Towards Unknown Objects Manipulation ⋆

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Abstract: We propose a simple but efficient control strategy to manipulate objects of unknown shape, weight, and friction properties – prerequisites which are necessary for classical offline grasping and manipulation methods. Instead, the proposed control strategy employs estimated contact point locations, which can be obtained from modern tactile sensors with good spatial resolution. The feasibility of the strategy is proven in simulation experiments employing a physics engine providing exact contact information. However, to motivate the applicability in real world scenarios, where only coarse and noisy contact information will be available, we also evaluated the performance of the approach when adding artificial noise.

Keywords: Multifinger robot hand; unknown object; reactive manipulation.

1. INTRODUCTION

We consider the challenging task of dexterously manipulating an object within a multi-fingered robot hand, i.e. moving the object with respect to the hand.

There exists a considerable amount of work to analytically describe the motion of the object, finger tips and contact points during manipulation. These theoretical approaches assume various things to be known: the hand kinematics, object properties like shape, mass and mass distribution, the contact locations and friction coefficients, and the local surface geometry of both the object and finger tips. Based on this knowledge it is possible to compute joint-level finger trajectories in an offline fashion, and even determine slipping and rolling motions of the fingertips (R.M.Murray et al. (1994)).

Recent approaches to object-in-hand manipulation avoid the complex analysis of geometric relations and apply state-of-the-art motion planning methods like RRT and PRM(Yashima (2004); Saut et al. (2007)) to the manipulation problem. Xue et al. (2008) tackled the problem of screwing a light bulb. Exploiting the axial symmetry of the object, they look for contact trajectories in a set of contact points previously obtained from classical grasp planning methods. All these approaches attempt to find feasible motion trajectories in an *offline fashion* utilizing a physics simulation to model the outcome of random actions. Again, this requires a considerable amount of prior knowledge about the manipulated object. Employing fast tactile feedback, Ishihara et al. (2006) propose a control law to spin a pen of known shape at an impressive speed. Tahara et al. (2010) point out a method to manipulate objects of unknown shape. They use a virtual object frame determined by the triangular finger-tip configuration of a three-fingered hand to derive a control law to manipulate the object's pose. However, without explicit sensory feedback, their method is limited in accuracy.

We prefer the feedback and *reactive* based strategy for object manipulation because feedforward execution of manipulation trajectories obtained in an offline optimization process cannot account for real-life deviations from the planned trajectory: The initial object pose might be estimated incorrectly, fingers might unpredictably slide or roll or even lose contact at all. Currently, we obtain this feedback from a physical simulation, which is used to show the feasibility of the approach. However, the pose feedback can also be estimated from visual features. To confirm the applicability of our method in noisy real-world scenarios, we add artificial noise to the accurate sensor readings obtained from simulation.

Conceptually, the object manipulation process can be divided into two stages: a local manipulation controller and a globally acting regrasp planner. The local controller reactively moves the object by a small amount only. When the joint limits or the boundary of the object's configuration space is encountered, a higher level planning step becomes necessary, also known as finger gait planning. During local manipulation, a state monitor can be used to check the distance to configuration space limits. Once a limitation is reached, regrasp planning is employed to adapt the

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grasp configuration. Subsequently, local manipulation is continued. This paper only focuses on local manipulation.

The paper is arranged as following. In section 2 we summarize our assumptions for the local manipulation controller. In section 3 the reactive manipulation strategy is introduced, comprising a contact position and force planner, a composite position/force controller, and the inverse hand kinematics. In section 4, the physical simulation setup used for evaluation is introduced. In section 5 we discuss simulation results and open issues to be addressed in future work. Finally, section 6 summarizes our work.

2. ASSUMPTIONS OF CONTROL STRATEGY

2.1 Point contacts

The real contact geometry between the fingertip and the object is complex and difficult to model, even if geometric shape information is available. Usually, the contact force is distributed on a larger contact area. In this paper, we assume that there is only one contact point on every finger and the distributed contact force is concentrated on this point. We do not explicitly model friction properties. However, the physical simulation adopts a Coulomb friction model approximating circular friction cones by four-sided pyramids. The contact is assumed to be compliant, due to elasticity of either the body or the finger tip. This assumption is important to realize the contact force controller on top of a joint position controller employing a linear spring model.

2.2 Micro manipulation assumption

In our control strategy we do not explicitly generate rolling or sliding. Rather, we assume that all contact locations stay fixed for every control cycle, i.e. contact frames C_i relative to the object frame O and relative to the finger tip frames F_i do not change (see Fig. 4). This also implies, that the contact points on the object and on the finger tip move with identical velocity. Obviously this assumption will be often violated in practice, e.g. by occurring slip. However, employing the feedback from observed contact locations we can determine changes of the grasp configuration (including sliding and rolling) after each control cycle.

2.3 Available Sensory Feedback

In order to facilitate the application of our manipulation strategy in real world scenarios we follow a two-fold strategy: (i) We replace offline motion planning by an online control strategy generating joint angle control signals based on current sensory feedback. (ii) We avoid as much information about the object as possible. Especially, we assume that the global object shape, mass and mass distribution, as well as local contact properties like surface geometry and friction properties are not known to the robot.

3. REACTIVE MANIPULATION STRATEGY

Conventional grasp and manipulation planning methods (A.A.Cole et al. (1989); M.Zribi et al. (1999)) uncoupled the planning from the control stage. The planning

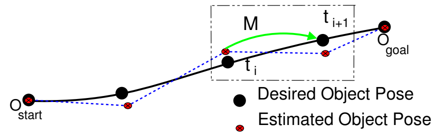

Fig. 1. Incremental manipulation of object pose O.

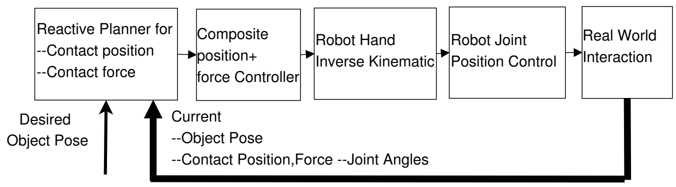

Fig. 2. Components of closed loop control scheme.

stage strongly depended on global knowledge about the geometry of the object and fingertips. Some work also explicitly considers spherical finger tips to facilitate the geometry-based planning process (Tahara et al. (2010)). Furthermore, the friction coefficients for all contacts are required to evaluate grasp stability to obtain optimally stable grasps.

In real world scenarios, especially when handling unknown objects, this information is not available. Here we propose to employ tactile feedback to estimate contact positions and forces and introduce a manipulation strategy solely based on this feedback. If friction properties and joint torques are not available anymore, we cannot actively control rolling and slipping anymore, because internal forces cannot be designed. However, as we will show, local object manipulation is possible without explicitly designing all details of physical hand-object interaction.

Based on an estimation of the current pose O of the object and its target pose O', we derive the required object motion M to realize the target pose within the next control cycle (cf. Fig. 1). Box in the figure shows the one step plan. Knowing the current contact locations $\boldsymbol{p}_i$, we determine the current grasp configuration, i.e. contact positions relative to the object's frame. Assuming a static grasp configuration within each control cycle, we can easily compute the contact locations $\boldsymbol{p}'_i$ associated to the target pose and subsequently obtain joint angles realizing those contact locations employing the inverse hand kinematics (Li et al. (2011)). Because the local object and finger tip geometries as well as grasp stability measures are not explicitly taken into account, the actual grasp configuration might have changed after application of the computed hand pose. This corresponds to sliding or rolling contacts or even to a loss of a contact. In order to maintain stable contacts anyway, we apply a force-control scheme additionally to the position-controlled object manipulation. All components of the closed-loop control system are summarized in Fig. 2 and will be detailed in the following. The only exception is the servo controller for the finger joints, which is described in Roethling et al. (2007).

3.1 Obtaining Object Pose and Contact Locations

The minimal requirements for deliberative object pose control are the knowledge of current object pose and coarse contact point locations. We assume, that the object pose can be estimated from vision, e.g. employing markers or

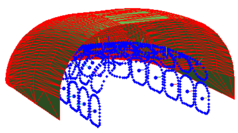

Fig. 3. Tactile sensor covered by a conductive foam.

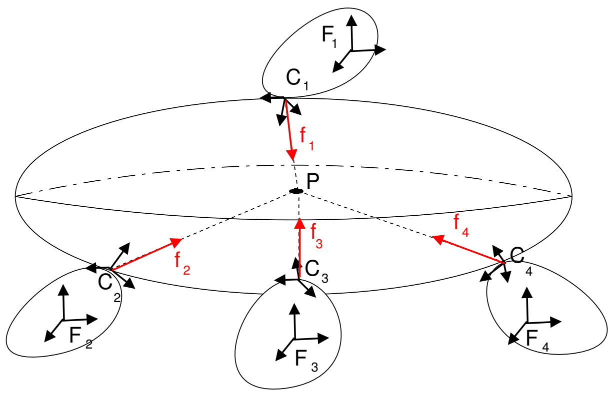

Fig. 4. Planner employs centroid $\bar{\boldsymbol{p}}$ of contact points.

modern 3D vision approaches. However, we do not consider these vision aspects within this paper, but obtain the object's pose from physical simulation in our experiments.

The contact locations can be obtained from tactile finger tip sensors providing enough spatial resolution. For example, our Shadow Robot Hands are equipped with tactile sensors comprising 34 tactile elements (tactels), thus providing a spatial resolution of approx. 3mm (cf. Fig. 3). From the known shape of the finger tip and the known hand kinematics, we can easily compute the location of a contact spot relative to the coordinate frame of the palm, employing the forward kinematics. This is enough for hand-only manipulation.

3.2 Contact Position Planning

Denoting the current and targeted object pose with O and O' resp., we can easily compute the transformation matrix M describing the required finite object motion:

$$O' = O \cdot M \qquad \Leftrightarrow \qquad M = O^{-1} \cdot O' \,. \tag{1}$$

Assuming, that contact positions do not move relative to the object within the control cycle (micro manipulation assumption), we can calculate the new contact positions $\boldsymbol{p}'_i$ (w.r.t. the palm). The contact positions $\boldsymbol{p}^o_i$ expressed relative to the object frame stay fixed:

$$\boldsymbol{p}'_i = O' \cdot \boldsymbol{p}^o_i = O \cdot M \cdot O^{-1} \boldsymbol{p}_i \,. \tag{2}$$

From this we can compute the required positional changes $\Delta \boldsymbol{p}_i = \boldsymbol{p}'_i - \boldsymbol{p}_i$ for all contact points as input to the inverse hand kinematics.

3.3 Contact Force Planning

A mere kinematic consideration of the problem is not sufficient. In order to maintain a stable grasp and to not break the object, we have to control contact forces as well. Conventional contact force planners strive for a globally optimal contact force distribution ensuring grasp stability, i.e. all contact forces staying within corresponding friction cones, the totally applied force exactly resisting external forces (e.g. gravity), and limiting local contact forces. This general solution is meaningful only if the contact force is controllable. However, we assume that there is no 3D contact force feedback (obtained directly or indirectly), but only the force magnitude is available from tactile sensors. Following concepts from Tahara et al. (2010) the central idea is to plan the force direction such, that the resultant moment will be zero, and to plan the force magnitudes along these directions such that the resultant force applied to the object becomes zero.

Obviously the resultant moment is zero, if the contact force directions of all fingers intersect in one point. As illustrated in Fig. 4, we chose the intersection point as the centroid $\bar{\boldsymbol{p}}$ of all contact points $\boldsymbol{p}_i$, i.e. $\bar{\boldsymbol{p}} = \frac{1}{N}\sum_{i=1}^{N} \boldsymbol{p}_i$. Accordingly, normalized contact force direction vectors can be computed as follows:

$$\hat{\boldsymbol{f}}_i = \frac{\bar{\boldsymbol{p}} - \boldsymbol{p}_i}{\|\bar{\boldsymbol{p}} - \boldsymbol{p}_i\|} \,, \tag{3}$$

where $\boldsymbol{f}_i$ denotes the contact force of i-th finger. The force magnitudes f_i are constrained by

$$\sum_{i=1}^{N} \boldsymbol{f}_i = \sum_{i=1}^{N} f_i \cdot \hat{\boldsymbol{f}}_i = 0 \,, \tag{4}$$

which defines a system of linear equation. Denoting the matrix of normalized force directions with $\hat{F} \in \mathbb{R}^{3\times N}$ and the vector of desired force magnitudes with $F \in \mathbb{R}^N$, we can summarize the latter equation in matrix form:

$$\hat{F} \cdot F = 0 \tag{5}$$

We find a positive solution ($f_i > 0$) to this equation using singular value decomposition (SVD). As the problem is under determined, there exists a non-zero null space of $\hat{F}$. The desired solution can be expressed as a linear combination of the null space basis. The superposition coefficients should be selected as small as possible to improve the grasp stability under the condition of the manipulability of the object.

3.4 Composite Position+Force Controller

This controller's task is to map the desired translational motion of contact positions as obtained from the position planner as well as the contact force deviation obtained from the force planner to a composite control signal determining the resulting translational motion of each fingertip. Conventional solutions for a simultaneous position and force control are the hybrid position/force controller and the indirect force control. The hybrid position/force controller decouples the control problem based on the task constraint defined by the contact frame: Force is controlled along the surface normal of the contact, while position is controlled in the tangent plane.

However in our scenario, both components cannot be separated, because there is a motion component along the force direction and vice versa. That's why we prefer the indirect force control scheme and propose the composite position+force controller. The schema diagram is shown in

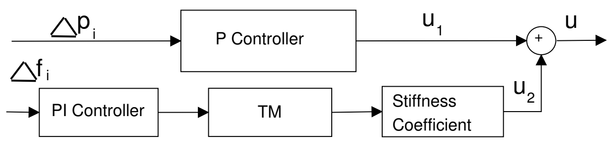

Fig. 5. Composite Position + Force Control Scheme.

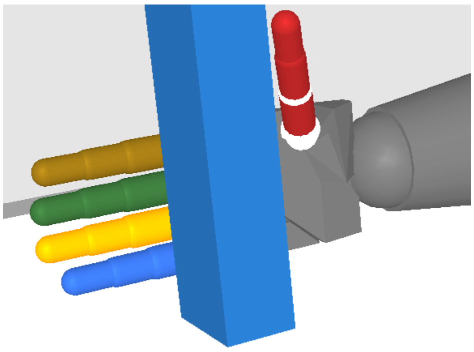

Fig. 6. Simulation scenario

Fig.(5). The control signals $\boldsymbol{u}_1$ and $\boldsymbol{u}_2$ from both branches are additively superimposed to form the composite translational motion $\boldsymbol{u}$ of a single finger tip send to the inverse kinematics module. The position controller is realized as a P controller parameterized by gain k_P^p, while the force controller is a PI controller parameterized by gains k_P^f and k_I^f. A PI controller is used in order to guarantee a higher priority level for force control. TM transforms the scalar force magnitude deviation Δf_i into the vector-valued error $\Delta \boldsymbol{f}_i$ pointing towards from the contact point towards the centroid $\hat{\boldsymbol{p}}$. The stiffness coefficient k_{stiff} transfers the force deviation to a displacement error. The whole controller can be summarized as

$$\boldsymbol{u} = k_P^p \cdot \Delta \boldsymbol{p}_i + k_{\text{stiff}} \cdot \left(k_P^f \cdot \Delta f + k_I^f \cdot \int \Delta f \right) \cdot \hat{\boldsymbol{f}} \,. \quad (6)$$

4. SIMULATION

The object manipulation algorithm is validated in a physical simulation experiment. We use the Vortex physics engine to obtain real-time contact information (i.e. contact position and contact force magnitude), and the object's pose (object position and orientation). Currently three geometric primitives, namely sphere (radius=2.5cm), cylinder (radius=1.4cm, height=9cm), box (sized $6\times4\times21\text{cm}^3$) are evaluated. The tested objects are sized middle-scale compared to the robot hand, so rolling and slipping between the fingertips and the object will occur during the course of the manipulation. Object shape and size information and friction information are not available to the manipulation strategy. The simulation scenario is shown in Fig. 6 resembling our real robot setup to facilitate future transfer into real world, once the required tactile feedback is robustly available from finger tip sensors. The controller gains k_P^p, k_P^f, k_I^f are manually set to guarantee the stability of the object manipulation in all dexterous simulation.

The whole manipulation process comprises three phases:

(1) Grasping of the object, when it is fixed in the world. This is necessary to achieve a successful grasp without kicking the object off.
(2) Unfreeze the object and stabilize the grasp employing active force control in order to prepare manipulation.
(3) Actually manipulate the object, i.e. change its pose relative to the palm of the hand.

Only the latter manipulation phase is considered in this paper. Without loss the generality, the orientation of the object is aligned to the world reference frame, such that the principal axes of cylinder or box are parallel to the z-axis of the world frame. The object is grasped with the thumb opposing three fingers. The contact normals of all contacts are roughly aligned to the y-axis of the world frame.

Simulation experiments are used to validate our manipulation strategy in two aspects. (1) to show it can deal with the unknown object geometry, friction coefficient. (2) to show it can deal with the uncertainty measurement from the object's pose and contact position/force magnitude. According to the Eq .1, 2, matrix M represents the uncertainty of object's pose measure and $\boldsymbol{p}_i$ represents the uncertainty of contact position. So the desired linear velocity calculation is effected by the two uncertainty in position planner.We, however, focus the uncertainty on one parameter e.g.contact point position in the simulation since the two uncertainty are coupled relation.

- Translational/rotational movement of object.

Three basic geometry primitive are tested. Motion scale is 0.5cm/0.2rad along/around the y-axis. The exemplary simulation results are shown with red solid line in Fig. 7 and Fig. 8.

- Move the object along a complex trajectory. e.g tracking a figure eight.

This simulation can show that the approach is potentially applicable to writing figures with a pen. The simulation result is shown in Fig. 9. The pink solid line represents the nominal plan trajectory of the object and blue dashed line represents the implementation result. The figure's height and width are 1cm and 0.5cm resp.

- Repeat the transition/rotation and tracking simulation but with the superimposed artificial measurement noise to the values obtained from the physics engine.

The standard deviations of the added Gaussian noise are: 0.5cm for contact positions(the spatial accuracy of our available tactile sensor is 0.3cm), and 0.3 for contact force magnitude (desired contact force is 1.0). The exemplary simulation results are shown in Fig. 7, 8, 9 in order to compare with the no noise case. There are tiny inti position offset between the no noise case and noise case, which are caused by the biased actively stable grasp with noisy measurement in unfreezing object process.

Simulation results with/without noise measurement show that although we did not explicitly modeling the fingertip rolling on the object, our proposal manipulation strategy deal with this unexpected phenomenon by the compact control-closedloop and realize the unknown object local manipulation(simple and complex trajectory tracking). noisy feedback simulation also shows that the complex object manipulation tracking performance is not as good

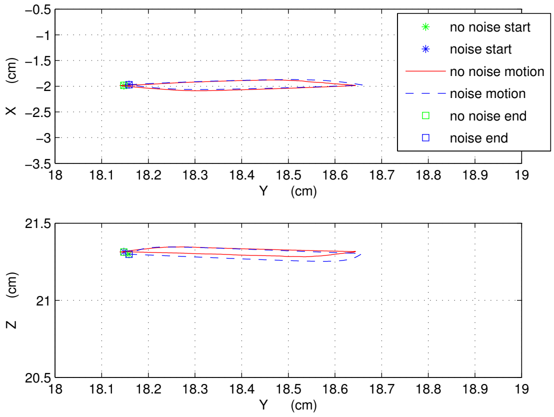

Fig. 7. Object motion parallel to contact normals (y-axis)

as the ideal manipulation. Tracking error(maximum) is less than 20%. Multi simulation results, changing the controller parameters in Eq. 6 show that the composite controller parameters have the direct affection on the tracing error accuracy. A adaptive controller parameters regulation algorithm will be helpful in increasing the tracking accuracy comparing with this manual setting parameters.

- The sensitivity evaluation of object manipulation to the measurement error. The object(cylinder) is moved 0.5cm along y axis(step responding test).

In this simulation we continuously change the variance of contact position (step = 0.1cm) and contact force magnitude (step = 0.1) to check the manipulation accuracy under the difference noise measure and the manipulation stochastic performance. The qualitative and quantitative tests are simulated to check the sensitivity of our strategy to measurement parameters uncertainty. In Exp1, we add no force magnitude noise but change the error variance of contact position from 0.1cm to 1 cm. In Exp2, we add a fixed position noise (variance is 0.5cm) and the force magnitude noise whose variance change from 0.1 to 1. Experiments are run ten times for every parameter. The qualitative test result is shown in Fig. 10. Manipulation failure analysis shows the reasons of failure are (1)unsuccessfully grasp in the first stage (19 times) (2)the finger collision (22 times) (3)finger move from one contact surface to another one (once). Not considering grasp failure factors, our manipulation strategy successful rate is 87.3%. The quantitative results are shown in Fig. 11,12. Manipulation error accuracy is lower than 20% and the contact force magnitude measurement error has important affection on the manipulation error variance.

5. DISCUSSION

In the proposed strategy, both contact position planning and contact force planning are reactive. Both planners work independently of each other and their results are combined by the composite position/force controller, which thus can be regarded as a plan coordinator.

If unexpected disturbances change the object's pose, the position planner will drive the fingers reactively to counteract these disturbances. Consider for example the grasp

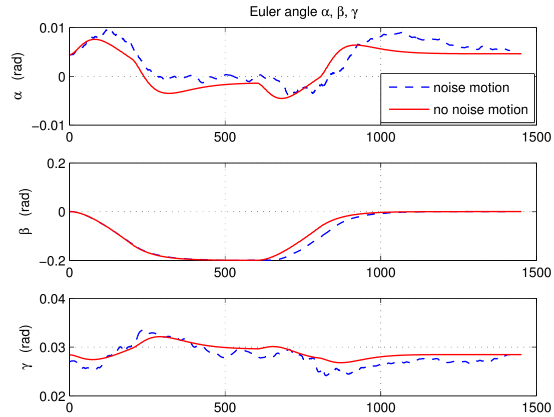

Fig. 8. Object motion around (y-axis)

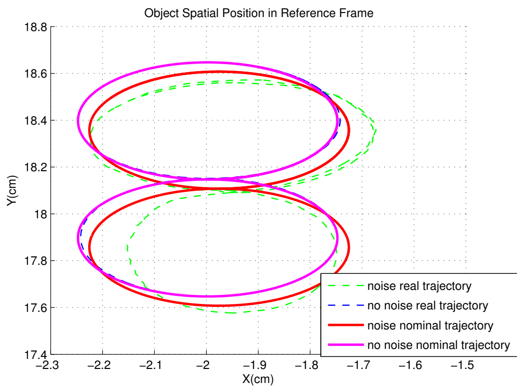

Fig. 9. Tracking a figure eight.

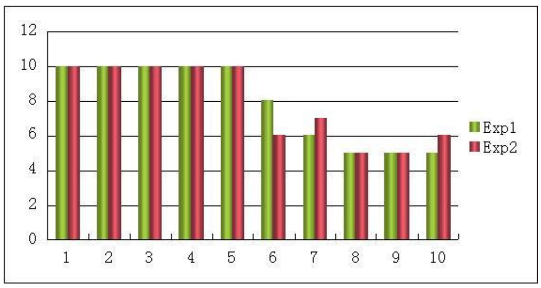

Fig. 10. Stochastic experiment object manipulation in-hand.

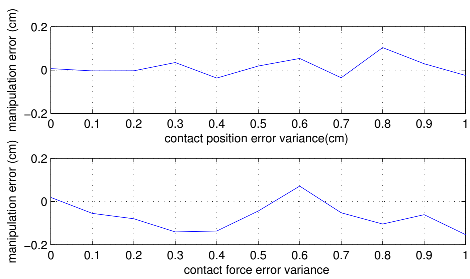

Fig. 11. Manipulation error average value.

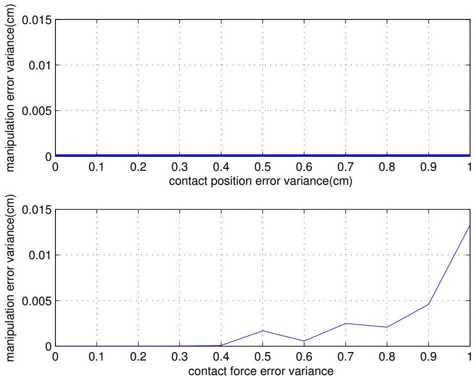

Fig. 12. Manipulation error variance.

stabilization process, when the initially frozen object is released to freely move. Because the desired contact force during the initial grasping stage is chosen arbitrarily, unbalanced forces will trigger unexpected object motions, when the object is released. The fingers will move along the surface of the object to counteract this motion.

In the contact force planning process, we assume that the desired contact force magnitude is realizable. But, in practice this depends on the friction properties. If the planned contact force direction is located inside the friction cone, the reactive contact force plan can be realized. Otherwise slip between the fingertip and the object will occur. In the next control cycle, the new desired contact force direction and magnitude will be planned based on the update contact situation.

From Eq. 6, it can be seen that the control signal is composed from two components. The integral component of the force controller guarantees that force trajectory tracking is prior level at the steady state – at the expense of losing positional control accuracy. The contact point motion will stop at an equilibrium position with a tiny positional error (10^{-2}mm) but almost no force deviation. If the integral contribution would be missing, both force deviation and position deviation would exist simultaneously. We also consider about the contribution of two components. Position controller parameter k_P^p can be used to modified the tracking velocity. The higher value can improve the tracking accuracy, but can cause the vibration of object manipulation. The stiff coefficient k_{stiff} can be use to modify the compliance of the grasp. The lower value can improve the smooth performance of manipulation but can cause the decreased manipulation accuracy performance. So an online adaptive controller parameters regulation algorithm is more useful in order to balance the manipulation accuracy and tracking velocity.

Several research issues have not been considered in this paper but they are also important for successful object manipulation. (i) Gravity issue. In our simulation, we only assume the light object. (ii) finger collision avoidance and (iii) guarantee of positive force magnitudes. So far, every finger motion is controlled independently. A finger motion coordination strategy should be used to avoid collisions between fingers and thus to improve the robustness of the manipulation strategy. The contact force magnitude of all fingers should always be positive, because only "pushing" forces can be applied. However, in our simulations we only observed null space basis vectors having identical sign, such that positive force magnitudes could be chosen in all cases. But no strict mathematical proof is given here. These three issues will be addressed in our future work.

6. SUMMARY

We propose a reactive control strategy to realize local manipulation motions for unknown objects. In contrast to traditional manipulation strategies, which require a lot of information about the object and plan in an offline fashion, our method plans in an online fashion and employs minimal sensory information. The position and contact force planners are designed independently and are coordinated by a composite controller. In physical simulation experiments we proved the feasibility of the method to manipulate objects of various basic geometries even with the simulated noisy feedback.

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