Computation of Realistic Contact Forces in Grasping

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***Abstract*— Traditional grasping assumes normalized contact forces for planning contact points. However, in a robotic hand the forces that each finger can apply strongly depend on the hand configuration and torque limits of the actuators. This work presents a computation of physically achievable contact forces for fingertip grasps. Thus, the maximal magnitude of an external wrench that can be resisted with the chosen contact points is computed based on a ray-shooting algorithm.**

I. Introduction

Grasp planning implies finding contact points and contact forces that can be applied by the robotic hand and that guarantee a good performance in the real environment. Traditionally, contact points that lead to a force closure grasp are planned before calculating the contact forces [1], and the grasp is ranked according to some grasp quality, e.g. the largest resisted wrench or physically motivated task wrench spaces [2]. These works assume that the maximum contact force per finger is smaller or equal to one, which leads to a normalized grasp quality, but they are neglecting that the maximum force that a robotic finger can apply in a certain direction changes drastically within its workspace. Therefore, these grasps are only valid in real applications if the robotic hand is strong enough to apply the required forces at the planned contact points in the presence of the expected disturbance forces. Hence it is essential to consider the available forces during the process of ranking grasps and planning contact points.

II. Method

To overcome the limitation of normalized fingertip forces, a generalization of a ray-shooting algorithm [3] is used to take the achievable forces into account. The resulting contact forces are guaranteed to be physically achievable by the hand, while still lying within the friction cone.

The proposed approach assumes that the object is represented as a pointcloud with associated surface normals, the kinematics and the joint torque limits of the robotic hand are known, and the direction of an external wrench to be resisted is given. Based only on the relative pose between hand and object, a set of reachable independent contact regions is computed [4]. The final contact points are chosen as the centroid of each region, and the largest external wrench that the hand can counteract in the given disturbance direction is also computed.

The calculation of contact forces must be based on the forces that the robotic finger can apply at the contact points.

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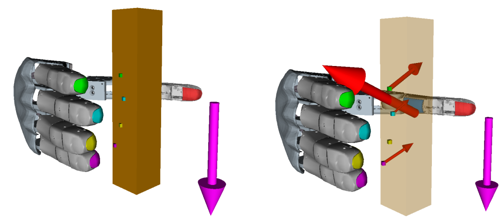

(a) (b)

Fig. 1. (a) Given grasp on a box. The direction of gravity $\mathbf{g}$ is shown in pink. Using normalized contact forces of maximum 1N, the maximum force of the object weight can be 1N (not displayed). (b) Using the physically achievable forces of the fingers, the maximum force of the object is 11.1N.

Those forces depend on the joint configuration of the finger, i.e. they change not only within the hand workspace but also depending on the particular contact point and the direction of the desired force. The workspace of the robotic hand is analyzed only once in an offline process, and represented as a voxelized structure [5] where each voxel stores information on the finger configuration that leads to that location. In this work, we assume that the fingers are not kinematically redundant, and represent the fingertip as a sphere. The end of the kinematic chain is the center of such sphere.

This workspace analysis is then used online to obtain the physically achievable forces of the robotic hand at each potential contact point. The Voxmap-Pointshell (VPS) algorithm [6] is used to calculate the intersecting points between the voxelized workspace and the pointshell representation of the object (within 1ms). The VPS allows direct access to the indices of the both the colliding points of the pointshell and the colliding voxels. The indices of the pointshell are used to calculate the set of reachable contact regions, as described in [4]. The voxmap index indicates also the joint configuration that leads to the fingertip being on the object surface. For each finger, the joint torques needed to apply a force $\boldsymbol{f}_i$ can be calculated with the joint configuration and the corresponding body Jacobian. The maximal magnitude of the force $\boldsymbol{f}_i$ is obtained by scaling the relation $\boldsymbol{\tau}_i = \mathbf{J}_i^T \mathbf{f}_i$ such that at least one entry of the torque vector is equal to the corresponding torque limit.

This maximally achievable contact force is used to shape the sets of contact forces within the friction cone in order to reflect the physical limitations of the robotic hand. We generalize the ray-shooting algorithm of [3] to include these achievable forces and overcome the assumption of normalized forces. Additionally, we use forces that are within the friction cone and not only on its boundary. The ray-shooting algorithm allows to compute an intersection point between a ray and the convex hull of the contact wrenches possible for a particular grasp. The norm of the intersection point defines the maximum magnitude of the external wrench that the hand can counteract. The overall algorithm is as follows:

Given: hand pose relative to the object
Output: maximum magnitude of an external wrench along a ray with predefined direction
Compute reachable contact regions [4];
Get contact points;
Find the intersection point between ray and the convex hull
- using a modified ray-shooting algorithm
- obtaining physically achievable forces
- using several layers within each friction cone

Return contact forces and maximal magnitude of the external wrench.

III. Evaluation and Discussion

The algorithm is evaluated for the DLR-HIT Hand II, an anthropomorphic hand with five modular fingers. Each finger has three degrees of freedom, and all joints have the same motors and torque limits of $\tau_{\text{min}} = -1$Nm and $\tau_{\text{max}} = 1$Nm. A particularity of the anthropomorphic design is the opposing thumb that leads to an asymmetric distribution of possible contact forces. During grasping, the thumb needs to counteract the forces of all other fingers plus the external wrench to guarantee a firm grasp on the object. Therefore, it is often the critical finger for a stable grasp.

The workspace of each finger is voxelized with 0.001m voxel size. The external wrench represents the gravity force on the object, $\mathbf{w}_{\text{ext}} = m_o \cdot \mathbf{g}$, where m_o is the mass of the object and $\mathbf{g}$ is the acceleration of gravity (indicated as a pink arrow in the figures). The algorithm was implemented in Matlab/Simulink and runs on a standard Desktop PC with a Intel(R) Xeon(R) CPU, 2.8GHz.

As an evaluation of the algorithm, we show the computation of achievable contact forces given one grasp with five contact points on a box as shown in Fig. 1(a). The box has a mass of $m_o = 0.5$kg which corresponds to a weight of $\|\mathbf{w}_{\text{ext}}\| = 4.91$N. Using normalized contact forces (Ray-shooting algorithm in [3]), the calculated maximum force that the grasp can counteract is 1N. Computing the physically achievable contact forces with a friction coefficient of $\mu = 0.5$ and three inner layers for each friction cone, the realistic maximum force that the hand can counteract is 11.1N (Fig. 1(b)).

The computation of achievable contact forces allows the determination of the realistic maximum weight that the hand can counteract, and its importance becomes obvious when the object is rotated, as shown in Fig. 2. The contact points, the hand pose relative to the object and the standard grasp quality are the same as in Fig. 1. When the weight of the object has to be counteracted mostly by the thumb (Fig. 2(c)), its torque limits are critical for the maximum weight that can be resisted, and the magnitude of the achievable external force decreases to 7.18N for a rotation angle of 90°. If the object is rotated -90°, the weight can be counteracted by four fingers of the hand, and the maximum magnitude of the allowed external force increases to 31.32N.

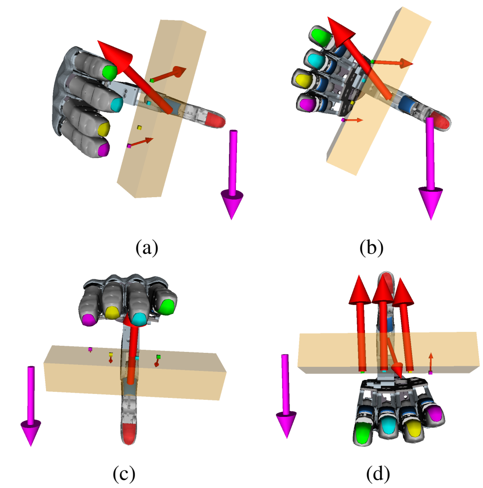

Fig. 2. Display of forces is downscaled with a factor of 0.1. (a) Rotation angle 17°, maximal external force 10.01N (b) Rotation angle 28°, maximal external force 9.72N (c) Rotation angle 90°, maximal external force 7.18N (d) Rotation angle -90°, maximal external force 31.32N

The computation time for the contact forces depends on the direction of the gravity force. For all shown grasps (Fig. 1 and 2), the average computation time of the algorithm [3] is 5.9ms (min 2.9ms, max 12ms). The presented algorithm takes 6.8ms in average (min 3.1ms, max 13.8ms). The slightly higher calculation times are due to the use of inner layers inside each friction cone. The technical implementation allows the interactive online use of the planner, for instance in telemanipulation scenarios [7], due to its low computation time.

The algorithm presented can be used to adapt the contact forces to changes in the external wrench and to monitor the maximum external wrench that can be counteracted by the robotic hand. This allows the robot to predict grasp failures due to movements of the grasped object, or to define online the limitations of manipulation actions on the grasped object.

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