Adaptive contact point estimation for autonomous tool manipulation

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***Abstract*— Autonomous grasping and manipulation of tools enables robots to perform a large variety of tasks in unstructured environments such as households. Many common household tasks involve controlling the motion of the tip of a tool while it is in contact with another object. Thus, for these types of tasks the robot requires knowledge of the location of the contact point while it is executing the task in order to accomplish the manipulation objective. In this work we propose an integral adaptive control law that uses force/torque measurements to estimate online the location of the contact point between the tool manipulated by the robot and the surface which the tool touches.**

I. Introduction

Many of the kinds of tasks that humans execute with tools require contact between the tip of the tool and some other object. Cleaning a dish, flipping a pancake on a stove, writing on paper are among a few examples of tasks that require contact forces to be exerted with the tool while controlling the position of the contact point relative to the object.

As robots start making their way into household environments, they must perform such kinds of tasks autonomously without relying on strong assumptions such as perfectly known models of the tool and the environment and known pose of the tool with respect to the robot's hand.

In this work we propose an adaptive estimation scheme that takes as input force/torque measurements to yield online estimates of the position of the contact point between the tool and the environment. Our estimator does not require previous calibration or modeling of the tool. Additionally, we propose a second adaptive estimator that determines the normal direction of the surface by using proprioception and the estimated contact point. An adaptive force controller then uses these estimates to regulate the interaction forces.

II. Related Work

Previous works on tool calibration have used different types of sensory modalities. Bruyninckx *et. al.* have solved peg-in-hole insertion tasks through force sensing by estimating alignment errors without explicitly estimating the contact point [1].

Kubus *et. al.* used proprioception and force/torque sensing to estimate inertial parameters of objects, and then used these estimated parameters in turn to estimate the pose of the object when it was grasped in a different configuration [2]. Hebert *et. al.* fuse proprioception, force/torque sensing as well as estimation of finger-object contact points to estimate the pose of objects held by the robot [3]. Vision-based approaches normally rely on previously modeled objects to extract visual features and use these to estimate the pose of the object in the image.

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III. Kineto-static modeling

We consider a robotic manipulator with a wrist-mounted force/torque sensor that uses a tool to trace on a given surface. Here we introduce notation for the variables that are relevant to the contact point estimation problem and describe the constraints and assumptions that we use in our formulation.

A. Notation and kinematics

We denote with $\{e\}$ the end-effector frame and we assume that the tool touches the surface at a single point $\mathbf{p}_c$, whose normal direction we denote $\mathbf{n}_c$. The variable that we are interested in estimating is the position of the contact point relative to the end effector frame ${}^e\mathbf{r}$. We assume that the grasp is rigid so that the contact point is constant in the end-effector frame. Furthermore, we assume that the surface is rigid and fixed so that the linear velocity of the end-effector is constrained to be parallel to the surface.

B. Statics

In the tracing task there are both gravitational forces and contact forces acting on the tip of the tool. The contact forces can be decomposed in a normal component $\mathbf{n}_c f_n$ due to the rigid contact and a tangential component $\mathbf{f}_t$ due to dynamic friction. In our analysis we assume that the gravitational forces are precalibrated or are negligible in comparison to the interaction forces.

IV. Adaptive estimation and control

Fig. 1 shows an overall diagram of our adaptive control scheme, in which the robot performs a tracing task over a surface and uses proprioceptive and force-torque sensory feedback to simultaneously estimate the location of the contact point and the surface normal. These estimates are then used in the force/motion controller to regulate the interactions forces and to provide sufficient excitation to the estimators. Once the robot starts tracing on the surface, the contact of the tool with the surface produces both normal contact forces and dynamic friction forces. In the following sections we explain which inputs are required by each estimator/controller and how the controller design affects the convergence of the estimators.

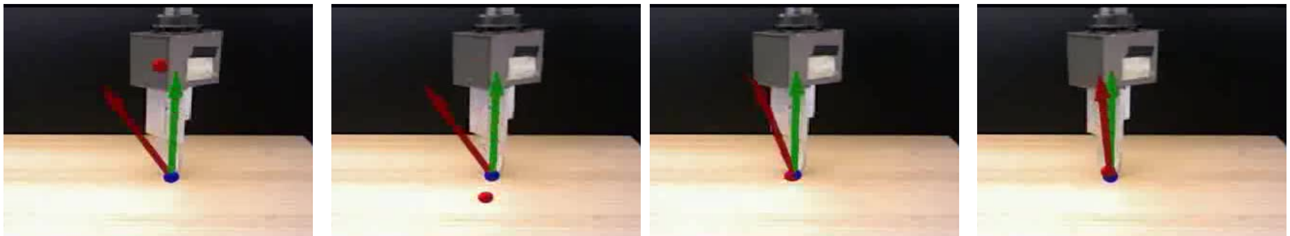

Fig. 2 : Image sequence that illustrates our contact point estimator and surface normal estimator. The contact point estimate is depicted as a red dot, while the ground truth is depicted as a blue dot. The surface normal estimate is shown as a red vector while the true surface normal is shown in green.

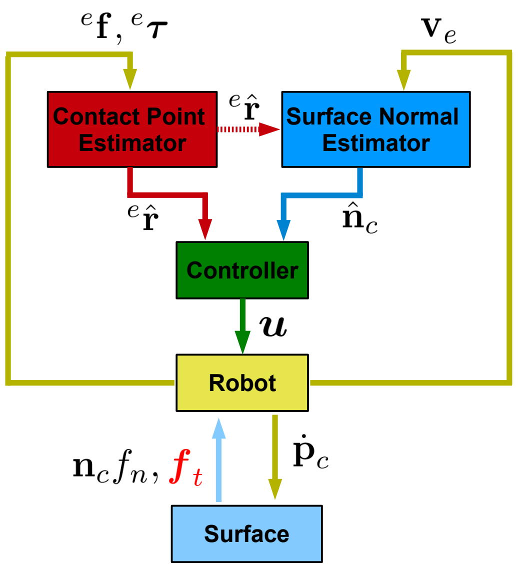

Fig. 1 : Diagram of the proposed adaptive control and estimation scheme.

A. *Contact Point Estimator*

We design the contact point estimator as an integral adaptive control law that takes as input force-torque measurements $({}^{e}\mathbf{f}, {}^{e}\boldsymbol{\tau})$ measured from the end-effector to produce estimates of the contact point relative to the end-effector frame ${}^{e}\hat{\mathbf{r}}$. The convergence of this estimator depends on the angle spread of the forces measured by the robot, which in this case will depend on the spread of the dynamic friction forces at the tool-tip.

B. *Surface Normal Estimator*

The surface normal estimator is also an integral adaptive estimator. This estimator integrates the linear velocity of the contact point $\dot{\mathbf{p}}_c$ to obtain estimates of the normal direction $\hat{\mathbf{n}}_c$ of the surface at the contact point. However, since we assume that the contact point is not known a priori, we estimate the velocity of the contact point by using proprioceptive measurements from the robot end-effector, in this case the end-effector twist $\mathbf{v}_e$, and the contact point estimate ${}^{e}\hat{\mathbf{r}}$. For simplification, one can command zero angular velocity to the end-effector $(\boldsymbol{\omega}_e = \mathbf{0})$ so that $\dot{\mathbf{p}}_c = \dot{\mathbf{p}}_e$ and the estimator becomes independent of the contact point estimate.

C. *Force/motion Control*

The controller takes as input the estimates ${}^{e}\hat{\mathbf{r}}, \hat{\mathbf{n}}_c$ and produces a velocity control input to the robot which we decompose in a PI force control loop along the normal direction of the surface that regulates the contact force and a motion controller along the surface which can follow a predefined trajectory or control the position of the contact point. These controllers affect the performance of the estimators since the end-effector twist $\mathbf{v}_e$ generated by the motion controller provides direct excitation to the surface normal estimator and this velocity generates the necessary dynamic friction forces $\mathbf{f}_t$ at the tool-tip for estimating the location of the contact point. The normal force set-point of the force controller is also an important design parameter given that it directly affects the magnitude of the dynamic friction forces.

V. Experimental Results and Conclusions

We tested the proposed estimators on our robot platform equipped with a 7 DOF manipulator and a wrist-mounted force/torque sensor. Fig. 2 shows a sequence of images of the experimental trial which illustrate the convergence of the estimators. We set a feedforward circular trajectory with zero angular velocity and an initial 35 cm error for the contact point estimate and a 30 degree initial error for the surface normal. The contact point estimate converged to an error of approximately 5 mm while the surface normal converged with a 1.5 degree error.

The system is shown to converge both theoretically and experimentally, given proper parameter excitation signals. The method is however restricted to rigid grasps, and we are currently studying how to generalize the model for some cases in which the tool might slip in the robot's hand.

Acknowledgment

This work has been supported by the Swedish Research Council (VR), the European Union FP7 project Robo-How.Cog (FP7-ICT-288533), and the Swedish Foundation for Strategic Research. The authors gratefully acknowledge the support.

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