Robot Control for Nonprehensile Dynamic Manipulation Tasks

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1 RESEARCH PROBLEM

The robotic manipulation problem aims at finding a set of suitable controls to change the state of an object from an initial to a desired configuration. In the last decades, with the increase of powerful technology in both sensing and actuation speed, it has become possible to manipulate an object in a very fast way. Indeed, robotic manipulation can be intended as both prehensile and nonprehensile. Manipulating in a nonprehensile way means that the object is not directly caged between the fingertips or the palm of the hand. The force closure constraint (Murray et al., 1994) does not hold during a nonprehensile manipulation action. The grasp is then performed only exploiting unilateral constraints, allowing the object to roll, slide, and break the contacts with the robot manipulating it. Examples of nonprehensile manipulation are in everyday life such as pushing objects, folding clothes, bringing wineglass on a tray, cooking in a pan, and so on, Figure 1. Nonprehensile manipulation can also by identified as *dynamic* when the dynamics of both the object and the robot are essential to successfully accomplish the task.

The class of nonprehensile dynamic manipulation problems is still rather far from being fully solved and applied in robotic applications. In this kind of manipulation it cannot be always closed a kinematic chain, with the drawback of not having always a direct kinematics available. Besides, when one of more contacts change their status, the dynamics of the system changes in a non-smooth manner making difficult the choice of a good control law. Moreover, since the object can perform a large variety of motions, most of nonprehensile systems are underactuated, arising controllability issues. Nevertheless, nonprehensile dynamic manipulation offers several advantages, such as increase of available robot actions, bigger operative workspace, reduction of task execution time, enhanced dexterity in dynamic tasks.

Applications of nonprehensile dynamic manipulation through robots span industrial, surgical, humanoid and service robotics. As a matter of fact, it can be applied to control vibratory platforms, usually employed in those applications where it is not directly possible to manipulate small or damageable objects; in surgical robotics, to push away arteries and reshape muscles or organs; and in service robotics, where the development of humanoid robots assisting elderly people in everyday tasks can be sped up with the extension of the set of available robot movements. Last but not least, many similarities exist between dexterous nonprehensile manipulation and robotic walking. Therefore, this research topic may have repercussions in the design of advanced legged robots, in the same way as the framework of frictional grasping can be applied to compensate disturbance and balance a legged robot.

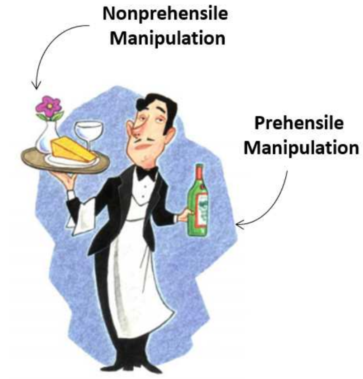

Figure 1: Nonprehensile and prehensile manipulation examples.

As it is possible to figure out so far, a nonprehensile manipulation action is a complicated, skillful and dexterous task. It can be usually undertaken by splitting in simpler subtasks, usually called *primitives*, such as rolling, pushing, throwing, batting, dynamic catching, and so on. A supervisory control is then required to detect, identify and switch between the available primitives to perform the original complex dynamic nonprehensile manipulation task.

The primitives inspected during this Ph.D. research program are mainly related to rolling tasks, involving a rolling constraint for balancing tasks in both planar and 3D contexts. Impact tasks are investigated at the same way. These last involve intermittent contacts between the object and the robot, exhibiting in this way a hybrid dynamics.

The problems of pushing, orienting and assembling parts have been extensively investigated for factory automation. The analysis of objects with multiple frictional contacts poses two interesting problems. The former, the forward problem, predicts the motion of an object given the applied force. Solving this is essential for simulation aspects. The latter, the inverse problem, predicts the applied forces producing a desired object motion, or the set of applied forces producing a desired contact mode. Solving this is essential for planning and control aspects. The presented Ph.D. research program is mainly devoted to the inverse problem.

2 OUTLINE OF OBJECTIVES

Many existing works in the robotic literature deal with the problem of nonprehensile dynamic manipulation. However, as it is clear from the following state of the art, a unified control framework does not exist so far. Therefore, the two main objectives of the described Ph.D. project are shown below:

- on one hand, an ambitious goal of the project is to contribute to identify classes of control frameworks solving appropriate nonprehensile dynamic manipulation tasks, dealing with the non linearity of their dynamic models and with the complexity of the control design;
- on the other hand, a technological challenge is also addressed for implementing the designed control actions on a physical prototype, that is performing a number of nonprehensile dynamic tasks on a mobile dual-arm/hands robotic platform.

3 STATE OF THE ART

Nonprehensile manipulation was firstly introduced in (Lynch and Mason, 1996a) and (Mason and Lynch, 1993). The following state of the art is focused on the classes of nonprehensile rolling and impact tasks. However, other classes of nonprehensile manipulations could be inspected, like sliding (Lynch and Mason, 1996b). This literature review can be very useful to understand the great deal of effort that many researchers have put at understanding the complex dynamics hidden in the control of such nonprehensile tasks.

3.1 Rolling Tasks

The class of rolling tasks is deeply investigated by the research community. Some benchmarks within this class are the ball and beam system, the circular ball and beam system, the ball and plate system, the disk on disk, and the butterfly robot.

3.1.1 Ball and Beam

In the ball on beam benchmark system, a ball rolls on a one degree of freedom (DoF) linear beam. This system was extensively studied in the past years because of its peculiar feature: it fails to have a well defined relative degree, thus feedback linearization cannot be applied. The authors of (Hauser et al., 1992) propose an approximate input-output linearization of this nonlinear systems. While, in (Ortega et al., 2002a) a Passivity-Based Control (PBC), known as Interconnection and Damping Assignment (IDA) is applied to the problem of stabilization of underactuated mechanical systems, like the ball and beam, which requires the modification of both the potential and the kinetic energies. The authors of (Gordillo et al., 2002) show a technique for obtaining stable and robust oscillations. The method consists of two steps: in the first one, a second order generalized Hamiltonian subsystem, which presents stable oscillations, is matched; in the second step, the controller is extended to the full system using backstepping. In (Ryu and Oh, 2011) a control method of the redundant manipulator to balance the ball-beam system is showed. The force/torque sensor attached to the end-effector of the manipulator is used for estimating the ball position. Because it involves significant noise, they employ a state feedback controller with an observer. Experiments with a 7 DoFs manipulator show that the proposed method enables the robot to balance the ball on the beam even though the external forces are applied in both the elbow of the manipulator and the ball.

A variation of the ball and beam system that is proposed in (Aoustin and Formal'sky, 2007), is the circular ball and beam, where the lower disk has a decentralized center of mass. The main difference with the straight ball-beam system is that the linear model of the second system has two eigenvalues in the right-half complex plane. Then it is more difficult to stabilize the circular ball-beam system than the straight one.

3.1.2 Disk on Disk

Another nonprehensile dynamic manipulation case study is the so called disk on a disk. The system consists of two disks in which the upper disk (object) is free to roll on the lower disk (hand) under the influence of gravity. The goal is to stabilize the object at the unstable upright position directly above the hand. In (Ryu et al., 2012) the authors present a backstepping approach to derive a control law yielding global asymptotic stability.

3.1.3 Butterfly Task

In (Lynch et al., 1998), a robotic task called butterfly is proposed. Starting with a ball resting on the palm of an open hand, the robot can accelerate and shape the hand so that the ball rolls up the fingers, over the top, and back down to the back of the hand. In (Surov et al., 2015) a method based on virtual-holonomic-constraints-based motion planning and transverse-linearization-based orbital stabilization is applied to this nonprehensile task.

3.1.4 Ball and Plate

In the literature the ball and plate is often intended as a laboratory benchmark system where the aim is to control the ball position only. However, in the research community other challenges have been tackled, such as the position and orientation control. In this task, the main complexity is the nonholonomic constraint induced by the non-slipping and non-twist conditions. In (Bicchi and Marigo, 2002)the manipulation of a sphere by rolling it between the jaws of a parallel jaw gripper is considered. They ensured rolling contacts by coating the gripper with a high friction material. They explored both the problem of shape recovery from tactile information and the problem of planning jaw motions for the desired manipulation of the object. However, the task considered by (Bicchi and Marigo, 2002) can be still considered prehensile, while in (Lee et al., 2008) the authors present a basketball balancing control scheme based on pure haptic information without using visual information. This is effectively a nonprehensile task, since the ball is not caged between two parallel grippers. They propose a control scheme that consists of three parts including balancing control, impedance control, and inner position control.

3.2 Impact Tasks

The control of impact systems is another very active research area over the last years. Several impact tasks are investigated, such as juggling, dribbling, batting, catching, etc.

3.2.1 Juggling Task

For the juggling tasks, the continuous motion of the actuator is used to control the continuous motion of the ball through an intermittent contact with the aim to keep the ball airborne continuously. In (Sanfelice et al., 2007) a hybrid systems approach to trajectory tracking control for a one DoF juggling system, also with multiple balls, is proposed. They model mechanical systems with impacts as hybrid dynamical systems where flows are given by a differential equation/inclusion and jumps by a difference equation/inclusion, on specific subsets of the state space. In (Tian et al., 2013) juggling experiments are presented to validate the hybrid control algorithm, that is capable of tracking a periodic reference trajectory. The one DoF juggling system consists of a nearly smooth vertical shaft with a piston-actuated bouncing ball. In (Biemond et al., 2013) the authors formulate Lyapunov based conditions for the global asymptotic stability of the hybrid reference trajectory. Using these conditions, they design hysteresis based controllers solving the hybrid tracking problem for the bouncing ball system. In (Naldi and Sanfelice, 2013) a study on the design of passivity-based controllers for a class of hybrid systems, in which the energy dissipation may only happen along either the continuous or the discrete dynamics, is described. In this work, they consider the bouncing ball actuated by a moving surface as example. A general definition of passivity is introduced, allowing to take advantage of the passivity property of the system at flows or at jumps. In (Reist and D'Andrea, 2009) and (Reist and D'Andrea, 2012) the authors show the design of a juggling robot that is able to vertically bounce a completely unconstrained ball without any sensing in 3D. They took the impact time measurements as feedback and proved that the closed-loop performance is only marginally improved as compared to open-loop control. The derived mapping allows to find the stabilizing design parameters: the paddle's acceleration at impact and the curvature of the paddle. In (Fontana et al., 2013) the authors present the Swinging Blind Juggler. It can juggle balls with a single actuated paddle that swings from side-to-side and is attached to the tip of a pendulum. Optimal control is used to compute paddle motions that synchronize the pendulum to the ball.

3.2.2 Dribbling Task

The authors of (Haddadin et al., 2011) present the analysis of an elastic dribbling robot with one DoF. The ball motion is modeled as a hybrid system and a simplified robot model is used to study the essential elements of the vertical elastic dribbling cycles. As the ball can only be controlled during contact, an intrinsically elastic hand extends the contact time and improves the energetic characteristics of the process. For investigating stability, as in (Reist and D'Andrea, 2009), they suppose to have found parameters for a closed cycle. By perturbing the initial conditions of the cycle they elaborate a mapping of the error from the cycle start to its end. To solve the issues related to the hybrid nature of the system in the robotic dribbling task, Bätz et al. propose to add an elastic element to the manipulator so the ball can be controlled in a continuous-time phase instead of an intermittent contact (Batz et al., 2010). In (Batz et al., 2009) two control designs for ball dribbling with an industrial robot are compared. For the two strategies, the ball position is determined either through force/torque or visual sensor feedback, and the ball trajectory is predicted with a recursive least squares algorithm. The vision-based approach performs better as compared to the force/torque-based approach, in particular for imprecise estimates of the coefficient of restitution.

3.2.3 Batting Task

Batting is a nonprehensile task similar to juggling, but with the main difference that the ball is thrown towards a precise goal; a practical example is given by the table tennis game. Such a task requires so high velocities and precision that robotic companies take it as an example to display the high performances of their products. For instance, Kuka has chosen the table tennis game to promote its wares in a thrilling commercial spot (Kuka, 2014), showing the potential abilities of robots. The Omron automation company has also broadcast a video showing its parallel Delta robot playing table tennis and coaching humans at CEATEC Japan 2015 exhibition, (Omron, 2015). In the scientific community, (Senoo et al., 2006) proposed an high-speed trajectory planner applied to the batting task. The authors also consider the robot dynamic model within their framework, and they rely upon a 1kHz high-speed vision system. Some impressive table tennis games between two humanoid robots are performed using the adaptive trajectory prediction developed by (Zhang et al., 2012). This model involves an offline training of the parameters on the base of the recorded state of the ball. Afterwards, the model parameters are online adapted for estimation and prediction processes. In (Serra et al., 2016a) the authors propose an optimal trajectory planner for the batting task and a method to control the ball dealing with the real-time constraints imposed by the fast dynamics.

4 METHODOLOGY

The main objectives of the Ph.D. project, illustrated in Section 2, are dealt with the following methodologies.

4.1 Nonprehensile Manipulation Control Design

In order to understand and recognize the dynamic effects which play a relevant role in nonprehensile manipulation tasks, a top-down approach is pursued. The robot is firstly modeled as an ideal system with a simplified dynamics and with available perceptual information. With these hypotheses, it becomes easier to investigate controllers where dynamic manipulation issues can be brought back.

In a subsequent stage, the presence of the robot dynamics can be considered. The effects of the robot dynamics on the classes of manipulation tasks can be evaluated, with the resulting adjustment of the corresponding control laws. Moreover, the introduction of redundancy in the robotic system can be evaluated to take advantage of its extra DoFs, and the motor dynamics can be examined. Joint-space controllers can be designed to consider also the effects of motor constraints in the whole system. Additionally, the perceptual information retrieved from sensors can be introduced. It is remarkable that the perception tasks in this Ph.D. research project will heavily focus on the real-time requirements posed by the fast dynamics involved in this kind of manipulation tasks.

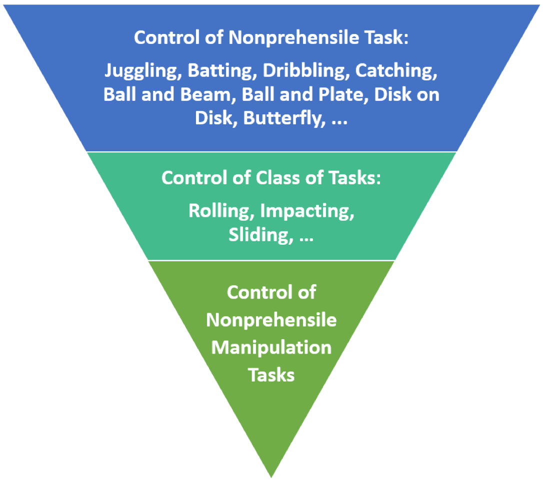

Figure 2: Bottom-up approach to develop a unified control methodology for dynamic manipulation.

4.2 General Control Design

In the opposite direction goes the methodology employed to identify control frameworks that are able to deal with classes of nonprehensile dynamic manipulation tasks. In fact, in this case, a bottom-up methodology is pursued. As stated in Sections 1 and 2, the complex task is split many primitives, such as rolling, pushing, throwing, batting, etc., see Figure 2. A supervisory controller is then assumed to identify the complex task and its primitives, and to properly switch between them. The pursued methodology is then to study step by step each nonprehensile manipulation primitive, equipping this last with the proper motion planner and controller.

In the presented Ph.D. project, passivity-based approaches and robust optimal control methods are currently inspected. The IDA-PBC framework allows to shape the energy of the controlled system, setting properly the kinetic and potential energy matching equations (Ortega et al., 2002b). This framework provides fast and analytic control laws, exploiting the nonlinear dynamics of the task, and taking advantage of the Lyapunov control theory to deal with the stability issues. The IDA-PBC is well suited to control Hamiltonian mechanical systems and provides physical interpretations to the control action. Therefore, it has been chosen to control the class of planar nonprehensile rolling manipulation tasks. However, the bottleneck of the approach is the solution of the matching equations that are typically partial differential equations. In fact, this framework in the 3D rolling configuration is quite challenging to apply.

Predictive optimal control (Mayne et al., 2000) is an alternative framework under investigation for nonprehensile dynamic manipulation tasks, because of the general structure of its inequality constraints and cost function. Linear models of the system dynamics allow to keep the computational time compatible with the real-time. Interesting examples of the application of the Model Predictive Control (MPC) framework to fast dynamics can be found in the locomotion control (see further details in Section 6.4). Nevertheless, the stability can be challenging to demonstrate since typically it is hard to obtain an analytic solution of the underlying optimization problem.

5 EXPECTED OUTCOME

The expected outcome of this research activity is to contribute in developing a unified framework for nonprehensile dynamic manipulation control, both in a theoretical and in a technological sense. The theoretical challenges involved in this study are related to the design of different control schemes for nonprehensile manipulation tasks, dealing with the identification of a general control framework suitable for a class of nonprehensile tasks. The technological challenge is instead related to the implementation of such control actions, filling the gap between ideal and the physical systems.

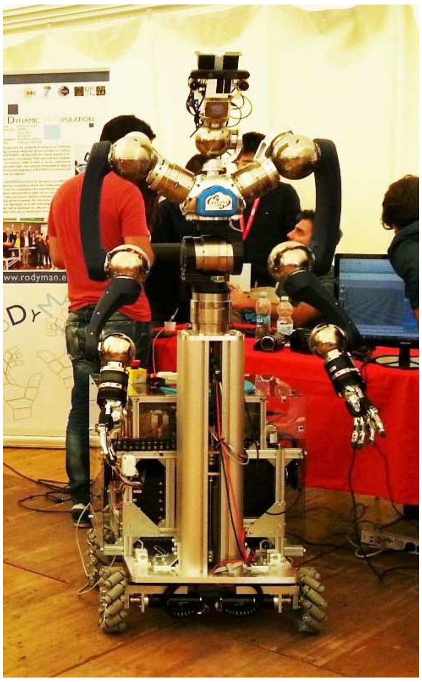

Figure 3: RoDyMan humanoid robotic platform available at PRISMA Lab. The humanoid is equipped with an omnidirectional mobile base, a torso, two Schunk robotic arms, two Schunk hands and a head provided with two cameras.

In particular, the control laws designed for each specific nonprehensile task are validated with simulations in Matlab R2015a, whereas experiments are going to be performed by using the humanoid available at PRISMA Lab (www.prisma.unina.it). Such humanoid, showed in Figure 3, is named RoDyMan.

It has a mobile base, a 2 DoFs torso, a pan and tilt neck, two 7 DoFs arms and two multifigered hands. In order not to directly test the designed controller on such complicated platform, some preliminary tests can be conducted either in a dynamic simulator like V-Rep, or on smaller dedicated setups. This is the case, for instance, of the disk on disk system (see Figure 4).

Besides, some methods investigated during this research can be transferred to other underactuated systems, like walking robots, since they share common features with the dynamic manipulation tasks. To this aim, it will be possible in a near future to modify the RoDyMan humanoid in Figure 3 to have at

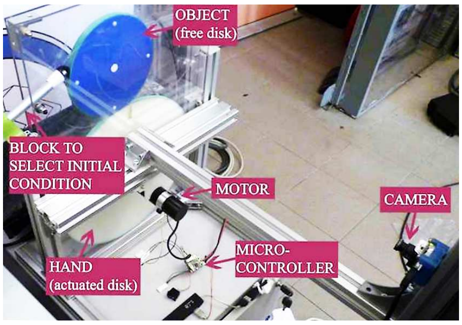

Figure 4: Disk on disk prototype available at PRISMA Lab.

disposition a legged robot where testing the derived controllers.

6 STAGE OF THE RESEARCH

Currently, the nonprehensile tasks under investigation are the ball and beam, the circular ball and beam, the ball and plate, the disk on disk, the juggling and the batting primitive, which belong the classes of nonprehensile rolling and impact systems. The passivity based control method is applied to the planar rolling manipulation of two arbitrary shapes. The problem of position and orientation control of a rolling ball acted by an underlying moving plate (ball and plate) is examined. Then, an optimum planner for the batting task applied to the table tennis game is implemented.

6.1 Planar Rolling Manipulation Control

The goal of this work is the application of IDA-PBC to the planar rolling manipulation between two arbitrary shapes, providing an extension of the work (Lippiello et al., 2016).

In this work a general planar model is introduced, where one shape is actuated (hand), the other one is free to move (object), and the object is restricted to roll without sliding on the hand. The object and the hand are assumed to maintain contact for all time. The curve of the object/hand is parameterized by an arclength parameter, and its shape is given by a chart in the object/hand frame, which is a function of the curve parameter, see Figure 5. The rolling assumption is modeled as an holonomic constraint. The corresponding Hamiltonian model of the system his derived, this has the advantage to represent the model as a general nonlinear system, suitable for the application of passivity based control methods.

The Port-Hamiltonian framework allows modeling of mechanical systems, preserving physical phenomenon information; the dynamical system is intended as an energy-transformation device. The action of a controller is understood in energy terms as another dynamical system interconnected with the process to modify its behavior. The control problem can then be recast as finding a dynamical system and an interconnection pattern such that the overall energy function takes the desired form. Additionally, shaping the energy permits to deal with not just stabilization, but also performance objectives. Hence, assuming constant mass matrix for the general system, an energy shaping control law that contains the arclength parametrization of the object/hand shapes is derived.

The balancing of the disk on disk is the case study considered to validate this approach, since in this system the assumption of constant inertia is valid. The proposed approach allows to find a general analytic expression of the desired potential energy for this class of system; overcoming the problem of solving the partial differential equations, which appear in the matching equations.

Moreover, removing the simplifying assumption of constant mass matrix, a new method to derive an IDA-PBC control law, relevant to this kind of rolling underactuated system, is proposed.

The approach employs a target potential energy matching equation which is an additional DoF, to select a suitable desired energy function for the closed loop system, and simultaneously to simplify the recognition of the desired closed loop mass matrix.

The procedure is applied to both the ball and beam and the circular ball and beam systems. Other tasks

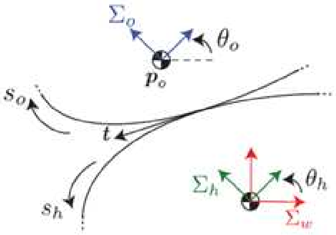

Figure 5: Scheme of the general nonprehensile planar rolling model.

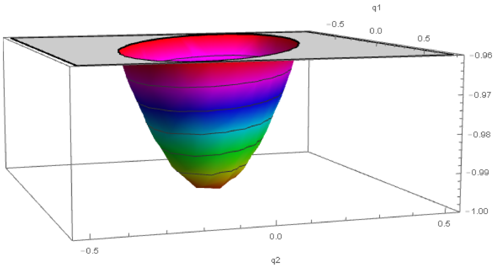

Figure 6: Desired potential energy for the ball and beam system obtained with a modified version of IDA-PBC.

could be considered, like a more general version of the circular ball and beam, which includes a decentralized center of mass of the object, or the butterfly task, taking into account a switching between charts.

Simulations demonstrate the effectiveness of the approach. A picture of the resulting desired potential energy function for the ball and beam is showed in Figure 6. The picture shows that the function presents a minimum in the equilibrium configuration, confirming the analytic result.

6.2 Ball and Plate Task Control

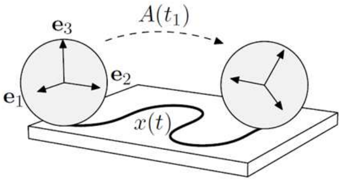

Figure 7: Ball and plate system.

The robotic nonprehensile manipulation of a 3D rolling ball is a challenging task because of the nonholonomic constraint induced by the non-twist and non-slipping conditions. In addition, this system is not asymptotically stabilizable with a smooth or time-invariant feedback because the Brockett's necessary condition (Block et al., 1992) is not satisfied. For this reason, many nonlinear control techniques, such as feedback linearization or passivity based control, fail for this kind of system. It could be interesting to investigate non-smooth or time-variant control approaches, like the MPC for nonholonomic systems (ACC Fontes, 2003).

However, here the focus is on how to plan a path for the ball position and orientation through the rolling motions obtained moving the plate (see Figure 7), taking into account the nonholonomic constraint. With this aim, a dynamic model of the ball and plate system is derived according to the Boltzmann-Hamel equations, taking into account the nonholonomic constraint. A controllability analysis reveals that the whole dynamics is not controllable, only a linear relation exists between ball position and plate position. Whereas, the ball dynamics is controllable.

Therefore, a geometric planning and control method is implemented to steer the rolling ball between two arbitrary position and orientation configurations. The algorithm previously computes the ball position, velocity and acceleration trajectories to reach a desired configuration. In a second stage it computes a feedback control for the plate to track the path planned for the ball. The linear relation between the ball and the plate position allows to constrain the movements of the plate within a pre-computed region.

The approach is validated in simulation, the Figure 8 shows the task to place the ball in the original position and to reorient it, with an angle of $-\frac{\pi}{2}$ around the z-axis of the world frame. The picture shows the linear relation between the Cartesian path of the ball in blue and the plate path in magenta.

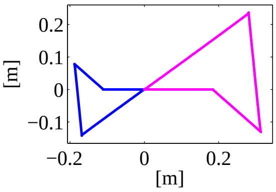

Figure 8: Ball (blue) and plate (magenta) paths to reorient the 3D rolling sphere, obtained in the first stage of the algorithm.

6.3 Batting Task Control

The other class of nonprehensile manipulation tasks considered in this Ph.D. project is the class of impact tasks. In particular, the batting task is deeply inspected and as benchmark example the table tennis game is considered, Figure 10. A method to compute the paddle state to return the ball at a desired position with a desired spin, is proposed in (Serra et al., 2016a). The method takes into account the dynamic model of the ball in free flight as well as the state transition at the impact (the reset map).

The optimal paddle trajectory to achieve the batting task is computed in four stages. The first one has the aim to predict the impact position and velocity of the ball, supposing to have at disposition the estimated trajectory of the ball from the visual system and the desired final configuration of the ball. The second stage computes the velocity of the ball after the impact such that it reaches the goal position at the desired time. Consequently, the paddle configuration at impact is computed solving the reset map. And, finally, the problem of generating an optimal trajectory for the end-effector of the paddle is tackled. The optimal trajectory minimizes the paddle acceleration functional, solving a two boundary value problem on SE(3).

The novelties introduced by this work are twofold. Firstly, in comparison to the state-of-the-art, the proposed method improves the control accuracy by considering a full aerodynamic model of the ball, and taking into account drag and lift forces. The computation time of the algorithm is also fast enough to guarantee it can suitably be implemented in real-time. Secondly, rigorous methods from calculus on manifolds are borrowed to generate an optimal trajectory on SE(3) for the paddle to strike the ball at the impact time.

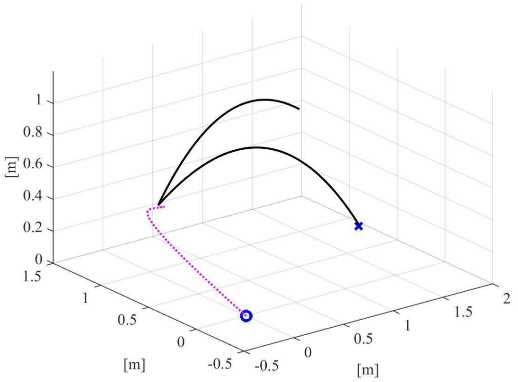

Figure 9: 3D trajectories of the ball, solid line, and the paddle, dashed line, obtained with the proposed method to control the batting task. The blue circle represents the initial position of the paddle, while the blue cross is the desired final position of the ball.

An exemplar simulation of the proposed algorithm is shown in Figure 9. The results are also confirmed through a comparison with state-of-the-art methods reported in (Serra et al., 2016a). A visualization of the simulation can be found in (Serra et al., 2016b) where a virtual simulator of the RoDyMan humanoid robot in the V-Rep environment, showed in Figure 10, is employed.

The same approach can be applied to the nonprehensile juggling task assuming that the batting is done between the two hands of the robot, and iterating the described algorithm.

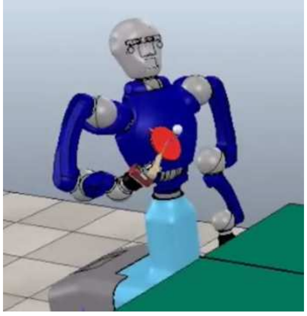

Figure 10: Visualization of the RoDyMan humanoid robot in the V-Rep software environment.

6.4 Locomotion Control and Dynamic Manipulation

Currently, the relation between manipulation and the locomotion is under investigation. Just as a legged robot places and removes feet on the ground, a robotic hand places and removes fingers on an object.

Methods for grasp analysis deal with the same constraints on contact forces and center of mass position that arise for legged robots on irregular and steep terrain, since during manipulation the surface of the object is rarely flat and horizontal.

A bipedal legged robot is typically modeled as a cart pendulum system, see Figure 11. This simplified model has some analytic properties very similar to the class of models of nonprehensile planar rolling systems, therefore the modified IDA-PBC control framework, developed for them, could be applied to the locomotion control.

Evidently, several analogies exist between nonprehensile manipulation and legged robots. For example, the equivalent of a bouncing ball system is an hopping robot, pushing an object can be related to the walking task, and there is a clear analogy between the juggling and the running task.

The MPC framework, widely used in the generation of walking patterns, provides the ability to forecast one or two contact sequences ahead and exploit robots dynamic to generate the motion that will go through. This can be an advantageous property to exploit with fast dynamics, like in nonprehensile manipulation. This control framework is very successful when constraints are involved in the control action. In the walking task, the main constraint to satisfy is balance; similarly, the constraints to apply for each class of nonprehensile tasks, while guaranteeing their linear structure, should be identified.

Therefore, the solution of the inverse manipulation problem, i.e. to predict the applied forces producing a desired object motion, with the MPC framework, for some classes of nonprehensile tasks, is the next challenge.

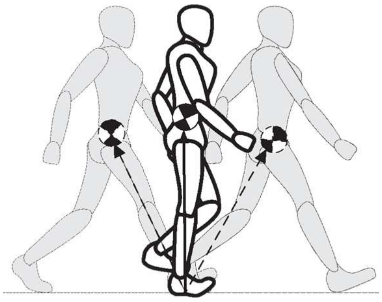

Figure 11: Walking robot as inverted pendulum.

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REFERENCES

ACC Fontes, F. (2003). Discontinuous feedbacks, discontinuous optimal controls, and continuous-time model predictive control. *International Journal of Robust and Nonlinear Control*, 13(3-4):191–209.

Aoustin, Y. and Formal'sky, A. (2007). An original circular ball-and-beam system: stabilization strategy under saturating control with large basin of attraction. In *Control Conference (ECC), 2007 European*, pages 4833–4838. IEEE.

Batz, G., Lee, K.-K., Wollherr, D., and Buss, M. (2009). Robot basketball: A comparison of ball dribbling with visual and force/torque feedback. In *Robotics and Automation, 2009. ICRA'09. IEEE International Conference on*, pages 514–519. IEEE.

Batz, G., Mettin, U., Schmidts, A., Scheint, M., Wollherr, D., and Shiriaev, A. S. (2010). Ball dribbling with an underactuated continuous-time control phase: Theory & experiments. In *Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on*, pages 2890–2895. IEEE.

Bicchi, A. and Marigo, A. (2002). Dexterous grippers: Putting nonholonomy to work for fine manipulation. *The International Journal of Robotics Research*, 21(5-6):427–442.

Biemond, J. B., van de Wouw, N., Heemels, W. H., and Nijmeijer, H. (2013). Tracking control for hybrid systems with state-triggered jumps. *Automatic Control, IEEE Transactions on*, 58(4):876–890.

Block, A., Reyhanoglu, M., and McClamroch, N. H. (1992). Control and stabilization of nonholonomic dynamical systems. *IEEE Transactions on Automatic Control*, 37(11):1746–1757.

Fontana, F., Reist, P., and D'Andrea, R. (2013). Control of a swinging juggling robot. In *Control Conference (ECC), 2013 European*, pages 2317–2322. IEEE.

Gordillo, F., Aracil, J., and Gómez-Estern, F. (2002). Stabilization of autonomous oscillations and the hopf bifurcation in the ball and beam. In *Decision and Control, 2002, Proceedings of the 41st IEEE Conference on*, volume 4, pages 3924–3925. IEEE.

Haddadin, S., Krieger, K., Kunze, M., and Albu-Schaffer, A. (2011). Exploiting potential energy storage for cyclic manipulation: An analysis for elastic dribbling with an anthropomorphic robot. In *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on*, pages 1789–1796. IEEE.

Hauser, J., Sastry, S., and Kokotovic, P. (1992). Nonlinear control via approximate input-output linearization: The ball and beam example. *IEEE transactions on automatic control*, 37(3):392–398.

Kuka (2014). The Duel: Timo Boll vs. KUKA Robot. [web page] `https://youtu.be/tIIJME8-au8`.

Lee, K.-K., Batz, G., and Wollherr, D. (2008). Basketball robot: Ball-on-plate with pure haptic information. In *Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on*, pages 2410–2415. IEEE.

Lippiello, V., Ruggiero, F., and Siciliano, B. (2016). The effects of shapes in input-state linearization for stabilization of nonprehensile planar rolling dynamic manipulation. *Robotics and Automation Letters, IEEE*, 1(1):492–499.

Lynch, K. M. and Mason, M. T. (1996a). Dynamic underactuated nonprehensile manipulation. In *Intelligent Robots and Systems' 96, IROS 96, Proceedings of the 1996 IEEE/RSJ International Conference on*, volume 2, pages 889–896. IEEE.

Lynch, K. M. and Mason, M. T. (1996b). Stable pushing: Mechanics, controllability, and planning. *The International Journal of Robotics Research*, 15(6):533–556.

Lynch, K. M., Shiroma, N., Arai, H., and Tanie, K. (1998). The roles of shape and motion in dynamic manipulation: The butterfly example. In *Robotics and Automation, 1998. Proceedings. 1998 IEEE International Conference on*, volume 3, pages 1958–1963. IEEE.

Mason, M. and Lynch, K. (1993). Dynamic manipulation. In *Proceedings of the IEEE/RSJ International Workshop on Intelligent Robots and Systems (IROS-93)*, volume 1, pages 152–159.

Mayne, D. Q., Rawlings, J. B., Rao, C. V., and Scokaert, P. O. M. (2000). Constrained model predictive control: Stability and optimality. *Automatica*, 36(6):789–814.

Murray, R. M., Li, Z., Sastry, S. S., and Sastry, S. S. (1994). *A mathematical introduction to robotic manipulation*. CRC press.

Naldi, R. and Sanfelice, R. G. (2013). Passivity-based control for hybrid systems with applications to mechanical systems exhibiting impacts. *Automatica*, 49(5):1104–1116.

Omron (2015). CEATEC 2015: Omron's Ping Pong Robot. [web page] `https://youtu.be/6MRxwPHH0Fc`.

Ortega, R., Spong, M. W., Gómez-Estern, F., and Blankenstein, G. (2002a). Stabilization of a class of underactuated mechanical systems via interconnection and damping assignment. *Automatic Control, IEEE Transactions on*, 47(8):1218–1233.

Ortega, R., Van Der Schaft, A., Maschke, B., and Escobar, G. (2002b). Interconnection and damping assignment passivity-based control of port-controlled hamiltonian systems. *Automatica*, 38(4):585–596.

Reist, P. and D'Andrea, R. (2009). Bouncing an unconstrained ball in three dimensions with a blind juggling robot. In *Robotics and Automation, 2009. ICRA'09. IEEE International Conference on*, pages 1774–1781. IEEE.

Reist, P. and D'Andrea, R. (2012). Design and analysis of a blind juggling robot. *Robotics, IEEE Transactions on*, 28(6):1228–1243.

Ryu, J.-C., Ruggiero, F., and Lynch, K. M. (2012). Control of nonprehensile rolling manipulation: Balancing a disk on a disk. In *Robotics and Automation (ICRA), 2012 IEEE International Conference on*, pages 3232–3237. IEEE.

Ryu, K. and Oh, Y. (2011). Balance control of ball-beam system using redundant manipulator. In *Mechatronics (ICM), 2011 IEEE International Conference on*, pages 403–408. IEEE.

Sanfelice, R. G., Teel, A. R., and Sepulchre, R. (2007). A hybrid systems approach to trajectory tracking control for juggling systems. In *Decision and Control, 2007 46th IEEE Conference on*, pages 5282–5287. IEEE.

Senoo, T., Namiki, A., and Ishikawa, M. (2006). Ball control in high-speed batting motion using hybrid trajectory generator. In *IEEE International Conference on Robotics and Automation*, pages 1762–1767, Orlando, FL, USA.

Serra, D., Aykut, C. S., Ruggiero, F., Lippiello, V., and Siciliano, B. (2016a). An optimal trajectory planner for a robotic batting task: the table tennis example. In *International Conference on Informatics in Control, Automation and Robotics, Proceedings of*, volume 13.

Serra, D., Satici, A. C., Ruggiero, F., Lippiello, V., and Siciliano, B. (2016b). An optimal trajectory planner for a robotic batting task: The table tennis example. [web page] `https://youtu.be/GXtBvbUHu5s`.

Surov, M., Shiriaev, A., Freidovich, L., Gusev, S., and Paramonov, L. (2015). Case study in non-prehensile manipulation: planning and orbital stabilization of one-directional rollings for the butterfly robot. In *Robotics and Automation (ICRA), 2015 IEEE International Conference on*, pages 1484–1489. IEEE.

Tian, X., Koessler, J. H., and Sanfelice, R. G. (2013). Juggling on a bouncing ball apparatus via hybrid control. In *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on*, pages 1848–1853. IEEE.

Zhang, Y., Xiong, R., Zhao, Y., and Chu, J. (2012). An adaptive trajectory prediction method for ping-pong robots. In *Intelligent Robotics and Applications*, pages 448–459. Springer.