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Nonprehensile Manipulation of Deformable Objects

Achievements and Perspectives from the Robotic Dynamic Manipulation Project

The goal of this article is to disseminate the planning and control strategies for robotic nonprehensile manipulation results achieved so far with the Robotic Dynamic Manipulation (RoDyMan) project. The goal of the project is to advance the state of the art of nonprehensile dynamic manipulation of rigid and deformable objects to enhance the possibility of employing robots in anthropic environments. RoDyMan project's final demonstration will be acting as an autonomous pizza maker. This article highlights the lessons learned and paves the way toward critical discussions and future research.

Overview of Nonprehensile Manipulation

Manipulating an object entails changing its current state to a desired one. Suppose an object on a table has to be moved from location A to B on the same table. How would you move it? The two most common answers might be 1) grab the object, lift it up, and place it back on the table in location B, or 2) push the object on the table from A to B. In case 1, the object is gripped between the fingertips and/or the palm, and the hand is theoretically able to resist any external disturbance applied to the object (force closure), even preventing infinitesimal motions (form closure) [1]. Bilateral constraints are exhibited by the grasp in both closures. In case 2, the object is instead pushed by one or more of the fingertips, and the fingertips are able to resist only forces counteracting the direction of the pushing; hence, nonprehensile or graspless manipulation occurs because only unilateral constraints are involved. These tasks can also be

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referred to as *dynamic* when the dynamics of both the object and the robot are essential to successful task execution.

A nonprehensile dynamic manipulation task can be generally described as a task where the object is subject only to unilateral constraints, and the dynamics of both the object and the manipulating hand as well as the related kinematics and the (quasi-)static forces play a crucial role. Pushing objects, folding clothes, carrying items on a tray, cooking in a pan, and performing some surgeries are examples of nonprehensile manipulation tasks. From a robotic point of view, most nonprehensile manipulation systems are underactuated, raising controllability challenges. However, dynamic nonprehensile manipulation has several advantages, such as the increase in available robot actions, bigger operative workspaces, and enhanced dexterity in dynamic tasks.

Literature

The literature contains well-established grasping techniques [1] and control methods for manipulation tasks with grasp [2]. Within industrial applications, where simplicity and cost are most relevant, grippers or special-purpose devices are widely used. Nevertheless, the necessity for robots working in anthropic environments is growing rapidly, as shown by the European Strategic Research Agenda (eSRA) [23], which states that robots will pervade a portion of the market in domestic appliances, assisted living, entertainment, and education. Therefore, robots should not need specific tools for each action, but they should exploit multipurpose devices, such as multifingered hands, and they should rely on the dexterity conferred by the designed control algorithms.

Manipulation dexterity is one of the main research challenges currently being addressed by the robotics community. As explained previously, a nonprehensile manipulation task is a dexterous task par excellence. Some tasks are intrinsically prehensile, e.g., screwing on or unscrewing a bottle cap. Other tasks can be tackled both in a prehensile or a nonprehensile manner, such as the aforementioned example of moving an object on a table. Some tasks are inherently nonprehensile, e.g., carrying a glass full of water on a plate. Other tasks are hybrid, in the sense that, to reach the goal, both prehensile and nonprehensile actions are required, such as when a juggler has to repetitively catch and throw balls in a cascade juggling pattern.

The literature, however, is not fully developed for nonprehensile manipulation tasks. The classic way to cope with them is to split a task into simpler subtasks, referred to as *nonprehensile manipulation primitives* [3], such as throwing [4], dynamic catching [5], batting [6], juggling [7], dribbling [8], pushing [9], sliding [10], rolling [11], and so on [27]. Each primitive, equipped with its own motion planner and controller, is then turned on and off during a complex manipulation task by a high-level supervisor [12]. Among the mentioned nonprehensile manipulation primitives, only rolling and batting are fully covered in the literature. There is also a lack of a general unified theoretical framework in the field, causing the continuous investigation of ad hoc motion planners and controllers to individually solve the specific

tasks. The main reason may be found in the possible change of the contact status during a nonprehensile manipulation task, leading to nonsmooth dynamics of the entire system, which complicates the control design. For this reason, dynamic nonprehensile manipulation may be considered the most complex manipulation action, deserving attention as requested by the eSRA, and posing many research challenges to be solved.

The RoDyMan Project

In the described context, the RoDyMan project aims to develop a service robot able to manipulate elastic, soft objects, and both rigid and nonrigid objects in a nonprehensile way; the ambitious goal is to bridge the gap between robotic and human task execution capability. To reach the planned goals, three main research challenges have been identified:

- *Mechatronic development and assembly*: A mobile robotic platform equipped with two commercial arms and multifingered hands are necessary to perform the dynamic manipulation tasks planned for the project.
- *Modeling and perception*: Real-time requirements posed by robot interaction with deformable objects during dynamic nonprehensile manipulation actions are essential to fulfill the required tasks.
- *Control techniques for nonprehensile dynamic manipulation*: The goal of the project is to advance the state of the art in controlling rigid objects in a nonprehensile way and to begin investigating the problems relative to the prehensile and nonprehensile manipulation control of deformable objects.

The final demonstrator of the project will be an autonomous pizza maker since preparing a pizza involves an extraordinary level of manual dexterity.

Other Approaches

Other projects have attempted to address nonprehensile manipulation problems using different approaches. The RIBA robot is able to lift patients up from and set them down on their beds and/or wheelchairs [24]. The soft body of the robot is designed to make the interaction with humans safe. The transporting task performed is nonprehensile, but the manipulation task is not dynamic because the patient's body is considered a rigid object, and only motion-planning techniques for lifting the body up are investigated. The task is very similar to a pick-and-place operation where the transporting motion is addressed in a nonprehensile fashion.

The ERC SHRINE project goals focus on enhancing robot manipulation capabilities to overcome barriers preventing robots from safe and smooth operations within anthropic environments [25]. The objective of the RoDyMan, in some cases also performed in a nonprehensile way, is to cooperate with humans.

The results achieved so far within the RoDyMan project for the aforementioned three research challenges are described in the following, and videos of the related experiments can be found on the PRISMA Lab YouTube channel [26].

Design and Architecture

Mechatronic Design

The mechatronic setup, referred to as *RoDyMan* like the project name, is a 21-degrees-of-freedom (DoF) humanoid robot (see Figure 1). An omnidirectional mobile platform allows the robot to move. An actuated mechanism gives the ability to enlarge the support polygon during the execution of dynamic and rapid movements of the upper body. The battery pack and uninterruptible power supply unit used to provide power to all of the devices are housed within the mobile platform and provide the weight to stabilize the platform. Two standard personal computers (PCs) are also located in the base. One is a QNX-based PC used to control the motors in real time and for the implementation of safety procedures. The second is a Linux-based PC used for perception and high-level planning and control algorithms.

The upper-body limbs of the robot are two SCHUNK LWA 4P arms with 6 DoF each. The seventh joint of each arm, required to add human-like kinematics, is provided by a SCHUNK PRL-100 integrated into the shoulder. To the best of our knowledge, the SCHUNK were the only arms on the market to have both dimensions similar to human arms and also the control directly on the controller area network bus without an external controller box. Nevertheless, experimental results show that the high friction and the low-joint velocities exhibited by these arms represent a limitation on the execution of particular and complex tasks like tossing. However, this solution represents only a first prototype, and the design of new arms, with advanced dynamical characteristics, is within the RoDyMan project plan.

Moreover, the dynamic model of the whole structure is derived in a symbolic form. The linear matrix inequality (LMI) method in [13] was employed to obtain the identification of the dynamic parameters by absorbing the physical constraints within the optimization procedure. Experimental results have shown that friction, mostly the static part, is the dominant component in the measured torque. Therefore, friction identification has first been performed separately, and then the friction parameters have been used as constraints within the LMI optimization procedure.

The RoDyMan platform is completed by two motors to actuate the torso and one for the pan-tilt neck. To provide enhanced dexterous manipulation skills, two anthropomorphic SCHUNK Servo-electric 5-Finger SVH hands can be applied at the end-effector tip of the two arms. However, these hands are very delicate, and they are replaced with suitable three-dimensional (3-D)-printed tools for those tasks requiring nontrivial weights in action, such as the pizza-peel task. From the perception point of view, the platform is equipped with two laser scanners in the base for odometry operation. Two force sensors can be mounted on the wrist to measure the interaction forces between the end effector and the environment, while the interaction forces exerted on the robot structure can also be obtained using proper estimators [14]. Finally, the head is equipped with a stereo camera system, a red-green-blue depth (RGB-D) sensor, and a time-of-flight camera to obtain precise depth estimation.

High-Level Software Architecture

To carry out the expected activities involving complex manipulation actions, control architecture is designed to handle high-level planning tasks. A sketch of the control architecture is shown in Figure 2.

The human–robot interaction (HRI) interface module is used to specify high-level tasks as inputs for the system (e.g., the pizza tossing). The supervisor module is responsible for the task decomposition process and for splitting the high-level actions received by the HRI interface into lower-level actions, which considers both the state of the robot and the information generated by the perception module. After the decomposition process, each lower-level action can be executed. Examples of high-level tasks include grasp, search, or toss for objects and sequences of nonprehensile manipulation primitives.

To suitably perform the task decomposition process, the supervisor module is provided with multiple hierarchical tasks, similar to hierarchical task networks, which can be
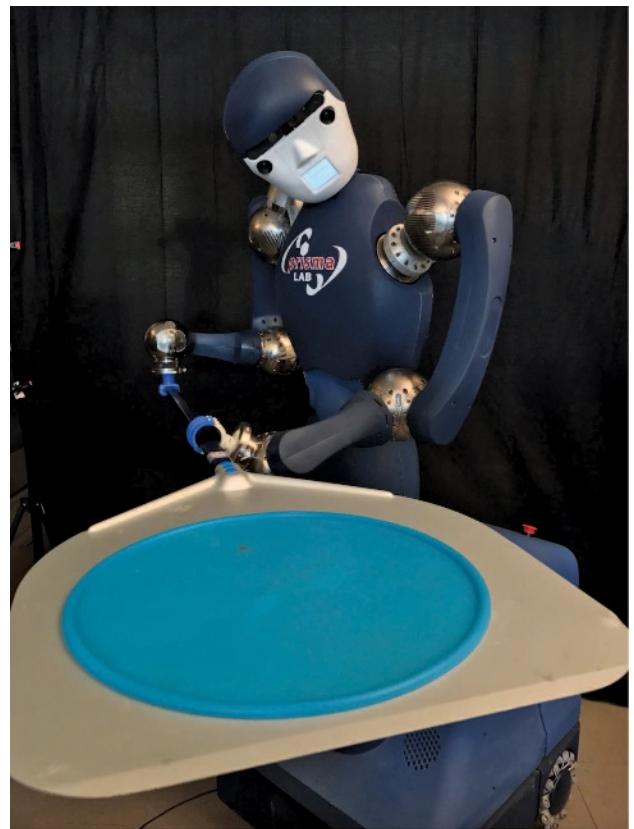

Figure 1. The RoDyMan platform handling the peel with two arms and two proper grippers at the end effectors. The displayed tool is a real pizza peel employed by chefs to cook the dough in the oven. A blue silicon disk, usually employed by acrobatic pizza chefs for training, is employed in the experiments.
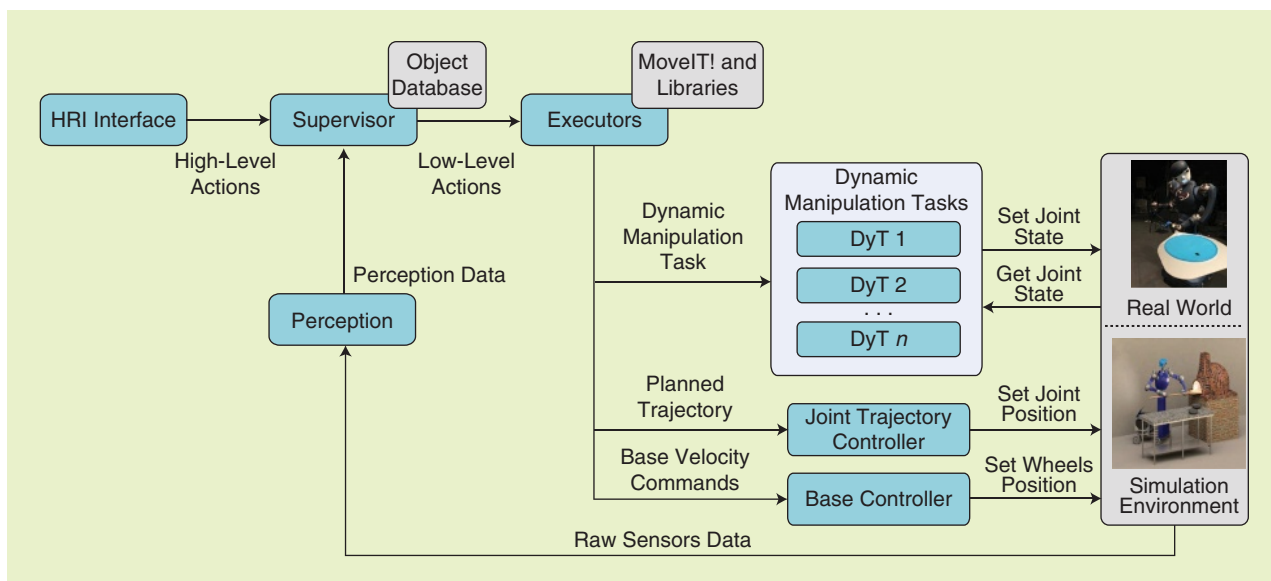
Figure 2. The RoDyMan high-level control architecture. DyT: dynamic manipulation task.
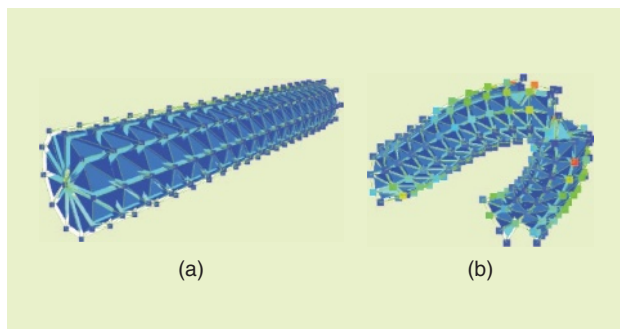

Figure 3. (a) The volumetric tetrahedral mesh (elements in blue colors), and (b) the modeling of fractures.

composed by the system to achieve the desired goal [15]. In this context, if a nonprehensile manipulation action is required, the related low-level controller is invoked from the dynamic manipulation task list while the supervisor awaits its termination. Otherwise, the executor module is responsible for the action by implementing both the path and the motion-planning functionalities to find an obstacle-free route for the end effectors of the robot and its base. This module relies on MoveIT! [16], a framework that integrates a universal robot description file, an open motion-planning library, and other tool kits. The generated trajectories for the joints and the base of the robot are streamed to the robot actuators from the controller modules. Information about the robot's environment is then extracted from the perception module via image-elaboration algorithms.

The proposed high-level control architecture perfectly matches the requirements of the RoDyMan robotic platform, statically allocating the best low-level controller to accomplish desired actions. This improves the current literature because very few methods of decomposing a high-level task for nonprehensile manipulation have been

developed [12]. Future opportunities for the platform include increasing the level of collaboration between the robot and human operators, allowing for shared-task planning and execution.

Perception of Deformable Objects

In this section, we present a method to cope with real-time (35 ft/s) tracking of a deformable object using the point cloud data provided by the RGB-D sensor. We propose several contributions, such as handling various large elastic deformations while ensuring physical consistency and coping with fractures, rigid motions, and occlusions [17]. An example is stretching and tossing pizza dough.

Because the considered system attempts to deal with large deformations and elastic volumetric strains, a realistic mechanical model is employed that is based on continuum mechanics and on a volumetric tetrahedral finite element method (FEM). This model can be used for real-time applications through the Simulation Open Framework Architecture. Explicit physical modeling would enable a reliable prediction of internal forces undergone by the object.

To model elastic deformations, the infinitesimal strain theory and Hooke's law are taken into account, providing a linear relation between the displacement of the tetrahedral elements of the mesh and the internal forces exerted on their nodes. The corotational approach is used as a compromise between the ability to model large deformations of the elements and the computational efficiency.

Based on the FEM corotational 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; this is done through something called a *separation tensor*. The fracture is propagated by simply removing attached elements intersected by the fracture plane. The model is illustrated in Figure 3.

The frame-by-frame tracking framework in Figure 4 relies on a prior visual segmentation of the object in the image, based on a graph-cut-based segmentation technique using color cues. The corresponding segmented point cloud is first registered through a classical iterative closest point method and then by fitting the known meshes of the object on the point cloud. The basic idea is to derive external forces exerted by the point cloud on the mesh and to integrate
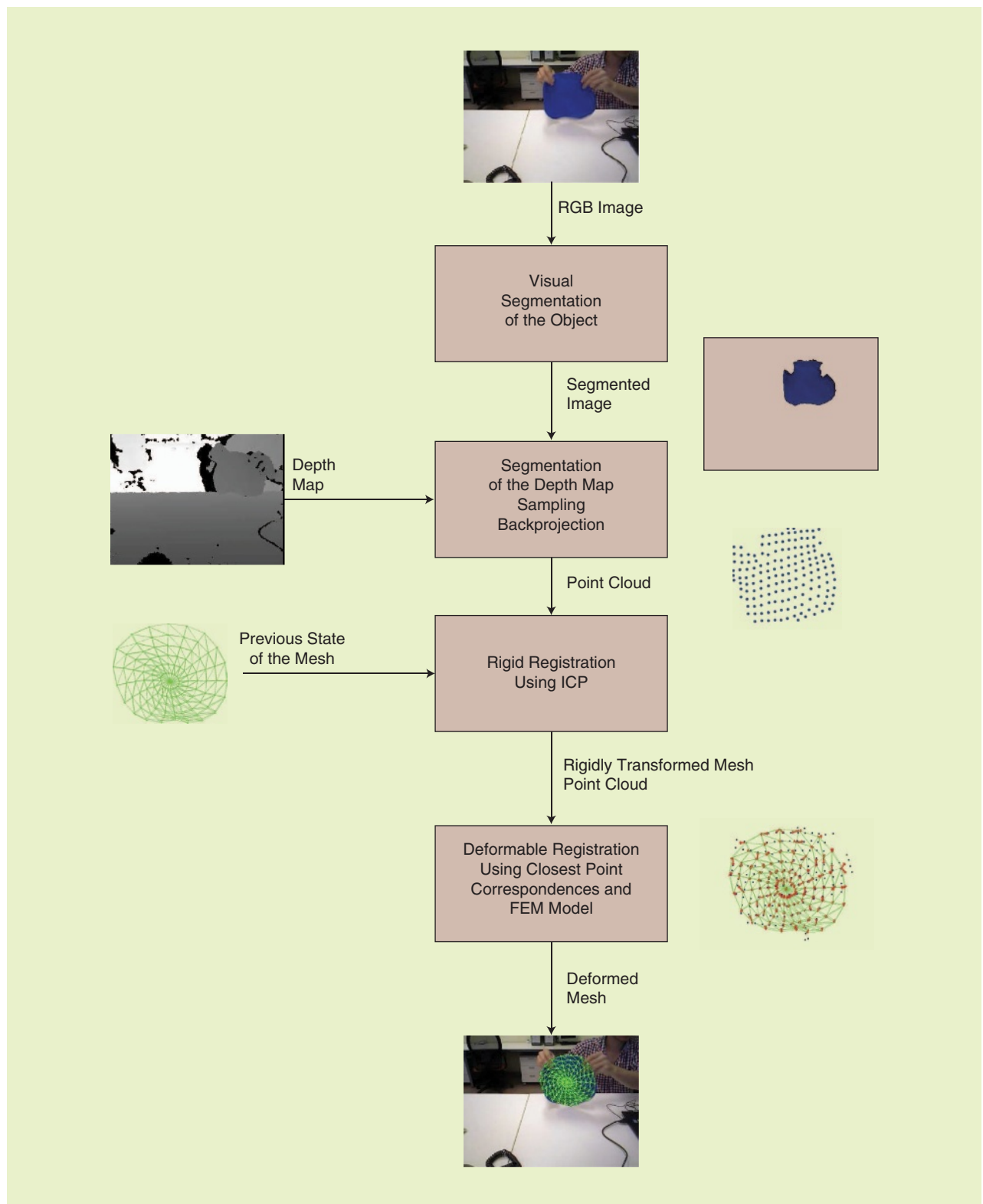

Figure 4. An overview of the developed approach for deformable object tracking. ICP: iterative closest point.
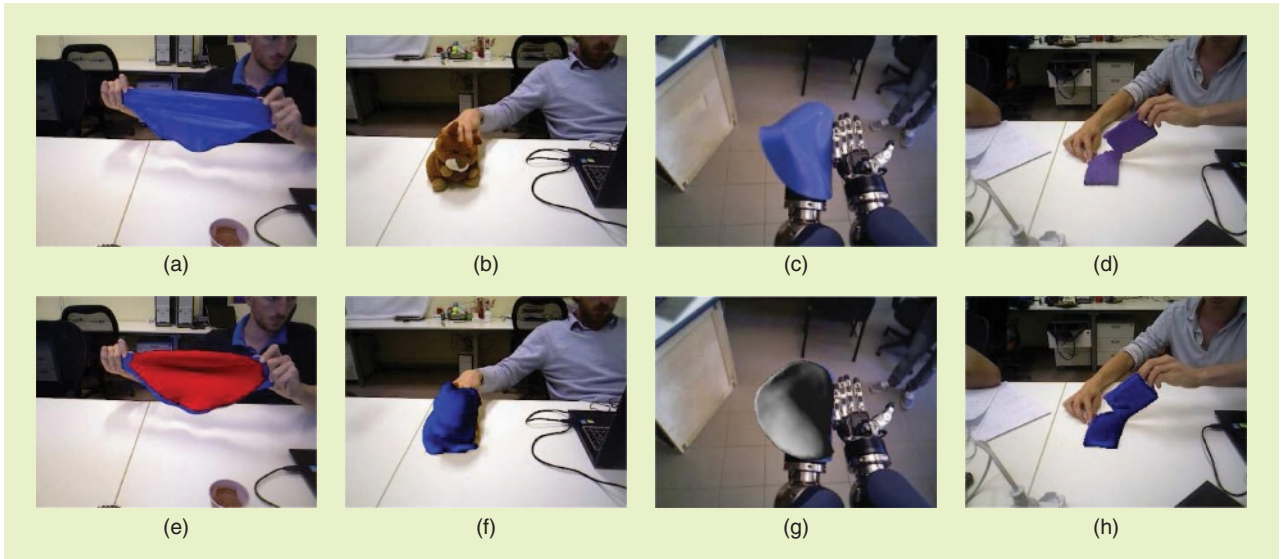
Figure 5. The results of the tracking process with the (a)–(d) input images (four different objects), and (e)–(h) the corresponding registered reprojected mesh.

them with the internal forces computed using the physical model of Lagrangian mechanical equations: $M\ddot{x} + C\dot{x} + K'x + f_0 = f_{ext}$, where $x \in \mathbb{R}^n$ contains the positions of the n vertices, $M \in \mathbb{R}^{n \times n}$, $C \in \mathbb{R}^{n \times n}$, and $K' \in \mathbb{R}^{n \times n}$ are the mass, damping, and stiffness matrices, $f_{ext} \in \mathbb{R}^n$ is the external forces vector, and $f_0 \in \mathbb{R}^n$ is an offset on the internal forces due to rotational effects. A Euler implicit integration scheme and a conjugate gradient method are used to solve the system with respect to x. The elastic forces f_{ext} are based on geometrical correspondences between the point cloud and the mesh [17].

To validate the method, some results have been obtained with various soft objects that include deformations due to bending and stretching or compression actions and fractures obtained under challenging conditions, like occlusions or fast motions (see Figure 5). Some preliminary experiments integrating the method into a robotic manipulation task with a silicon pizza dough have also been carried out [see Figure 5(g) and the "Friction-Induced Manipulation Primitive" section].

Nonprehensile Motion Planning and Control

Four manipulation primitives have been considered so far within the RoDyMan project: nonprehensile rolling, sliding, tossing, and batting/juggling. Sliding and tossing take into account deformable objects, while rolling and batting/juggling only consider rigid objects. It is difficult to find relevant applications involving deformable objects in pure rolling and juggling tasks. In the following sections, the controller and/or motion planner designed for the aforementioned primitives are described.

Nonprehensile Rolling

An actuated manipulator of a given shape, referred to as the *hand*, manipulates an object purely through rotations and without grasping or caging it. Therefore, the object can only roll on the shape of the hand. Case studies like the manipulation of a ball on a plate, a ball on a beam, and so on are thoroughly examined in the literature [27]. In this article, only planar rolling is described.

Because highly geared harmonic drives are present within the RoDyMan mechatronic platform, we use the acceleration of the hand $\ddot{\theta}_h \in \mathbb{R}$ as input $a_h \in \mathbb{R}$ for the system. The dynamic model for a nonprehensile planar rolling manipulation system, in which the hand can only rotate around its center of mass, is described by

$$\ddot{\theta}_h = a_h, \tag{1a}$$

and

$$\ddot{s}_h = -b_{22}^{-1}(b_{12}a_h + c_{21}\dot{\theta}_h + c_{22}\dot{s}_h + g_2), \tag{1b}$$

where $s_h \in \mathbb{R}$ is the contact position of the object on the hand, whose shape is parametrized through arc length, $b_{12} \in \mathbb{R}$ and $b_{22} \in \mathbb{R}$ are entries of the inertia matrix $B \in \mathbb{R}^{2 \times 2}$, while $c_{21} \in \mathbb{R}$ and $c_{22} \in \mathbb{R}$ are entries of the (2×2) Coriolis matrix of the mechanical system, and $g_2 \in \mathbb{R}$ is the second element of the (2×1) gravity-force vector. Detailed expressions of each term are provided in [18], which also notes that, if the Coriolis terms are zero, a nonprehensile planar rolling manipulation system is differentially flat with the output $(b_{12}/b_{22})\theta_h + s_h$. Among the class of systems for which the aforementioned assumption is true, we recall the ball-on-disk (BoD) system, which is mathematically equivalent to the disk-on-disk (DoD) system in the transversal plane [11].

The BoD consists of a ball rolling on top of a disk, as shown in Figure 6. The disk is the actuated hand, and the ball rolling on the hand is the object. The control problem for the BoD is to balance the object in the upright position while

driving the hand to a desired angular set point. This problem is solved using passivity-based control (PBC) for port-Hamiltonian (pH) systems. In its standard form, this approach applied to nonprehensile rolling aims to find a control law for system (1a) and (1b) such that the closed-loop dynamics can be written as

$$
\begin{bmatrix} \dot{\boldsymbol{q}} \\ \dot{\boldsymbol{p}} \end{bmatrix} = \begin{bmatrix} 0 & \boldsymbol{B}^{-1}\boldsymbol{B}_d \\ -\boldsymbol{B}_d\boldsymbol{B}^{-1} & \boldsymbol{J}_2(\boldsymbol{q},\boldsymbol{p}) - \boldsymbol{R}_d(\boldsymbol{q},\boldsymbol{p}) \end{bmatrix} \nabla H_d(\boldsymbol{q},\boldsymbol{p}), \qquad (2)
$$

where $\boldsymbol{q} \in \mathbb{R}^2$ and $\boldsymbol{p} \in \mathbb{R}^2$ are the generalized coordinate and moment vectors, $H_d = (1/2)\boldsymbol{p}^\top \boldsymbol{B}_d^{-1}(\boldsymbol{q})\boldsymbol{p} + V_d(\boldsymbol{q}) \in \mathbb{R}$ is the desired total energy of the closed-loop system, $\boldsymbol{B}_d \in \mathbb{R}^{2\times2}$ and $V_d \in \mathbb{R}$ are the desired mass matrix and potential energy, respectively, and $\boldsymbol{J}_2 \in \mathbb{R}^{2\times2}$ and $\boldsymbol{R}_d \in \mathbb{R}^{2\times2}$ represent the gyroscopic forces and damping injection of the closed loop, respectively. The objective is to shape the desired energy of the closed-loop dynamics to produce a minimum potential energy at the desired equilibrium. The asymptotic stability of the closed loop is ensured by using the desired energy as the Lyapunov function and the detectability of the passive output. The full development of the control design for the DoD example is reported in [11].

Within the RoDyMan project, control laws related to the nonprehensile rolling primitive have also been developed for the 3-D case, such as the stabilization of a ball on a flat plate and the control of a robotic hula-hoop [19]. As a milestone, it is affirmed that nonprehensile rolling can be successfully modeled through the pH formalism and, consequently, controlled with PBC approaches. This means that a unified framework exists at least for this class of nonprehensile manipulation primitive.

Friction-Induced Manipulation Primitive

As a case study, to uniformly cook a pizza, the dough must be rotated through a peel inside a wooden oven, where the heat source is present only on one side of the structure. Similar actions are performed by chefs when food must be browned or rotated in a pan.

From a dynamic point of view, friction plays a key role because of the sliding manipulation primitive between the tool and the manipulated part. In the literature, friction-induced manipulation was extensively studied to create virtual velocity fields on a vibrating plate actuated by a mechanical system equal or similar to a Stewart platform [10]. A similar concept was suitably modified for the pizza case [20].

The RoDyMan platform has successfully achieved a bimanual nonprehensile manipulation task through sliding by handling a peel to rotate the pizza placed on it. With reference to Figure 1, the peel is chosen to only be translated (and rotated) along (and around) its longitudinal direction. A suitable combination of these two movements creates the desired motion of the object on the peel: acceleration along the longitudinal direction moves the object back and forth on the peel once static friction is overcome, while an angular acceleration

around the same axis creates a nonuniform pressure distribution on the object. This, together with the linear acceleration, creates a rotation of the object. The object rotation is not decoupled from a linear displacement on the peel. Adaptations from [20] have been necessary to apply the concepts on the RoDyMan platform. Two suitable smooth sinusoidal accelerations with the same tunable frequency and different tunable amplitudes and phases are planned for the linear and angular accelerations of the peel. The motion of the RoDyMan joints is then retrieved by means of a standard closed-loop inverse kinematic algorithm. The previously described tracking of deformable objects is employed to control the center of mass of the pizza toward the center of the peel through a simple proportional-integral controller while a complete rotation of the circular shape is requested.

Friction estimation is crucial within this task, and several tests have been performed to suitably tune all of the parameters of the control model to fit the real setup. Current work aims at finding structural properties for the controller, such as the design of orbital stabilization for the object on the peel (i.e., to reach a desired rotational velocity).

Tossing Task

Tossing and catching a deformable object, like pizza dough, is a procedure that is frequently dexterously performed by human pizza chefs. There are at least three reasons why tossing the dough during the preparation of the pizza is attractive: 1) the dough is stretched to a desired size, 2) the dough
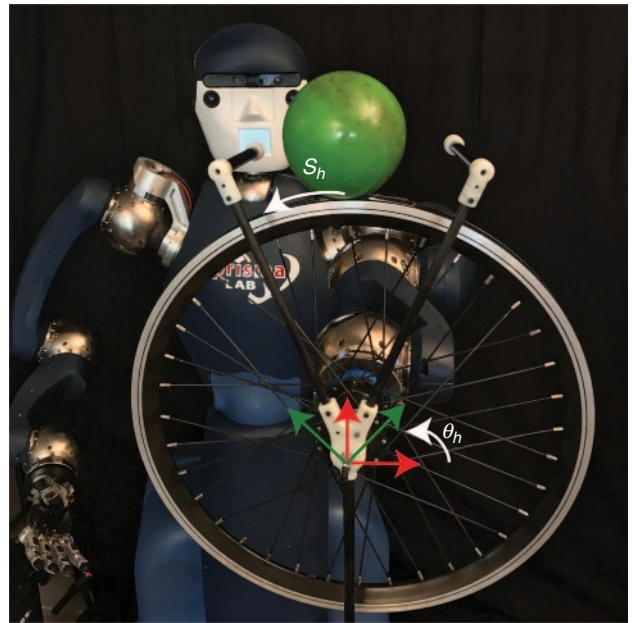

Figure 6. The RoDyMan platform actuating the BoD system. The disk is actuated by the movement of the RoDyMan joints. The displayed structure, made by three connected bars, is employed to start the experiments with the ball in a position that is different from the desired equilibrium on the top of the disk. The world frame is depicted in red, the one attached to the rotating wheel is in green, θ_h represents the angle between the two, and s_h measures the contact position of the ball on the wheel.

naturally assumes a consistency that is thicker at the ends and thinner in the middle, and 3) as the spinning dough freely falls, the outside of the dough dries, making it crunchy on the outside but soft in the middle. The pizza chef is trained to perform a streamlined hand motion to toss and catch the dough, and a similar feat is desired for the RoDyMan robot.

The combined model of the dough grasped with robotic fingers through unilateral constraints and the kinematics and dynamics of the robot manipulator is derived in [4], on which a control law achieving the desired tossing motion can be designed. Furthermore, with a perfect knowledge of the motion of the dough, optimal trajectories can be generated in the special Euclidean group SE(3) for the catching phase. The optimal trajectory generation is repeated as new sensor information is available. The trajectories are generated in such a way that the initial position, velocity, and acceleration and final velocity and acceleration are matched, and therefore it is continuously differentiable at least three times. An optimal trajectory, whose initial and final accelerations are prescribed, has to satisfy a sixth-order boundary value problem (BVP). Such BVP is generated by using the necessary conditions for a path to minimize a convex combination of the jerk functional and the acceleration functional. While minimizing the jerk functional reduces the vibrations in the structure of the robotic manipulator, minimizing the acceleration functional reduces the total amount of energy expended during the catching motion. The only case that we consider is the one where the final position is left free and is part of the minimization problem. More details can be found in [4].

Experimental validations are in progress. Nevertheless, preliminary results show that such tasks require high-peak currents in the motors to toss the dough for more than 10 cm. As anticipated, the motors of RoDyMan do not have such skills. Analogies between tossing and walking gaits can be found within mathematical models. Similar to robotic legs, hydraulic actuators seem to have better performance, and the same might hold true for tossing tasks. The stretching-the-dough task can also be performed in alternative manners, which will be explored in the future.

Batting/Juggling Skills

A very challenging primitive from the control viewpoint is the one involving impacts. Inside, batting an object (a ball) is intercepted by the end effector (a paddle) without grasping it, and the object is thrown toward a precise goal. This motion primitive is typically used by athletes, i.e., baseball or table-tennis players. Jugglers use this primitive when their hands control the continuous motion of one or more objects through intermittent contacts. These dynamic motions require high velocity and precision. The design of planning and control methods to deal with this would strongly enhance capabilities of robot manipulators, extending the workspace size and enhancing dexterity.

The batting task dynamic is typically defined as hybrid because it consists of the continuous aerodynamics of the manipulated ball (a differential equation) and the discontinu-

ous reset of the velocity at impact time (two difference equations), given by

$$\ddot{\boldsymbol{p}}_b = -\boldsymbol{g} - k_d \,\|\,\dot{\boldsymbol{p}}_b\,\|\,\dot{\boldsymbol{p}}_b + k_l \boldsymbol{S}(\boldsymbol{\omega}_b)\dot{\boldsymbol{p}}_b, \tag{3a}$$

$$\dot{\boldsymbol{p}}_b^+ = \boldsymbol{v}_p + \boldsymbol{\Gamma}_a(\dot{\boldsymbol{p}}_{\bar{b}} - \boldsymbol{v}_p) + \boldsymbol{\Gamma}_b \boldsymbol{\omega}_{\bar{b}}, \tag{3b}$$

and

$$\boldsymbol{\omega}_b^+ = \boldsymbol{\Gamma}_c(\dot{\boldsymbol{p}}_{\bar{b}} - \boldsymbol{v}_p) + \boldsymbol{\Gamma}_d \boldsymbol{\omega}_{\bar{b}}, \tag{3c}$$

where $\boldsymbol{p}_b \in \mathbb{R}^3$ and $\boldsymbol{\omega}_b \in \mathbb{R}^3$ are the position and the spin of the ball, respectively; $\boldsymbol{v}_p \in \mathbb{R}^3$ is the paddle velocity; $\boldsymbol{\Gamma}_j(\boldsymbol{R}_p) \in \mathbb{R}^{3 \times 3}$ and $j = \{a, b, c, d\}$ are transformation matrices dependent on the rebound parameters and on the orientation of the paddle $\boldsymbol{R}_p \in SO(3)$ at the impact time; $k_d(\boldsymbol{p}_b, \boldsymbol{\omega}_b) \in \mathbb{R}$ and $k_l(\boldsymbol{p}_b, \boldsymbol{\omega}_b) \in \mathbb{R}$ are, respectively, drag and lift parameters; $\boldsymbol{g} \in \mathbb{R}^3$ is the gravity acceleration vector; $\|\cdot\|$ denotes the Euclidean norm; $\boldsymbol{S}(\cdot) \in \mathbb{R}^{3 \times 3}$ is the skew-symmetric matrix; and superscripts – and + represent the state before and after the impact, respectively. The matrices $\boldsymbol{\Gamma}_j$ can be detailed on the basis of the addressed rebound (ball impacting the table and/or a rubber paddle). Their expression may become complicated in nontrivial situations (like nonspherical objects), leading to the use of some (strong) assumptions and model reductions.

Five different phases have been considered to solve the batting problem by using the RoDyMan platform simulator. First, a vision system is assumed to measure the trajectory of the ball. By assigning the impact time, the prediction of the impact position and preimpact velocity of the ball are obtained numerically by solving the aerodynamic model (3a). Then, the postimpact velocity of the ball, such that it goes toward a desired goal in a predefined time, is computed solving (3a) backward in time. The analytic solution of the discontinuous part of the ball paddle model, given by (3b) and (3c), determines the configuration of the paddle to generate such velocity of the ball. Thereafter, the motion of the paddle to reach the desired configuration is a result of the minimization of its linear and angular acceleration with a coordinate-free approach, assuming that the path is generated on an arbitrary Riemannian manifold, similar to the tossing primitive. Finally, the motion of the RoDyMan joints is derived from a classical second-order closed-loop kinematic inversion. More details can be found in [6].

A similar algorithm can be used to accomplish different juggling patterns. The lesson learned is that these techniques may also be applied to other dynamic tasks that share the same hybrid nature with impacting manipulations, such as walking or running tasks.

Final Discussion

Despite the progress made with the RoDyMan project thus far, including real-time tracking of deformable objects employed in tossing and sliding tasks, several problems remain. The mechatronic platform should be revised to cope with issues caused by the high velocity of some nonprehensile manipulation primitives. In general, experiments involving nonprehensile actions are not easy to solve because of the

Figure 7. The renowned pizza chef Enzo Coccia wearing the Xsens MVN suit, with the RoDyMan avatar in the background acquiring and repeating the movements of the chef.

uncertain dynamics mainly due to friction; parameter estimation and/or robust controllers are thus essential. Moreover, physics terms causing nonsmooth behavior are often neglected when deriving the mathematical model of a given nonprehensile task, which makes the nonprehensile system look like a prehensile one. This happens with rolling, sliding, and pushing nonprehensile manipulation primitives. The proof that the designed controller does not violate the given assumptions is usually performed a posteriori. A method to directly control the contact forces should be addressed, and this might be a future research direction, leading to the design of nonsmooth and hybrid controllers that are also new frontiers for the research community.

Another approach might be to observe a pizza chef's activities to learn task simplification and to synthesize human-inspired control strategies, e.g., an integrated robotic platform able to acquire and transfer human-body motion to a robotic system is obtained by interfacing RoDyMan with a low-cost motion-capture system (see Figure 7). Once the teleoperation algorithm for real-time replication of human motion on RoDyMan is developed, a comprehensive taxonomy of dynamic prehensile and nonprehensile tasks, ordered for different levels of hand–arm and dual-arm coordination, can be built from scratch. To this aim, taking inspiration from the research conducted on anthropomorphic hands [21] or a single hand–arm system [22], a study on postural synergies for dual-arm robotic manipulation can be conducted to develop a framework simplifying learning strategies from human imitation. Such an approach will also take advantage of dimensionality reduction strategy to successfully apply supervised reinforcement-learning algorithms using synergistic motion. These observations showed that the motion planner is crucial for nonprehensile tasks because the repetitive actions seem well imprinted in the pizza chef's mind, while the corrections made by the hands are very small despite the difference between various doughs. Therefore, a good motion planner is the essential instrument within nonprehensile manipulation.

Another question that may arise is why the pizza-making procedure was used as an example. Is there a need to have a robot make pizza? In truth, the pizza-making process is only a convenient media expedient with scientific purpose. It is clear that, if a robot is able to manipulate pizza dough, it might be able to perform similar difficult manipulation tasks. In 1997, the RoboCup began; the intent certainly was not to replace real soccer players, but rather to advance the state of the art while facing both gaming and difficult problems for robots. With the same aim, RoDyMan is trying to mimic the artistic ability of a pizza chef. While facing this big challenge, many subproblems have to be addressed in parallel, which could have an impact in other domains. The perception of elastic objects is currently being applied in the medical context to shape variations in muscles and organs. The manipulation performed while tossing the deformable dough is currently under investigation to improve the automation of gluing a shoe's lower surfaces. The batting process has similar dynamics to walking gaits, and it could be used to improve autonomy of humanoids or employed for actuated prostheses.

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