Nonprehensile Dynamic Manipulation: A Survey

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***Abstract*—Nonprehensile dynamic manipulation can be reasonably considered as the most complex manipulation task. It might be argued that such a task is still rather far from being fully solved and applied in robotics. This survey tries to collect the results reached so far by the research community about planning and control in the nonprehensile dynamic manipulation domain. A discussion about current open issues is addressed as well.**

***Index Terms*—Nonprehensile manipulation, dexterous manipulation.**

I. Introduction

ROBOTIC manipulation has drastically improved during the last decades: thanks to the increase of powerful technology in both sensing and actuation, it has become possible to manipulate different kinds of objects in a fast way. Nevertheless, the sought human dexterous capabilities are still out of reach for robots. A taxonomy about manipulation is briefly recapped in [1].

Kinematic manipulation can be analyzed using only kinematics, and every motion of the manipulated object can be obtained by the knowledge of the movements of the robotic hand. An example might be the programming of a pick-and-place operation based on a purely kinematic representation of the task. *Static manipulation* is instead studied through both kinematics and static forces. An example might be the object grasped by a parallel-jaw gripper where frictional forces are required to verify stability. *Quasi-static manipulation* makes use of kinematics, static and quasi-static forces, like frictional forces in sliding contacts. An illustrative example might be pushing an object on a table. Within *dynamic manipulation*, forces due to accelerations play a relevant role along with kinematics, static and quasi-static forces. A simple example is the balance of a rolling object on the palm of the hand. It is thus apparent that each level of the taxonomy encompasses the previous one. Hence, a dynamic manipulation task deals also with kinematic, static and quasi-static sub-problems.

The literature related to robotic grasping mechanisms and dexterous manipulation recognizes two main characterizations of grasp restraint: *form closure* and *force closure* [2]. The former means that an analysis of the contacts reveals that even infinitesimal movements of the object are prevented, i.e., the object is immobile. The latter, instead, means that there exist contact forces, feasible with the considered friction models, counteracting any external wrench applied to the object. It goes without saying that form closure implies force closure.

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While an object is subject to bilateral constraints in case of a set of contacts satisfying either form or force closure, a manipulation task is said to be *nonprehensile* if the object is subject only to unilateral constraints [1]. In this case, the object can still be manipulated by the hand, but it is possible neither to prevent any infinitesimal motions of the object nor to resist all external wrenches applied to it. Think again of an object held by the palm of a human hand: the object is sustained, and it is not dropped; however, it is not possible to resist to a force lifting up the object, while it is possible to manipulate it by either moving the hand or breaking the contact by throwing.

Having the above definitions in mind, it is possible to describe a *nonprehensile dynamic manipulation* task. This is an action where the object's motion is not strictly constrained to follow the movement of the hand. The object is then subject only to unilateral constraints and, in order to accomplish the manipulation goal, the dynamics of both the object and the hand manipulating it, the related kinematics, static and quasi-static forces play a relevant role. Pushing objects, folding clothes, cooking in a pan, bringing a pitcher on a tray, and performing some surgery operations are examples of dynamic nonprehensile manipulation tasks.

This survey tackles three main aspects related to the application of dynamic nonprehensile manipulation in robotics: the benefits of investigating such kind of sophisticated manipulation actions; the approach employed so far in the literature to deal with dynamic nonprehensile manipulation and the related state of the art; and a general discussion related to current open problems. To the best of the authors' knowledge, the present letter is also the first complete survey on the topic. Other reviews are given in [3] and [4].

II. Overview About Nonprehensile Dynamic Manipulation in Robotics

Some manipulation tasks are intrinsically prehensile like (un)screwing a bottle cap. Others are instead inherently nonprehensile, like carrying a glass full of liquid on a tray. Some other manipulation tasks can be alternatively achieved in both a prehensile and a nonprehensile way: if an object on a table has to be moved from position A to position B, one can either grasp the object and move it (pick-and-place), or (s)he can push the object from A to B. Finally, manipulation tasks can also need both prehensile and nonprehensile actions. An illustrative example is given by the cascade juggling pattern where a juggler has to throw a ball with one hand (nonprehensile operation), while the other hand has to firmly catch another ball (nonprehensile for the dynamic catching part and prehensile when the ball is grasped between the fingertips).

In general, robot manipulators are very efficient in pick-and-place operations. This is reasonable since once the robot has firmly grasped the object between the gripper's fingers, it can rely upon its position accuracy capability to move the object without the need of continuously sensing the state thereof [5]. The manipulation capabilities are thus strongly related to those of the robot. Although the robot dynamics can be fully exploited during pick-and-place operations, the object is constrained within the robot workspace. Nonprehensile dynamic manipulation offers instead several advantages [4]:

- since the manipulated object has not to be firmly grasped, then it is possible to use simpler manipulators structures because it is sufficient to use any available surface of the robot to manipulate the object through proper forces;
- the workspace can be increased since the continuous contact between the robot and the object is not always required within a nonprehensile dynamic manipulation task (e.g., the robot may throw the object and dynamically catch it thereafter);
- since the degrees of freedom of the object are no longer limited by the ones of the manipulator because of a form/force closure grasp, then it is possible to control more degrees of freedom than the manipulator itself, increasing in this way the dexterity of the manipulation process.

The price to pay for these benefits is the increase of complexity in planning and control since the whole dynamics have to be adequately taken into account. Moreover, nonprehensile dynamic manipulation tasks may be hybrid, i.e., they exhibit non-smooth dynamics. As a matter of fact, it is possible to think of a situation where the contact between the manipulator and the object changes: initially the object sticks on the manipulator's surface, then it can slip on it and, later, the contact can be lost since the manipulator may throw the object. As a result, given the (possible) non-smooth dynamics of the system, the purposes of the planner and the controller are the generation of suitable trajectories (e.g., a sequence of contact states) to lead the system along the desired (time-varying) goal [6].

From an analysis of the related literature, it is possible to figure out that the conventional way to cope with a nonprehensile dynamic manipulation task is to split it into simpler subtasks. These are usually referred to as *nonprehensile manipulation primitives*. Therefore, a typical nonprehensile dynamic manipulation task is a proper planned sequence of these primitives. Each primitive should be equipped with an appropriate motion planner and a controller, while a high-level supervisor has to switch between the various tasks suitably. In the following, a list of such possible primitives is given [1], [6].

- *Throwing*: the manipulator has to throw the object in a desired location, possibly with a desired orientation. This primitive leads the object from a steady-state configuration attached to the manipulator to a complete freedom situation in a free-flight condition. The primitive is thus modeled as a hybrid system, establishing several problems like the lack of either the existence or the uniqueness of solutions, difficulties in performing proper and trustworthy simulations, controllability issues, scalability hurdles and so on.
- *Dynamic catching*: the manipulator has to dynamically stop the object on its surface by dissipating the energy of the impact without using any form or force closure grasp. As an example, one may think to a thrown ball that is caught in the palm of the hand without closing the fingers on it. This primitive is referred to as a *dynamic grasp*, and it exhibits non-smooth dynamics: hence, related problems are similar to the throwing task.
- *Batting*: this primitive combines dynamic catching and throwing in a single collision. An illustrative example is the rebound of the ball with the baseball bat. Iterative batting motion primitives may create *juggling* or *dribbling* tasks.
- *Pushing*: the manipulator pushes the object towards the desired configuration. Friction plays a critical role, and this establishes several issues: friction identification is indeed a difficult challenge. Hence, robust controllers are often designed, but nonlinear controllability is not easy to verify when friction is addressed. Reliable planners are crucial as well.
- *Sliding*: the motion of the objects sliding on the surface of the manipulator can be controlled using friction forces, as the robot moves or vibrates like in the parts reorienting task using vibratory systems (i.e., the Stewart platform). Since friction plays a vital role for this primitive, related problems are similar to the pushing task.
- *Rolling*: the object rolls upon the surface of the manipulator. Assuming to consider only pure rolling, the constraint is holonomic in case of 2D scenarios, like the ball-and-beam and disk-on-disk systems; the constraint becomes nonholonomic in case instead of 3D situations, like the ball/disk-on-plate examples. Nonholonomic constraints complicate system dynamics. The major issues are related to the controllability analysis and the controller design, yielding to either time-varying or switching solutions.

The following section reviews the state of the art for each of the aforementioned nonprehensile manipulation primitives. Notice that, in the literature, it is possible to find references to other nonprehensile manipulation primitives, such as snatching [1], tapping [7], etc. However, it is possible to see them as a combination of the ones listed above.

III. Manipulation Primitives

A. Throwing

Three stages can be identified within the nonprehensile throwing manipulation primitive: the acceleration part, in which the robot confers to the object an initial velocity/acceleration and both are in contact; the release part, where the object's degrees of freedom are released; and the free-flight part, in which the object separates from the manipulator. During the first phase, the robot motion is planned so that the object can reach the desired state (position, velocity, and acceleration) for the release. During this stage, either the object can be firmly grasped by the gripper, or it can merely be in contact with it in a nonprehensile configuration. From the considered grasp, the second stage changes. If the object was simply in contact, the object could be released instantaneously: the free-flight condition for the object immediately starts. If the object was instead firmly grasped, then the gripper gradually relaxes the grasp around the object that appears in a free-flight condition after a certain amount of time. Think of a baseball pitcher: he can impart a significant angular velocity to the ball since, before the release, the ball is allowed to roll out of his hand [1].

Reviewing the literature, throwing a club with a robot has been one of the very first example investigated by the robotic community [1]. Learning approaches are instead studied in [8]. Recently, tossing of a deformable object has been tackled in [9]: a coordinate-free method is employed to model the dynamics of both the robot and the deformable object. Finally, the task of striking an object that is allowed to slide on a surface can be considered as a kind of 2D throwing [7], [10].

B. Dynamic Catching

Dynamic catching is a primitive aimed at stopping a thrown object upon the surface of the robot in a nonprehensile configuration. As highlighted in [1], dynamic catching would be theoretically similar to throwing with reversed time in case the system was energy-conserving. In practice, due to the uncertainties about the arrival state, energy dissipation is instead crucial to cease the motion of the object upon the manipulator's surface.

The collision between the object and the robot can be either inelastic or elastic. In the former case, the object's energy is absorbed in a certain amount of time due to the material of the manipulator's surface and/or the material of the object's surface. In this way, rebounds can be avoided. However, this complicates the control design. On the other hand, an elastic collision unavoidably creates a sequence of bounces with the final objective to stop the object's motion. Elastic collisions can then be regarded as a particular type of batting manipulation primitive (see next subsection) with the purpose of making the object motionless.

Reviewing the literature, a sequence of collisions is planned for a ball through energy-absorbing padding [11]. Three different approaches are used in [12] to palm a ball on a planar paddle. A motionless surface is instead considered in [4], where the final state of the object is chosen to make the catch robust. The surface is instead active in [13] to dynamically catch a basketball on a planar paddle mounted on the end-effector of an industrial robot, and in [14] where imprecise knowledge of the object state is addressed. A non-spherical object is instead considered in [15] for the devil stick task, where a thrown stick has to be dynamically caught by another actuated stick. Regarding inelastic collisions, an optimal trajectory in $SE(3)$ is planned for the end-effector to catch a falling deformable object [9] dynamically.

Notice that absorbing the energy of a thrown object is also an issue faced by researchers working with prehensile grasps, as in the *ball catching* applications [16].

It is worth noticing that both throwing and dynamic catching tasks are usually not considered standalone, but they merge in the batting primitive as described below.

C. Batting

Batting absorbs the two previous primitives in a single collision. No doubt, the most famous examples are the baseball and the table tennis games, where the stick/paddle intercepts the ball and simultaneously redirects it.

By reviewing the literature, a commercial PUMA 260 has been among the first industrial robots to play table tennis game in real-time [17]. A low-cost ping-pong player prototype is instead proposed in [18]. A high-speed and reactive motion trajectory planner is described in [19], where the batting task is accomplished by modifying the hitting point through visual feedback. As evident in [20], also bipedal robots can be used to play the table tennis game: in that work, an optimal momentum compensation approach is used to cancel the momentum generated by the arms to bat the ball. An approximated hybrid aerodynamics of the ball is taken into account in [21] to bestow the ball with the desired spin, too. An optimal trajectory planner with the imposed spin is also considered in [22], where full aerodynamics of the ball is employed within an optimization problem, and the trajectory of the paddle is directly planned on $SE(3)$. Table tennis games have also been addressed from the artificial intelligence community through learning techniques [23]–[26], fuzzy systems [27] and probabilistic approaches [28]. Nonprehensile batting applications can also be found within aerial robotics: an open-loop trajectory and a Kalman filter are employed in [29] to guide the quadrotor towards the predicted impact position; a commercial drone is instead used in [30] along with learning techniques to estimate where and when hit the ball; an optimal trajectory generation method is adopted in [31] so as to obtain a minimum-jerk trajectory.

A periodic application of the batting manipulation primitives creates a juggling or a dribbling task. In the former, the object is simultaneously caught and thrown towards a receiving actuated platform performing in turn, and iteratively, the same action. An example is given by the single- or double-paddle juggling [32]. In the latter, the object is redirected towards a fixed surface: the continuous batting of the robot and the consequent rebound on the surface creates the dribbling task. A simple example is given by a basketball player repetitively bouncing the ball on the ground [33].

By reviewing the juggling literature, the stabilization of a puck which is juggled by a bar actuated by a revolute joint is investigated in [34] and [35]. A similar robotic platform is employed in [36] to demonstrate the juggling of a planar disk in a gravity field stabilizing the desired limit cycle. Some feedback control strategies are employed in [37] to continuously bounce a ball in the air, also discussing robustness properties due to parametric uncertainties. A multiple balls juggling task is addressed and experimentally validated in [38]. A hybrid control algorithm able to track a periodic reference trajectory is instead proposed in [39]. The so-called *blind juggler* is presented in [40]. The idea is to completely rely on the suitable design of the mechanical structure of the robot to repetitively bounce a ball without using any external sensor. The concept of iteratively passing objects between two hands or two manipulators is also an example of a juggling task based on the batting manipulation primitive [41]–[43]. Finally, learning aspects in juggling tasks are examined in [32], [44]–[46].

About the dribbling task, a one-degree-of-freedom elastic robot is considered in [47]: the ball motion is modeled as a hybrid system, while a simplified robot model is derived from studying the essential elements of the resulting dribbling cycles. Notice that the presence of the elastic component intrinsically extends the contact time between the ball and the robot. A similar concept has been exploited in [33], [48]: in this way, the ball can be controlled in a continuous time fashion instead of coping with issues related to the hybrid nature of the intermittent contacts.

D. Pushing

Pick-and-place operations are not always feasible. In those cases in which the object is too heavy or too large to be grasped, other solutions have to be considered. Pushing an object is a simple solution widely adopted by humans, and the same concept can be thus transferred to robots. As described in [49], the control problem is made difficult by some indeterminacy about the presence of friction forces, also causing an unpredictability of the precise object's motion.

By reviewing the related literature, a complete survey about the pushing manipulation primitive before 1996 can be found in [49]. It is worth remarking that within [49] it has also been demonstrated that, supposing to have a non-zero friction coefficient, for any polygonal object there exists an edge from which the object is controllable through stable pushes (the object remains in contact with the manipulator pushing it). A sufficient condition to switch between edges is also provided. Necessary and sufficient conditions are instead found in [50] for small-time local controllability. A quasi-static analysis is employed in [51] to suitably plan 2D manipulation through pushing operations, interrupted by some tumbling actions, under Coulomb friction assumption. The method has been extended in [52] to cope with computational burden and control mode of the single fingers. A global rapidly-exploring random tree (RRT) together with a local planner is introduced in [53] to plan sequences of pushes steering the object towards the desired position and orientation. The RRT approach is also employed in [54], in which the planner explores the configuration space by randomly sampling dynamic nonprehensile pushing actions and utilizing a black box physics models to predict the outcomes of the planned actions.

The presence of obstacles is addressed in [55]: the object exploits the compliance given by the environment. An object can also be pushed away because it is itself an obstacle towards the reachability of another object that has instead to be grasped. Such a problem is addressed within the *push-grasping* task in [56]: the robot manipulator pushes away the obstacles during the approaching path for object grasping. A similar idea is also adopted in [57].

When a mobile manipulator pushes an object, the stability of the robot has to be considered as well. For instance, if a humanoid pushes a heavy object, conditions regarding the internal forces and the position of the foot preventing the robot from sliping have to be found [58]. Body posture and contact placements are examined in [59] for object pushing through a wheeled dynamically balanced robot.

Finally, pneumatic manipulation using air-flow may fit the pushing nonprehensile manipulation primitive. In this case, the contact is established between the air gust delivered by the robot and the object: there is not a direct touch between the manipulator and the manipulated part. A survey about this specific topic is available in [60].

E. Sliding

This primitive is often referred to as *vibratory-induced* or *friction-induced* manipulation . The sliding behavior is indeed exhibited in other manipulation primitives like pushing, where friction and supporting forces are relevant as well. However, sliding might be distinguished from pushing by whether the object is moved by the motion of the supporting surface or by the action of a separate pusher. Moreover, the nonprehensile pushing manipulation primitive is addressed from a quasi-static point of view. Vibratory- or friction-induced manipulation is instead discussed from a dynamic point of view, and then the effects of sliding and friction are considered differently. Therefore, to be consistent with the rest of the letter, the term sliding is preferred.

The vibration of a three-degree-of-freedom platform can create virtual force/velocity fields on its rigid horizontal plate as proved in [61] and [62]. This virtual field is generated by asymmetric periodic plate motions such that the resulting net force, including friction, is non-zero on the manipulated object. The work has been extended in [63] using a six-degree-of-freedom actuated platform. Virtual fields able to move the desired object(s) on an attraction/repulsion line are investigated in [64]. These fields are often referred to as *squeeze fields*, and they have also been examined in [65]–[68]. The proof that every periodic plate motion maps to a unique asymptotic velocity field is provided in [69]. Further types of virtual velocity fields are instead introduced in [70]. The effect of anisotropic friction on vibratory-induced velocity fields is analyzed in [71].

By taking inspiration from the pizza chefs, a two-degrees-of-freedom platform is used in [72] to create a virtual force field on a peel to translate and rotate a rigid disk. Such work has been extended to cope with deformable objects in [73], a sheet-like viscoelastic object in [74] and a thin rheological object in [75].

F. Rolling

Once the friction between two surfaces in contact is such that there is a direct proportionality between the linear and angular velocity of the rolling object, while twist motion is not allowed, then the assumption of pure rolling holds. In case the object can freely roll subject only to unilateral constraints, then it is possible to talk about the nonprehensile rolling manipulation primitive. Inevitably, local rolling motion places a restriction on the relative curvature at the contact point. However, a nonprehensile pivoting action, i.e., rotating an object around either a corner or an edge, can be treated as rolling [52], [76].

If the rolling object is a sphere, the related literature becomes wider. It is worth splitting the analysis in case of planar (holonomic) and spatial (nonholonomic) examples.

1) Nonprehensile Holonomic Rolling: For this class of nonprehensile manipulation primitive, many illustrative examples have turned into benchmark platforms for testing different control approaches and methodologies.

In the *ball-and-beam* system, a sphere freely rolls upon a bar pivoting at a point that is actuated by a motor. The rolling sphere has just one degree of freedom, but it is possible to show that feedback linearization cannot be applied. An approximate input-output linearization is proposed in [77], while an output feedback controller is investigated in [78]. A flatness-based approach with an exact feedforward linearization is instead introduced in [79]. The so-called *passivity-based control* (PBC) based on an *interconnection and damping assignment* (IDA) is applied in [80], modifying both the related potential and kinetic energies. Stable and robust oscillations of the rolling sphere on the linear beam are obtained in [81], while a redundant manipulator is employed in [82].

An evolution of the ball-and-beam system is given by the *disk-on-disk*, where the linear-actuated beam is replaced by a homogeneous actuated disk that has to balance the upright disk in full gravity. A feedback stabilization control is designed in [83], while a backstepping approach is employed in [84] to stabilize the upright position of the free rolling disk. An IDA-PBC approach is instead introduced in [85], while a passivity-based technique to deal with matched input disturbances is addressed in [86]. The case where the actuated disk is not homogeneous is referred to as *circular ball-and-beam* [87].

The so-called *butterfly robot* is a further complication of the shape of the actuated surface. This is inspired by a juggler's skill in which the ball starts in the palm of the juggler's open hand. By accelerating and adequately shaping the hand, the juggler can roll up the ball on the fingers top, and then down to the back of the other side of the hand. From a robotic point of view, the analysis of proper shape to perform such an experiment is studied in [88], in which a feedforward motion solution is also found. Energy-based control is proposed in [89], while an elegant controller to stabilize the periodic motion is designed in [90].

Finally, planning and control on generally curved shapes are investigated in [91]. The shape of the manipulator and the related motion are optimized in [92] through a nonlinear optimization problem handling splines. Nonprehensile rolling systems where the object's center of mass does not coincide with its geometric center are analyzed in [93]. The assumptions such that a general planar nonprehensile rolling system must have to be input-state linearizable are found in [94].

2) Nonprehensile Nonholonomic Rolling: The *ball-on-plate* gives the most illustrative example of a nonprehensile nonholonomic rolling system. The primary objective is to steer the free-rolling sphere toward the desired position and/or orientation or along a desired path. The kinematics of rolling contacts is firstly introduced in [95]: using chart representation and differential geometry tools, the motion of a contact point over the surfaces of the rolling object in contact with the plate can be described. It is worth pointing out that most of the works addressing the ball-and-plate application consider the prehensile case obtained by caging the sphere between two plates [96]–[99]. Usually, in that configuration, one plate is actuated while the other one is fixed. Nevertheless, by dismissing the fixed plate, the ball-and-plate application is addressed as a nonprehensile rolling manipulation system in which the ball is controlled by the sole supporting moving plate. Therefore, position control of a basketball on a plate is addressed in [100]. An analysis of the kinematics of rolling, based on a coordinate-free approach, considering the cases of either pure rolling or twist-rolling, is proposed in [101]. A single actuator is instead employed in [102] to control a rolling ball in an asymmetric bowl.

An extension of the disk-on-disk system to the 3D case is given by the stabilization of a ball free to roll on an actuated sphere in full gravity. The stabilization of the upright ball is obtained through a linearization around the equilibrium point in [103]. A feedback linearization and a sliding mode controller are instead derived in [104].

The *hula-hoop* task belongs to the nonprehensile rolling primitive as well. From a robotic point of view, this can be schematized through a hoop freely rolling around an actuated pole. A first mathematical derivation is proposed in [105] without taking correctly into account the nonholonomic constraints. This issue is overcome in [106], in which a control approach without velocity measurement is proposed. A formal mathematical analysis which guarantees ultimate boundedness of all coordinates is developed in [107].

IV. Discussion and Open Problems

Advancements in the domain of robotic nonprehensile manipulation have been relatively slow. Two main reasons can be identified: i) technology has provided fast actuation and reliable sensing to deal with problems placed by nonprehensile manipulation only within the last decades; ii) nonprehensile manipulation encompasses so many different types of manipulation, and the lack of a reliable theoretical background, preventing the development of a community growing around some well-established concepts, limits the applications to strewn research centres creating ad-hoc solutions for particular tasks. Several control problems in nonprehensile dynamic manipulation are listed in [6]. These span from defining reasonable and testable controllability notions; identifying feasible assumptions in which some applications can be reduced from dynamic and/or quasi-static systems into kinematic ones; generating suitable trajectories for non-smooth and hybrid systems; and stabilizing desired trajectories and equilibrium configurations. From the above literature review, it is not difficult to argue that much progress has been made during the last decade regarding the above list of problems. Nevertheless, there are still three main aspects that are not yet fully solved.

The first aspect is indeed the lack of a general unified theoretical framework in this field, determining the design of ad-hoc controllers to solve the aforementioned nonprehensile manipulation primitives task by task. Within the prehensile manipulation domain, for instance, the grasp matrix tool is the starting point to analyze the stability of a grasp and a prehensile manipulation task. The equivalent to the grasp matrix does not exist within the nonprehensile manipulation domain. Nonetheless, the IDA-PBC has been recently identified as a possible unifying approach at least for the rolling nonprehensile manipulation primitive [108].

The second aspect is the recurring adoption of assumptions to mathematically model a nonprehensile system as a prehensile one. Such approach simplifies the control law design. To better explain the concept, focusing on sliding, rolling and pushing nonprehensile primitives, the assumption of continuous sliding, rolling and pushing contacts is often considered for control design purposes. This somehow renders the nonprehensile system as instead a prehensile one. The reason is straightforward: the control design can be done in a "simpler" way, even though system dynamics remains very cumbersome in most of the cases. The proof that the designed controller does not violate the given assumptions is often performed *a-posteriori*. Therefore, a method to directly control the contact forces should be indeed addressed. This might be a future research direction, even though it requires to cope with complicated hybrid dynamics where friction is predominant.

The third aspect not adequately addressed yet is the suitable design of the high-level supervisor enabling the correct switching between different nonprehensile manipulation primitives. A recent attempt is carried out in [5]. Learning-based approaches may indeed be helpful to design such supervisor since task simplification, and human-inspired control strategies may be the key towards the fulfilling of the whole complex nonprehensile manipulation task. By learning the intricate and dexterous manipulation skills of humans, it would be possible to understand how to switch between the different nonprehensile manipulation primitives whose models, except the mentioned concerns, are reliable, and for which suitable model-based control solutions already exist as highlighted in the carried out survey.

As a lesson learned from this comprehensive literature review, it is worth highlighting the feeling that high-speed performance is requested for most of the nonprehensile manipulation primitives. By observing a skilled juggler, it is possible to notice that repetitive actions are well imprinted in her/his mind, while only small corrections are made by her/his hands/fingers/arms. Then, it is possible to affirm that a proper motion planner is essentially most of all. Besides, it is also possible to find interesting connections between different domains: for instance, in the same way as a robotic hand creates intermittent contacts with an object in a nonprehensile manipulation task, a legged robot places and removes feet on the ground during a walking gait. A link between grasping and balancing of a legged robot already exists. It would be interesting to find a similar connection between dynamic walking and nonprehensile manipulation.

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