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Dexterous grasping under shape uncertainty

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HIGHLIGHTS

- We considered object shape uncertainty in grasp planning and control.
- We proposed a probabilistic model to solve hand inverse kinematics.
- Our grasp planning approach is hand interchangeable.
- We presented a compliant uncertainty-aware controller for finger closing during grasp execution.

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ABSTRACT

An important challenge in robotics is to achieve robust performance in object grasping and manipulation, dealing with noise and uncertainty. This paper presents an approach for addressing the performance of dexterous grasping under shape uncertainty. In our approach, the uncertainty in object shape is parametrized and incorporated as a constraint into grasp planning. The proposed approach is used to plan feasible hand configurations for realizing planned contacts using different robotic hands. A compliant finger closing scheme is devised by exploiting both the object shape uncertainty and tactile sensing at fingertips. Experimental evaluation demonstrates that our method improves the performance of dexterous grasping under shape uncertainty.

1. Introduction

Dexterous grasping is an essential skill for many tasks that robots are expected to perform, ranging from the assembly of workpieces in a factory setup to advanced manipulation of cutlery in a household environment. The core requirement of a successful dexterous grasping system is to place the fingertips on the relevant locations of an object, applying sufficient contact forces and maintaining grasp stability. To achieve this, a common approach is to address two subproblems: *grasp planning* and *grasp execution*. Considerable progress has been made during the last couple of years and efficient grasp planning algorithms have been proposed to generate grasps for known, partially known or unknown objects in structured or unstructured environments [1–5]. Robust and reactive grasp control techniques have been developed and validated on different robotic platforms relying on single or multiple sensory feedback. Despite these achievements, demonstrating robust and flexible object grasping and manipulation in natural environments taking into account uncertainties in perception and control remains a challenge.

In this paper, we address the problem of uncertain shape perception in a system considering fingertip grasping. Uncertain shape perception may originate from occlusion, partial view or issue with sensor calibration. We present a system which takes into account shape uncertainty during grasp planning and execution. Shape uncertainty is parametrized using Gaussian Processes (GP) and it is incorporated as a constraint into a contact-level grasp synthesis algorithm. The output of the algorithm is a set of contacts defining a grasp with an associated shape uncertainty that determines the maximum uncertainty a grasp can withstand, as shown in the left upper part of Fig. 1(1). Given the desired grasping contacts, the feasible hand configuration (hand pose and finger joint configuration), is computed using a probabilistic model. The probabilistic model is learned offline for each hand and is frame invariant thanks to the use of a *Virtual Frame* (VF) approach. The learned model is hence, independent of the choice of hand and object frame. VF relies on a set of parameters defined to encode grasps as shown in the right upper part of Fig. 1(2). Since a grasp is first planned in the object frame by generating a set of contact locations, it is not dependent on a specific hand design.

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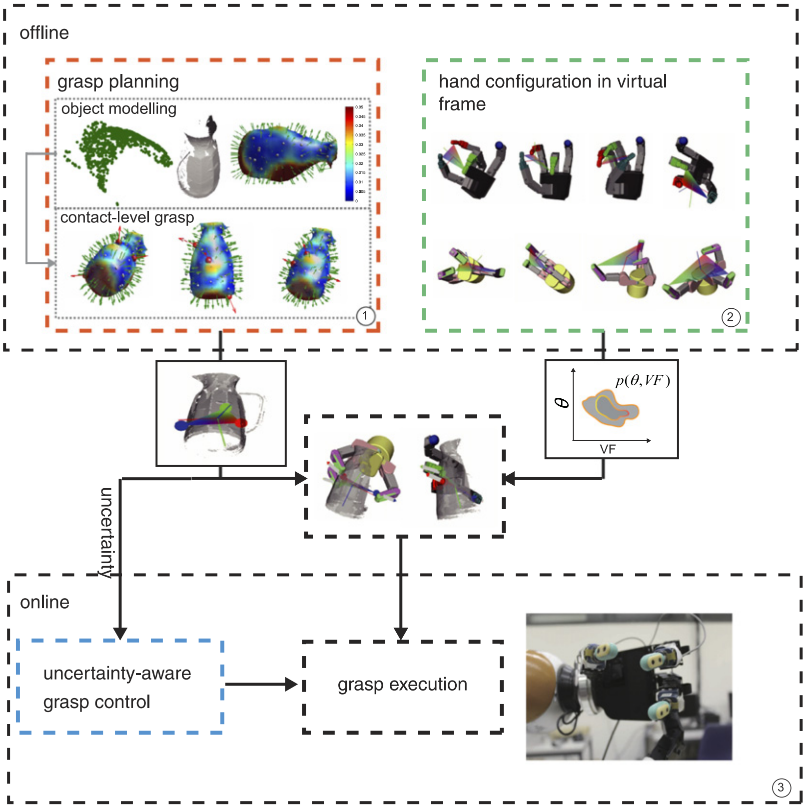

Fig. 1. The overview of the proposed approach. ①: The contact-level grasp planning with shape uncertainty. The output is a set of contacts defining a grasp with associated shape uncertainty these can withstand. ②: The probabilistic model for the hand inverse kinematics is learned offline and is frame invariant. ③: Given the desired grasping points and the employed hand, the corresponding hand configuration is obtained in real time. ④: The obtained hand configuration and the uncertainty information are passed to the controller for compliant grasp execution.

Similarly, the learned probabilistic model for the hand inverse kinematics is not constrained by object shape. Therefore, given a new hand with its learned probabilistic model, the corresponding hand configuration that matches the generated grasping contacts can be obtained in real time. For grasp execution, a compliant finger closing scheme is devised. A parallel position/force (tactile) controller is implemented by exploiting the uncertainty in shape and contact force based on our previous work [6]. An overview of the system is shown in Fig. 1.

The paper is organized as follows: Section 2 provides a review of the related work. Section 3 gives an introduction to object surface modeling using GP, along with its application in grasp planning. Section 4 presents a learning-based approach for the hand inverse kinematics. A compliant finger closing scheme is depicted in Section 5. Implementation details and experimental results are described in Section 6, followed by a discussion and conclusion in Section 7.

2. Related work

We provide an overview of related work considering dexterous grasp planning, control systems for grasping and grasping under uncertainty.

Early work on grasp planning focused on finding the optimal contact points considering force closure as a grasp quality measure [7–10]. More recently, hand kinematics has been taken into account when estimating the feasible hand configuration for realizing the grasping points [11,12]. A drawback of this approach is that the valid hand configuration to realize the contacts may not be found. An alternative approach is to optimize the contact locations and the hand configurations simultaneously. Due to the high dimensionality of the problem, the optimization is conducted in a projected space of lower dimensionality using hand synergies [13] or eigen grasps [14]. There are also works that formulate the optimization in the original hand configuration space [15,16]. However, this is computationally expensive and the obtained grasps are hand-dependent. In this paper, we decouple contact synthesis and hand configuration estimation and rely on an offline learning process to obtain the relevant hand configuration.

Learning-based approaches have been proposed before and most of these use data-driven model to learn "rules" between object shape and feasible hand configurations [1]. In [17–19], objects are represented as basic shape primitives and then associated with predefined grasp primitives. In [20], a support vector machine (SVM) is used to learn the grasp quality manifold for a specific hand and simple object shapes. The manifold represents the mapping from grasp parameters and object shape to the grasp quality and new optimal grasps are found through interpolation on the manifold. Most of these methods are either limited to basic shapes or simple grasp primitives and cannot be used to execute a set of specific contact locations. Along this direction, [21] learns the joint density function of hand pose and finger joints from a large set of grasps. This density function is used later to retrieve finger joints online given any query hand pose. However, learning is conducted in the object frame and with specific hand–object combination. As a result, a new learning model is required for each new pair of hand–object combination. The authors in [22] learn two separate models, i.e., the contact model to express the relationship between fingers and object local features, and the hand configuration model to represent whole hand configuration during approach to grasp. They show this approach can generalize to new objects for given grasp types. In this work, we follow a similar principle as [22] to address the grasp planning in two steps. With the help of Virtual Frame, planning

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