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Towards informative sensor-based grasp planning

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HIGHLIGHTS

- A probabilistic framework for sensor-based grasping is presented.
- Two approaches based on stability maximization and entropy minimization are proposed.
- Probabilistic grasping improves the probability of success in a series of attempts.
- Under big uncertainties, explorative actions help to achieve successful grasps faster.

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ABSTRACT

This paper proposes a probabilistic framework for sensor-based grasping and describes how information about object attributes, such as position and orientation, can be updated using on-line sensor information gained during grasping. This allows learning about the target object even with a failed grasp, leading to replanning with improved performance at each successive attempt. Two grasp planning approaches utilizing the framework are proposed. Firstly, an approach maximizing the expected posterior stability of a grasp is suggested. Secondly, the approach is extended to use an entropy-based explorative procedure, which allows gathering more information when the current belief about the grasp stability does not allow robust grasping. In the framework, both object and grasp attributes as well as the stability of the grasp and on-line sensor information are represented by probabilistic models. Experiments show that the probabilistic treatment of grasping allows improving the probability of success in a series of grasping attempts. Moreover, experimental results on a real platform using the basic stability maximizing approach not only validate the proposed probabilistic framework but also show that under large initial uncertainties, explorative actions help to achieve successful grasps faster.

1. Introduction

General service robot applications require grasping skills in complex and uncertain environments. Grasp planning implies choosing the position of a robot hand so that a desired object can be robustly held by the hand. Most existing grasp planning approaches consider target objects without taking into account the uncertainty in knowledge of object parameters. Nevertheless, in many real-world manipulation scenarios, knowledge about the world state cannot be exactly known. Thus, errors in attributes, such as object position and orientation, can be crucial while performing different manipulation tasks. Moreover, in most cases a geometric model of the object is required for planning and such a model is not always available or can be inaccurate.

The lack of exact geometric information about an object can be compensated by the use of sensor feedback. It has been shown that for instance tactile sensor measurements allow to solve a variety of robotics problems, despite the fact that accurate object models are often unavailable in such methods. Over the past years, tactile sensors have been applied in numerous tasks, including object classification, recognition [1–3], and pose estimation [4,5], as well as estimation of grasp stability [6,7].

One major challenge in the use of tactile sensors is that most available sensors show characteristics such as drift, systematic errors and random noise. In addition, tactile measurements can provide only local information and are highly dependent on unique robot hardware. Coping with the uncertainties is thus crucial to success.

Recent works such as [8–10] show a trend towards the probabilistic interpretation of tactile manipulation. However, the existing works do not consider the task goals in the probabilistic

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setting. For example, in pose estimation, tactile probing is continued until the pose distribution converges. However, for many tasks such as grasping, convergence of the belief is not necessary, and in the case of objects with symmetries, it can even be impossible to attain.

This paper proposes a probabilistic framework for grasp planning under uncertainty using on-line sensor information and simultaneously updating the information about object pose. Under significant uncertainties a first grasp attempt cannot be guaranteed to succeed but the failure can be detected using tactile sensors. The proposed approach then uses information obtained during the attempt to refine object knowledge. The method plans for the most stable grasp based on a probabilistic stability model by maximizing the expected stability. In the context of simulations, stability of a grasp is defined using a grasp quality metric representing the largest minimum disturbance wrench that can be resisted by the contacts. In real experiments, stability is defined as a binary variable indicating whether a grasped object was fully immobilized by the hand when the hand performs a series of motions after lifting the object. When the uncertainty of the current belief for an object pose is large, the predicted stability can be relatively small and in these cases exploration would be more useful than maximizing the stability. We then also present an extension to the approach which poses grasp planning as choosing the most informative grasp, that is, the grasp that maximally reduces the uncertainty about object attributes.

The proposed approach for stability-maximizing grasp planning allows grasp planning, measurements, and corrective motions to interact, leading to a system where the uncertainty about the environment can be decreased simultaneously while planning and executing statistically optimally stable grasps. The method is demonstrated by building the necessary probabilistic models using Gaussian process regression, and using the models with a Markov chain Monte Carlo (MCMC) approach to estimate a target object's pose and grasp stability during grasp attempts. A Bayesian approach is used, so that estimates are obtained by marginalizing over the current knowledge. Thus, having models for object attributes and grasp stability, the most stable grasp can be found as the maximum of the posterior probability. The second planning technique extends the basic probabilistic framework by incorporating an exploration stage, which allows the interplay between stability maximization and entropy minimization (entropy in the information theoretic sense). Whenever the expected stability of a grasp is not sufficient the most informative grasp is executed instead. This informative grasp is chosen to minimize the expected entropy of the object attributes at the next time step given the current knowledge of the object attributes. A particular challenge in this is how to measure the entropy of a distribution of the object pose attributes represented in this paper by a set of particles. A particle based representation was chosen as it is non-parametric and can represent any distribution. This is especially important as the true distribution of the object pose can be complex and may be impossible to be represented well by a simple parametric model.

The main contributions of our work are, first, the probabilistic framework for grasp planning with uncertainties in the target object's pose. The framework allows simultaneously planning, executing optimal grasps, and reducing the uncertainty about the environment. Moreover, two approaches utilizing the probabilistic framework for finding stable grasps while reducing the uncertainty in an object's attributes are proposed. The first approach plans for maximally stable grasps while the second approach is supplemented with entropy prediction based exploration which aims to find the most informative grasp. For the entropy calculations we use an efficient discrete entropy estimate that uses only particle weights. Both methods are experimentally demonstrated and studied in simulation. The experiments show that both approaches allow to perform a stable grasp in an uncertain environment and at the same time reduce the uncertainty in the knowledge about the object's parameters. However, the explorative technique produces more reliable results compared to the initial stability maximization method. We also present an experimental validation of the basic stability maximizing approach using a real robot platform. These experiments also prove the benefit of including an exploratory stage to increase the probability of achieving stable grasps.

Preliminary results of the approach have been published in [11–13]. This work extends the earlier studies by including the experimental comparison and providing a detailed analysis of the exploration approach.

2. Related work

Learning has become an important part of robotic systems because it can provide a robot with the capability to cope with uncertainties to some extent. Over the past years, many approaches have been proposed to apply reinforcement learning in robotic manipulation, starting from simple learning control of a peg-in-hole task [14] to learning of complex motor skills (e.g. [15,16]).

While allowing to cope with model uncertainties by essentially learning the models, reinforcement learning approaches do not typically consider uncertain beliefs, or use simple (e.g. Gaussian) uncertainty models. At the same time, multi-modal uncertainties are common in tactile manipulation because of the local nature of tactile measurements which are not always capable to approximate the part of global system. For example, when estimating object pose through tactile exploration, dozens or even hundreds of exploration attempts are typically needed to converge to a single solution.

One key problem is then how to represent such multi-modal uncertainties. One possible solution is to apply particle filters (PFs). The particle filter is an MCMC method which models probability distributions with a cloud of particles. Existing applications of PFs in manipulation include mainly pose estimation [17–19]. The idea was later extended to include shape in addition to pose [5]. Similarly, the recently proposed Grasp-SLAM system aims to localize an object while simultaneously updating the system model and manipulating the object [20]. Platt et al. explore the possibility of using particle filtering to localize features embedded in flexible materials during robot manipulation based on tactile information [21]. Our work is closely connected to grasp planning. The key aim of grasp planning algorithms is to find the best possible grasp to a given object. The goodness of a grasp is usually measured using a quality metric [22]. Unlike our approach most of the existing grasp planning algorithms do not consider the information uncertainty about an object's parameters. More than that, they usually require an accurate geometric model of the object. In addition to finding a stable grasp, the proposed method allows to select a grasp which maximizes the expected information obtained by the resulting contact with the object.

Another approach for finding grasps is object affordance modeling. While object affordance is a broader subject, the affordances can also be thought of in the sense of grasp stability. In some of the grasp related studies, grasp affordances consider the overall stability of the grasp [23,24] or the grasp affordance in specific tasks [25].

The idea of probabilistic grasping formulation was presented in Hsiao et al. [8], which considered a full Partially Observable Markov Decision Process (POMDP) formulation of an abstracted state space, in a simple one-dimensional case of unknown object pose in a long time horizon. Thus, the paper contained all the basic