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Dynamic regrasping by in-hand orienting of grasped objects using non-dexterous robotic grippers

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ABSTRACT

Almost any task on an object requires regrasping of the object prior to performing an intended task by varying between grasp configurations. The human hand uses many methods to perform regrasping manipulations such as in-hand sliding, finger gaiting, juggling, picking and placing, etc. The most complex and inspiring approach is the in-hand orienting dynamic regrasping where an object is released into mid air and regrasped in a different orientation. This manipulation is useful in industrial robotics for rapid manufacturing and reducing the number of robotic arms in production lines. In this work, we present a novel approach for performing in-hand orienting regrasping using computed torque control. To maintain an efficient and low-cost approach, the regrasping is performed using a non-dexterous two-jaw gripper and by utilizing the robotic arm's dynamics. We focus on the motion planning for the motion and propose a novel stochastic algorithm for performing an optimal manipulation satisfying the kinematic and dynamic constraints. The algorithm optimizes the initial pose of the arm and the control gains. Statistical analysis shows the probability for the algorithm to find a solution if such exists. Simulations on a KUKA arm and demonstration on a planar 3R arm validate the feasibility of the proposed regrasping approach and planning algorithm.

1. Introduction

When the human hand holds an object with a grasp not compatible with the task to be done, it performs *Regrasping*. In other words, the hand executes a set of manipulations backed by eye feedback to alternate the grasp configuration with respect to the intended task (Fig. 1). The regrasping manipulations of humans have encouraged many robotic researchers to take inspiration for different regrasping motions and mimic them using dexterous robotic arms and hands. The ability of robots to perform regrasping tasks enhances their capabilities and dexterity. The main impact of regrasping manipulations is in industrial applications. For instance, current production lines utilize numerous robotic arms, each with an end-effector especially designed for grasping a specific part and to perform one designated task. This makes the end-effectors inflexible in handling variations in component shape or in task. Using an efficient regrasping method, the same arm can perform multiple operations on the same part and by that decrease the number of robotic arms in the plant. However, current regrasping methodologies work only with highly redundant (and hence expensive) hand architectures, and require agile sensory feedback, thus, not fitted for industrial applications. In this paper, we present a novel motion planning approach to perform a rapid and optimal dynamic regrasp manipulation with a robotic arm and a non-dexterous simple gripper. Such approach would enable industrial practitioners to use existing robotic arms in the plant and low-cost grippers for performing multiple tasks on the same part. By that, the number of required robotic arms in the plant would be reduced, as well as the gripper design and manufacturing time, and at the end reduce the final product cost. In terms of robotic manipulation, the problem introduced in this paper and the proposed algorithm will increase the dexterity of any robotic arm and will expand its library of motions. Our long-term goal is to build a library of basic dynamic regrasping manipulations that will serve as building blocks for higher task executions to be performed by autonomous robots.

Previous work on regrasping used quasi-static motions and high dexterity manipulations. The alternative of dynamic regrasping using a single robot arm with a non-dexterous end-effector offers an attractive solution in terms of cost as well as task completion time. In this research, we focus on a simple robotic system that will perform transition between two or more grasps of an object. As mentioned, we focus on non-dexterous two-jaw grippers. That is, the gripper would only have a minimal number of primitive degrees of freedom (DOF) to only fixture the object after the manipulation is finished, e.g., a jaw gripper, a clamp, etc. Hence, we rely on the dynamics of the arm rather than on a highly dexterous hand or, as defined by [1], we use extrinsic dexter-

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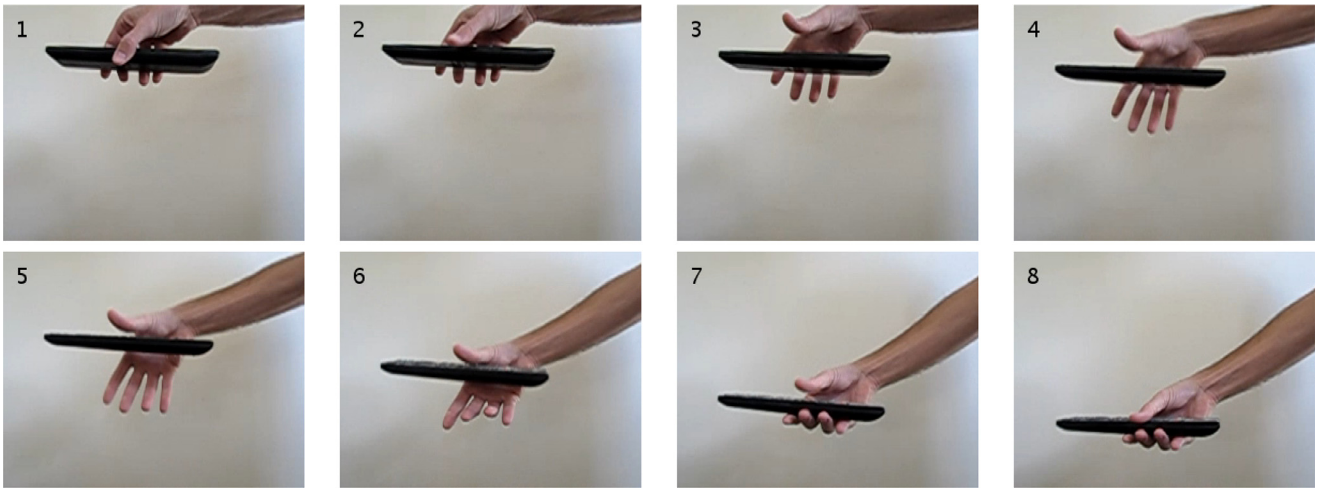

Fig. 1. Snapshots of a human hand performing in-hand orienting dynamic regrasping on a TV remote control.

ity. It should be noted that in this work we do not deal with regrasp synthesis of where on the object's surface to grasp while maintaining a force-closure grasp, as done by [2] and [3]. The idea of the regrasping problem in our context is grasping with a very simple gripper and regrasping by means of changing the relative position and orientation between the object and gripper.

The dynamic regrasping strategy for which we propose a motion planning algorithm in this paper is termed *in-hand Orienting*. The object is released into mid-air after opening the gripper. The robotic arm will then move the gripper in tandem with the falling object, but without disturbing the object. When the gripper reaches a new desired orientation relative to the object, its jaws will capture the object by closing around it. It should be mentioned that the capturing is done with matched velocities between the object and gripper for soft catch to prevent undesired shocks to the object. We use a novel Stochastic KInodynamic Planning (SKIP) algorithm for planning and optimizing the motion. A preliminary version of the algorithm was first introduced in [4] for object throwing where polynomial trajectories were optimized. In contrast, in this work we use a modified version of the algorithm to optimize the initial state of releasing the object and provide a profound analysis. Optimizing the state of releasing the object is essential to enable a feasible motion and can reduce joint torques and motion time. The algorithm parameterizes the proposed motion of the arm and object, including the control gains and the initial state of the system from where to release the object. To our knowledge, no optimal control or trajectory optimization methods can find a solution while choosing the best initial state of the system. Other methods such as sampling-based planners [5] plan the motion from a given initial state. The parameterized motion is the input of the SKIP algorithm, which outputs the optimal solution (based on a given cost function) satisfying the kinodynamic constraints of the problem. The algorithm is based on the use of the Computed Torque (CT) control and its response on the arm. The CT control enables good prediction of the motion which is essential for the implementation of the planning algorithm. Due to the fact that the CT control is model based, we perform model identification for approximating the dynamic parameters of the robotic arm. The proposed planning and control scheme is presented in Fig. 2.

In this work we focus on the motion planning problem for performing the proposed regrasping strategy. Nevertheless, we choose a control method that will enable the planning approach. However, we acknowledge that additional work must be done before regrasping of this type can be implemented in industrial applications. In particular, we do not discuss the visual feedback and estimation problem necessary for a robust manipulation. We assume full knowledge of the object pose at all times and leave the tracking problem beyond the scope of this paper. However, we will provide further discussion about future requirements regarding this in the conclusions section. It is also important to note that the regrasping manipulation is done in a priori known environment. This is a reasonable assumption for industrial applications where the robots are isolated and monitored. Thus, off-line planning is feasible.

The paper is organized as follows. In Section 2 we present related work on regrasping and dynamic manipulations. Section 3 is the formal regrasping problem definition. In Section 4 we present the CT control. The parameterization, constraint formulation, and SKIP algorithm are presented in Section 5. In Section 6 we present performance analysis and complexity of the algorithm. Simulations and experiments are presented in Section 7. Finally, we conclude the algorithm and results in Section 8.

2. Related work

This paper discusses a dynamic manipulation approach for performing the regrasping motion of a human hand for future industrial implementations such as assembly tasks. Let us first describe the two regrasping approaches taken by industrial practitioners. The first approach is the common *pick and place* method that designates a special work area near each robotic arm, where the grasped workpiece can be dropped in a controlled manner, then picked up again at a new grasp configuration [6–8]. Alternatively, some high-end industrial practitioners resort to "unthreading" the regrasping task by placing several (hugely expensive) robot arms along a long production or assembly line, each picking a moving workpiece at a new grasp configuration [9,10]. While both regrasping methods work nicely in practice, they consume valuable production time, occupy a substantial work area, and are highly expensive when multiple robot arms are being used.

In the robotics literature, there are four known approaches for regrasping (excluding picking and placing); First, the use of the gripper's DOF to move between contact points while maintaining a force-closure grasp during the entire process [2,11–16]. This approach is also called *quasi-static finger gaiting* in the robotics literature. However, quasi-static finger gaiting is quite wasteful, as it requires sufficiently many DOFs (requiring highly redundant finger linkages) to manipulate the grasped object between two grasp configurations while maintaining force closure grasps. Most of the finger gaiting algorithms use at least another extra finger that can be lifted at each step [17–20]. Such motion results in a slow quasi-static manipulation, maintaining a state of constant contact with the object. This has an analogy to gait, where advancement is done only with one leg lifted at a time (when dynamic forces are not taken into consideration) so that the other legs can maintain balance. Such a process can take a valuable amount of time.