Push-Grasp Quality Evaluation for Polygonal Parts under Pose Uncertainty using Quasi-static Simulation

Ben Kehoe Sachin Patil Matei Ciocarlie James Kuffner Ken Goldberg

Abstract—**We present a framework for analyzing the quality of push-grasps of extruded polygonal parts under pose uncertainty using a parallel jaw gripper. Performing a push-grasp involves using the first jaw to push the part into stable alignment, after which the second jaw closes onto the part. The motion of parts pushed on a work surface is difficult to predict if the precise interactions between the part and the work surface are not known. However, the relative motion of the part can be easily calculated. We use a quasi-static simulation to predict this relative motion. Given a nominal part shape and anticipated uncertainty in the part pose, we use a Monte Carlo sampling approach to evaluate grasp quality under pose uncertainty. We sample poses from the uncertainty distribution, and execute simulations to evaluate if the grasp is successful, i.e., if force-closure is achieved. We then calculate the overall grasp quality as a weighted average across samples, where the weight for each sample is the probability of that sample occurring. Since each sample can be analyzed in parallel, this approach is well-suited for Cloud-based execution. We also present a sensitivity analysis of the grasp quality for a given grasp on a non-convex polygonal part under varying position and orientation uncertainty. Our experiments suggest that while position uncertainty has a direct effect on quality, orientation uncertainty has complex effects which depend on part shape and symmetry. This supports our hypothesis that a simulation-based grasp quality metric is important for comparing different grasps under varying levels of pose uncertainty.**

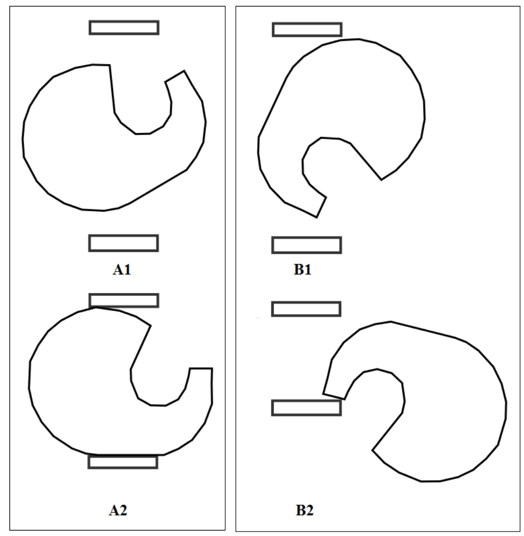

Fig. 1. Example of execution of the same grasp on two different poses for a part modeled on a tape dispenser. The pre-grasps are labeled A1 and B1. Grasp A is successful at achieving force closure, as shown in A2. Grasp B is unsuccessful, with the part being pushed out of the gripper, as shown in B2. We use quasi-static simulation to evaluate grasp success/failure.

I. Introduction

Many tasks in automation involve grasping and manipulation of extruded parts on planar work surfaces using parallel jaw grippers. However, the pose (position and orientation) of the part on the work surface is not always precisely known during operation. In automation, the accuracy of sensing the part pose can be varied as a design parameter, but generally there is a trade-off between task throughput and sensing overhead. Increasing accuracy can therefore reduce speed. However, greater uncertainty can cause more grasp failures, also reducing speed. A grasp quality metric that can evaluate this trade-off could help with the design process. In this work, we consider the scenario of grasps on extruded polygonal parts, and present a framework for evaluating the reliability of grasps under pose uncertainty.

There is a large body of work on computing grasp quality metrics [1, 6, 12]. However, the vast majority of these methods do not consider uncertainty in the pose of the part. In previous work, we have considered grasping with shape uncertainty for polygonal parts using a very conservative geometric test to speed the evaluation of grasps [9]. Other approaches have allowed for grasping of parts where the pose is completely unknown due to absence of sensing [7]; however, this requires multiple grasps to be executed. Confidence levels can also allow different sensing modalities to be combined for grasp planning [2].

Grasping with pose uncertainty has also been explored for general 3D parts [4, 8, 11]. While this work could, in theory, be used for parts that can be modeled as extruded polygons, there are two aspects which motivate our approach. First, planar grasping on a surface requires reasoning about pushing the part on the work surface using the gripper surface, which can be very difficult to model with a dynamic simulator. Second, efficiency is important when the grasp quality evaluation is part of an iterative design procedure. A cycle time of hours or greater reduces the ability of the designer to test different configurations, limiting their flexibility.

In this work, we present a framework for efficient evaluation of push-grasps for extruded polygonal parts on a planar work surface using a parallel jaw gripper. While the exact interaction between the gripper and part is difficult to determine or model, the relative motion between them can be calculated. We use a quasi-static simulation to predict this relative motion. We use a Monte Carlo approach similar to Kim et al. [11] to accommodate pose uncertainty. We sample poses from the uncertainty distribution, and execute simulations to evaluate grasp success. Instead of just using the average of grasp success across the samples [11], the overall grasp quality is calculated using a weighted average, where the weight for each sample is the probability of that sample occurring.

With a Monte Carlo approach, every sample could be processed independently. This aspect means that the algorithm can take advantage of the massively parallel computing power available in the Cloud, dramatically shortening the execution time [10].

Our experiments suggest that while position uncertainty has a direct effect on quality, orientation uncertainty has complex effects which depend on part shape and symmetry. This supports our hypothesis that a simulation-based grasp quality metric is important for comparing different grasps under varying levels of pose uncertainty.

II. Problem Statement

We consider a parallel jaw gripper attempting to grasp an extruded polygonal part of uniform density from above. We assume that we have a conservative estimate of the coefficient of friction between the gripper and the part, denoted as μ. The gripper-part interaction is assumed to be quasi-static, such that the inertia of the part is negligible. We assume that the uncertainty in the part pose can be modeled as independent Gaussian distributions on the position and orientation; because of the nature of parallel jaw grippers, we only consider uncertainty in the direction perpendicular to the closing axis of the gripper.

The input to the algorithm is a polygonal part, the gripper width and friction, a pre-grasp pose, and the standard deviation for both position and orientation uncertainty. The output of the algorithm is a quality between 0 and 1, estimating the probability of success of the grasp on the object under the given pose uncertainty.

III. Method

We use a quasi-static simulation to determine grasp quality based on a Monte Carlo sampling approach. We use Box2D [3], a dynamic simulation engine written in C++, to efficiently simulate push-grasps. Accurately simulating the interactions between the part and work surface as part of the push-grasping procedure is difficult since it requires calculation of the center of rotation, which requires empirical testing to determine the pressure distribution on the surface. This is not provided in Box2D. Instead, we model quasi-static motion using Box2D with a model similar to that proposed by Dogar et al. [5].

The quasi-static simulation is distinguished from using slow-moving objects in a dynamic simulation in that the *relative* motion of the objects in simulation is correct, but the *absolute* motions of the objects required to produce these relative motions cannot be accurately predicted by the simulation.

Once the simulation has converged, i.e., the part and gripper jaws have stopped moving, we determine if force-closure is achieved using the test provided by Nguyen [13]. We note that other grasp quality measures can also be used for the force-closure test [1, 6].

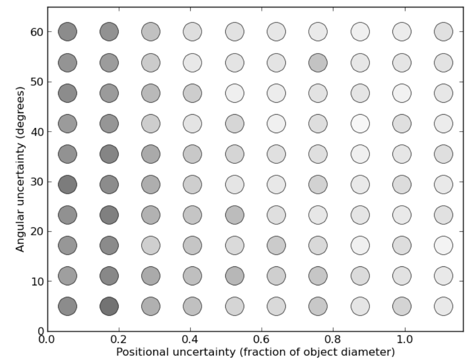

Fig. 2. Simulation results for the part and grasp shown in A1 of Fig. 1. Each dot indicates a test using 100 samples from the distribution using the parameters indicated, with the position uncertainty ranging from $0.055d$ to $1.11d$, where d is the diameter of the part, and the orientation uncertainty ranges from $5°$ to $60°$. The color of the dot indicates the quality, with a fully black dot indicating a quality of 1 (i.e., all samples successful) to white for a quality of 0. The dots shown range in quality from 0.550 to 0.033.

A fixed number of samples are drawn from the pose distribution, and the simulation is used to analyze if force closure is achieved for each one, resulting in a quality of either 0 or 1. The grasp quality is calculated as a weighted average of these 0s and 1s, where the weight for each result is the value of the probability density function for the pose of that sample.

IV. Results

We demonstrate an example analysis of a single grasp, using the grasp and polygonal part shown as A1 in Fig. 1 under varying levels of position and orientation uncertainty. In this section, the uncertainties are all zero-mean Gaussians and are specified in terms of standard deviation.

We tested the part under varying both the position and orientation uncertainty, where each position-orientation uncertainty pair was tested using 100 samples. We tested 100 such uncertainty pairs, using 10 linearly-spaced values for position uncertainty, ranging from $0.055d$ to $1.11d$, where d is the diameter of the part, and 10 linearly-spaced values for orientation uncertainty, ranging from $5°$ to $60°$.

The results are shown in Fig. 2. As expected, the quality decreases with increasing position uncertainty. The quality does not, however, uniformly decrease with increasing orientation uncertainty. With varying orientation, different features of the part are contacted by the pushing gripper jaw. Depending on the shape of the part, higher orientation uncertainty could in fact be beneficial to grasp quality if it makes features amenable to push grasps more likely to come into contact with the pushing gripper jaw.

The maximum quality, 0.550, was achieved with a position uncertainty of $0.172d$ and an orientation uncertainty of $60°$. The minimum uncertainty, $0.055d$ and $5°$, had a quality of 0.452. The minimum quality, 0.033, occurred with a position uncertainty of $0.874d$ and an orientation uncertainty of $41.7°$. This suggests that the relationship between the level of uncertainty in part pose and grasp quality is not trivial, and that simulation-based evaluation of the grasp quality can be beneficial.

The overall execution time for this test, which tested a single grasp on a total of $10,000$ samples, was 317 seconds. This time could be substantially reduced through elimination of simulation steps. For example, the grippers start at a distance guaranteed to be out of collision with the part; the position of initial collision could be determined and the gripper could start at that position.

V. Conclusion

We have presented a framework for efficiently analyzing planar, parallel-jaw grasps on extruded polygonal parts under pose uncertainty using a quasi-static simulation. Increasing position uncertainty uniformly decreases grasp quality, but increasing orientation uncertainty has more complex effects.

In future work, we will improve our grasp analysis to include non-binary grasp quality metrics, reduce simulation time, and include uncertainty in part shape. We will integrate this grasp analysis method with grasp planning using adaptive sampling from the candidate grasp space. Additionally, we will take advantage of the nature of Monte Carlo sampling and the Google Compute Engine to parallelize our implementation.

References

[1] A. Bicchi and V. Kumar. Robotic grasping and contact: a review. In *Proc. IEEE Int. Conf. Robotics and Automation (ICRA)*, pages 348–353. IEEE.

[2] Peter Brook, Matei Ciocarlie, and Kaijen Hsiao. Collaborative grasp planning with multiple object representations. In *Proc. IEEE Int. Conf. Robotics and Automation (ICRA)*, pages 2851–2858, 2011.

[3] E Catto. Box2d–c++ 2d physics engine for games.

[4] Hao Dang and Peter K Allen. Stable grasping under pose uncertainty using tactile feedback. *Autonomous Robots*, pages 1–22, 2013.

[5] Mehmet R Dogar, Kaijen Hsaio, Matei Ciocarlie, and Siddhartha Srinivasa. Physics-based grasp planning through clutter. In *Proc. Robotics: Science and Systems (RSS)*, 2012.

[6] C. Ferrari and J. Canny. Planning optimal grasps. In *Proc. IEEE Int. Conf. Robotics and Automation (ICRA)*, pages 2290–2295, 1992.

[7] Ken Goldberg. Orienting polygonal parts without sensors. *Algorithmica*, 10(2-4):201–225, 1993.

[8] Kaijen Hsiao, Leslie Pack Kaelbling, and Tomás Lozano-Pérez. Robust grasping under object pose uncertainty. *Autonomous Robots*, 31(2-3):253–268, 2011.

[9] Ben Kehoe, D Berenson, and K Goldberg. Estimating Part Tolerance Bounds Based on Adaptive Cloud-Based Grasp Planning with Slip. In *IEEE Int. Conf. on Automation Science and Engineering (CASE)*. IEEE, 2012.

[10] Ben Kehoe, Deepak Warrier, Sachin Patil, and Ken Goldberg. Cloud-Based Grasp Analysis and Planning for Toleranced Parts Using Parallelized Monte Carlo Sampling. *IEEE Transactions on Automation Science and Engineering (T-ASE): Special Issue on Cloud Robotics and Automation (under review)*, 2014.

[11] Junggon Kim, Kunihiro Iwamoto, James J Kuffner, Yasuhiro Ota, and Nancy S Pollard. Physically-based grasp quality evaluation under uncertainty. *IEEE Trans. Robotics*, 29(6): 1424–1439, 2013.

[12] B. Mishra. Grasp metrics: Optimality and complexity. In *Algorithmic Foundations of Robotics*, 1995.

[13] Van-Duc Nguyen. Constructing Stable Grasps. *Int. J. Robotics Research (IJRR)*, 8(1):26–37, 1989.