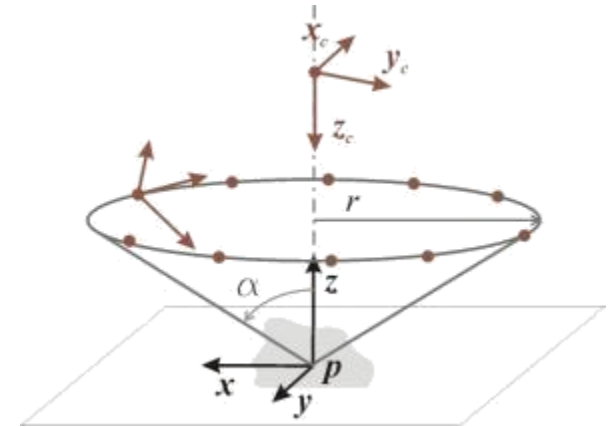
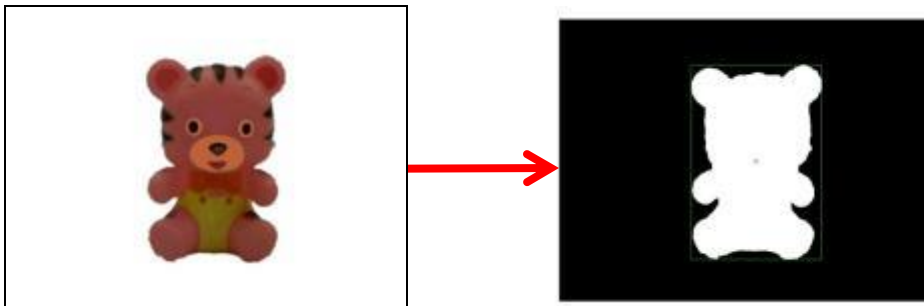
■ Goals

- Grasp a 3D unknown object while reconstructing **at the same time** its surface
 - The reconstruction of the object is a secondary outcome of the proposed method
 - The fingers move on the current (virtual) reconstructed surface towards **local minima** according to suitable grasp quality measures
 - A safety distance is held resulting in a **floating** effect around the object

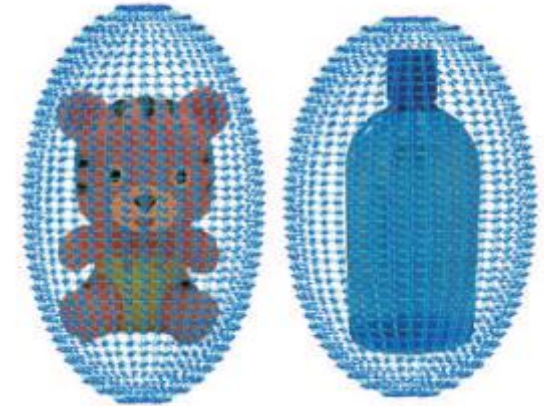
- Data flow
 - Some preparation steps
 - Object surface reconstruction
 - Local grasp planner
- The reconstruction algorithm updates in real-time the estimation of the current reconstructed object surface
- The local planner, on the basis of the current surface estimation, computes the fingers trajectories toward the current local optimal configuration for the grasp
- Reconstruction and local planning can be run in parallel resulting in a very fast grasp method



- Image acquisition **stations**
 - One, two or more **circular trajectories** at a constant distance from the object with different view angles
 - n acquired images
- Object **silhouettes** extraction
 - Elaborations to enhance the quality of silhouettes



- **Preshaping** algorithm
 - The aim is to find the **minimum ellipsoid** which surrounds the object
 - For each image, the four planes of the Cartesian space containing the origin of the camera frame and two adjacent vertices of the corresponding silhouette bounding-box in the image plane are considered, resulting in $4n$ Cartesian planes
 - The intersections of these planes create a **polyhedron** which contains the object visual hull and whose **vertices** can be easily computed by solving a linear programming problem
 - Once the vertices have been computed, the **central moments** can be evaluated and thus the **pseudo-inertia tensor**; its **eigenvectors** and **eigenvalues** define the **principal axes of inertia of the ellipsoid** surrounding the object

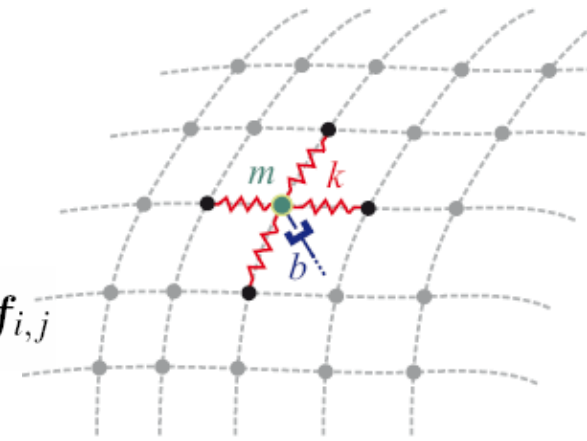


$$\mu_{i,j,k} = \sum_{\mathbf{x}_v \in \mathcal{P}} (x_{v_x} - \bar{x}_{v_x})^i (x_{v_y} - \bar{x}_{v_y})^j (x_{v_z} - \bar{x}_{v_z})^k$$

$$I = \begin{bmatrix} \mu_{2,0,0} & \mu_{1,1,0} & \mu_{1,0,1} \\ \mu_{1,1,0} & \mu_{0,2,0} & \mu_{0,1,1} \\ \mu_{1,0,1} & \mu_{0,1,1} & \mu_{0,0,2} \end{bmatrix}$$

- **Cross reticular topology** with a virtual mass associated to each ellipsoid sample point, with springs linked to closest cross points and a spatial damper

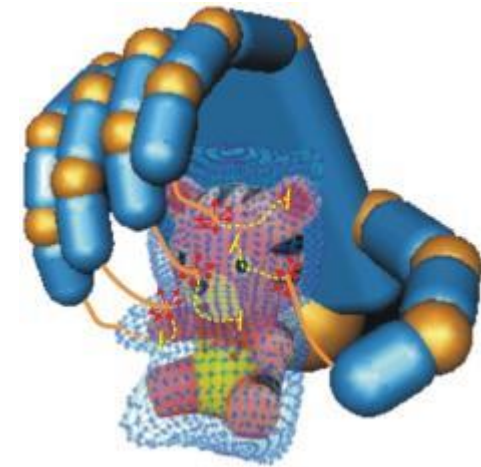
$$m\ddot{x}_{i,j} + b\dot{x}_{i,j} + k(4x_{i,j} - x_{i-1,j} - x_{i,j+1} - x_{i+1,j} - x_{i,j-1}) = f_{i,j}$$



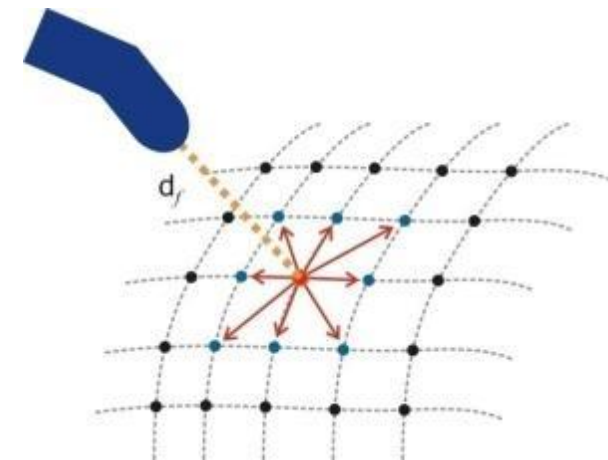
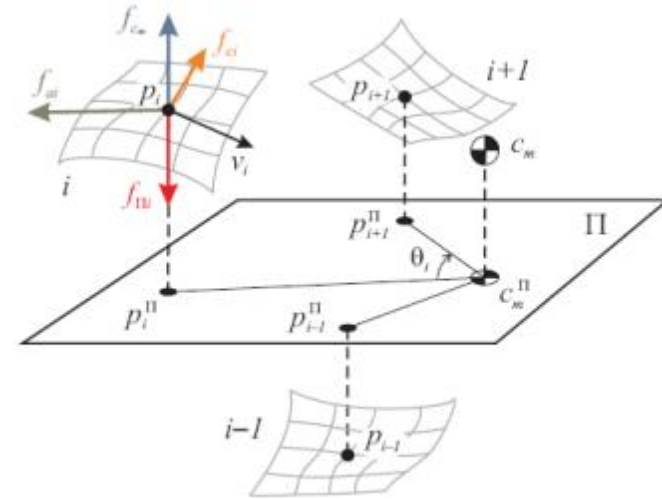
- The equilibrium is achieved when **the elastic forces generated by the grid and the attractive forces generated by the visual hull become equal**
- The **accuracy** of the reconstruction process depends
 - on the number of views
 - on the distribution of the acquisition stations
 - on the density of the reconstruction sphere



- The **local grasp planner** generates the fingertips trajectories on the **current reconstructed surface** (keeping a **fixed floating safety distance**)
 - Starting from the current grasp configuration, the planner generates the motion of the fingertips from the current position to a new set of points of the update surface
 - At each contact point of the current grasp configuration is associated a suitable **field of forces**, which is used to generate the motion of the fingertips
 - The process is repeated in a **recursive** manner, until improvements of the quality measure are obtained
 - The planner ends its job when the object reconstruction algorithm reaches an equilibrium; then, the planner computes the final grasp configuration and the floating distance is **progressively reduced** to achieve the desired grasp action
- For fine manipulation the **initial grasp configuration** is chosen as an **equilateral grasp in a plane parallel to the two minor axes of the ellipsoid**



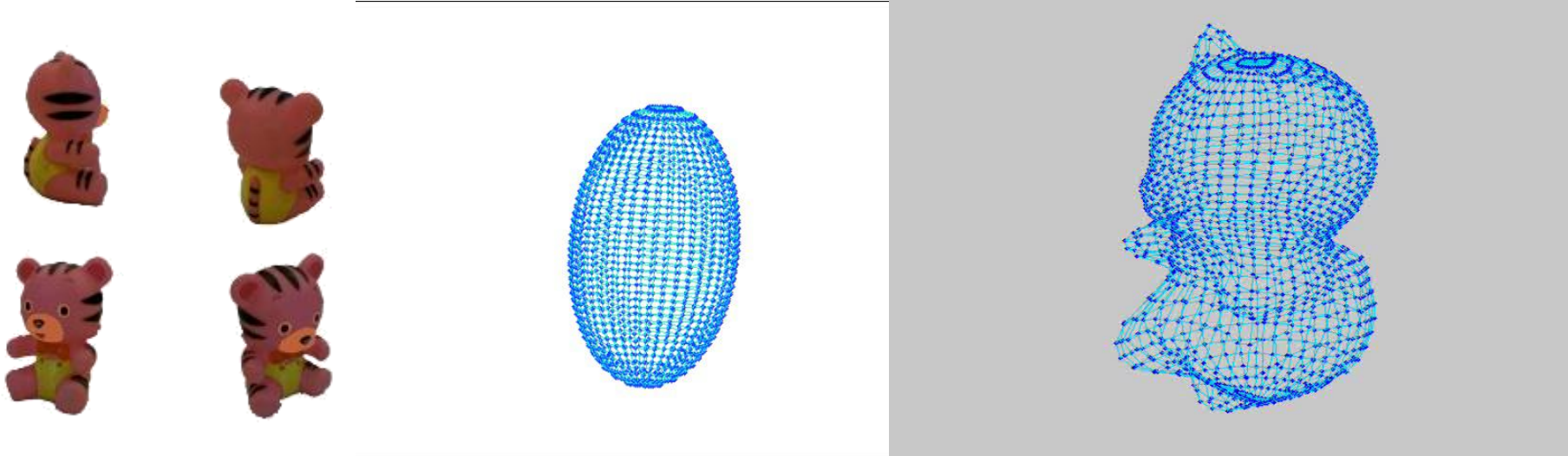
- Planar grasps in 3D space where the contact points lie in the same grasp plane
- At each current contact point, a field of forces is computed as a sum of suitable contributions:
 - Aligning the contact points in the same grasp plane
 - Attracting the grasp plane towards the center of mass of the current reconstruction surface
 - Attaining an equilateral grasp configuration
 - Enlarging the area of the grasp polygon
 - Avoiding joint limits overcoming kinematic singularities and finger collisions
- This field is projected onto the tangential plane to the current reconstruction surface at the current contact point





- The **local grasp planner** produces a sequence of **intermediate target grasp configurations** at each iteration of the object reconstruction algorithm
 - The intermediate configurations are used to generate the **fingers paths**
- The sequence of intermediate configurations can be suitably **filtered by a spatial low-pass filter** in order to achieve a **smooth path** for the fingers on the object surface
 - Only the **final configuration** has to be reached exactly, while the intermediate configurations can be considered as **"via points"**
- A **fixed floating distance** is held during the motion and is **progressively reduced** at the end of the reconstruction process to produce the final grasp action

- Performance of the reconstruction algorithm
 - Object: **teddy bear** (12 images with $\alpha=80^\circ$, 6 images with $\alpha=50^\circ$, 1 image from the top)

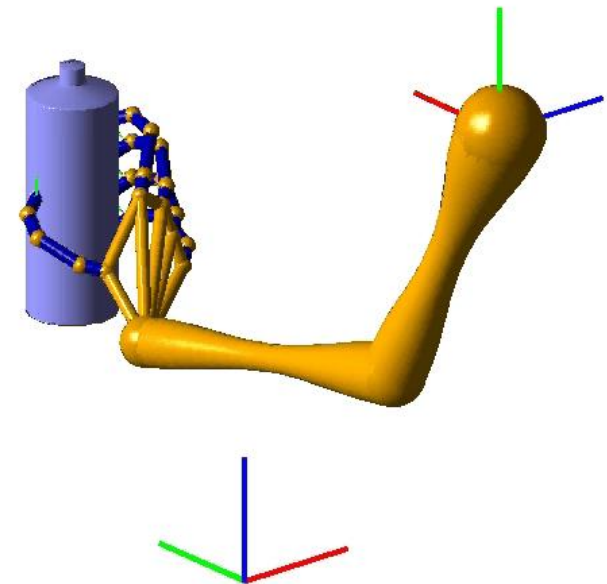
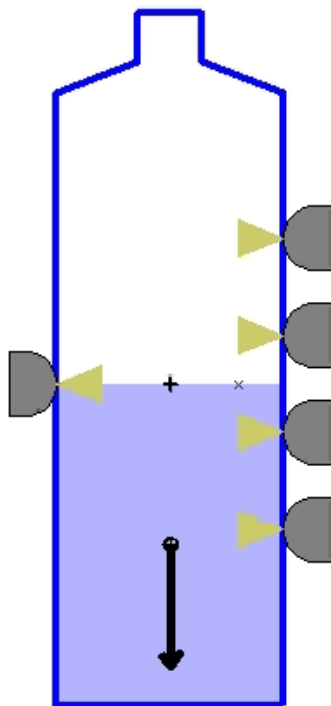


- Dynamic parameters
 - $M = 10^{-3} \text{ kg}$, $k = 0.3 \cdot 10^{-3} \text{ N/m}$, $b = 0.09 \cdot 10^{-3} \text{ Ns/m}$, and $F_a = 5 \text{ N}$



- Visual grasp of unknown objects
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- 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**





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 dimensions**
 - **Dynamic selection** of joint-torque constraints

- Grasp equilibrium equation $h_e = Gc$

- Friction constraints

$$F(c) = \text{diag}(F_1(c_1), \dots, F_n(c_n)) > 0 \quad \begin{cases} \text{point contact with friction} \\ \text{soft finger contact} \end{cases}$$

- Residual joint torques at equilibrium

$$\tau_B = \begin{bmatrix} \tau_{B,L} \\ \tau_{B,H} \end{bmatrix} = \begin{bmatrix} J^T(q)c - \tau_L + \tau_e \\ -J^T(q)c + \tau_H - \tau_e \end{bmatrix}$$

- Joint torque limits constraints $T(c, q, \tau_e) = \text{diag}(\tau_B) > 0$

- Compact formulation

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

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

$$A\xi(P) = b \quad \xi(P) = [c(F)^T, \tau_B(T)^T]^T$$

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

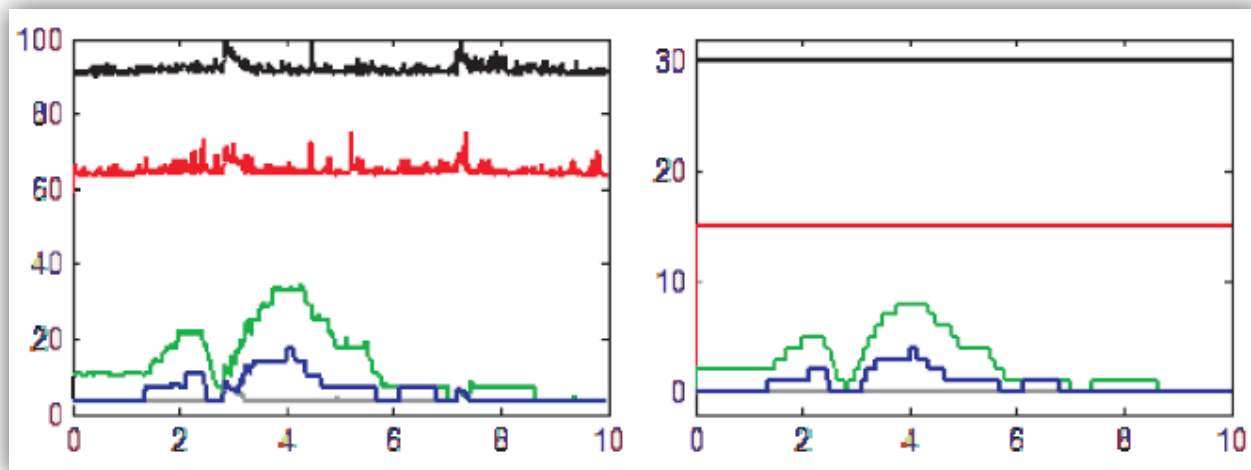
$$\Phi(\mathbf{P}) = \text{tr}(\mathbf{W}_p \mathbf{P} + \mathbf{W}_b \mathbf{P}^{-1})$$

- 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**

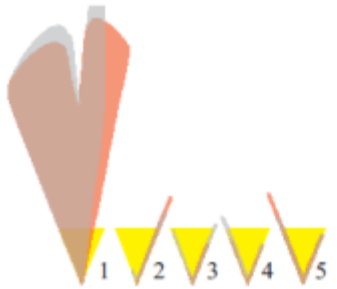
$$\xi(\dot{\mathbf{P}}) = \mathbf{Q} \xi(\mathbf{P}^{-1} \mathbf{W}_b \mathbf{P}^{-1} - \mathbf{W}_p) \quad \mathbf{Q} = (\mathbf{I} - \mathbf{A}^\dagger \mathbf{A})$$

- 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

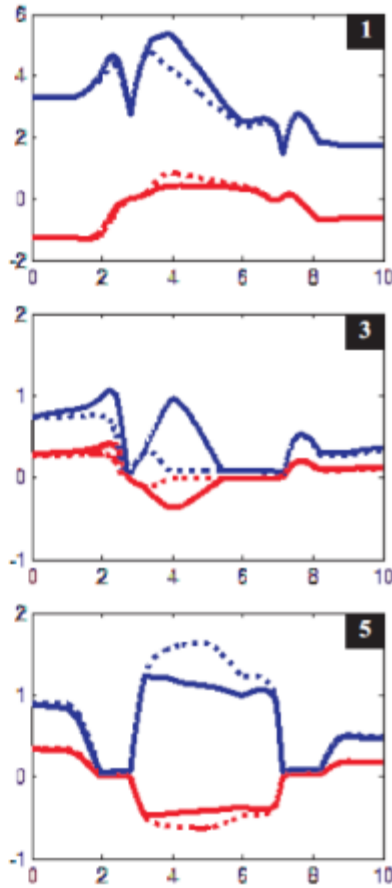
normalized computation time # of active joint constraints



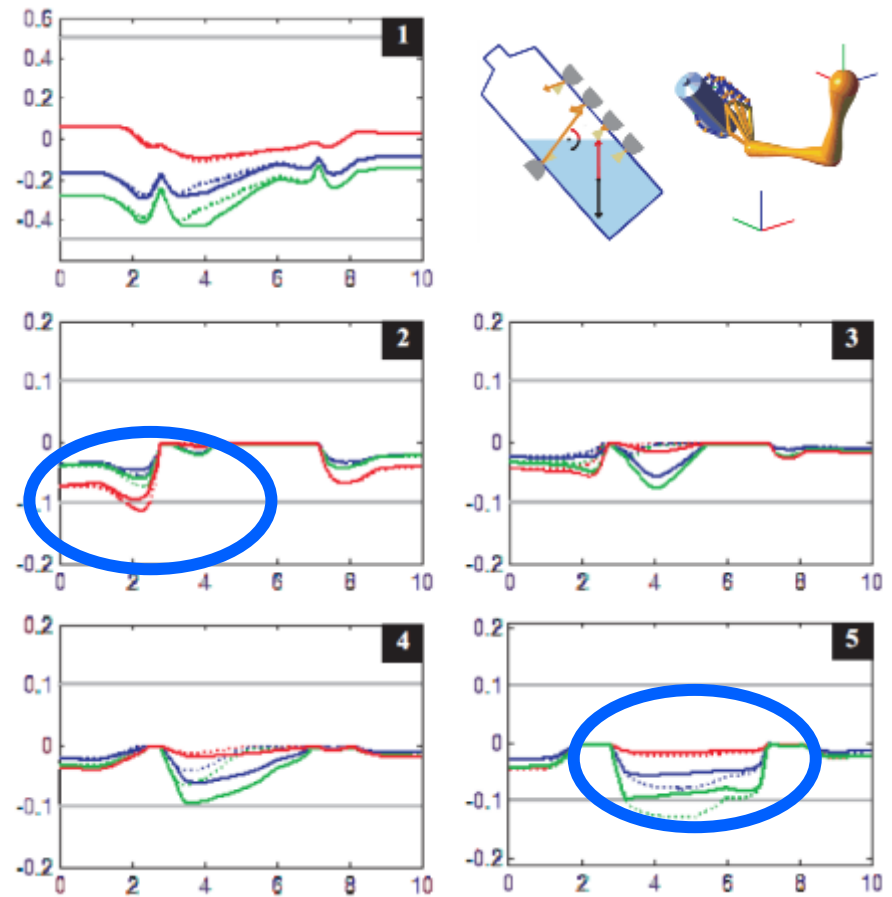
frictional cones



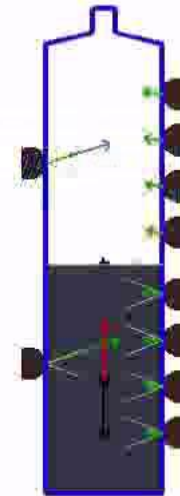
contact forces



joint torque limits

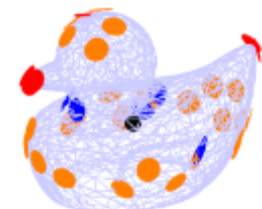
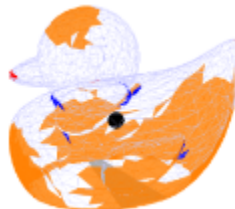
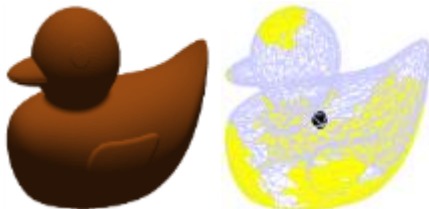
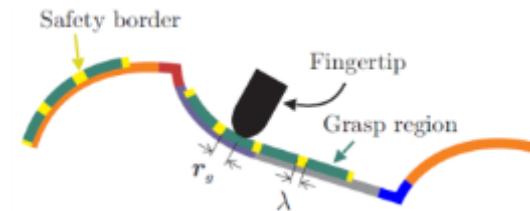
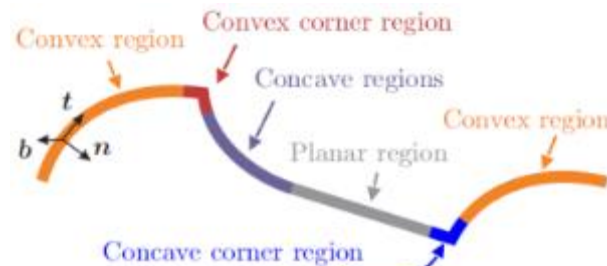
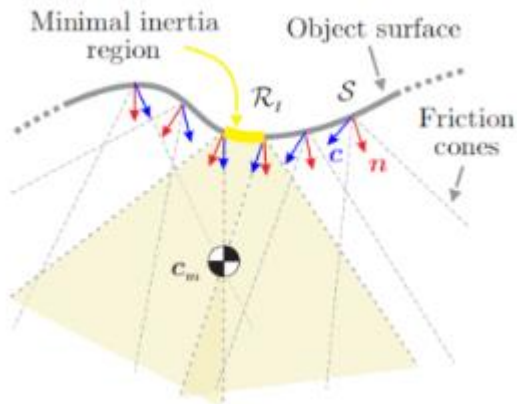


load sharing



Function of Active Joint Control

- Synthesis of optimal n-fingered grasp configuration for 3D complex objects
 - Minimization of gravitational and inertial effects considered
 - Reduced computational complexity by adopting innovative discretization algorithm of the object surface driven by significant grasp indices:
 - A prioritized synthesis approach applied to rank the grasp configurations

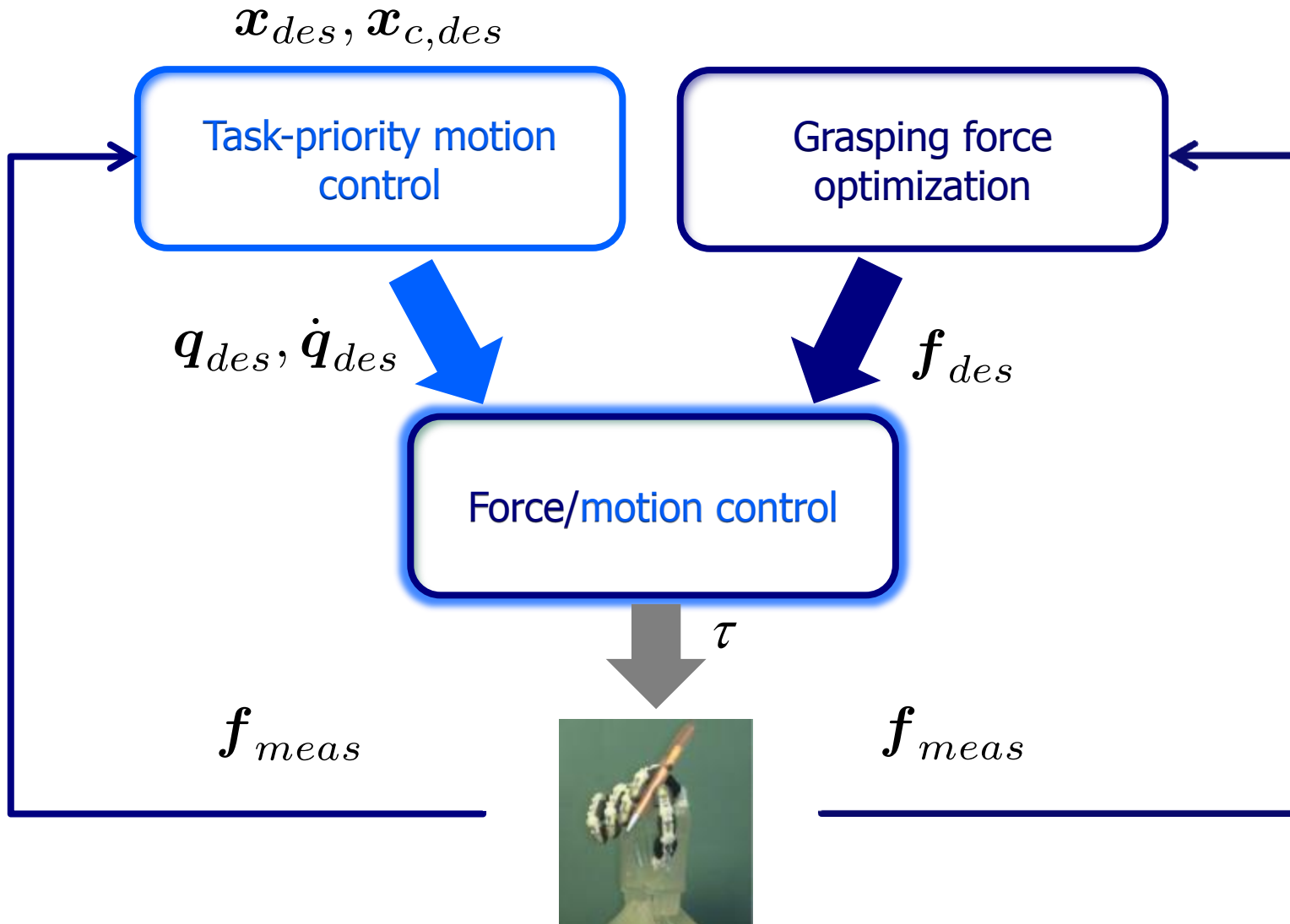




- Visual grasp of unknown objects
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- **Grasp control exploiting redundancy**
- Grasp control using postural synergies



- 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



- The **augmented projection method** allows fulfilling multiple tasks with desired hierarchy

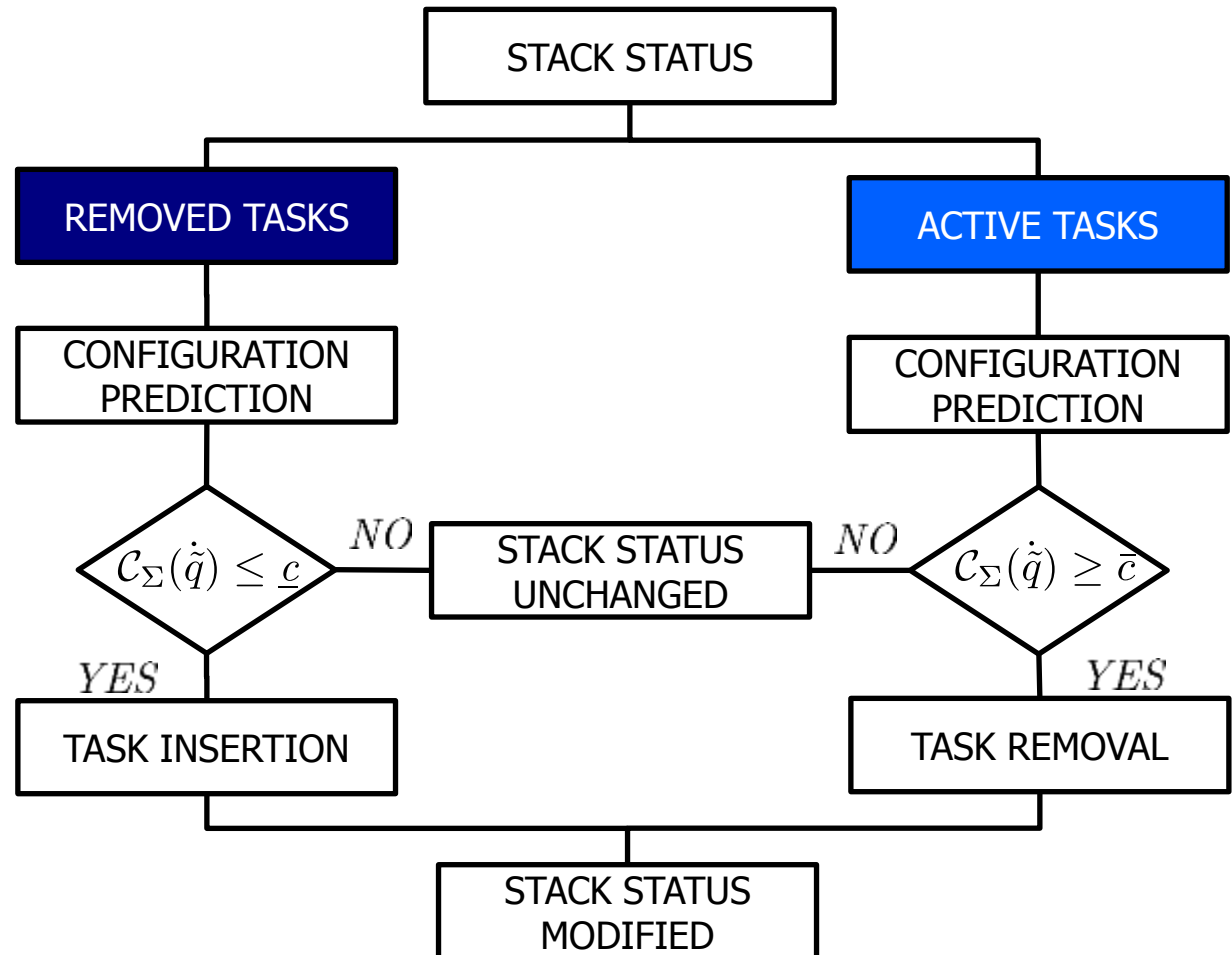
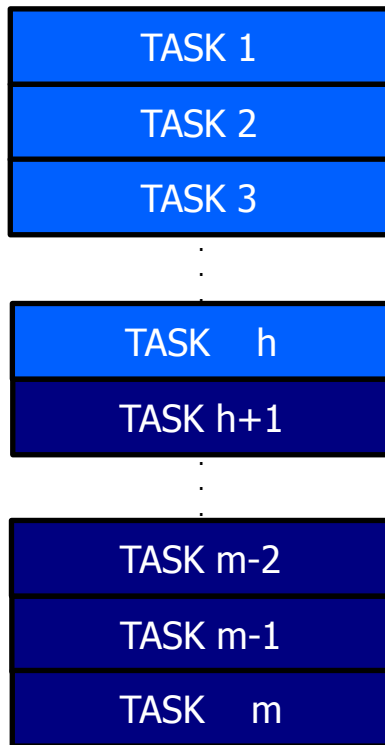
$$\dot{\tilde{q}} = \tilde{J}^\dagger(\tilde{q}, \Delta l_d) G^T (\tilde{v}_{o_d} + K_o \tilde{e}_o) \quad \text{primary task}$$

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

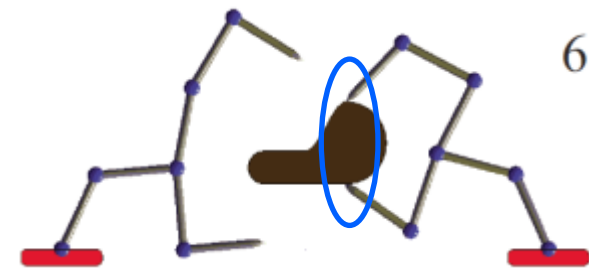
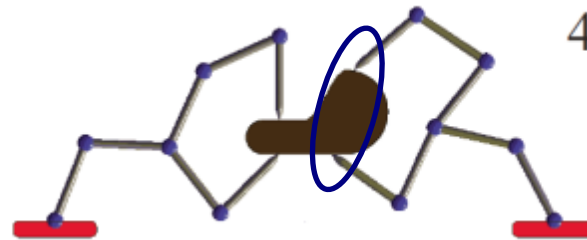
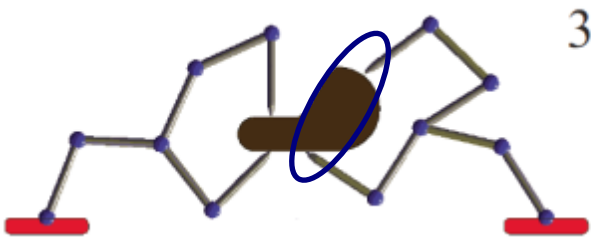
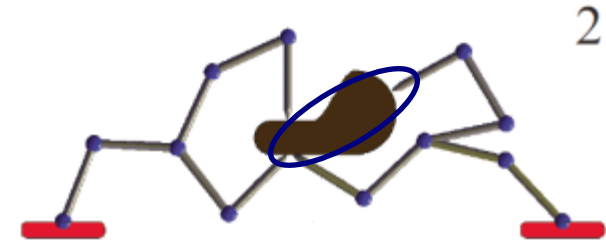
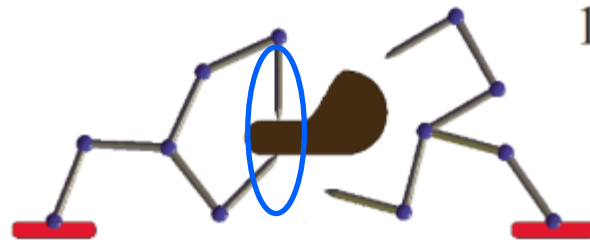
$$- k \nabla N(J_{t_{m+1}}^A) \nabla_{\tilde{q}}^T C_\Sigma \quad \text{constraints}$$

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

- Task sequencing with smooth transitions



exchanging an object between left and right hand using thumb and index



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

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

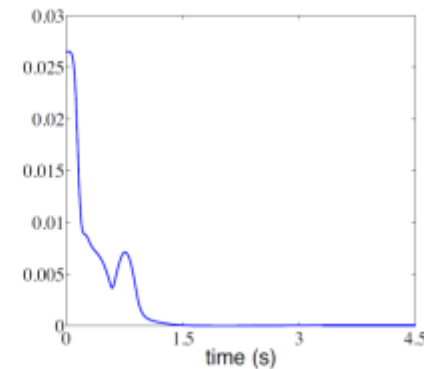
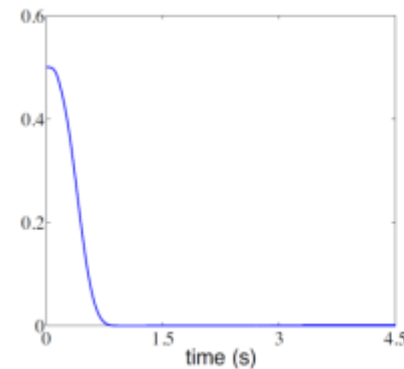
$$\varepsilon_m = \frac{1}{2} \mathbf{m}^T \mathbf{m}, \quad \mathbf{m} = \sum_{i=1}^4 \mathbf{c}_i^o \times \hat{\mathbf{n}}_i^o$$

- Manipulability

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

- Distance of object from palms ...
- Constraints
 - Joint limits
 - Collisions avoidance

force and moment residuals



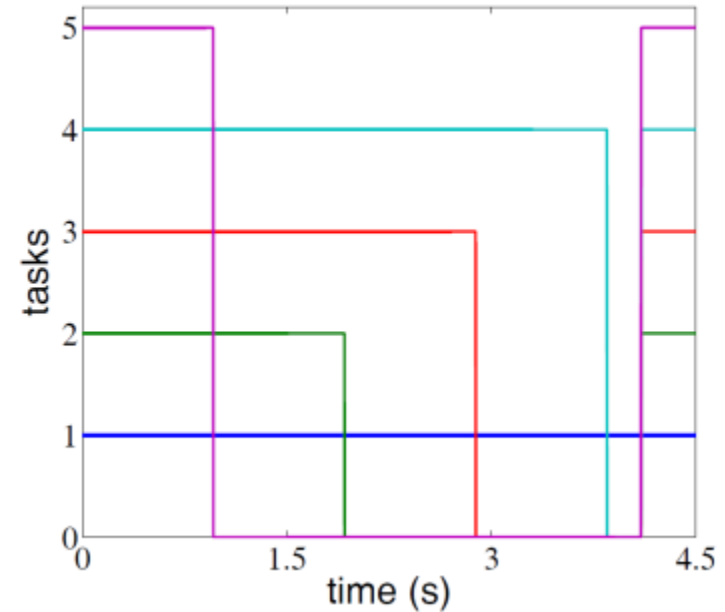
Kinematic Control with Force Feedback for a Redundant Bimanual Robotic System with Elastic Contact

F. Caccavale, V. Lippiello, G. Muscio, F. Pierri, F. Ruggiero, L. Villani

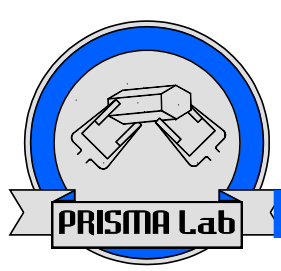
PRISMA Lab
www.prisma.unina.it

March 2011

active tasks



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



- Visual grasp of unknown objects
- Grasping force optimization
- Grasp control exploiting redundancy
- **Grasp control using postural synergies**

- The mechanical structure

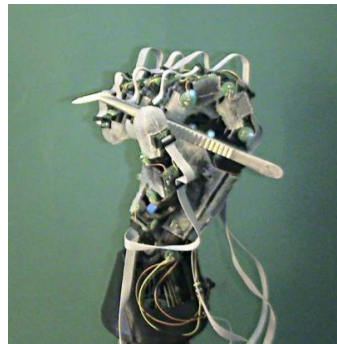
- Remotely located actuators with tendon-based transmissions routed through fixed paths (**sliding tendons**), N+1 tendon configuration
- Surface compliance is introduced through a purposely designed soft cover

- The kinematic structure

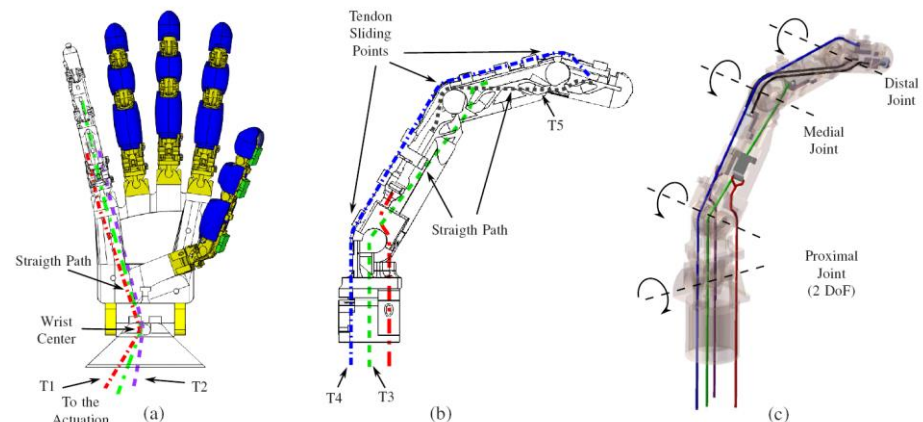
- The DEXMART Hand presents a total amount of **20 DOFs**, **the medial and the distal joints are coupled** by means of an internal tendon
- **Thumb with different kinematics** and joint limits w.r.t. the other fingers, human-like manipulation capabilities and mobility (opposition with the other four fingers)



UB Hand IV




DEXMART Hand



- 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](#))

$$\hat{E} = [e_1 \quad e_2 \quad e_3]$$

- The three first eigenpostures account for [>85% of hand postures](#)

POWER	PALM	  
	PAD	
INTERMEDIATE	SIDE	
PRECISION	PAD	 
	SIDE	
CONFIG. WITHOUT OBJECTS		

- Hand configuration for the i -th grasp computed as

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

First
Postural Synergy

Second
Postural Synergy

Third
Postural Synergy

the third synergy is mainly useful for precision grasps and intermediate side grasps

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

zero offset

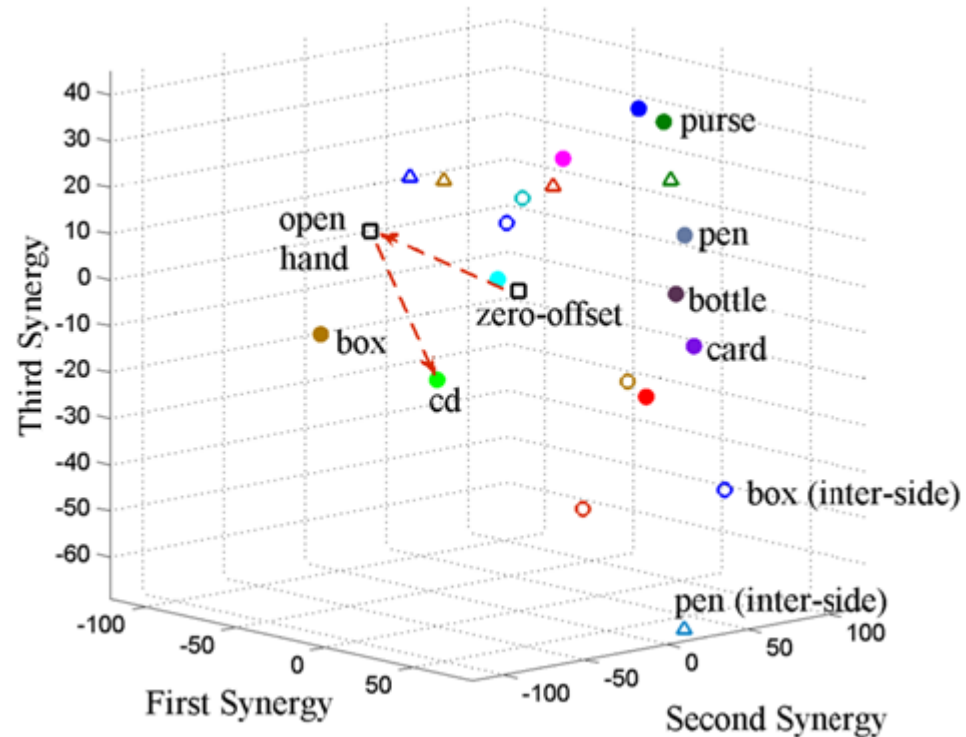
$$\bar{c}_h \implies \alpha = 0$$

open hand

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

desired grasp

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





Grasps Synthesis (by Postural Synergies Subspace Projection)



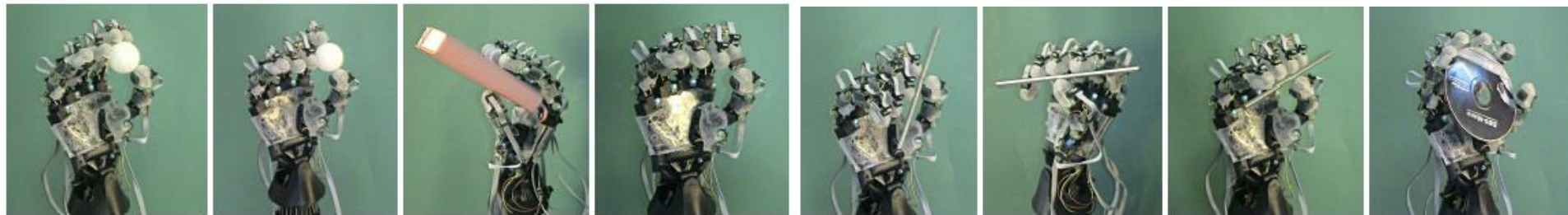
power



intermediate side



precision



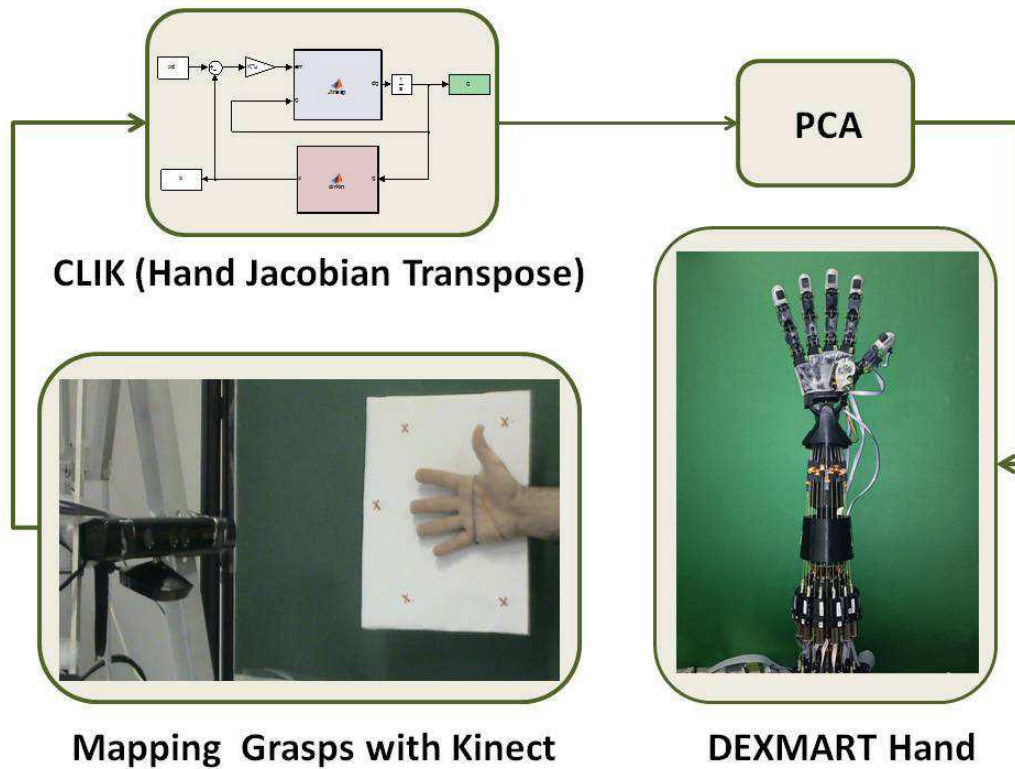
Power grasps

Intermediate side grasps

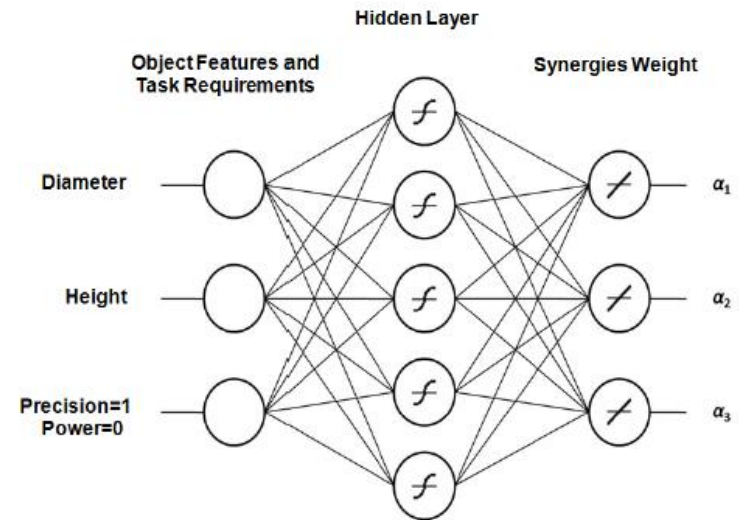
Precision grasps



kinematics suitably scaled on the basis of the human hand dimension



Neural Network for autonomous grasping



- Four steps forward toward **grasping and control of multi-fingered robotic hands**
 - Fast visual grasp of unknown objects
 - Online grasping force optimization
 - Grasp control exploiting redundancy
 - Grasp control based on synergies





- F. Caccavale, V. Lippiello, G. Muscio, F. Pierri, 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*, San Francisco, CA, pp. 4194–4200, Sep. 2011
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■ Robotic Dynamic Manipulation

- ERC Advanced Grant (AdG)
- 2.5 M€ for five years started June 2013
- Only “robotics” proposal among the 302 selected in Physical Sciences and Engineering in the 2012 call out of a total of 2304 proposals



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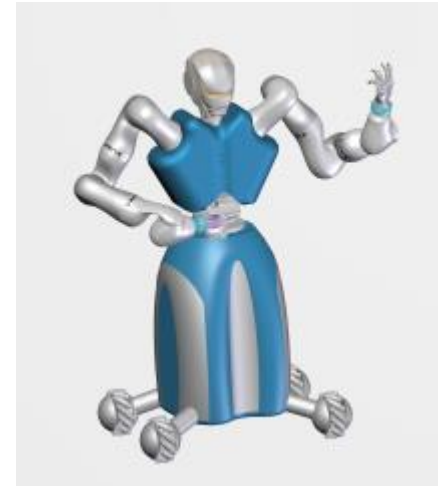
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■ Goal

- Derivation of a unified framework for dynamic manipulation where the mobile nature of the robotic system and the **manipulation of non-prehensile non-rigid or deformable objects** will explicitly be taken into account

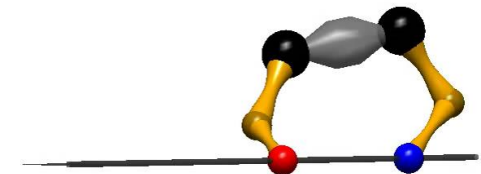
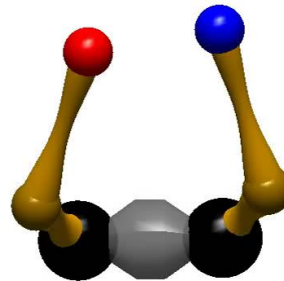
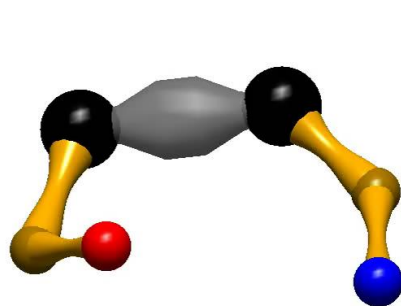
■ Achievements

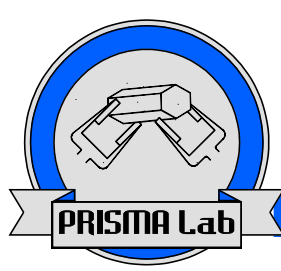
- Novel techniques for 3D object perception, dynamic manipulation control and reactive planning will be proposed
- **Innovative mobile platform** with a torso, two lightweight arms with multi-fingered hands, and a sensorized head will be developed for effective execution of complex manipulation tasks, also in the presence of humans



■ Validation

- Dynamic manipulation will be tested on an **advanced demonstrator**, i.e. **pizza making process**, which is currently unfeasible with the prototypes available in the labs, where the application scenario is conceived to emulate the human ability to carry out a challenging robotic task



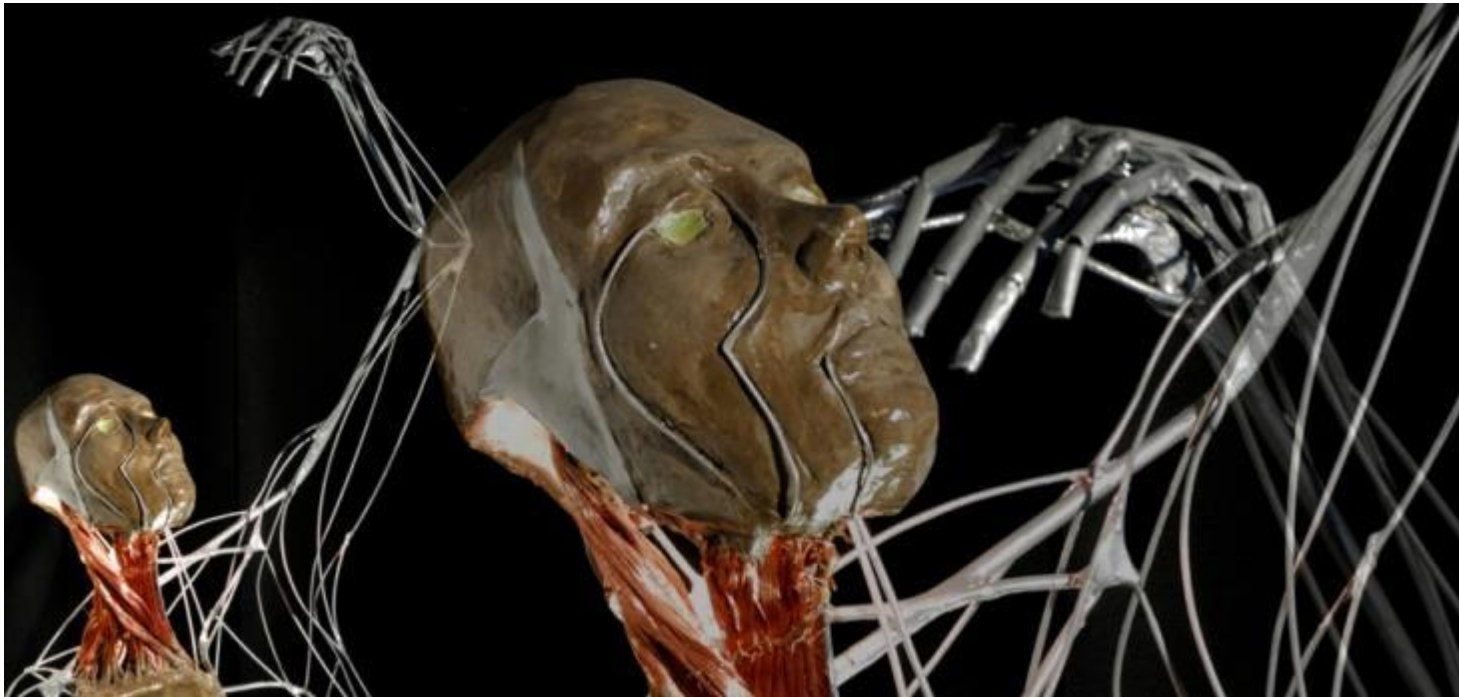


■ Schedule

- **November 2014** – Robot prototype is available
- **May 2016** – The first step of the pizza maker demonstrator is executed: the built robot prototype turns the pizza peel considering the dough as a rigid object
- **May 2017** – The next step of the pizza maker demonstrator is executed: now the dough is considered as a non-rigid object and some stretching actions are shown
- **May 2018** – The full demonstrator is at work

■ Ambition

- This platform will be able to perform **dynamic manipulation tasks**, thus becoming a **reference platform in the field of mobile manipulation for the next years**



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