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Nonprehensile Manipulation of Deformable Objects: Achievements and Perspectives from the RoDyMan Project

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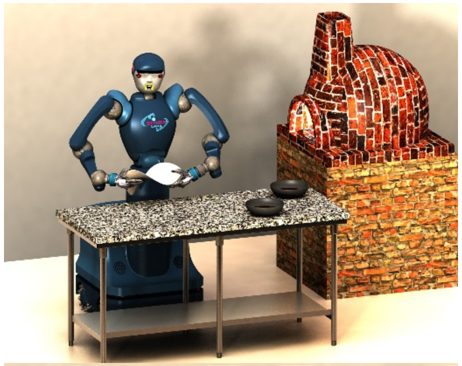
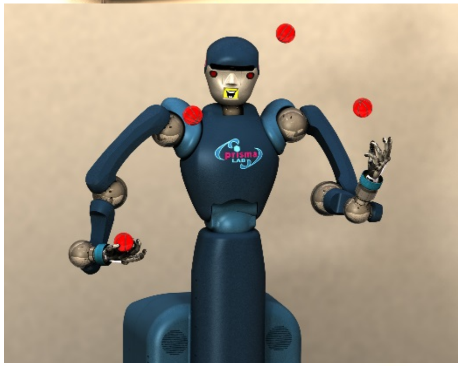
The RoDyMan Project

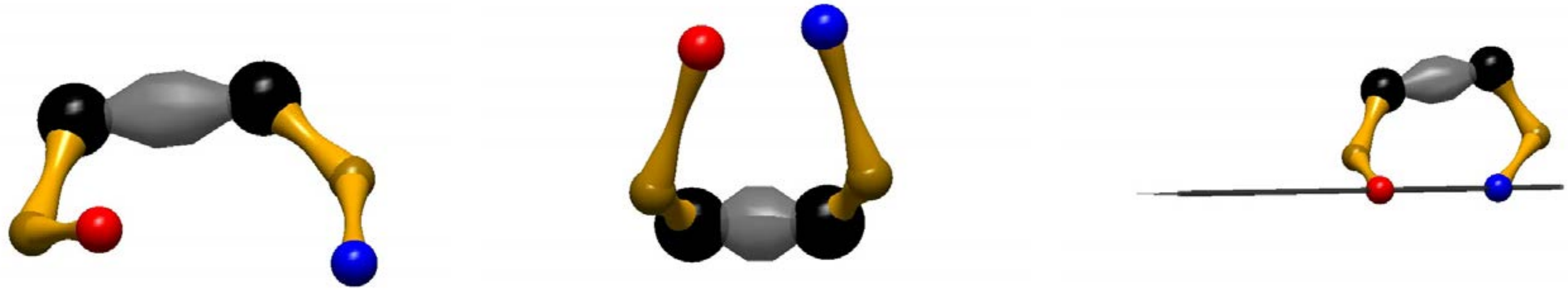
- Goal
  - Derivation of a unified framework for dynamic manipulation where the mobile nature of the robotic system and the manipulation of nonprehensile non-rigid or deformable objects are explicitly taken into account
- Achievements
  - Novel techniques for 3D object perception, dynamic manipulation control and reactive planning
  - Innovative mobile platform with a torso, two lightweight arms with multi-fingered hands, and a sensorized head for effective execution of complex manipulation tasks, also in the presence of humans
- Team
  - 16 researchers engaged, including Post-docs and Ph.D. students from 4 different continents



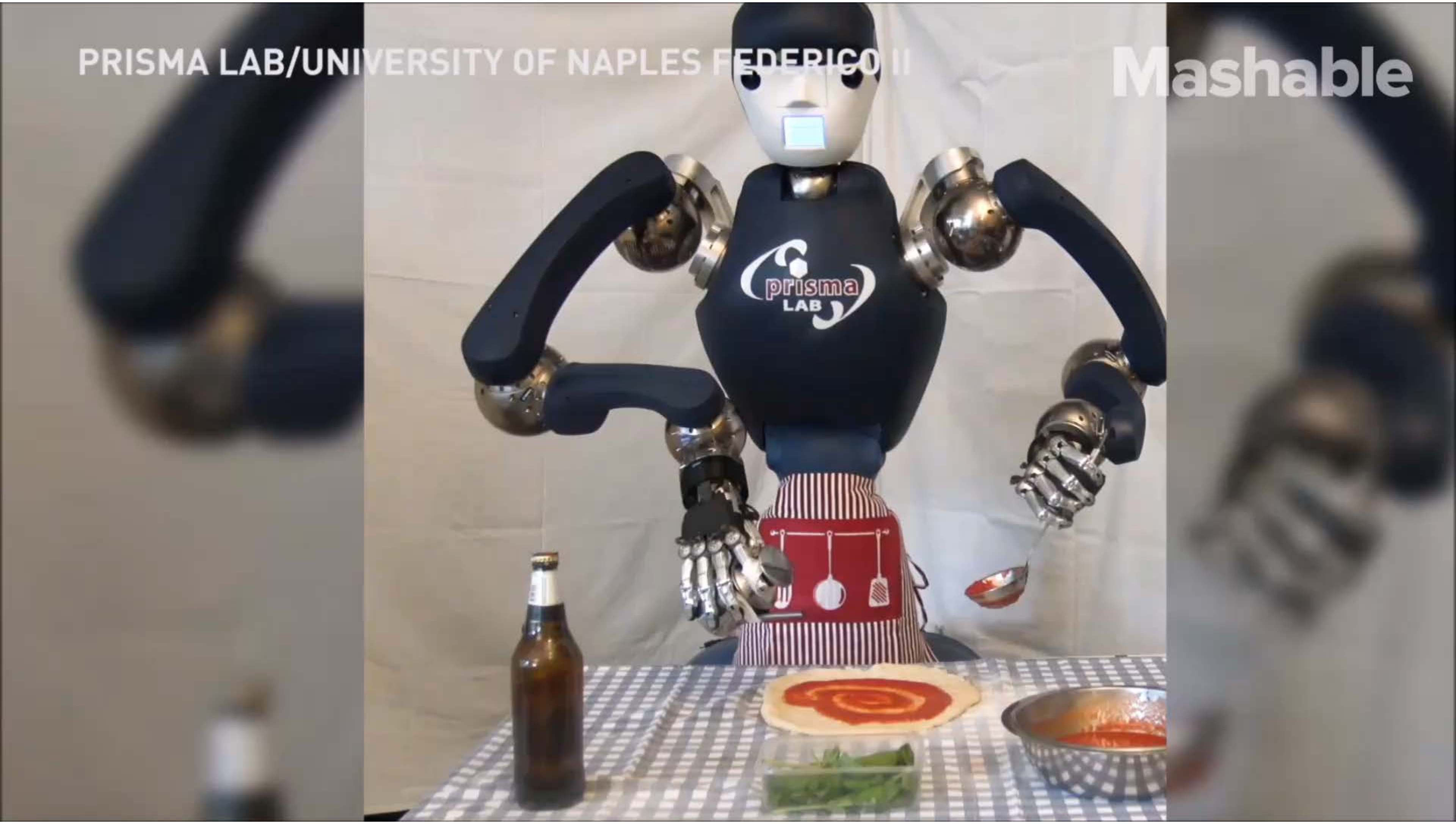


A Challenging Benchmark

- Validation
  - Dynamic manipulation is 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

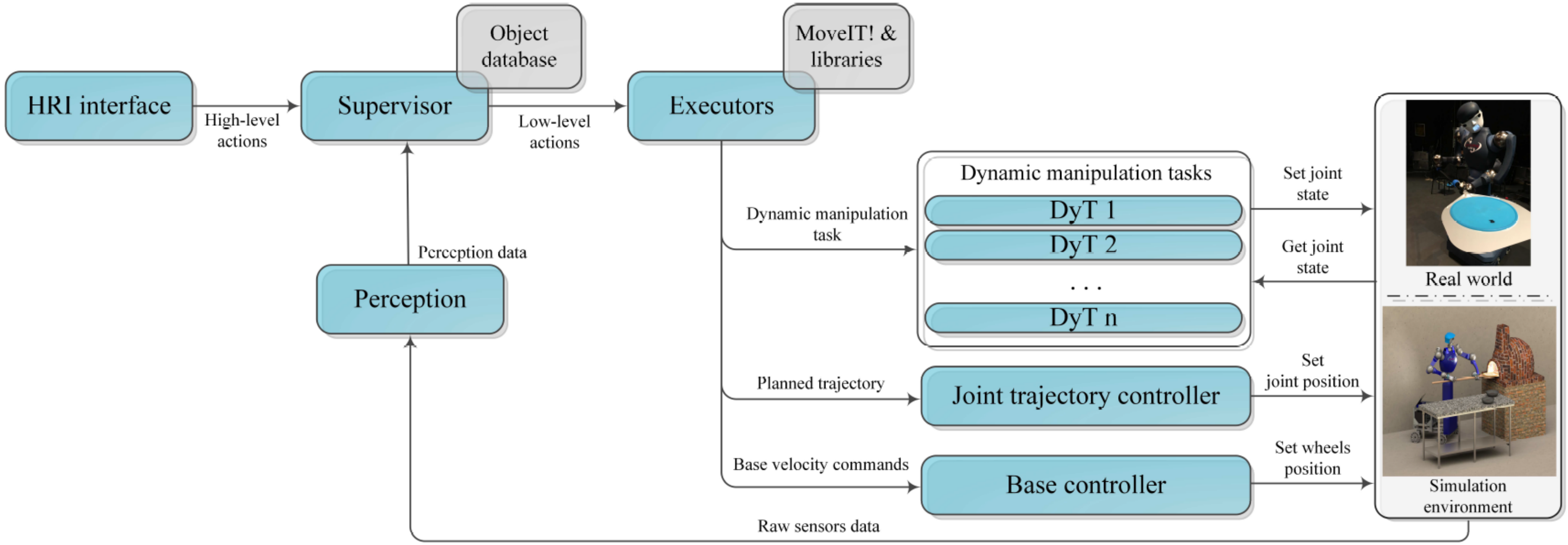


Learning from Observation



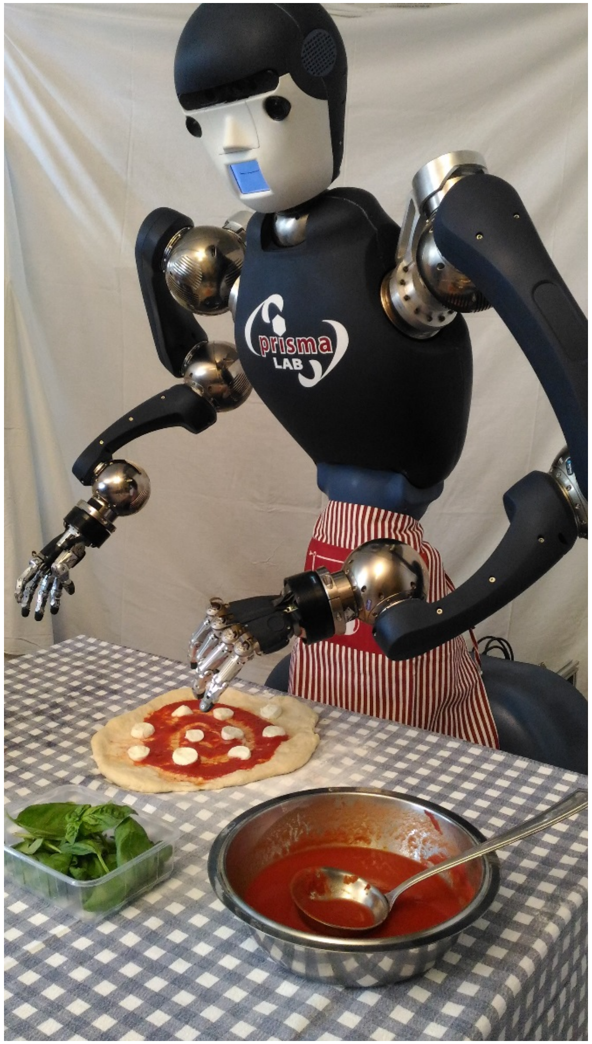
Control Architecture

- Two arms and additional servos controlled by a single control unit
  - PC-based solution, compact and modular
- Hard real time at 2ms
  - Torque control
- Easy integration of external sensors and arms



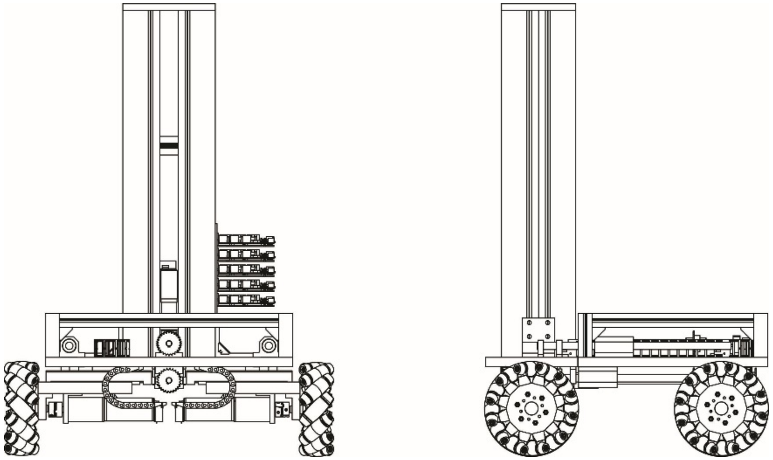
Mechatronic Design

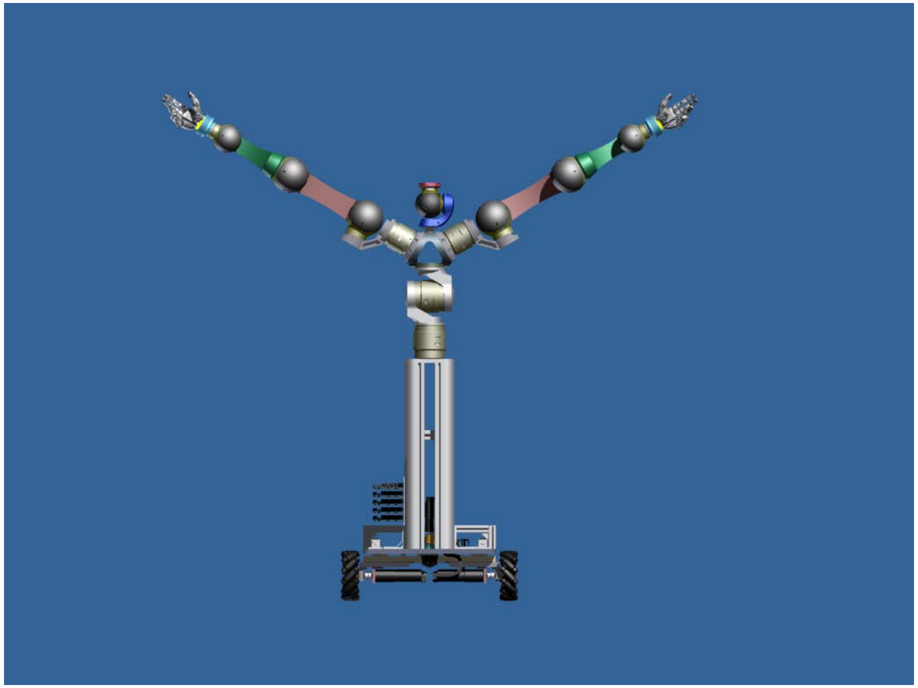
- Two SCHUNK PowerBall Arms LWA 4P
  - One extra DoF added to the arm base
  - Links equipped with torque sensors
  - CANopen protocol replaced with EtherCAT
- Two SCHUNK hands and force/torque sensors
  - Right + Left Hand mounted on the most distal joints
  - Force/Torque sensor based on strain gauge
- Neck
  - Pan-tilt robotic head equipped with stereo camera and structured lighting system (full perception)
- Torso
  - 2 DoFs with torque sensors (active role in dynamic manipulation tasks)



Mechatronic Design

- Extendable omnidirectional mobile platform
  - Leg expansion mechanism in order to increase robot stability during dynamic movement of torso
  - Mecanum wheels
  - One actuator per each wheel
  - Standard MISUMI parts in the design





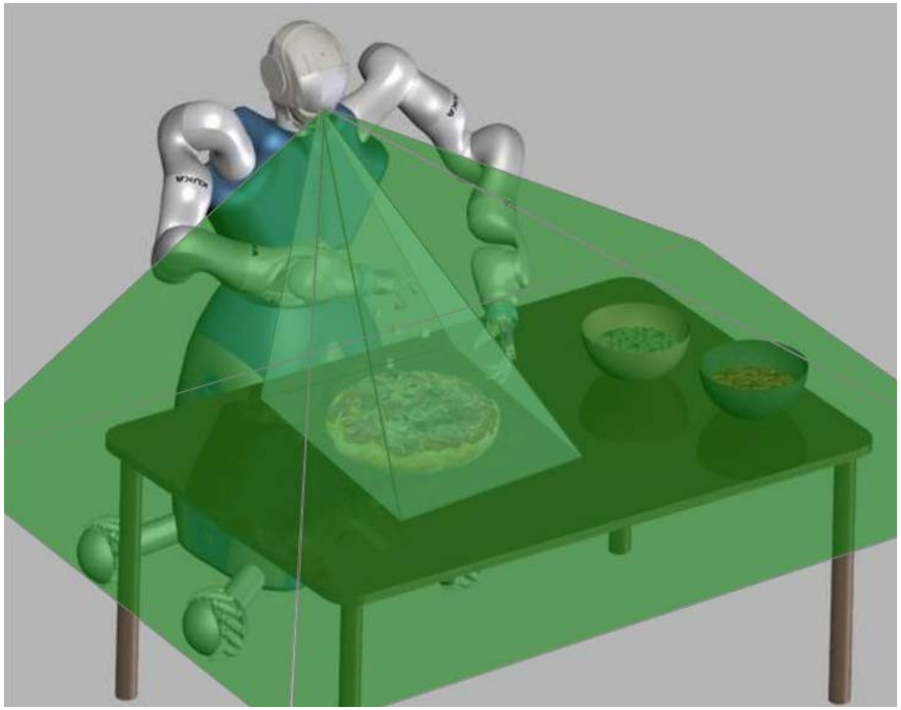
Prototype Platform

Nonprehensile Manipulation

- Nonprehensile manipulation allows
  - Manipulating objects that are either too heavy or too large to be grasped
  - Manipulating more objects at the same time
  - Enlarging robot workspace
- Nonprehensile manipulation is subject only to unilateral constraints
  - More difficult to model due to dynamics of both the object and the end-effector
  - Objects changing shape as they move
  - Kinematics and (quasi-)static forces play a crucial role
  - Complex planning
  - Controllability issues arise due to under-actuation of most nonprehensile manipulation tasks

Perception

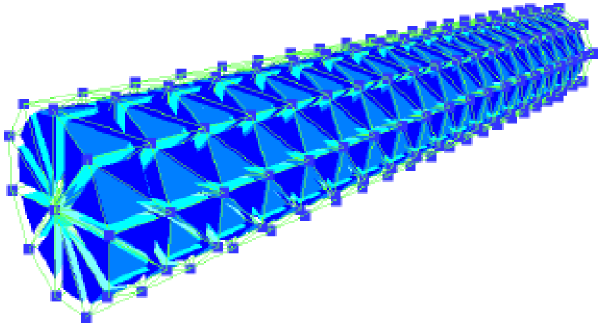
- Dynamic manipulation of deformable objects
  - Perception is a main challenge
  - Use of passive (monocular, stereo cameras) or active (laser scanners, ToF cameras, …) vision sensors
    - Real-time deformable object tracking (e.g. the pizza dough)
    - Environment awareness
      - Localize other objects, robots, people
      - Obstacle avoidance, path planning



Real-time Deformable Object Tracking

- Challenges
  - Large deformations, plastic deformations
  - Textureless object
  - Occlusions and fractures
  - Real-time
- RGB-D sensor (active depth sensor)
- Modelling
  - Physics-based model
    - Finite Element Method
- Tracking
  - Prior segmentation of the object
  - Rigid and non-rigid Iterative Closest Point (ICP) algorithms

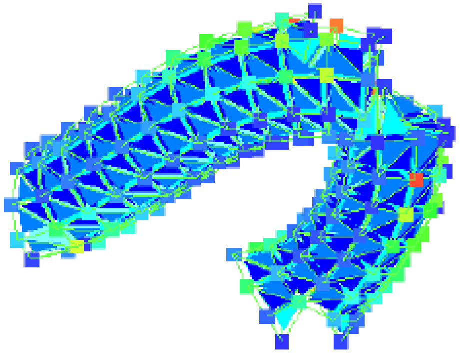
- Finite Element Method (FEM)
  - Based on continuous mechanics
  - Approximation over elements (tetrahedrons) of a mesh representing the object



  - W.r.t. other models (parametric, mass-spring systems), able to model various sorts of deformations (highly elastic, viscous, plastic), better propagation of deformations (volumetric effects)
  - Computationally challenging

Linear Co-rotational Approach

- Model of elastic deformations: Infinitesimal strain theory and Hooke's law
  - Linear relation between displacement of the tetrahedral elements of the mesh and internal forces exerted on their nodes
- Co-rotational approach as a good compromise between ability to model large deformations of the elements and computational efficiency
- Based on FEM co-rotational model, fractures in the mesh are detected by decomposing the internal forces on the nodes into tensile and compressive forces to measure pure tensile forces acting on each node, through a so-called separation tensor
  - The fracture is propagated by simply removing attached elements intersected by the fracture plane

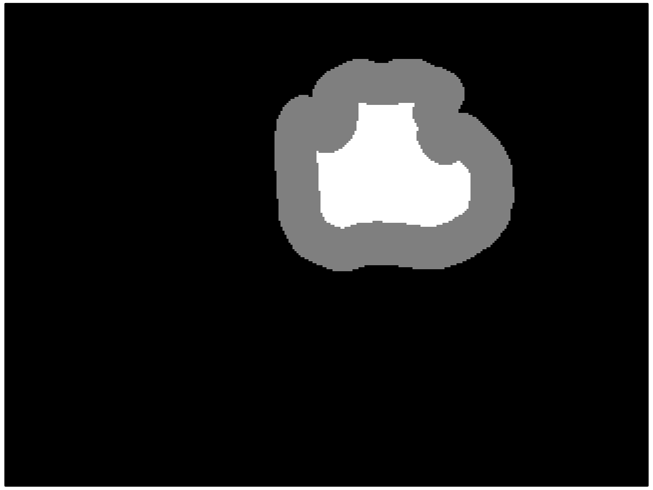


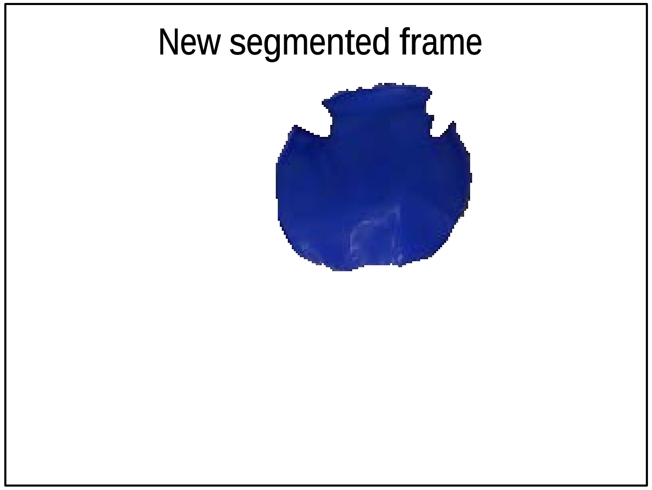
Elastoplastic Deformations

- Point cloud matching process
  - Using visual information (contours, color, 2D/3D local visual features), instead of pure geometrical correspondences
  - Using filtering predictions for the vertices of the mesh
- Plastic deformations (plastic strain based on elastic/plastic transition thresholds)
- Estimating elastic parameters
- Speed-up computations
  - Code optimization and parallelization (OpenMP, other CUDA implementations)
- Hardware
  - Suitable RGB-D sensors (SoftKinetic DepthSense, BlueTechnix Argos3D P100)

Segmentation

- Temporal coherence by adapting frame-by-frame the segmented area to a strip around the contour





  - Energy minimization effective on the strip
  - Faster
- Real-time issues: CUDA implementation

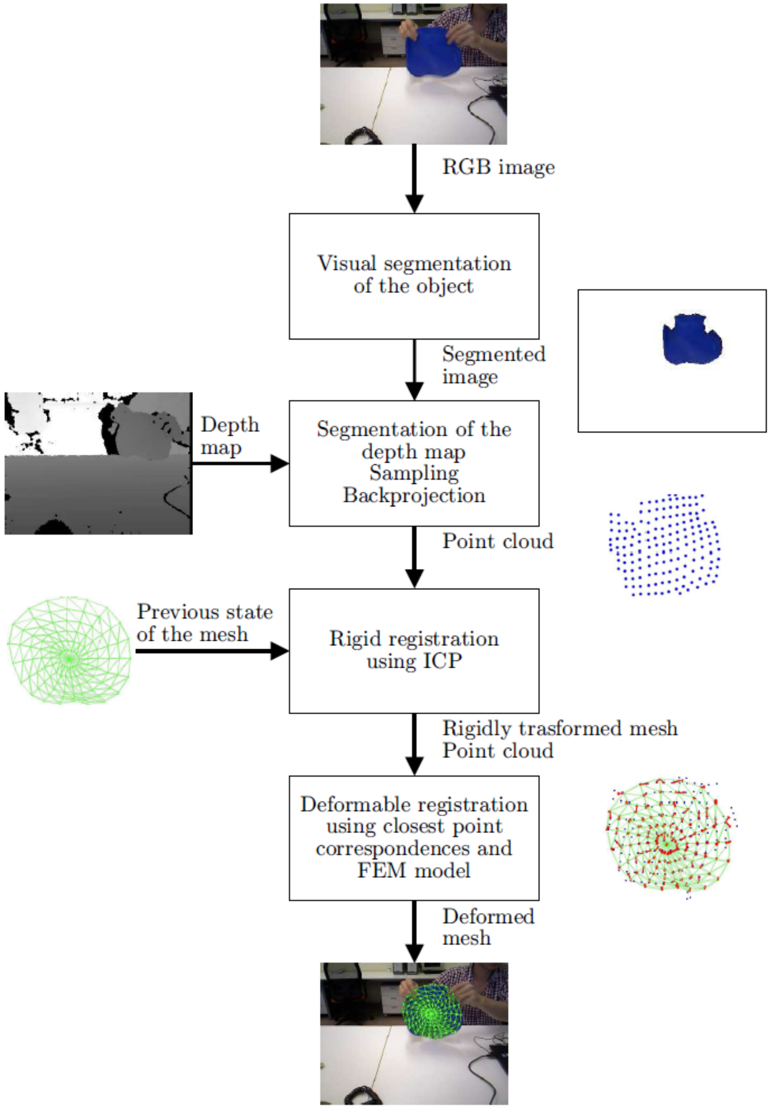
Real-time Tracking

- Rigid process
  - Iterative Closest Point algorithm, between the mesh (rigid) and the segmented point cloud, to track fast rigid motions
- Non-rigid process
  - Computation of external forces $\boldsymbol{f}_{ext}$ exerted on the vertices based on the segmented point cloud
- Numerical resolution of the ODEs integrating the internal and external forces (Euler implicit integration + conjugate gradient), to update the mesh

$$\boldsymbol{M}\ddot{\boldsymbol{x}} + \boldsymbol{C}\dot{\boldsymbol{x}} + \boldsymbol{K}'\boldsymbol{x} + \boldsymbol{f}_0 = \boldsymbol{f}_{ext}$$

- Process iteratively repeated
- Real-time implementation based on SOFA library

Tracking Framework



Results

Nonprehensile Manipulation Primitives

- The classic way to cope with nonprehensile manipulation tasks is to split them in simpler subtasks, referred to as primitives
  - Rolling
  - Sliding
  - Tossing/Catching
  - Batting/Juggling
  - Throwing
  - Dribbling
  - Pushing
  - ...
- Each primitive is equipped with its own motion planner and controller
- A high-level supervisor is in charge of activating/deactivating each primitive to deal with the complex task

Rolling: Holonomic Constraints

- An actuated manipulator of a given shape, referred to as hand, manipulates an object only through pure rotations without grasping it
- Examples are given by stabilization of
  - Ball on disk
  - Disk on disk
  - Ball and beam
  - Ball and bowl

Disk on Disk

- The problem of stabilizing a free rolling disk on an actuated disk is solved using passivity-based control for port-Hamiltonian systems
  - Closed-loop dynamics

$$\begin{bmatrix} \dot{\boldsymbol{q}} \\ \dot{\boldsymbol{p}} \end{bmatrix} = \begin{bmatrix} 0 & \boldsymbol{B}^{-1}\boldsymbol{B}_d \\ -\boldsymbol{B}_d\boldsymbol{B}^{-1} & \boldsymbol{J}_2(\boldsymbol{q},\boldsymbol{p}) - \boldsymbol{R}_d(\boldsymbol{q},\boldsymbol{p}) \end{bmatrix} \nabla H_d(\boldsymbol{q},\boldsymbol{p})$$

$\boldsymbol{q} \in \mathbb{R}^2$: generalized coordinate vector

$\boldsymbol{p} \in \mathbb{R}^2$: moment vector

$H_d = \frac{1}{2}\boldsymbol{p}^\top \boldsymbol{B}_d^{-1}(\boldsymbol{q})\boldsymbol{p} + V_d(\boldsymbol{q}) \in \mathbb{R}$: desired total energy

$\boldsymbol{B}_d \in \mathbb{R}^{2\times 2}$: desired mass matrix

$V_d \in \mathbb{R}$: desired potential energy

$\boldsymbol{J}_2 \in \mathbb{R}^{2\times 2}$: gyroscopic force vector

$\boldsymbol{R}_d \in \mathbb{R}^{2\times 2}$: damping injection

Passivity-based control for a rolling-balancing system: The nonprehensile disk-on-disk

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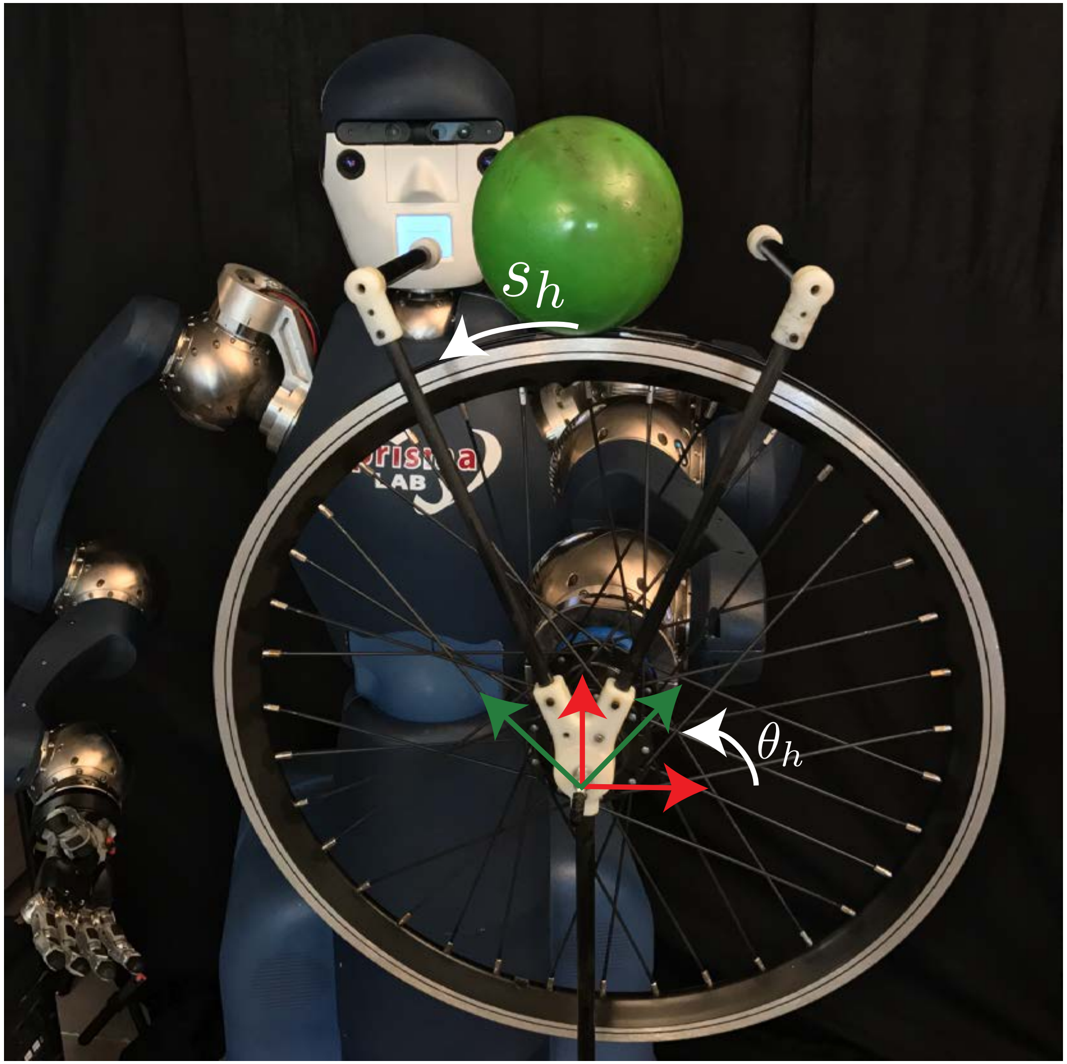
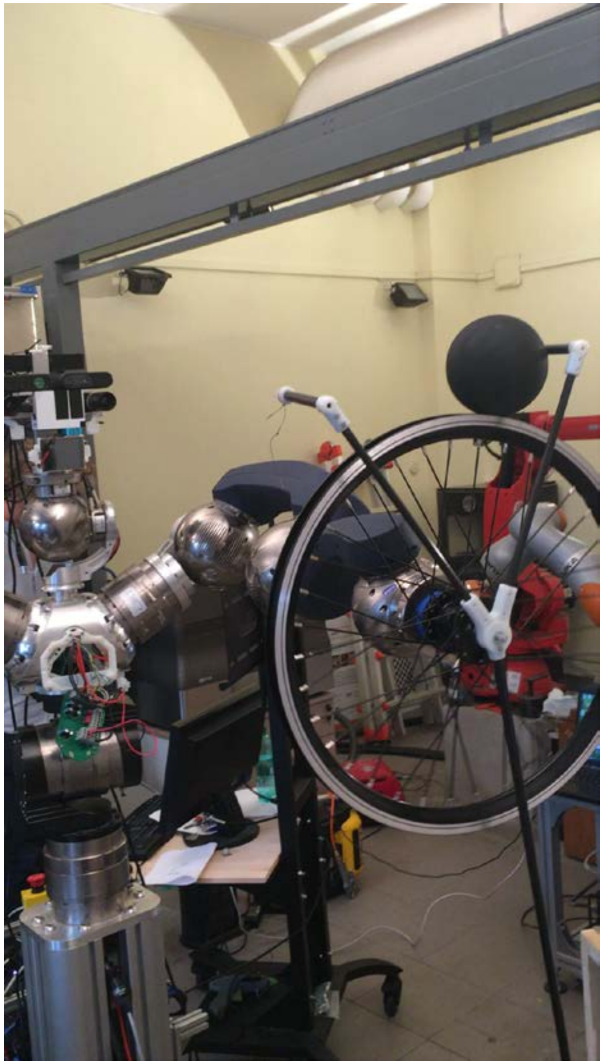
More Results





Rolling: Non-holonomic Constraints

- In case the rolling motion is not executed in a plane, the constraints become nonholonomic
  - Modelling of the systems become even more cumbersome
  - Planning and control design increase in complexity
  - Brockett's necessary condition for stability via smooth feedback often fails
- Two examples are briefly presented in the following videos
  - Stabilization and tracking of a ball on a plate
  - Robotic hula-hoop

On the experiments about the nonprehensile reconfiguration of a rolling sphere on a plate

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Nonprehensile manipulation of an underactuated mechanical system with second order nonholonomic constraints: The robotic hula-hoop

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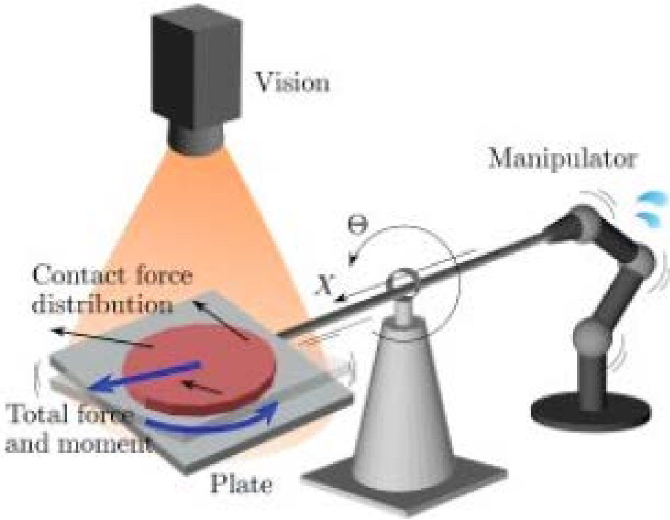
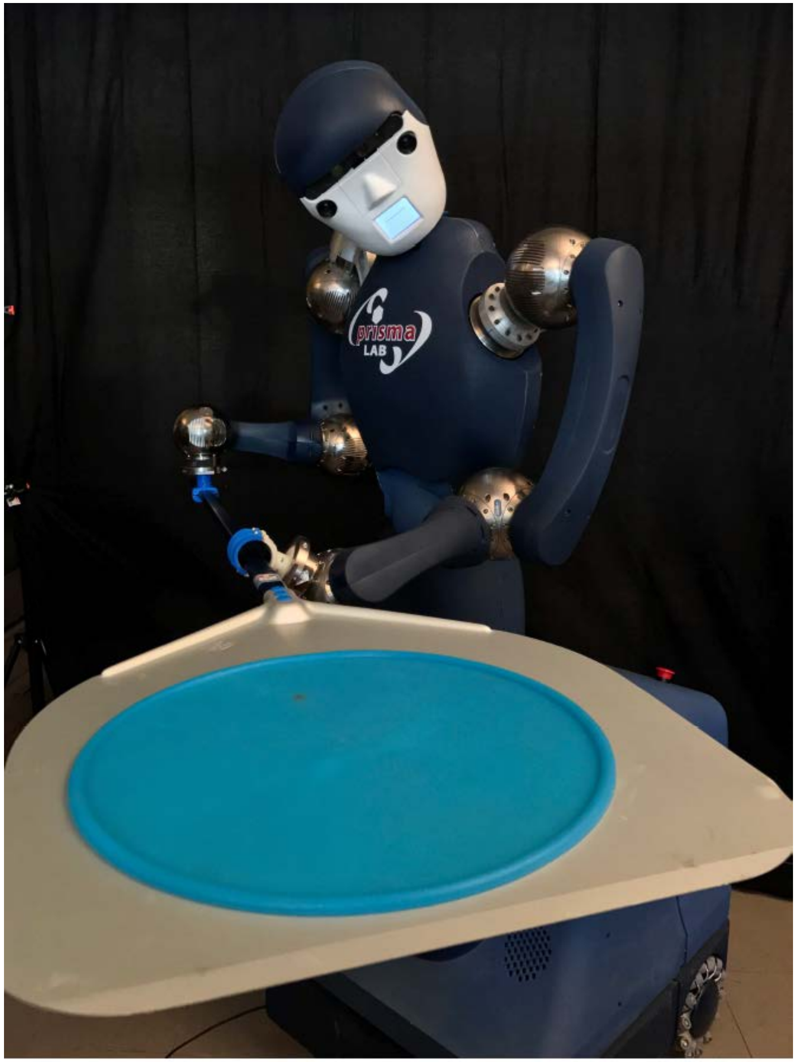
- Pizza peel


X
Θ

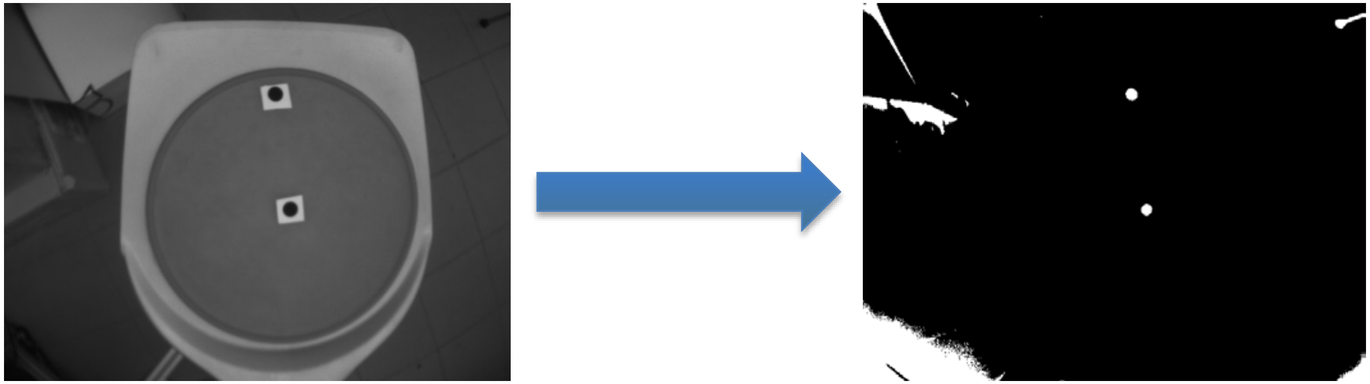

Vision
Manipulator
Θ
X
Contact force distribution
Plate

Modelling

- Friction-induced manipulation primitive
  - Both object and plate are rigid
  - The object has a uniform mass distribution and negligible thickness
  - The plate is larger than the object
  - Coriolis and centrifugal terms are negligible
  - The contact area between the object and the plate is constant during the whole experiment
  - The nominal pressure distribution on the object is uniform
  - The friction is based on Coulomb law



- Equipment
  - Professional pizza peel “4 stagioni pizza max”, made of aluminum (length 140 cm, plate’s diameter 40 cm)
  - Silicon pizza, employed by training juggler pizzaioli, with diameter of 33 cm
  - End-effector tool designed and 3D printed in-house
  - Asus Xtion, 640x480 pixel, 30Hz, shape-based tracking algorithm (the marker is only for the user to appreciate the rotation of the disk)



Results


Maker Faire
C9
SAPIENZA UNIVERSITÀ DI ROMA
COMPETIZIONI ROBOTICHE: ROBOT DOMESTICI
ROME
Maker Faire
THE EUROPEAN EDITION
C8
RODYMAN
RoDyMan
ROBOTIC DYNAMIC MANIPULATION
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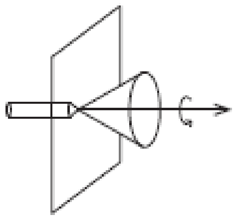
DIAG

Tossing

- Contact constraint

Contact Type	Picture	Wrench Basis, B_c	Friction Cone
Soft-finger		$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$	$\sqrt{f_1^2+f_2^2} \leq \mu f_3$ $f_3 \geq 0$ $\lvert f_4 \rvert \leq \beta f_3$

  - Each finger contact is modeled as two rigid bodies in soft contact

$$B_{c_i} V_{f_i c_i}^b = 0$$

  - When expressed in terms of the joint velocities and the object velocity

$$B_{c_i}^T \left(-Ad_{g_{oc_i}}^{-1} J_{st}^b \dot{\theta} + Ad_{g_{oc_i}}^{-1} V_{so}^b \right) = AV = 0$$

$$V := \begin{bmatrix} V_{so}^b \\ \dot{\theta} \end{bmatrix}$$

Catching

- Trajectory planning for catching
  - Specify initial position, velocity, acceleration and final velocity and acceleration
  - The final position and time to catch are determined by optimization
- Minimization of convex combination of acceleration and jerk functional in $SE(3)$
  - Ending up with sixth-order differential equation
  - Tuning weight of each term in the functional to give more importance to minimizing control effort or minimizing vibrational load
- Optimization on general Riemannian manifolds, leaving derivation coordinate-invariant from start to finish

A Coordinate-Free Framework for Robotic Pizza Tossing and Catching

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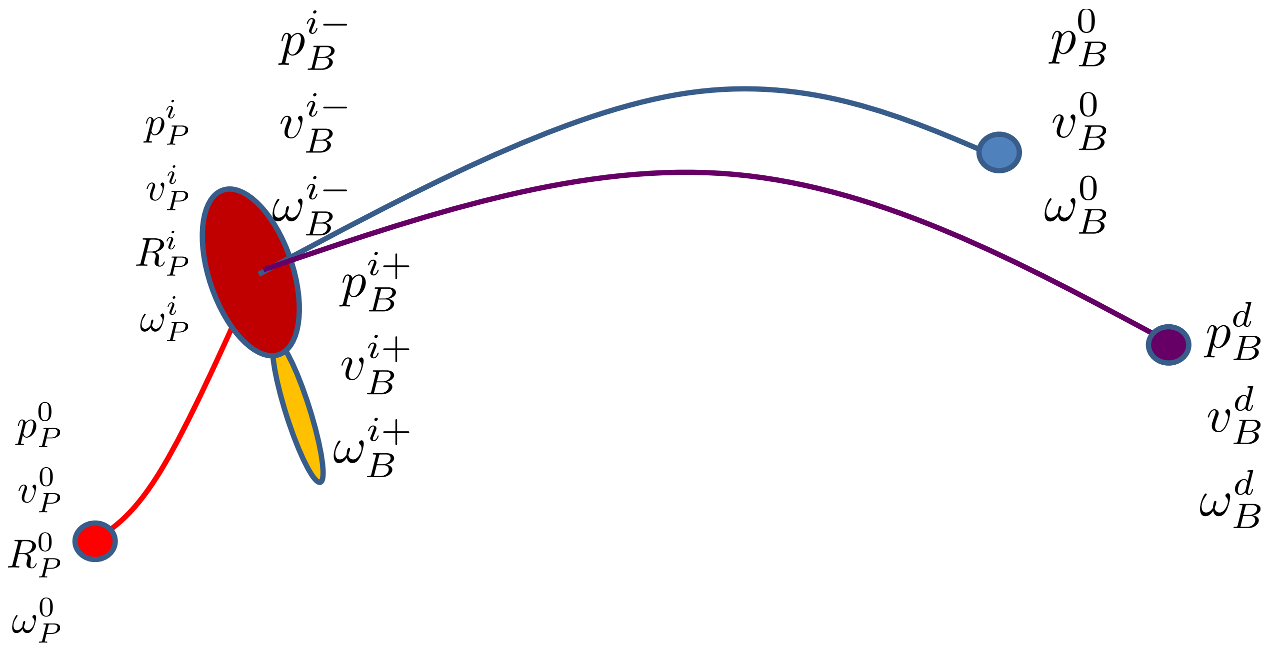
Batting/Juggling

Vision system and desired impact time → **Forward solution of the ball aerodynamics**

→ **Inverse solution of the ball aerodynamics** ← Desired final state of the ball

→ **Ball reset map**

→ **Optimal planner for the paddle** → Paddle trajectory



An Optimal Trajectory Planner for a Robotic Batting Task:
The Table Tennis Example

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More Results

A nonlinear least squares approach for nonprehensile dual-hand robotic ball juggling

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Timeline

- Schedule
  - November 2015 – Robot platform was available
  - May 2016 – The first step of the pizza maker demonstrator was executed: the robot turns the pizza peel considering the dough as a rigid object
  - November 2017 – The next step of the pizza maker demonstrator is executed: the dough is considered as a non-rigid object and some stretching actions are shown
  - May 2019 – The full demonstrator is at work …

You are all invited to the degustation in Napoli ☺

- Follow-up
  - Reference platform in the field of dynamic manipulation for the next years
  - Manipulation of deformable objects applied to shoe industry (ATOM Lab in Vigevano)
  - Physical modeling and RGB-D registration for contact force sensing on deformable objects applied to surgical field

Thank You very much indeed
for Your kind attention ☺
Any questions?

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http://www.beforetheabstract.com/2018/07/10/
bruno-siciliano-from-pizza-making-to-human-care/