The Closure Signature and the Stiffness Signature: a Functional Approach to Model Underactuated Compliant Robotic Hands

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***Abstract*— A new trend in the design of robotic hands is to make them compliant and underactuated. These hands are able to safely interact with the environment and adapt to different objects. However, due to the high number of DoFs and of hand/object and hand/environment interactions, it is difficult to predict their behavior with classical kinematic and dynamic models. To effectively plan grasping and manipulation tasks with such types of hands, there is the need to model their capabilities. Here we present two tools, namely the *closure signature* and the *stiffness signature*, that can be used to describe the hand's open/close motion and its stiffness distribution, with a reduced number of parameters. We also show how the information provided by the closure signature can be effectively exploited to plan top-grasps. Future work will concentrate on computing the two signatures for several robotic hands, and use them in tasks involving the exploitation of environmental constraints.**

I. Introduction

Grasping with robotic hands is still an open problem in robotics. The human hand has undergone thousands of years of evolution, and it is almost unbeatable in terms of optimized mechanical design, materials, sensors, and control. What roboticists are trying to achieve is a satisfactory functional approximation of the human hand, and recently this problem has been tackled by designing compliant and underactuated robotic hands. The intrinsic compliance that these hands have in their structure allows them to adapt to different objects [1], and to effectively exploit environmental constraints to fulfill a certain manipulation task [2]. Underactuation can be implemented using relatively simple differential and elastic elements [3] or by coupling different DoFs [4]. Important examples of underactuated compliant hands are the Pisa/IIT SoftHand [5], the RBO Hand 2 [6], and the SDM Hand [1].

Even though a substantial part of the research efforts have focused on the realization of suitable *soft-bodied* hands, the way manipulation is planned and controlled is not a lesser issue. For any given actuation, the actual behavior and final configuration of the hand severely depend on the interaction between hand, object, and the environment surrounding them [7]. We believe that finding new ways of modeling soft hands independently from their specific hardware realization, could be the first step towards their effective exploitation in grasping and manipulation tasks.

In this short paper, we propose a possible way to model underactuated compliant hands that does not rely on the kinematics and mechanics of the hand, but rather on the functioning of the hand. In Section II we introduce two mathematical tools, namely the *closure signature* and the *stiffness signature* able to describe the action of the hand over a grasped object, rather than the position of each single link or joint. Section III briefly explains how these concepts can be used in grasp planning, and Section IV summarizes our work in progress and our plans for extending the presented results.

We gratefully acknowledge the funding provided by the SOMA project (European Commission, Horizon 2020 Framework Programme, H2020-ICT-645599).

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II. Modeling Soft Hands

Classical grasp planning approaches generally identify a set of suitable contact points on the object and then, through inverse kinematic techniques, compute the correct joint angles to achieve a given grasp. This usually relies on a detailed kinematic model of the used robotic hand. In [7], we tried to extend the classical quasi-static analysis of the grasp to model also the interaction between the hand, the object and the environment considering stiffness at contact, joint and wrist level. However, this modeling approach still leverages on the definition of links and joints and assumes perfect knowledge of contact point locations, and an accurate estimation of all stiffness values.

One aspect of soft hands that can help in abstracting from the specific device's structure and in reducing the overall model complexity is underactuation. Let us assume, for the sake of simplicity, to have a hand with only one actuator that jointly moves all the DoFs. With such a hand, dexterity can be only achieved by acting on the wrist pose, since the motion of the fingers is constrained by underactuation, and most likely the hand will perform grasps that completely envelop objects, also known as power grasps [8], [9]. For this reason, we mainly target power grasps when defining a general model for underactuated compliant hands.

Let us consider a hand performing a simple closing motion in free space or around a predefined object, there are two main characteristics that can be extrapolated to characterize this action:

- In which direction does the hand deform more while closing?
- In which directions the hand is less or more stiff when it is closed over the object?

The first characteristic is captured by the closure signature, and the second by the stiffness signature.

A. *Closure Signature (CS)*

The CS describes the hand's closing motion not by looking at joint angles, but by focusing on the action that the hand would do on the grasped object. We will explore three possible solutions to compute the CS: minimum volume ellipsoid, principal component analysis, and mesh deformation.

As a first approach we decided to leverage upon the concept of virtual object mapping that we have already successfully used for the simplified control of a robotic hand [10] and for teleoperation [11]. In particular, we compute how the hand's closure in free space affects the deformation and translation of the axes of a virtual ellipsoid. The algorithm that we use is implemented in five main steps:

1) Define reference points on the hand that must describe the hand motion (e.g. position of the fingertips and of the wrist).
2) Define the initial ellipsoid as the minimum volume ellipsoid that contains all the reference points.
3) Track the reference points during hand closure.
4) Map the motion of the reference points onto the three axes of the ellipsoid.
5) At the end of the mapping procedure, compute the closure signature as the ellipsoid semi-axis that was deformed more with respect to the initial ellipsoid.

Notwithstanding its assumptions and simplifications (as for instance the choice of an ellipsoid as the shape of the virtual object, the criterion adopted to choose the main deformation direction, etc.) we believe that the main advantage of the proposed methodology is its generality and applicability to several types of robotic hands, independently on their structure.

B. *The Stiffness Signature (SS)*

The SS is a measure of the hand stiffness distribution. It is computed using the concept of grasp stiffness, presented in [12], where the whole hand is represented as a six degrees of freedom spring attached to the wrist. To evaluate it, we need to know stiffness at joints, so we are considering how to create lumped parameter models for hands where identifying joints is not a trivial task [6]. We then analyze in which direction a certain robotic hand performing a power grasp is more stiff by computing the pulling force that is needed to break the grasp of a given object in different directions.

III. Simulations and Experiments

In this section, we report our preliminary results concerning the CS. The CS can be interpreted as a direction that can be exploited to align the hand with the object to be grasped. In this section, we show experimental results that suggest that this procedure could be useful to plan top-grasps.

A. *Pisa/IIT SoftHand*

Our experimental setup includes a UR5 Universal Robots robot arm, an ATI Gamma force-torque sensor, and a Pisa/IIT SoftHand underactuated robot hand. We also used a depth camera for object detection.

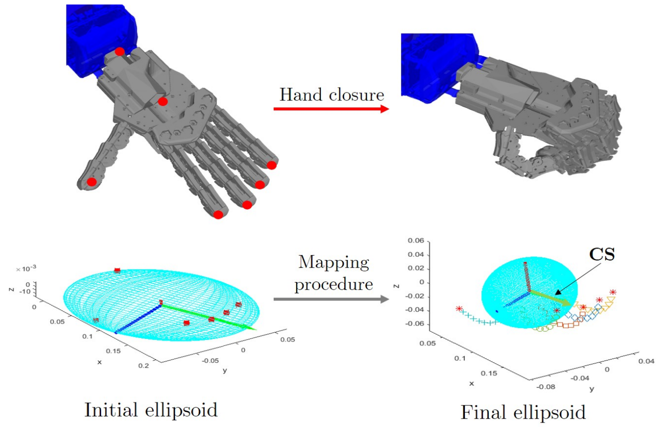

Fig. 1: Computation of the closure signature (CS) for the Pisa/IIT SoftHand.

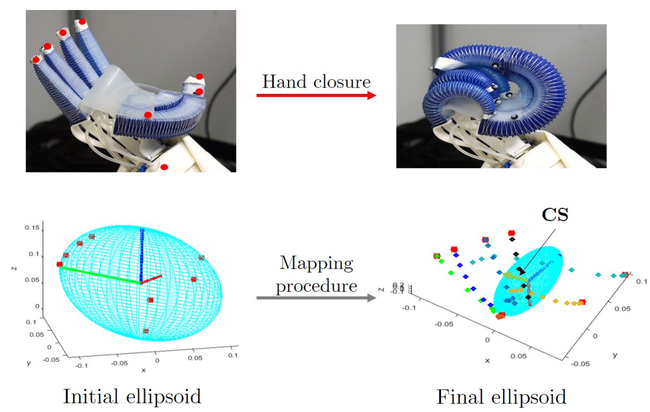

Fig. 2: Computation of the closure signature (CS) for the RBO Hand 2.

First of all, we computed the CS for the Pisa/IIT SoftHand considering reference points on the hand. Reference points can be obtained either placing markers on the robotic hand and tracking marker's motion during the closure, or simulating the hand motion. We simulated the Pisa/IIT SoftHand closing motion in Gazebo [13] so to have access to many possible reference point locations. In the following we will refer to reference points placed on the fingertips and on the wrist, see Fig. 1.

In order to compare our results with previous work in the field of grasp planning with soft hands, we referred to [14], where simulated grasps with the SoftHand are obtained by aligning the hand to the bounding boxes in which the object is decomposed. We refer to this method as "Straight alignment"(S). We used a simplified version of this alignment algorithm, where we considered the bounding box of the entire object. We tested the method S and the one based on the closure signature (C) in three different conditions (no uncertainty on the object pose, random rotation $r_r \sim \mathcal{N}(0, 0.01)$ around the z axis and translation $t = [t_x, t_y, 0]^T, \quad t_x, t_y \sim \mathcal{N}(0, 0.0001)$, random rotation

$r_r \sim \mathcal{N}(0, 0.04)$ around the z axis and translation $t_x, t_y \sim \mathcal{N}(0, 0.0004)$ and with three different objects (box, cylinder, apple).

The results of our experiments are summarized in Table I and show that our method is more robust to object pose uncertainty.

TABLE I: Top-grasps performed with the Pisa/IIT SoftHand in three different conditions of uncertainty on the object pose, for three objects and two strategies (Straight alignment (S) and Closure signature alignment (C)). For each of the 18 possible grasping scenarios we performed 20 trials and reported in the table the number of successes.

Condition	Algorithm	Box	Apple	Cylinder
$\sigma_r = 0$ rad	S	17	20	18
$\sigma_t = 0$ m	C	20	20	19
$\sigma_r = 0.1$ rad	S	15	19	10
$\sigma_t = 0.01$ m	C	16	19	16
$\sigma_r = 0.2$ rad	S	3	17	8
$\sigma_t = 0.02$ m	C	11	15	11

IV. CONCLUSION AND WORK IN PROGRESS

We computed the closure signature with the ellipsoid method also for the RBO Hand 2 (Fig. 2), and we are now trying to exploit this information to plan top–grasps with it. We are also exploring other ways to compute the closure signature and we will apply it also to other robotic hands. The computation of the stiffness signature is also work in progress.

An important extension of the work explained in this short paper, is to use the signatures not only to plan top–grasps, but also to plan other types of manipulation sequences, possibly involving the interaction between the hand and the environment.

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