Exploiting Object Symmetry for Efficient Grasping

Paper XXX

ABSTRACT

In this, paper we introduce an efficient representation for robot grasping that exploits symmetry properties of objects. The new representation forms a low-dimensional manifold, which can be used to identify the set of feasible grasps during a sequential manipulation task. We analyse the properties of this low-dimensional manifold and show that some of these properties can be used for fast manipulation planning. We apply the introduced representation and planner to bi-manual manipulation in humanoid robots.

1. INTRODUCTION

Robots with advanced dexterous capabilities have the potential to revolutionize important application domains such as healthcare, security, or manufacturing. Whether it is in structured environments such as factories, or unstructured environments such as homes, grasping is often the first step in the physical interaction between a robot and its surroundings. The generation of grasps on objects is therefore at the heart of planning physical tasks. However, to date, most grasp planning methods are mainly focused on generating physically stable grasps, without incorporating immediate or future task constraints.

Many well established algorithms assume only a single action, and do not include foresight and reasoning about next actions. However, when picking up a mug, it is important to select a grasp that facilitates the next action to be performed. In case the next action is a pouring motion, the robot needs avoid grasps that would cover the rim of the object. In contrast, if any of the next actions involves placing the mug on the table, the robot cannot choose any grasp in which fingers touch the mug's base. To date, many grasp representations are based on a floating hand representing only the end-effector and ignoring the embodiment of the entire robot in environment. As a result, infeasible grasps are generated and have to be pruned out in a post-processing step. Yet, selecting grasps that facilitate task completion is particularly important for bi-manual, sequential, and co-worker scenarios. In these scenarios, grasps need to be carefully chosen, such that they do not violate constraints imposed by a second arm, a human interaction partner, or a future action.

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In this paper, we address the issue of manipulation planning with task constraints. We are particularly interested in tasks that involve several subtasks or several interacting agents. Planning grasps for such tasks can rapidly become computationally infeasible due to a large search space. The key insight of this paper is that re-occurring patterns in the geometry of shapes can be exploited to drastically reduce the space of solutions. We will introduce an low-dimensional, object-centered representation for grasp planning which is based on rotational symmetries. The symmetric nature of the objects allows us to update our representation as the object rotated around the axis of symmetry. *Since the object is symmetric any stable grasp can be rotated around the axis yielding a family of feasible grasps.* We will show that this basic property leads to a significant reduction of search complexity in grasp planning. Specifically, this property allows us to generate multiple grasps around the object which is useful for bi-manual tasks and cooperative robot hand over tasks. In addition, it allows us to identify a single grasp that is useful for a sequence of tasks.

2. RELATED WORK

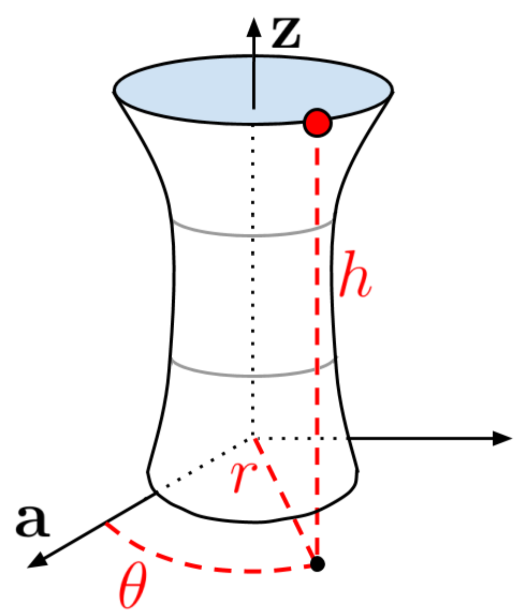
3. MANIFOLD REPRESENTATIONS FOR ROTATIONALLY SYMMETRIC OBJECTS

Projecting manipulation constraints such as collisions with the environment and robot manipulator limitations such as reachability onto object surfaces can facilitate the search for contact points for feasible grasps. In this work, we demonstrate that particularly for rotationally symmetric objects, which do not have any surface protrusions or cavities, a number of grasping subproblems such as finger placements, wrist pose, and collision-free inverse kinematics are simplified. Inspired by the texture mapping literature in computer graphics, we begin with the two-dimensional manifold representation of rotationally symmetric objects whose surfaces can be unwrapped into simple planes. The goal is to use this low-dimensional representation to accumulate multiple task constraints on the same local object space and then, efficiently identify grasps that satisfy all the future actions.

3.1 Cylindrical Surface Parametrization

Coordinate spaces characterized by rotations around an axis can be parameterized by cylindrical parameters where a vector $\mathbf{z}$ represents the principal orientation and the polar axis $\mathbf{a}$ captures the secondary direction in the reference plane perpendicular to $\mathbf{z}$. Using their intersection o as the origin, any point in the Euclidean coordinate system can be represented in this coordinate system by computing the projection of the point onto the $\mathbf{z}$ axis, its distance to the origin, and the angle between the $\mathbf{a}$ axes and its projection onto the reference plane.

Figure 3.1 demonstrates the representation of a contact point on a rotationally symmetric object in terms of the parameters $[h, r, \theta]^T$ that correspond to the height along $\mathbf{z}$, the radius r of the circle parallel to the reference plane that includes the point, and the angle θ between $\mathbf{a}$ and the point projection onto the reference plan. Note that the reference plane is arbitrarily placed on the bottom surface of the object and the polar axis points in a random direction.



A significant observation about the representation of rotationally symmetric objects in cylindrical coordinates is the dependency of the radius r and the height h parameters.

Using the principal axis $\mathbf{z}$, the polar axis $\mathbf{a}$, and their cross-product, we can define the local object frame L in the Euclidean coordinate frame. Transforming the coordinates of a point in the Euclidean world frame p^w to the local object frame p^l, and then finally utilizing the cylindrical

The manifold representation which will be discussed in the remainder of the paper is based on a cylindrical coordinate system. We will therefore start by introducing cylindrical coordinates.

Let $\mathbf{z}$ be the axis of symmetry, $\mathbf{o}$ be the origin, and $\mathbf{a}$ be the polar axis of the object. The polar axis lies in the reference plane of the object and is perpendicular to $\mathbf{z}$. Subsequently, we assume that the reference plane is the base of object. Note that $\mathbf{a}$ can be arbitrarily chosen, since the object is symmetric. Using $\mathbf{z}$, $\mathbf{a}$ and their cross-product, we can form a local coordinate frame L for an object. Any point $\mathbf{p} = [x, y, z]^T$ in the local coordinate frame L, can also be represented using a cylindrical parametrization of the coordinate system.

This parametrization leads to a point $[h, r, \theta]^T$ whose components correspond to the height, radius and angle of the point respectively as seen in Fig. **??**. The height is measured along the axis of symmetry $\mathbf{z}$, the radius r is the distance between $\mathbf{p}$ and $\mathbf{z}$, the angle θ is the angle between $\mathbf{a}$ and the projection of $\mathbf{p}$ onto the local reference plane of the object as can be seen in Fig. **??**.

In the following, we define the radius as a function $r(h)$ of the height, which results in a two-dimensional parametrization $[h, \theta]^T \in \mathbb{S}$ of point $\mathbf{p}$. Subsequently, we can define the function $f : \mathbb{S} \to \mathbb{R}^3$ that maps the cylindrical coordinates to the 3D local coordinates in the following way:

$$f(\mathbf{x}) = f([h, \theta]^T) = \begin{bmatrix} (h)\ cos(\theta) \\ r(h)\ sin(\theta) \\ h \end{bmatrix}. \tag{1}$$

Similarly, we can map from the 3D local coordinate space L back to the surface manifold using the inverse mapping, $f^{-1} : \mathbb{R}^3 \to \mathbb{S}$:

$$f^{-1}(\mathbf{p}) = f^{-1}([x, y, z]^T) = \begin{bmatrix} z \\ atan2(y, x) \end{bmatrix}. \tag{2}$$

The assumption of rotational symmetry along with the definition of the radius as a function of the height reduces the our parametrization to two variables. Fig. 1 depicts the mapping of a 3D cylinder onto the 2D manifold. In the next section, we will see how this can exploited for generating grasps.

3.2 Grasp Manifold

In this section, we demonstrate how to exploit the introduced representation and the symmetry properties of the object to efficiently sample feasible grasps. The key insight is that stable grasps can be rotated around the axis of symmetry without having to modify the hand shape. We begin the analysis with a simplified model where a point on the surface corresponds to a wrist position during grasping. Moreover, the hand is assumed to be parallel to the base of the object such that the plane between the grasping fingers is perpendicular to the axis of symmetry.

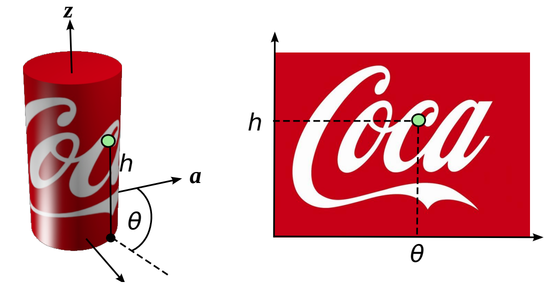


Figure 1: The points on the 3D surface (right) are projected onto a two-dimensional manifold using a cylindrical coordinate system.

The goal is to identify the set of feasible points the robot can grasp. This requires reasoning about reachability and collisions, where we need to ensure that there is a collision-free arm pose with the wrist touching the respective surface point. To sample this space, we propose discretizing the manifold by fixed step sizes for the height h and the angle θ. Refer to picture. For each patch of the discretized manifold, using the center point as the reference for the wrist, we attempt to compute a collision-free inverse kinematics solution. Refer to picture again showing red/blue and which collisions were caused.

A crucial property of this representation is that the produced map can be efficiently updated when the object is rotated around its axis of symmetry. More specifically, a rotation around the z-axis corresponds to a shift along the θ dimension.

1. Low-dimensional manifold for grasps on symmetric objects
   (a) Let $\mathbf{x} \in \mathbf{S}, where\mathbf{x} = [h, \theta]^T$
   (b) h is the height of the contact point along the axis of symmetry
   (c) r

4. TASK PLANNING WITH GRASP MANIFOLDS

4.1 Planning for Task Sequences

4.2 Planning for Bi-Manual and Cooperative Tasks

5. EXPERIMENTS

6. DISCUSSION

7. CONCLUSIONS