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Posture optimization for pre-grasp interaction planning

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***Abstract*— Many manipulation tasks involve grasping objects that are movable, not fixed, in the environment. An object's potential for motion does contribute to the challenge of estimating its pose with sufficient certainty for robust grasping. However, object movability also offers an opportunity for *pre-grasp interaction* strategies that adjust an object's placement in order to improve grasping conditions. Here we highlight the results of initial work that illustrate the potential utility of pre-grasp interaction for object acquisition into a desired grasp. We also present recent developments for refining the manipulator posture for pre-grasp rotation with respect to a payload cost metric. Optimization of the payload metric increase the safety margin with respect to uncertainty in the estimate of object weight.**

I. INTRODUCTION

One mode of robot interaction with the physical environment is the movement of objects through grasping. For example, tasks such as cleaning up toys or beverage delivery to a human involve first object acquisition by grasping and then transport to a new location. When the target objects are already conveniently placed in the environment, a manipulation plan consisting only of the robot arm motion may be sufficient to reach a desired grasp while the object remains stationary during the reaching motion. However, in more challenging scenarios the desired grasp may not be possible or easy to reach directly with the presented object placement.

In cases where a manipulator reaching motion alone is not sufficient to achieve a grasp, the addition of object motion to a new placement can make a desired grasp feasible. Our work investigates the utility of such *pre-grasp interaction* as a strategy for manipulating movable objects in the environment. The key idea is to take advantage of the fact that many grasped objects are also movable, not fixed, in the environment even before grasping and that object adjustment can improve the conditions for grasping.

In this paper, we review the results of our previous investigation of pre-grasp interaction, and specifically pre-grasp rotation, as a manipulation strategy for grasping tasks. First, Section II presents related literature. Section III summarizes the highlights from our studies of human pre-grasp rotation and the methods developed for robot pre-grasp rotation [1]–[3]. In particular, we found that pre-grasp interaction strategies may be used to reduce uncertainty in object configuration before grasping as well as the final placement of the object (see Section III-B.1).

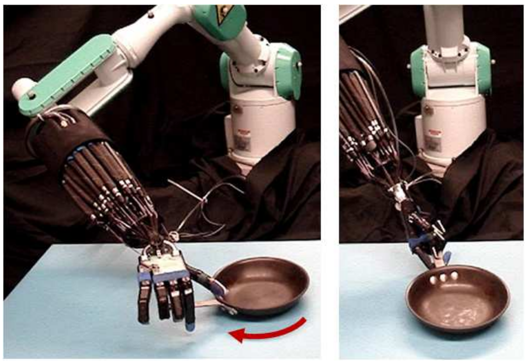

Fig. 1. Pre-grasp interaction adjusts the object placement in the environment prior to grasping. For example, a cooking pan can be pivoted to re-position the handle to a new orientation that can be reached with an underhand grasp.

In addition, pre-grasp interaction may also be used to plan grasping actions that are more tolerant to uncertainty in estimates of object attributes such as weight. In Section IV, we present recent work that examines methods for local optimization of grasping postures that affect the planning of pre-grasp rotation. Optimization of a payload cost metric can be used to increase the safety margin against the risk of under-estimated object weight.

Concluding remarks in Section V discuss the remaining challenges for achieving robust pre-grasp interaction with robot manipulators.

II. RELATED WORK

One major benefit of a pre-grasp interaction approach is that the manipulator can often adjust object placement with non-prehensile contact that is less constrained than grasping contact. For example, there may be several postures that achieve hand contact for pushing or pivoting a cooking pan (Fig. 1) that may be more robust or easier to achieve than postures for directly achieving the grasp of the handle for lifting it.

The insight that shared support with the surface allows for robust object manipulation has been examined in the previous literature. Automated push-planning techniques proposed by [4]–[6] synthesize non-prehensile manipulation plans for moving objects along a surface. Toppling actions [7] are another possible mode of non-prehensile pre-grasp

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interaction. Planning methods for pushing manipulation have been also demonstrated as part of multi-modal motions that combine pushing with locomotion [8]–[10]. In addition, a whole-body manipulation strategy for pivoting large, heavy objects has been presented by [11] as a way for a robot to move objects that it cannot lift.

Previous literature has also investigated the utility of pushing and sliding actions as methods for sensing object pose [12] or reducing uncertainty in the orientation of objects in sensorless manipulation [13]. These methods may be considered as potential pre-grasp interaction strategies that increase information about the object configuration to improve grasping success.

The combination of sliding motions with grasping and/or lifting actions has recently been a topic of growing interest in the manipulation community. Manipulation plans are synthesized in [14] and [15] as sequences of object dragging transfer actions with regrasping transit actions. A planning method for sliding actions along constraint manifolds presented in [16] enabled lifting of heavy objects that were already grasped but not liftable in the initial grasp posture due to manipulator torque constraints. Recent work [17] uses a push-grasp as a type of pre-grasp action primitive for bringing objects into the hand during a reaching motion. Human patterns for pre-grasp sliding have been adapted for synthesizing pushing actions that improve the success rate of grasp acquisition [18]. Much of our previous work [1]–[3] has focused on pre-grasp rotation as a simple form of pre-grasp interaction, and such object re-orientation has also been used by [19] to improve grasps of hard-to-reach object handles.

III. PRE-GRASP ROTATION OF HEAVY HANDLED OBJECTS

Planar displacement is a useful type of pre-grasp object adjustment because grasped objects are frequently grasped from flat surfaces such as tabletops, shelves, or the floor. A subset of planar displacement actions are 1-degree-of-freedom rotations of the object around a pivot axis normal to the surface. We use pre-grasp rotation to refer to object interactions where the sliding motion on the surface is dominated by planar re-orientation of the object with little translational movement. In particular, pre-grasp rotation is useful for re-orienting objects that have a single asymmetric handles, such as mugs, pitchers, and pans.

Here we review our previous studies of pre-grasp rotation in human examples [1], [2] and for robot manipulation [3].

A. Lessons from human pre-grasp rotation examples

Observation of human usage of pre-grasp rotation [1], [2] has resulted in three insights that are relevant to robot manipulation.

1) Grasp reuse in capture region: Pre-grasp rotation enabled the reuse of similar grasps for a particular object by re-orienting the object into a preferred capture region for the final lifting grasp [1].

2) Constraints and task difficulty: Selected object orientations for lifting were more constrained for increased task difficulty [2]. This relation suggests that the utility of pre-grasp rotation was greater in constrained or difficult manipulation tasks.

3) Lifting capability for posture selection: The amount of object rotation was correlated with the increase in posture-dependent lifting capability achievable from the initial to selected object orientation [2]. This correlation suggests a strength-based quality metric for selecting and optimizing robot postures with pre-grasp rotation.

B. Robot pre-grasp rotation

Initial work on robot pre-grasp rotation has demonstrated that large gains in grasping success are possible even with only 1-DoF object reconfiguration. For objects with specific desired grasping sites, or handles, re-orientation of an object can significantly change the end-effector location required to reach the grasp (Fig. 2).

1) Grasp reuse and workspace extension: We found previously that combining pre-grasp rotation with a well-tuned grasping routine enabled the reuse of the routine over a wider range of initial task conditions [1]. For a system with many degrees of freedom such as an anthropomorphic manipulator (Fig. 1), it is time-consuming to design, program, and tune a new action primitive. In [1], the manually programmed grasp routine was robust for a small set of initial object orientations in a 45-degree capture region. Instead of planning a new grasp routine for each region of initial object orientations, the demonstration included a single preparatory rotation routine that adjusted the object from any initial orientation into the grasp region. Thus the effective workspace of the original grasp routine was extended to robustly complete the grasping task.

One particular benefit of the pre-grasp rotation in this demonstration was that it reduced the uncertainty in the object orientation before the grasp. From initial object poses with handle directions spanning a range of 360 degrees, the manual pivoting action reduced the handle orientation to a 15-degree range. This reduced range was within the 45-degree range of the grasping routine, which resulted in more robust grasps that tightly-gripped the thin pan handle. In contrast, when only the direct grasping routine was used without the preparatory rotation, the pan was sometimes grasped in a looser grip that resulted in dragging or tilting during the grasping routine. Furthermore, with pre-grasp rotation, the increased consistency of the grasps then also resulted in further reduced uncertainty of the pan position to a 6-degree orientation range after the final grasping routine [1].

C. Posture selection for automated planning

Automated manipulation planning is needed in less structured scenarios to respond quickly to new task conditions. A key decision for automated grasping with pre-grasp interaction is the target object pose after the object adjustment. The new object pose should be reachable by the desired grasp,

Fig. 2. The grasping posture at the time of object lifting from the surface depends on the object pose. Even for a 1-DoF change of object orientation, the allowable manipulator configurations can change significantly due to the different end-effector poses required to reach the object handle.

and it also must be attainable by the pre-grasp interaction from the initial object state. The inclusion of the object pose increases the dimensionality of the search space for motion planning of the manipulator configuration. That is, the manipulator configuration for grasping the object depends on the new object pose (Fig. 2). Here we use *grasping posture* to refer to combined configuration of the manipulator and the object at the time of object lifting from the support surface.

To make the planning tractable, the method presented in [3] decomposes the transport task into component actions of the pre-grasp rotation, the reach-to-grasp motion to achieve the desired grasp, and the transport motion that satisfies the primary objective. The method samples and optimizes the intermediate states between the component actions in order for the decomposition to yield a whole successful transport plan.

An optimization metric is needed to evaluate and select from the sampled grasping postures. The lifting capability metric that was correlated with human pre-grasp rotation [2] is analogous to the maximum payload rating for a particular robot manipulator configuration. Selecting grasping postures with high maximum payload increases the safety margin of the actual load relative to the joint torque limits. Higher safety margins also reduce the risk of operating near load limits if there is uncertainty in the object weight.

In addition, in some of the examples tested in [2], the selection of high quality grasping postures for the lift-off time resulted in higher quality manipulator configurations that were planned for the following transport plan. This result occurred even though the motion planner for transport was agnostic to the quality metric. This influence of the grasping posture on the transport configurations suggests the importance of selecting good candidates for key transition points in a multi-step motion plan, an insight which has also been observed by others for multi-modal planning [20].

IV. LOCAL REFINEMENT OF GRASP POSTURE

In the initial planning method described above, candidate grasping postures were selected to determine intermediate goals and synthesize a feasible object transport plan that automatically incorporated pre-grasp rotation [2]. A finite set of candidate postures were sampled for evaluation in a pre-computation stage. One limitation of this method is the restriction of the motion planning goals to the exact sample configurations, which will miss candidate goals if sparse sampling is used for high-dimensional configurations. A related limitation is that the resulting motion plan was specific to the modeled object motion. The method did not account for uncertainty in the success of rotating the object to the selected target orientation.

Here we review some initial results for a method that locally refines a grasping posture for pre-grasp rotation. Starting from an initial valid grasping posture of the object, our method locally optimizes the payload margin metric. This local optimization framework is also used to compare possible optimization metrics for selecting the grasping posture. We show that in scenes where the same limiting joint restricts most of the feasible grasping postures, a simpler objective of minimizing a single joint torque value is a possible proxy cost function for locally improving a grasping posture.

This method of local refinement of an initial selected grasping posture could be used in a situation where the pre-grasp rotation plan fails to adjust the object completely to the desired orientation and only achieves an intermediate orientation from the initial orientation. If a feasible grasp of the intermediate orientation can be reached, the posture can be optimized while maintaining a grasp of the handle during rotation of the object on the surface. After the optimization, the object can then be lifted from the surface using the higher quality grasping posture.

A. Gradient-based optimization of joint torque cost

In the location optimization of a grasping posture, we assume that an initial feasible grasping posture for the intermediate object orientation has been reached (e.g. see the kettle grasp in Figure 2). The optimization goal is to improve the posture quality metric with respect to the manipulator's kinematic degrees-of-freedom (DoFs) as well as the object's single rotational degree of freedom. The object freedoms changed by pre-grasp rotation can be considered a passive joint added to the manipulator. For this "extended manipulator", the new "end-effector" frame is a fixed frame in the environment at the initial object position (i.e. a frame fixed to the support surface). The optimization of the grasping configuration from an initial feasible point must maintain the extended end-effector frame at this location, since the passive object links remain supported by the surface at all candidate configurations during any rotation.

For example, in Figure 2, the pivot axis of the kettle remains fixed relative to the table. The optimization changes only the robot arm configuration (N-DoF) and the kettle orientation (1-DoF) without lifting or translating the kettle on the table. The grasp of the handle (the relative configuration of the robot gripper to the object) remains fixed such that the object is considered part of the same link as the gripper.

The new extended "end-effector" frame differs by a 1-DoF rotation from the object frame.

Thus the configuration space for representing a single grasping posture is (N+1)-dimensional for an N-DoF manipulator and a single pivot freedom for object rotation. The constraint is the requirement that the extended "end-effector" frame matches a specified frame on the support surface defining the object location.

We found that a gradient-based search in the (N+1)-dimensional space resulted in unacceptable drift from the constraint manifold or increasing cost with re-projection onto the manifold. Instead, a manipulator-specific analytical IK solution was used in a gradient-based search within a subspace of the redundant DoFs while satisfying the end-effector constraint. In our example scenario (Fig. 2), the manipulator has N=7 DoFs, and the complete search space thus has 8 DoFs when the passive object rotation freedom is added. We searched in a 2-D subspace of the first manipulator joint axis and the object rotation axis. A manipulator-specific IK solution was used to convert any 2-D subspace configuration to a corresponding full 8-DoF grasping posture that satisfied the end-effector constraint. This approach was used to optimize the 8-DoF configuration while staying on the constraint manifold.

Our gradient subspace search was used to compare optimization cost functions. Specifically we compared a multi-joint payload metric with single joint cost proxies.

B. Cost functions for grasp-posture selection

The payload margin optimization metric is computed based on the torque limits of multiple joints, but its value is determined by the limiting or weakest joint for a particular manipulator configuration. In an analysis of the sampled grasping postures for example transport task scenes in [2], the limiting joint for the payload metric was dominated by a few particular joint axes, rather than being uniformly distributed across the 7 joint axes of the robot arm. Since the payload margin is determined by the limiting joint, an alternative cost function for evaluating the grasping postures is the torque magnitude of the predicted weakest joint.

We used the subspace gradient search described above to compare the optimization of two types of torque-based cost metrics for the grasping posture. The first is the payload safety margin cost, which depends on the torque limits of the manipulator's multiple joints. The second is a torque magnitude of a single selected joint expected to be the weakest joint.

For a single scene, multiple initial grasping postures are selected based on the discretized sampling method in [2]. The set of candidate postures are optimized separately with respect to the multi-joint payload margin cost and the single joint torque cost for joints 2, 5, and 6, which were most often the limiting joint.

Figure 3 shows the change in the optimization cost function from the initialization point to the final posture after optimization. In the sampled initialization postures, there were multiple grasping postures per sampled object orientation angle. For clarity, the plots show only the final optimized posture with the lowest cost for each group of postures with the same initialization object angle.

For the kettle grasps (Fig. 3), the limiting joint for the payload safety margin cost was most often joint 6, the wrist flexion, and otherwise joint 5, the forearm roll or pronation. Thus, joint 6 is considered the weakest joint for this task. When the single joint 6 torque cost was used as the cost function for optimizing the grasp postures, the resulting object angles and postures were similar to those resulting from the payload metric optimization (Fig. 4).

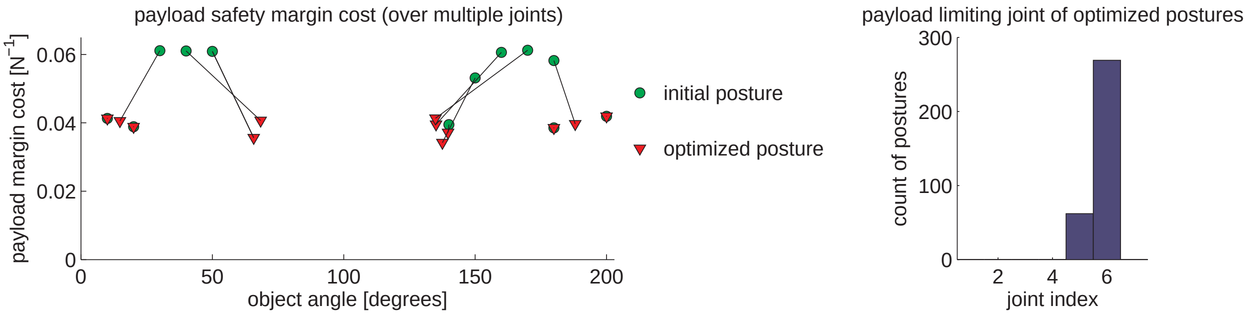
In contrast, while it was possible to achieve arm configurations with zero joint 5 torque, the resulting postures had higher payload margin costs than the original initialization postures. Optimizing the joint 2 shoulder elevation torque, however, yielded the lowest corresponding payload costs (see middle column of Fig. 3). This result demonstrates that optimizing a single joint torque independently is not sufficient to replicate the payload margin optimization, but it can provide a simple alternative cost funciton that results in similar object angles for target orientations of pre-grasp rotation.

V. DISCUSSION

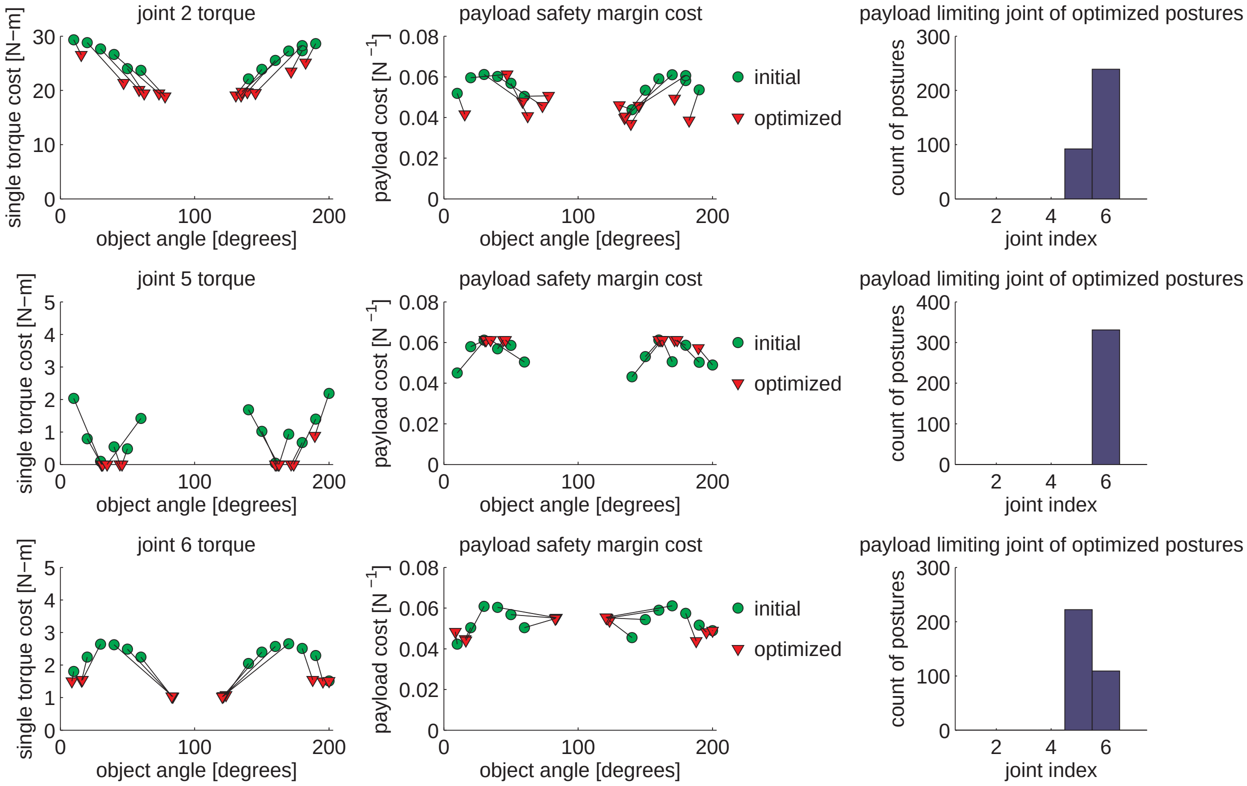
The initial investigation of pre-grasp rotation suggests promising benefits of incorporating pre-grasp interaction strategies into the repertoire of a robot manipulator. We have found that grasping success can be improved through reuse of robust grasps and the extension of the effective workspace of direct grasping.

Pre-grasp interaction may be a partial approach to address uncertainty in manipulation tasks. First, we found experimentally that a pre-grasp rotation routine reduced uncertainty in object pose before grasping and even after transport due to the increased consistency of the object grasp in the gripper. Further work is needed to develop methods for planning and predicting the pose outcomes from contact interaction, an area that has initially been investigated for sensorless manipulation by, e.g., [13], [21]. Second, our studies of human pre-grasp rotation found that object adjustment may be related to the optimization of the payload safety margin of the grasping posture for object lifting. The optimization of the grasping posture payload reduces the risk of operating beyond recommended actuation limits when the object weight is unknown or uncertain. In Section IV we presented recent results for local optimization of tje grasping posture as part of a pre-grasp rotation task.

In this paper, we have focused on 1-DoF object reorientation for a single-arm manipulator. The pre-grasp rotation plan consisted of a sequence of plans for object reorientation, reaching the grasping posture, and the object transport. Increasing the degrees of freedom for pre-grasp object motion and/or for the manipulator will also require decomposition methods to make planning tractable in high-dimensional search spaces. One recent approach explored by our group in [18] makes use of human demonstration

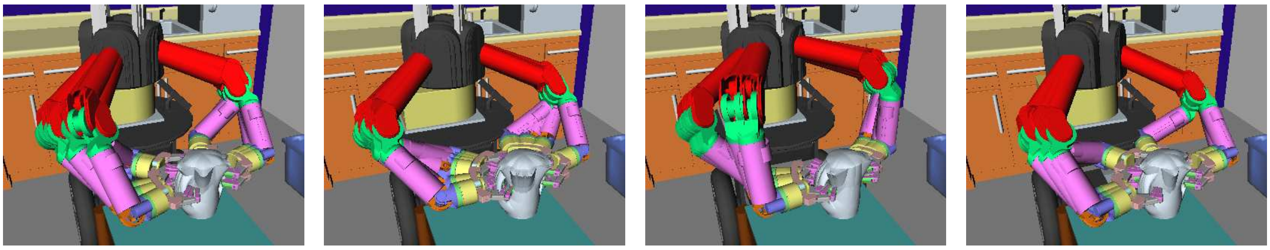


(a) Kettle on table: Payload safety margin optimization



(b) Kettle on table: Single joint torque minimization

Fig. 3. Optimization results for grasping the kettle from a table. (a) The change in the cost versus the passive object rotation freedom for optimizing the payload safety margin (left). For clarity, only the results with the lowest final cost from each group of postures with the same initial object angle are shown. Joint 6 was most often the limiting joint (right) for the entire set of final optimized postures for grasping the kettle. (b) The change in the joint torque cost versus object angle (left) when the optimization cost function is the torque magnitude at a single joint, for joints 2, 5, and 6. The corresponding changes in the payload margin cost are shown (center) for the postures resulting from single joint torque minimization. The limiting joint for the payload cost is shown (right) for the entire set of final postures resulting from single joint torque minimization.



(a) Payload margin (b) Joint 2 torque (c) Joint 5 torque (d) Joint 6 torque

Fig. 4. Optimized grasping postures for different torque-based cost functions. The illustrated robot grasps correspond to the final optimized postures whose object angles are shown in Fig. 3. For the kettle grasps, the object angles from payload margin optimization (a) are most similar to those for minimizing the joint 6 torque (d).

examples to narrow the search space of promising candidate grasps for pre-grasp pushing interactions.

A remaining challenge is to deal with the uncertainty in the planned object adjustment at the time of action execution. We presented initial investigation of motion planning techniques for identifying a desired manipulation plan that includes pre-grasp interaction. Future work is required to integrate the motion plan together with perceptual information during execution to realize robust task completion even under modeling uncertainty.

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