

In-hand manipulation using gravity and controlled slip

Francisco E. Viña B., Yiannis Karayiannidis, Karl Pauwels, Christian Smith and Danica Kragic

Abstract—In this work we propose a sliding mode controller for in-hand manipulation that repositions a tool in the robot’s hand by using gravity and controlling the slippage of the tool. In our approach, the robot holds the tool with a pinch grasp and we model the system as a link attached to the gripper via a passive revolute joint with friction, i.e., the grasp only affords rotational motions of the tool around a given axis of rotation. The robot controls the slippage by varying the opening between the fingers in order to allow the tool to move to the desired angular position following a reference trajectory. We show experimentally how the proposed controller achieves convergence to the desired tool orientation under variations of the tool’s inertial parameters.

I. INTRODUCTION

Many tasks robots are expected to do require complex interactions with objects. Although significant contributions have been achieved in the area of grasping, in-hand manipulation remains one of the open challenges [1]. In tasks that require tool use, the robot is expected to pick-up a tool and also choose a grasp that is suitable for the task. For example, a task such as hammering requires the robot to apply large forces with the tool in a given direction. Thus, the robot must ensure that it applies enough grasping force in a right direction and that the tool is correctly positioned in the hand to avoid undesired displacements while executing the task. However, even if the robot plans the grasp correctly, once it picks the tool up from a table or a shelf the resulting grasp configuration may be different to the planned one due to imprecise sensing, motion planning and control. Moreover, the grasp configuration can change as the robot performs the task due to externally applied forces such as unplanned collisions with the environment.

Thus, the robot must be capable of evaluating the state of the grasp, that is, its suitability for the task. The evaluation can result in the confirmation that the grasp configuration is still acceptable for performing the task or that an adjustment of the grasping force or repositioning of the tool is needed. Repositioning the tool in the hand can be done by regrasping: placing the tool on a fixed surface and picking it up again from a different position [2]. On the other hand, if the robot’s hand is dexterous and/or individual fingers have multiple degrees of freedom, the robot can coordinate their motion in such a way that the tool moves to the desired position. This is known as in-hand manipulation using the *intrinsic* dexterity

of the robot’s hand. If, however, the hand has a rather simple kinematic structure, it is perhaps more feasible to employ *extrinsic* dexterity, i.e. use resources that are external to the robot hand’s embodiment [3]. The robot may for instance push the tool against an external object or it may loosen the grip so that the tool falls to a desired position due to gravity.

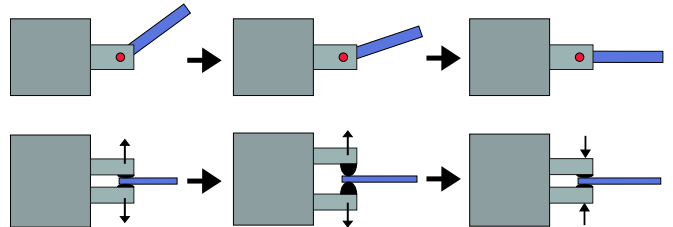


Fig. 1 : In-hand manipulation control using extrinsic dexterity by means of gravity and controlled slip. The top row depicts a side view of the gripper with the fixed axis of rotation marked with a red circle. The bottom row depicts a top view of the gripper as the robot opens and closes the fingers to allow the tool to fall to the desired configuration due to the gravitational pull.

The main contribution of our work is the design of a sliding mode control law for in-hand manipulation which uses an extrinsic resource, gravity, for reorienting a tool in the robot’s hand by regulating the friction exerted by the grasp. We assume that the robot has already performed a pinch grasp on the tool, such that the motion of the object is constrained to one rotational degree of freedom as shown in Fig. 1. We thus consider that the tool is attached to the robot hand via a passive revolute joint with friction. Furthermore, the controller regulates this friction by controlling the opening between the fingers of the hand. We show experimentally how the proposed control law achieves convergence to the desired angular trajectory of the tool with robustness to variations in the inertial parameters of the system.

One of the main differences between our work and the previous works on friction control comes from the fact that they focused mainly on friction compensation for servo motors or translation of objects on a surface. When working with robotic in-hand manipulation a number of challenges arise that we can enumerate as follows

- 1) The friction control literature mainly deals with friction *compensation*. The general approach in those studies is to estimate the friction parameters and use them in an additive compensation term in the control signal while in our case we actively regulate the friction through the grasping force and use gravity as actuation for the system.

The authors are with the Computer Vision and Active Perception Lab., Centre for Autonomous Systems, School of Computer Science and Communication, Royal Institute of Technology KTH, SE-100 44 Stockholm, Sweden. e-mail: {fevb|yiankar|kpauwels|ccs|dani}@kth.se. Y. Karayiannidis is also with the Dept. of Signals and Systems, Chalmers University of Technology, SE-412 96 Gothenburg, Sweden. e-mail: yiannis@chalmers.se.

- 2) The friction parameters of servo motors can be identified and used for compensating friction in the controller. Normally these parameters are considered fixed in the control law. In contrast, a robot may use different kinds of tools depending on the task, and each of these tools could potentially exhibit different friction characteristics.
- 3) In-hand manipulation is subject to loss of controllability since the manipulated tool can fall out of the robot's hand if not enough friction is applied at the contact.

This paper is organized as follows: Section II contains the related work, Section III derives the dynamic model of the system, Section IV describes our proposed sliding mode controller and Section V shows our experimental results. Finally, we present our conclusions and planned future work in Section VI.

II. RELATED WORK

Early works on regrasping focused on pick-and-place operations where the robot would release an object on a surface and pick it up from a different position. For instance, Tournassoud *et al.* identified sets of stable grasps and placements of polyhedral objects on a table and combined these in a discrete sequence of pick and place actions taking into account kinematic constraints of the manipulator [2].

Works in the intrinsic dexterity-based in-hand manipulation literature have studied planning and control aspects when coordinating multiple degrees of freedom of multifingered hands to move the manipulated object along a specified trajectory. Cole *et al.* designed a control scheme which coordinates sliding motions of two planar fingers over an object assuming Coulomb sliding friction at the contacts [4]. Han *et al.* proposed an in-hand manipulation framework that combines rolling and finger gaiting [5]. Hertkorn *et al.* formulated a planning framework which also takes into consideration kinematic and dynamic constraints of the task [6]. Okamura *et al.* formulated a survey of different dexterous manipulation techniques that have been proposed in the literature, as well as a summary of the main kinematic, contact and dynamic models used in those techniques [7].

On the other hand, the work of Brock provides one of the earliest analysis of controlled slip and how it can be useful for dexterous extrinsic manipulation [8]. The author studied how to determine the possible directions of motion of a grasped object and the effect of grasping forces and externally applied forces on the motion of the object. This knowledge is then used by the robot to reposition a grasped object by controlling the slippage when it comes in contact with other objects in the environment.

Dafle *et al.* presented a strong case for the benefits of extrinsic dexterity for in-hand manipulation [3]. Even though the robot used in the study is equipped with a rather simple gripper, the authors demonstrated that it is still physically possible to reposition the object in the hand of the robot by taking advantage of resources external to the robot's hand such as gravity, use of external objects for support and inertial forces due to the manipulator's acceleration.

The authors show this by implementing a discrete set of preprogrammed manipulation actions and combining them via a graph. In contrast with [3], our work focuses on one specific manipulation scenario but instead of using discrete preprogrammed actions we design a continuous closed loop control law to move the tool to the target position.

Senoo *et al.* used high speed manipulators and vision systems to manipulate objects within the robot's hand [9], [10]. The authors demonstrated that the high speed feedback and control allow them to perform fine in-hand manipulation using both intrinsic and extrinsic dexterity. In [10] the authors also proposed in-hand manipulation via a passive joint. However, these approaches are custom tailored for specialized high-speed hardware while in our case we use standard commercially available hardware.

Kappler *et al.* developed a high level representation framework of pregrasping manipulation actions that enable a robot to slide objects on a tabletop to positions which are suitable for generating more robust grasps [11].

Given that our in-hand manipulation control scheme relies on slippage control it is worth mentioning some of the previous works on friction modeling and control. This topic has been extensively studied in the control community given the widespread presence of friction in different kinds of mechanical systems. Olsson *et al.* provide a detailed survey of friction models and friction compensation schemes [12]. De Wit *et al.* proposed the LuGre friction model and designed friction compensation control schemes for this model [13]. Xie proposed an adaptive controller with sliding mode observer to estimate the friction parameters of a servo motor and perform position control with an unknown load [14].

Friction control is also a topic of interest in the design of Antilock Braking Systems (ABS) in vehicles. Ünsal *et al.* designed a sliding mode control law for the braking torque applied on a vehicle's wheel [15]. The main difference with our work is that the control objective consists in maximizing the tractive force exerted by the road on the wheels by regulating the wheel slip with respect to the road.

The contribution of our work is the design of a closed loop sliding mode control law which uses gravity and controlled slip. We track the position of the tool using a vision tracking system and control the slip by varying the opening between the gripper's fingers. We show experimentally that the proposed control law converges to the desired orientation of the tool despite changes in its inertial parameters.

III. MODELING

In our in-hand manipulation controller we assume a 1 DOF parallel gripper with soft fingertips that performs a pinch grasp on a tool as shown in Fig. 1. We assume that the pinch grasp affords only rotational motions around a fixed axis of rotation, which we assume is known a priori. The position of the tool with respect to the robot's hand can thus be described by the angle $\theta(t)$ with respect to the horizontal axis.

The control objective is to change the angular position of the tool to a desired set point $\theta_d(t_f)$ following a specified

trajectory $\theta_d(t)$. We assume that the manipulator is static and we only actuate the opening d between the fingers of the parallel gripper to control the grasping force applied on the tool, and hence the magnitude of the friction torque. We assume that the state of the tool $\mathbf{x}(t) = [\theta(t), \dot{\theta}(t)]^\top$ can be observed through sensor measurements.

Furthermore, we operate the gripper in such a way that the tool only rotates and does not fall out of the robot's hand. As one increases the opening d between the fingers the object will first experience rotational slippage and then a combination of rotational and translational slippage until it falls out of the robot's hand as depicted in Fig. 2.

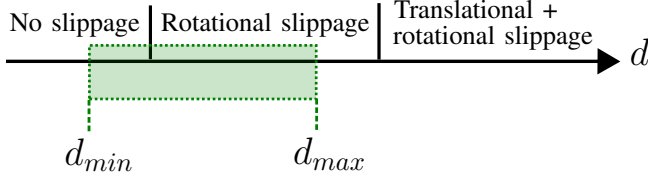


Fig. 2 : Slippage of an object grasped via a pinch grasp according to the separation d between the fingers of the parallel gripper. The object is assumed to be initially at rest.

We assume that the bounds $[d_{min}, d_{max}]$ are given beforehand, where d_{min} is a lower bound designed to avoid damages to the tool and/or gripper and to ensure that the friction torque is large enough to stop the object at the desired position $\theta_d(t_f)$, and d_{max} is set small enough to allow some safety margin and avoid translational motions of the tool but large enough to ensure that the gravitational torque can overcome the stiction torque.

A. Sliding friction model

Our proposed control scheme uses the sliding friction torque at the contact between the tool and the gripper to control the rotational motion of the tool.

We model the friction torque τ_f at the axis of rotation as Coulomb and viscous friction [12]

$$\tau_f(f_n, \dot{\theta}) = -\mu \operatorname{sgn}(\dot{\theta}) f_n - \sigma \dot{\theta} \quad (1)$$

where μ is the Coulomb sliding friction coefficient, f_n the normal force applied by the fingers of the gripper, $\dot{\theta}$ the angular velocity of the tool, $\operatorname{sgn}(\cdot)$ is the sign function and σ the viscous friction coefficient. From Eq. (1) we obtain a relation between the applied normal force and the resulting friction torque.

B. Deformation model

In principle the robot can control the friction torque described in Eq. (1) if measurements of the normal force f_n are available e.g. via tactile sensors.

However, we assume that such hardware capabilities are not available in our system and we control the normal force instead via the separation of the gripper fingers assuming a linear deformation model

$$f_n(x) = k(x - x_0) \quad (2)$$

where k is the stiffness of the fingers, x_0 is the position of zero deformation at which the fingers initiate contact with the tool and x is the position of the fingers. Replacing $x = -d$ and $-kx_0 = f_0$, the deformation model (2) can be rewritten as a function of the finger separation d

$$f_n(d) = f_0 - kd \quad (3)$$

C. Dynamic model

Since we assume that the tool moves along one rotational degree of freedom, it suffices to analyze the rotational dynamics of the system which is given by

$$I\ddot{\theta} = \tau_g + \tau_f \quad (4)$$

where I is the tool's moment of inertia with respect to the rotation axis, $\ddot{\theta}$ the tool's angular acceleration, τ_g the torque generated by the gravitational pull on the tool's center of mass and τ_f the torsional friction generated at the contact between the tool and the gripper.

Substituting the friction and deformation models (1) and (3) into (4) and adding the expression for the gravity induced torque we obtain the following dynamic model

$$I\ddot{\theta} = -mgl \cos \theta - \mu \operatorname{sgn}(\dot{\theta})(f_0 - kd) - \sigma \dot{\theta} \quad (5)$$

where m is the tool's mass, l the distance from the axis of rotation to the tool's center of mass and g the gravity.

IV. SLIDING MODE CONTROL DESIGN

To design a sliding mode control law we rewrite the dynamic model described by Eq. (5) as

$$\ddot{\theta} = h(\theta, \dot{\theta}) + b(\dot{\theta})u_d \quad (6)$$

where we denote u_d the gripper position control signal, i.e., the separation between the fingers of the gripper commanded by the controller. $h(\theta, \dot{\theta})$, $b(\dot{\theta})$ are given by

$$h(\theta, \dot{\theta}) = -\frac{mgl \cos(\theta)}{I} - \frac{\sigma \dot{\theta}}{I} - \frac{\mu f_0 \operatorname{sgn}(\dot{\theta})}{I} \quad (7a)$$

$$b(\dot{\theta}) = \frac{\mu \operatorname{sgn}(\dot{\theta})k}{I} \quad (7b)$$

The robot can determine the value of $\operatorname{sgn}(\dot{\theta})$ given the initial orientation of the tool with respect to gravity so that Eq. (7a) and (7b) become continuous functions of the state $\mathbf{x}(t) = [\theta(t), \dot{\theta}(t)]^\top$.

It is important to note the modeling uncertainties in Eq. (6). Even though the mass and center of mass can be estimated online by the robot just before running the controller by using a force-torque sensor, this estimate is subject to measurement errors arising from e.g. sensor noise. The moment of inertia and the friction and deformation model parameters are in general more difficult to estimate and require some form of pre-manipulation of the tool. Furthermore, in our formulation we have used a simplified friction model which ignores phenomena such as stiction, the Stribeck effect, hysteresis and stick-slip motion [13].

These observations make sliding mode control a natural choice since it is a robust control law when confronted with modeling imprecisions [16].

For the control law we define the first order sliding surface $s(t)$

$$s(t) = \dot{\tilde{\theta}}(t) + \lambda \tilde{\theta}(t) \quad (8)$$

where $\tilde{\theta}(t) = \theta(t) - \theta_d(t)$ and $\dot{\tilde{\theta}}(t) = \dot{\theta}(t) - \dot{\theta}_d(t)$ are the angle and angular velocity errors respectively with respect to a desired state trajectory and the control bandwidth λ is a positive constant. We design the reference trajectory $\mathbf{x}_d(t) = [\theta_d(t), \dot{\theta}_d(t)]^\top$ as the output of a second order critically damped system with unit DC gain with a trapezoidal angular velocity profile as input.

We can then formulate a sliding mode control law for the gripper position as follows [16]

$$u_d(t) = \hat{b}^{-1} \left(\hat{u}_d(t) - k_s \text{sat} \left(\frac{s(t)}{\phi} \right) \right) \quad (9)$$

where \hat{b} is an estimate of b in Eq. (7b) given the best available knowledge of the parameters, k_s is a positive switching control gain, ϕ is a constant parameter describing the boundary layer of the control signal whose purpose is to smooth the switching behavior of the control signal generated by the saturation function $\text{sat}(\cdot)$. This function is defined as

$$\text{sat}(z) = \begin{cases} z & \text{if } |z| \leq 1 \\ \text{sgn}(z) & \text{otherwise} \end{cases} \quad (10)$$

The nominal control signal $\hat{u}_d(t)$ is designed such that the dynamics of the sliding surface becomes $\dot{s} = 0$ assuming perfect knowledge of the system parameters. This yields

$$\hat{u}_d = -\hat{h} + \ddot{\theta}_d - \lambda \dot{\tilde{\theta}} \quad (11)$$

where we have dropped the time argument (t) for notational convenience. In this expression \hat{h} is an approximation of h given approximate estimates of the inertial, friction and deformation parameters in Eq. (7a).

In order to implement the position based control law (9) in our system we couple an additional proportional velocity control law for the fingers

$$u_v = -k_v \tilde{d} \quad (12)$$

where $\tilde{d} = d - u_d$ is the gripper position error, k_v a positive proportional control gain and u_v is the velocity that we command to the fingers of the gripper.

V. EXPERIMENTAL EVALUATION

We implemented the sliding controller proposed in Section IV on the 2-finger parallel gripper shown in Fig. 3. The gripper is equipped with semispherical rubber fingertips which allows us to execute pinch grasps on the tool and control the grasping force due to the deformation of the rubber.

We used the model-based visual tracking system *Simtrack* together with a standard 30fps RGB-D camera to estimate

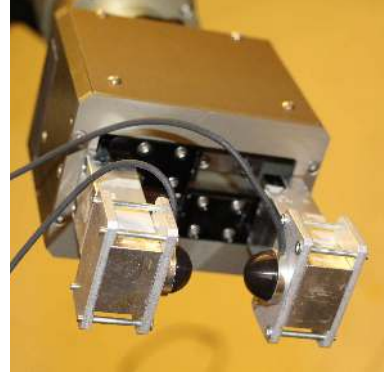


Fig. 3 : Parallel gripper with soft semispherical fingertips used in the experiments.

the angular position $\theta(t)$ of the tool [17]. We then fed this signal to a Kalman filter to obtain estimates of the angular velocity $\dot{\theta}(t)$.

At each iteration of the control loop we calculated the maximum gripper velocity so that the gripper position would remain within the bounds $[d_{min}, d_{max}]$ defined in Section III until the next control iteration. We then saturated the gripper velocity $u_v(t)$ from the controller if it exceeded this maximum velocity.

Experiment	$I[\text{kg} * \text{cm}^2]$	$m [\text{g}]$
1	10.64	52.83
2	14.27	68.50
3	17.90	84.17

TABLE I : Inertial parameters (moment of inertia and mass) of the tool used in the experiments.

$I[\text{kg} * \text{cm}^2]$	30
$m [\text{g}]$	100
$l [\text{cm}]$	12
μ	0.05
σ	0.2
$f_0 [\text{N}]$	175.0
$k [\text{N/m}]$	3871.0
λ	2.0
ϕ	0.05
k_s	600.0
k_v	4.0

TABLE II : Sliding mode controller parameters and gains.

We executed three experiments where we varied the inertial characteristics of the tool as shown in Table I with the controller parameters shown in Table II. We determined the parameters by trial and error and we kept them fixed throughout the experiments. Fig. 4 illustrates an example run of our sliding mode controller.

Fig. 5 shows the experimental results of our proposed controller. In the first experiment the robot grasped a 52.83g tool and controlled the gripper position to allow the object to fall to the zero degree position following the reference



Fig. 4 : Side view of an example run of the sliding mode controller with our experimental setup.

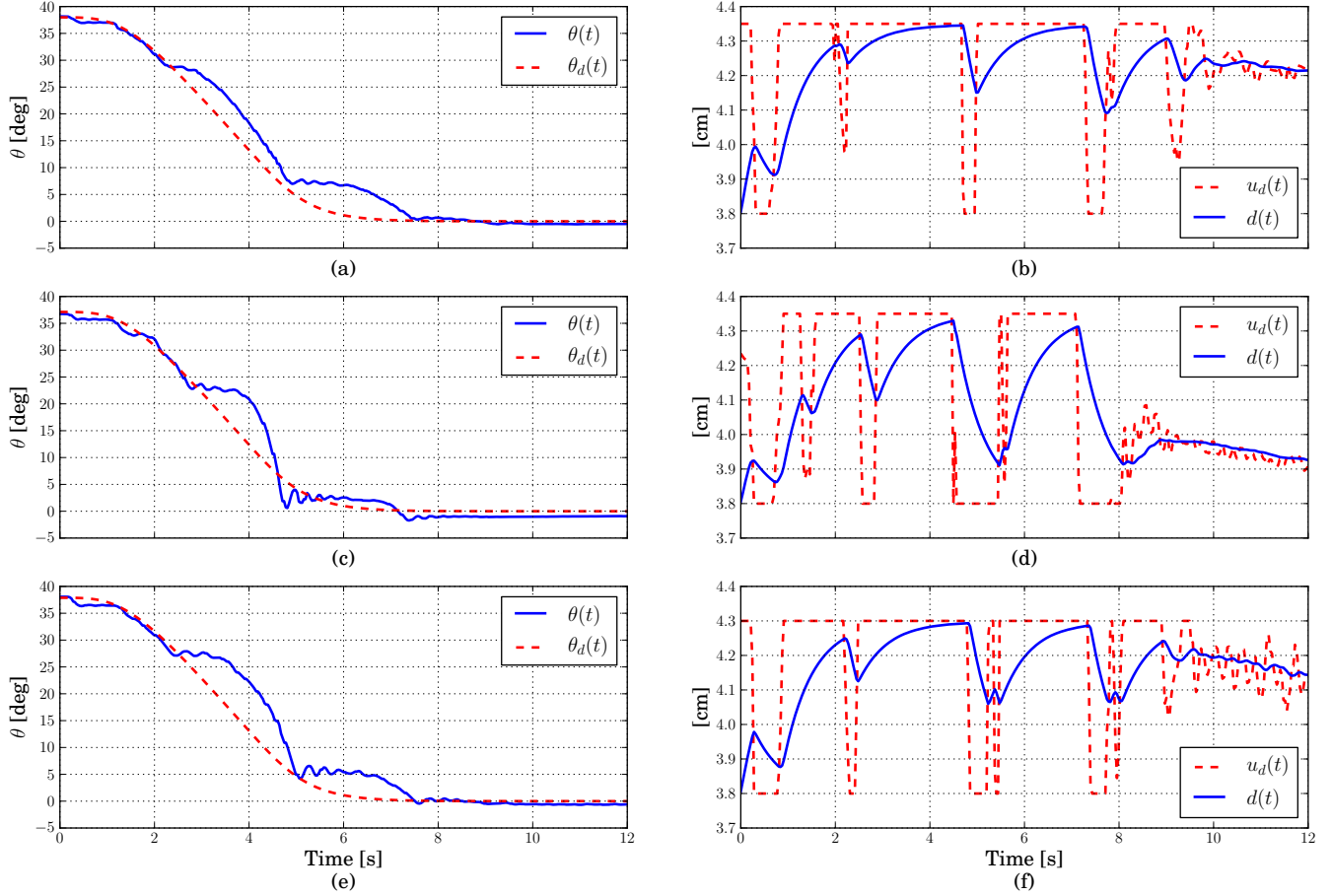


Fig. 5 : Experimental results of the proposed sliding mode controller. Each row corresponds to each of the experiments 1-3 from Table I. The left column shows the angular position $\theta(t)$ of the tool and reference angular position trajectory $\theta_d(t)$ for each experiment while the right column shows the corresponding position control signal $u_d(t)$ and gripper position $d(t)$.

trajectory $\theta_d(t)$. Despite the modeling uncertainties, the sliding controller managed to move the tool to the desired angular position as shown in Fig. 5a with a steady state error of approximately 0.5 degrees. However, we also see that the controller had difficulty in achieving tracking convergence around $t = 2.2$ s and $t = 5$ s. This is due to unmodeled friction phenomena such as the Stribeck effect, which makes the friction coefficient increase as the rotational velocity decreases. The tool abruptly stopped and continued to move once the separation between the fingers was increased enough.

Fig. 5b shows the switching control signal $u_d(t)$ in the first experiment. The figure also shows the resulting separation of the fingers $d(t)$ measured from the gripper encoders after feeding the position control signal to the gripper velocity

controller of Eq. (12). This figure highlights some of the difficulties when using friction as a control input for in-hand manipulation. First, even though we used soft fingertips which can deform and vary the friction torque, we see that the gripper can only operate in a limited range ($d_{max} - d_{min} = 5.5$ mm). Secondly, comparing with Fig. 5a we notice that e.g. between $t = 2.2$ s and $t = 5$ s the tool can abruptly transition between zero velocity and a large angular velocity with small motions of the fingers of approximately 1mm.

For the second experiment we attached a 15.67g mass to the tool at a 15 cm distance from the axis of rotation, which represents a 30% increase in the mass and roughly a 34% increase in the moment of inertia. Fig. 5c shows the angular position of the tool for this second experiment while Fig. 5d

shows the respective control signal.

Once again, the controller converged to the desired position, albeit with a larger steady state error of 1 degree. Furthermore, one can notice the larger control effort when compared to the previous experiment.

We then performed the third experiment by attaching two 15.67g masses to the tool 15cm away from the axis of rotation. This raised the mass by 60% and the moment of inertia by roughly 68% (see Table I). The results of the experiment are shown in Fig. 5e and Fig. 5f.

As shown in Fig. 5f we reduced the maximum finger separation d_{max} by 0.5mm with respect to the previous experiments in order to avoid loosing grip of the tool. We observe that this relatively small change in d_{max} has a critical impact on the controller performance and that the steady state error is 0.5 degrees. Furthermore, the control signal converged to a larger finger separation d than the previous experiment since by lowering d_{max} the gripper induced higher friction torque on the tool, resulting in lower angular accelerations.

VI. CONCLUSIONS AND FUTURE WORK

We have proposed a sliding mode controller for in-hand manipulation with extrinsic dexterity which uses gravity and slippage control to reorient a tool in the robot's hand. In the derivation of the control law we assume a pinch grasp so that the tool can be modeled as a link attached to the gripper through a passive revolute joint with friction and a fixed axis of rotation. We performed experiments by tracking the position of the tool using a model based vision tracking system and controlling the separation of the fingers of a parallel gripper. The proposed control law converges to the desired angular position despite changes in the inertial characteristics of the tool and uncertainties in the friction and deformation models.

As future work we plan to use more accurate dynamic friction models such as the LuGre-like model mentioned in [18] in order to analyze more rigorously the friction characteristics of the problem and propose more robust control schemes that could potentially improve the tracking performance. Even though we showed in our experiments the robustness of the control law to changes in the inertial parameters of the tool, we have yet to design a control law that can accommodate more appropriately for variations in the friction characteristics of the tool.

We also plan to incorporate tactile sensing to measure and control directly the grasping forces. Furthermore, one of the limitations of our controller is the limited control frequency due to the vision tracking system. One possibility to improve the controller performance is to incorporate optical sensors at the fingertips to obtain more local and faster estimates of the pose of the tool [19].

This work can also be extended by replacing gravity with inertial forces generated by accelerating the manipulator. Additionally, we will generalize the ideas presented in this work to apply closed loop control in other in-hand manipulation

scenarios by e.g. using external support objects and dual-arm manipulation.

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