Grasp Envelopes for Constraint-based Robot Motion Planning and Control

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Despite decades of research, robust and fast autonomous grasping/manipulation even of geometrically simple objects remains elusive in unstructured scenarios. Based on our experience and extensive experiments conducted in the EU-FP7 project RobLog [4], we came to the conclusion that one reason which prevents autonomous robotic systems to approach human-like performance lies in the inherent shortcomings of the frequently utilized sense-plan-act architectures. Here, global sampling-based planners attempt to generate valid approach trajectories for a large set of discrete (often pre-planned) candidate grasps associated to the target object until a feasible grasp is found which is then executed [2, 6]. Methods in this mold suffer from the well known problems of sampling-based planners (unnatural/sub-optimal trajectories, probabilistic completeness, termination issues) and tend to incur large idle times because clutter often causes many of the tested candidate grasp poses to be in collision.

Instead, we believe that reactive control-based approaches relying on constrained optimization [5, 9] as well as on compliance in the manipulator and the grasping device have a larger potential to achieve satisfactory performance in relevant applied scenarios. Optimal control-based methods for real-time motion planning- and generation are typically local and able to generate motions on-the-fly. Also, with respect to the grasping/manipulation problem, they have the capacity to exploit simplifying structures and redundancy by not fully constraining all Degrees of Freedom (DoF) of the manipulator.

To facilitate these approaches we suggest a grasp representation in form of a set of enveloping spatial constraints as illustrated in Fig. 1. Conceptually similar to the task space regions in [3], our representation transforms the grasp synthesis problem ($i.e.$, the question of where to position the grasping device) from finding a suitable discrete manipulator wrist pose to finding a suitable pose manifold. Also the corresponding motion planning and execution problem is relaxed – instead of transitioning the wrist to a discrete pose, it is enough to move it anywhere within the grasp envelope which allows to exploit kinematic redundancy. Traditionally, grasp synthesis methods have been seen as either "analytic" (using geometric as well as kinematic and/or dynamic formulations) or "data-driven/empiric" (mimic human strategies by classification and learning methods) [8]. Our solution to grasp envelope synthesis leverages elements from both approaches: we utilize a geometric representation in form of spatial constraints which are deliberately designed to incorporate additional empirical knowledge about desirable grasp poses. For example it has been shown that human grasps are roughly aligned with the target object's principal component directions to achieve robust grasping behavior [1]. This property is achieved by the cone constraints for the exemplary case depicted in Fig. 2.

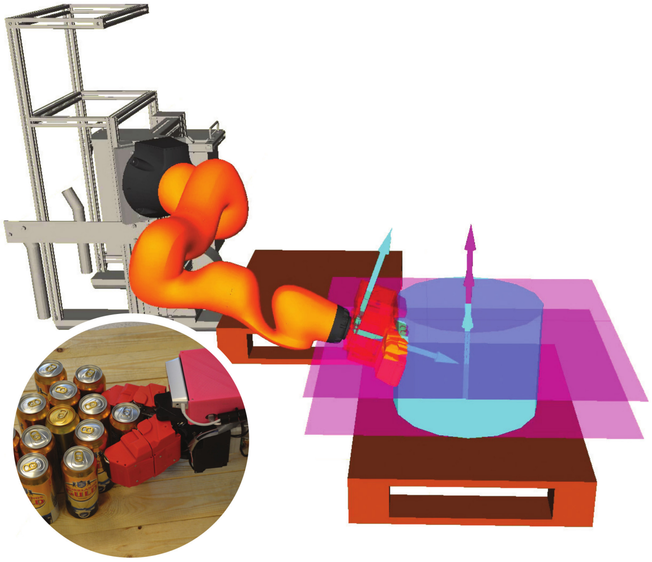

Fig. 1. *Constrained Grasp Planning- and Execution:* The region encompassed by the shaded constraints constitutes a grasp envelope which is constructed such that grasps resulting from pre-grasp wrist poses lying within the envelope can be executed successfully. Also shown is an example grasp carried out during a preliminary evaluation of the approach carried out with a platform comprising a Velvet Fingers gripper [10] mounted on a KUKA LBR iiwa manipulator.

For a preliminary evaluation of our approach we incorporated our grasp envelopes in the hierarchical Stack of Tasks (SoT) formulation in [5] and solve lower-ranked equality tasks in the null-space of tasks with higher priority. This method relies on embedded optimization and allows to generate reactive motions by computing locally optimal joint velocities/torques with additional constraints for, $e.g.$, obstacle avoidance or end-effector orientation. We successfully employed the suggested approach in a logistics setting for picking and palletizing of

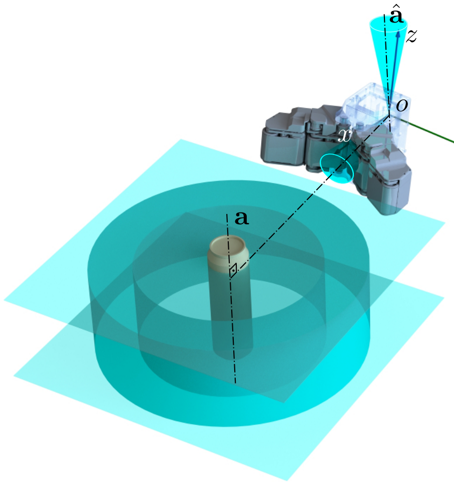

Fig. 2. *Grasp envelope:* The shaded cyan regions illustrate the side grasp envelope constraints for a cylindrical object. For a successful grasp, the palm frame origin $\boldsymbol{o}$ needs to lie inside the depicted cylindrical shell which is aligned with object axis $\boldsymbol{a}$. The cylinders height is limited by two planes which are normal to $\boldsymbol{a}$. Additionally, the gripper's vertical axis (z) is constrained to lie in a cone whose axis $\hat{\boldsymbol{a}}$ is parallel to the object axis $\boldsymbol{a}$. Furthermore, the gripper's approach axis (x) has to lie inside a cone centered on the normal which connects axis $\boldsymbol{a}$ and point $\boldsymbol{o}$.

cans in a simplified commissioning scenario, early results are presented in [7]. Currently, the parameters of the grasp envelopes such as the distance range between gripper and object have to be evaluated experimentally. During operation, after the target object pose is detected, the grasp envelope needs to be adapted to the specific scene and target object dimensions as illustrated in Fig. 3. In the early evaluation we pre-defined the corresponding parameters and gripper pre-grasp joint configurations, an appropriate programmatic approach is under development.

For future work, we plan to exploit another benefit of online control-based motion generation: the ability to take sensory feedback into account. The utilized framework [5] allows to specify desired task dynamics and it should be straightforward to modulate these with feedback from, *e. g.*, wrist-mounted force sensors or cameras to adjust grasp motions on-the-fly. Also, the grasp envelope representation should lend itself well to incorporate experience by sensorimotor exploration to adjust the constraints via reinforcement learning techniques. Furthermore, we plan to augment the approach with available semantic information via associating grasp affordances for a given task (*e. g.* the necessity of side grasps for pouring …) with appropriate constraint sets.

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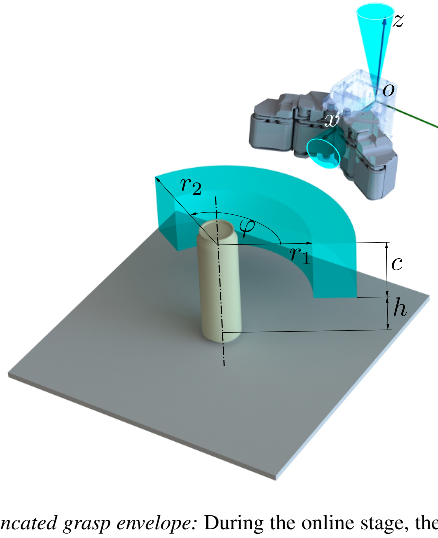

Fig. 3. *Truncated grasp envelope:* During the online stage, the corresponding grasp envelope shown in Fig. 2 needs to be truncated (*i. e.*, parameters for r_1, r_2, c, h and φ need to be determined) to accommodate the specific target object dimensions and to account for the fact that some regions of the grasp envelope might not be feasible due to obstruction by the environment.

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