Force-and-Motion Constrained Grasp Planning for Tool Use

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I. Introduction

Physical interactions that produce physical changes in the world requires work exchange, i.e., the application of purposeful *forces* along intentional *motions*. We can think of a robot as a programmable force/motion generation machine, and of the aim of robotic manipulation as mastering that force/motion generation process. For example, how do we get a robot to pick up a screw driver from a table, grasp its handle, latch gently onto the head of a screw, and turn it forcefully while maintaining a normal load?

We are particularly interested in the long-term decision making involved in selecting the grasp, the arm motions, and tool trajectory to satisfy the kinematic, actuation, friction, and environment constraints. Our overall goal is to enable robots to reason through that long-term combination of force and motion constraints to enable *forceful manipulation*. In this work we focus the grasp planning.

We study this problem in the context of robots using hand tools, as in Fig.1. As humans, we use a tool in a particular grasp to overcome limited reachability, but also–and often specially–to use appropriately sized muscles and sufficiently firm grasps for the tool to act on the environment.

These constraints, both force and motion related, govern our choice of grasp. In this paper we formulate a tool-use problem as a constraint-satisfaction problem over continuous decision variables and then detail the constraints that govern the grasp-related decision variables.

We investigate four tool-use tasks on a real robot platform: pulling a nail out with a hammer's claw (Fig.1), tightening a bolt with a wrench (Fig.3), driving a nail with a screwdriver and cutting wood with a knife. Exploring the restrictiveness of these constraints on our choice of grasp gives us an idea of the difficulty of each problem.

II. Problem Definition And Approach

Each of our tool-use tasks can decomposed into multiple stages: grasping the tool, making contact with the environment, exerting force along a motion, breaking contact and placing the tool down. Each stage has a set of "decision" variables that need to be solved for, such as grasps or kinematic paths. The dependencies between these variables, as well as task-specific constraints, limit the feasible choices. Tool use can therefore be viewed as an instance of a constraint satisfaction problem, but with variables whose domains are high-dimensional continuous values.

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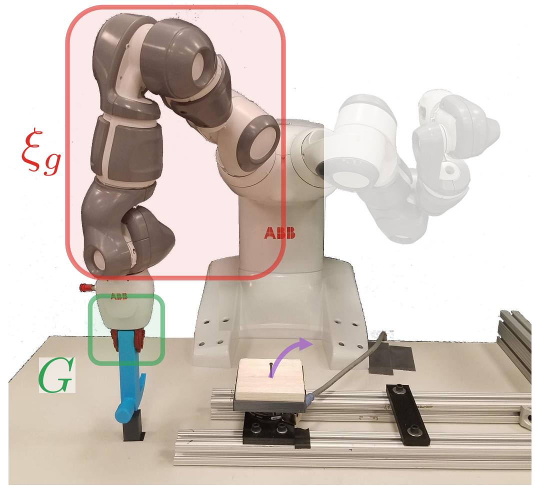


Fig. 1: We develop a system that enables a robot to reason about force and motion constraints in order to complete complex tasks pulling a nail out with a hammer. We frame this type of manipulation as a constraint-satisfaction problem where the first stage is to select the appropriate grasp G and a path to that grasp, ξ_g. The task motion, ξ_{action} is shown in purple.

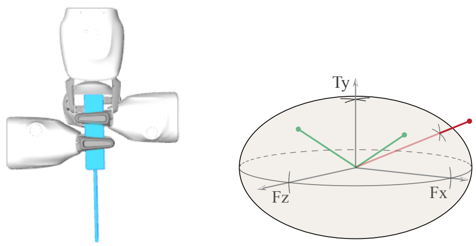
In this work we focus on the grasp-related variables: from some set of possible grasps (Fig.2a), the robot needs to pick a grasp G that is forcefully and kinematically suited to the task. The grasp must also be reachable, i.e. we must be able to plan some path collision-free ξ_{grasp} from the starting position to the grasp. For motion planning, we to use a bidirectional rapidly-exploring random tree (BiRRT) motion planner [1], [2]. Below we detail how we quantify what it means for a grasp to be forcefully and kinematically suitable.

A. Constraints

We define a grasp to be forcefully suitable if the grasp is stable under the force of gravity and any task-specific forces[1]. This ensures that the tool does not slip from the hand while in use. Given a parallel jaw gripper and prismatic tool handles, our finger contacts occur on parallel surfaces. We model each finger as a frictional hard patch contact, which means that the finger can exert normal and tangential forces as well as torque around the surface normal [3].

The boundary of this set of forces and torques is defined as the limit surface, which can be approximated as an ellipsoid (Fig.2b) [4], [5]. Its size and shape are a function of the grasping force, the size of the contact patch and the friction coefficient between the tool and the fingers.

[1]To avoid confusion between wrench (the tool) and wrenches (force and torque) we will refer to the later as "forces" even though there are torque components.



(a) Grasp Set (b) Limit Surface

Fig. 2: a) A subset of some of our possible grasps. Each tool has the same set of available grasps. b) We visualize the ellipsoidal approximation of the limit surface. The green wrenches lie within the boundary of the limit surface, representing stable grasps. The red wrench lies outside the boundary, representing an unstable grasp.

If the vector representing the task forces lies inside of the ellipsoid, the grasp is stable since the forces offered by the frictional contact exceed the task forces. In Fig.2b the two green vector lie inside the ellipse, corresponding to stable grasps. The red vector breaches the boundary of the ellipse, representing an unstable grasp.

Having defined forceful suitability, we next focus on kinematic suitability. In order to use the tool, we will plan a collision-free joint-space path ξ_{action} for the arm that enables the tool to follow that path and sustain the required forces. For example, the purple arrow in Fig.1 shows ξ_{action} for the hammer task.

We can think of grasping an object as augmenting the kinematic chain of the manipulator. The grasp relation serves as an additional joint, bounded by friction, between the hand and the tool and we want to select a value (i.e. a grasp G) such that the path ξ_{action} is in the reachable workspace of our augmented chain.

Given that we define ξ_{action} as a series of waypoints, a necessary condition is that there exists an inverse kinematic (IK) solution at each waypoint. The IK solution at each waypoint must also be able to resist gravity and the expected task forces, where the expected task forces were determined experimentally. We relate the external forces at the end effector to robot joint torques through the manipulator Jacobian, J. Specifically, given a joint configuration (i.e. our IK solution) q and external forces (task force and gravity) f_{ext}, the torque τ at the joints is given by $\tau = J^T(q)f_{ext}$. For a configuration to be suitable the expected τ does not exceed the robot's torque limits τ_{lim}. While these conditions are necessary, but not sufficient, to ξ_{action} existence[2], it serves as a useful heuristic.

III. Experiments and Discussion

We explore how our constraints, that a grasp must be force and kinematic suitable and reachable via collision-free path, impact the set of available grasps. From our continuous set of grasps (Fig.2a), we sample 500 grasps and evaluate all three constraints. Our results are given in Table I where C_0, C_1 and C_2 are force suitability, reachability and kinematic suitability,

[2]For our redundant manipulator, an IK solution at each waypoint is not sufficient because it does not guarantee a smooth, continuous path.

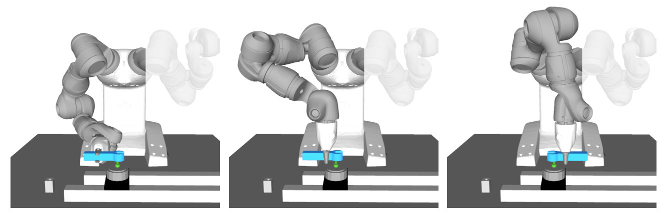


Fig. 3: Here we show three grasps for `wrench_turning`. The leftmost is kinematically suitable but not stable. The middle is stable but kinematically unsuitable. The right is both stable and kinematically suitable.

Task	C_0	C_1	C_2	$C_1 \cap C_2$	$C_0 \cap C_1 \cap C_2$
`screw_driving`	500	398	162	162	162
`wrench_turning`	52	369	220	219	27
`knife_cutting`	56	382	329	233	26
`hammer_pulling`	36	359	116	116	1

TABLE I: For each task we state the number of grasps (out of 500) that satisfy each constraints. C_0 is force suitability. C_1 is reachability. C_2 is kinematic suitability.

respectively. In addition to showing how many grasps satisfy each constraint, we show how many satisfy the two kinematic constraints (reachable and kinematically-suitable) and how many grasps lie at the intersection of all of our constraints. Fig.3 shows several grasps for the wrench tightening tasks that satisfy or fail various constraints.

For most tasks we see that the stability constraint is the most restrictive. The small size of the set of grasps at the intersection of all of our constraints illustrates each task's difficulty. In the `screw_driving` task, the force requirements are relatively smaller, leading to all grasps being suitable from a stability standpoint. In comparison, the remaining tasks involve much more torque, leading to a smaller intersection set. The `hammer_pulling` task is the most difficult, demanding grasps that can resist a significant amount of torque and can create a constrained arc-motion. For these more constrained tasks, incorporating regrasping could allow us greater flexibility and enable us to complete longer-scale tasks [6].

The goal of this work is to enable a robot to complete tasks that require both planning motions and controlling forces. We presented grasp constraints that enable forceful manipulation, taking tool use as an illustrative example. In addition to our simulation results, we have verified our system on the real robot and look forward to exploring more complex force-and-motion interactions.

References

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