Design criteria of the Passive Joints in Underactuated Modular Soft Hands

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Introduction

Underactuated compliant hands are spreading in the robotic community due to their robustness, adaptability, capability of exploiting environmental constraints while performing a task, availability and low cost. In particular the interaction with the environment and the simplification of the control is a central aspect in the design of the device.

In this paper we exploit the design of passive joints in underactuated robotic hands and in particular the role of joint stiffness in the definition of fingertip trajectory, grasp forces applied to object, and overall grasp stiffness.

In this work we mainly focus on passively compliant hands composed of deformable joints and rigid links, actuated with a tendon for each finger, connecting all the rigid links. Firstly we define a set of criteria and suitable procedures for the evaluation of the values of passive joint stiffness.

In our previous works we considered as main criterion the assignment of hand fingertips' trajectories: passive joint stiffness values were defined so that the fingertips of the robotic hand followed the trajectory that human hand fingers mainly follow when they freely move while approaching to an object to be grasped (first postural synergy). This criterion is useful to define the way the robotic hand is going to approach to an object: in our preliminary tests we observed that following this methodology a higher number of objects are reliably and efficiently grasped with respect to a hand in which passive joint stiffness are not optimized and are set equal for all the joints. In this paper we will go deeper in this analysis and we will consider other interesting criteria, which more in detail look at the interaction with an object and external surfaces.

The second aspect that will be considered deals with passive joint structural design: once stiffness values have been determined, methods for defining passive joints shape, dimension and material have to be defined. These components are realized with additive manufacturing techniques, using materials whose properties are highly variable and nonlinear: in this phase we are going to use COMSOL software. FEM structural simulation will allow to optimize geometrical and material parameters of passive joint to accomplish with the results of the specific optimization criteria. Results will be validated with experimental tests performed with a prototype. We furthermore are going to extend this methodology to continuous soft hands: in this framework the role of FEM simulation will be either more significant.

State of the art

A novel generation of underactuated compliant hands is growing in the robotic community in the last years, upgrading the preliminary attempts pioneered by Hirose et al., at the end of seventies [1]. Differently from classical rigid hands, in these soft hands the interaction with the environment and the simplification of the control is central to the device design. Underactuated hands have desirable adaptability to shapes, and can be effectively implemented using a reduced number of actuators, connecting the elements with relatively simple differential and elastic components [2, 3]. Passive adaptability allows controlling the device with a reduced number of input parameters. The devices are robust and can endure impact with hard objects without breaking into pieces. On the other hand they can adapt to object surface and grasp delicate objects without damaging them. Reasons for adding passive elements are manifold, including storing elastic energy, avoiding tendon slackness, passive compliance, distribution of forces over a large contact area and ensuring the uniqueness of the position. Shape adaptation increases the grasp performance by compensating the uncertainties in sensing, actuation and helps in stabilizing the grasp [4].

Most of the works in literature focus on the development of new devices proposing different solutions in terms of actuation and materials for hand realization. Fewer works are instead focusing on their modeling and systematically define the dexterity properties of new soft hands [5]. Considering a highly underactuated soft hand, there are few parameters to be tuned in order to design a desired motion for the robotic fingers. If the kinematic and the actuation system are fixed, a possible way to design a desired fingertip trajectory is to opportunely tune the stiffness of the passively compliant joints.

Figure 1: a modular underactuated gripper grasping a cubic object. In this example passive joints were designed in order that finger tips reproduce a given trajectory.

Methodology

In [6] we presented a systematic way to compute the stiffness ratio between the passive compliant joints so to obtain a desired trajectory for the fingertips. The proposed method assumes a given target motion of the fingertips and a given maximum actuation force for the tendon driven system to compute the stiffness value of the passive joints. It also assumes that the finger joints can be given specific stiffness and pre-form shapes such that a single-cable actuation can be used. Furthermore, we proposed a modular approach to define robotic hands. In most of the solutions existing in the literature, the hand is composed of a series of identical fingers, and the modularity is exploited at the finger level [7]. In the approach we propose, each phalanx, composed of a flexible and a stiff part, is modular. Beside the number and position of fingers in the hand, we can furthermore change the number of phalanges and some of their structural properties similar to what proposed in [8].
The problem that we attempted to solve was: how can we design finger joint stiffness so that, when applying a certain force to the tendons, the joint configuration vector $\boldsymbol{q}$ assumes a desired shape $\mathbf{q}_r$ and thus the fingertip follows a desired trajectory? To address this problem, we proposed a method to compute the stiffness given a certain kinematics of the robotic hand. We then exploited the main results on beam theory to find a way to compute the stiffness for a particular geometry of the soft parts. Differently from [9] where generic motion is obtained designing different planar linkages, we adopted a simple serial kinematic chain, in which we can choose the number of elements, and we focus on trajectories more common on power grasp executed by robotic hands, that can be obtained considering a deformation only at joint level.

Numerical Model and Simulation

The mathematical framework presented in [6] can be applied to a wide range of robotic grippers. Looking at the interesting additive manufacturing techniques that nowadays are rapidly increasing and offering interesting new opportunities, we analyzed the possibility of tuning finger joint stiffness values through exploiting the potentialities of 3D printing fabrication methods. In particular, choosing a material as the Thermoplastic Polyurethane for realizing the flexible parts, we can get different stiffness values, while maintaining the same geometric shape, by regulating the percentage of infill density. This parameter affects primarily material density, but also its mechanical properties. As an example, Table I summarizes the variation of Young's modulus E of the Thermoplastic Polyurethane as a function of the infill percentage density.

Infill density $\rho\%$	E (MPa)
10	1.07
30	1.38
50	2.07
70	6.53
90	9.45
100	10.50

Table 1: properties of TPU as a function of infill density percentage.

In a more general framework, the overall passive joint stiffness k depends mainly on joint geometry and material structural properties, and in particular, considering a linear elastic behavior, on Young's modulus E, *i.e.*

$$k = k(\mathbf{d}, E),$$

where $\mathbf{d}$ is a vector containing all the parameters defining joint geometry (e.g., for a parallelepiped joint, its length l, width w and thickness t, see Fig. 2). Young's modulus E depends on material parameters and fabrication methods, *i.e.*

$$E = E(p_1, p_2, \ldots, p_n),$$

where each value p_i indicates one specific material property. In particular we numerically investigated the dependency of k with respect to infill density percentage.
We evaluated with the Finite Element Method (FEM) based software COMSOL the stiffness of a modular element varying material properties. The dimensions of the elements are: length l = 13 mm, thickness t = 2.5 mm, width w = 21 mm. Fig. 2 shows the CAD model of the analysed passive element, while Fig. 3

shows the corresponding FEM mesh.
Fig. 3 and Tab. II summarize the main obtained results, in terms of stress and deformation of each module, and joint stiffness for different values of infill density percentage.
Another parameter that we need to consider in this type of application is the passive flexibility of the finger in the lateral direction and with respect to a torsional load, that cannot be controlled by actuators, and that could affect system functionality.
We therefore evaluated also the stiffness of each module in the lateral direction, k_l, and the torsional stiffness, k_t. We reported the main results in terms of lateral and torsional stiffness in Fig. 3 and Tab. II .
We can observe that, for the given geometry, the lateral stiffness is much higher than the bending one, due to the module geometry, while the torsional one is closer. A finger composed of simple modules as those considered in this analysis may therefore have an excessive torsional compliance, which however could be potentially compensated by modifying the design of the rigid part of the model.

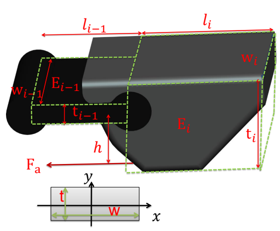

Figure 2: modular element of the gripper, composed of a rigid link and a passive elastic element. Main geometrical parameters.

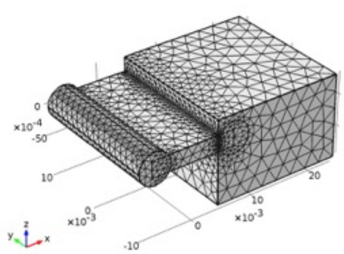

Figure 3: FEM discretization of the modular element.

Infill density $\rho\%$	$k(\rho)$ Nmm/rad	k_l Nmm/rad	k_t Nmm/rad
10	4.6930	331.3	24.9
30	6.0526	427.2	32.1
50	9.0789	640.8	48.1
70	28.6403	2021.6	151.7
90	41.4474	2925.6	219.7
100	46.052	3807.9	285.7

Table 2: Results of FEM analysis, equivalent stiffness in the longitudinal, lateral and torsional direction as a function of infill density percentage.

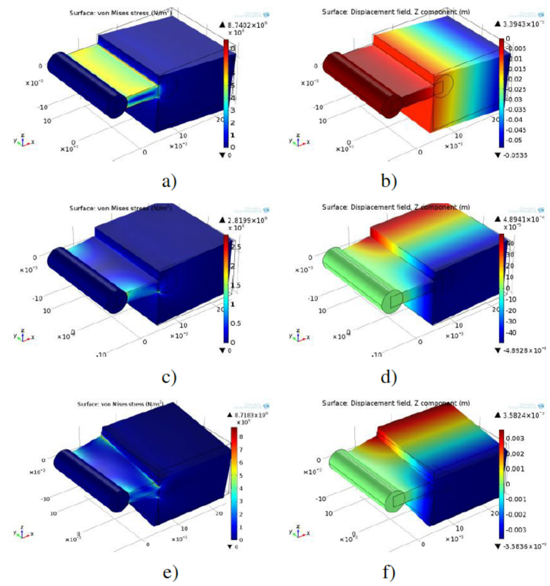

Figure 4: FEM model and stress/deformation analysis of the passive joint. In all the simulations, the left part of the flexible link was constrained to be fixed, while a load was applied to the rigid module connected to the right. Different loading conditions were applied to estimate the equivalent stiffness in different directions. The diagrams reported here summarize the results obtained for the 100% of infill density. a, b): bending in the principal direction, a 5 N load was applied to the free boundary of the rigid module in the z direction. a) stress distribution, b) module deformation. c, d): bending in the lateral direction, a 5 N load was applied to the free boundary of the rigid module in the y direction. c) stress distribution, d) module deformation. e, f): torsion, a ±5 N load was applied to the free lateral boundaries, so to produce an equivalent torsional moment of about 100Nmm with respect to the x direction. e) stress distribution, f) module deformation.

Experimental tests

As previously introduced, mechanical properties of TPU 3d printed materials depends on several parameters. To introduce other parameters in our analysis, we set up an experimental test bed to measure the bending profile of a set of flexible specimens (Fig. 5). The main objective is to experimentally define passive joint stiffness properties, and in particular the relationship between joint deflection and applied torque, as a function of the two printing parameters. Although the general principles for determining the tensile properties of the materials under defined conditions are described in specific regulations, we designed a customized test, good enough to obtain directly the data necessary to design the passive joints in modular underactuated hands.

Also in this case we considered a single module of the robotic finger introduced in [6]. In particular, the specimens used for the experimental tests have dimensions 24x20x3.75 mm. Two rigid parts are connected with a single flexible joint. One of the rigid parts is grounded (fixed), whereas the second rigid part is free to move parallel to a fixed plane. A marker is attached at the free tip of the rigid part, that is bent by applying a known force to the tendon. In the initial unloaded configuration the joint is fully open and the passive element is fully straight. Starting from this configuration, a force has been applied to bend the flexible part. The applied force is measured through a dynamometer (Vernier, USA). While the joint bends, the marker draws the resultant trajectory, as reported in Fig. 5. For each test, we recorded the trajectory produced by the joint deflection as a function of the applied force, the corresponding rotation angle and consequently the equivalent stiffness *k*.

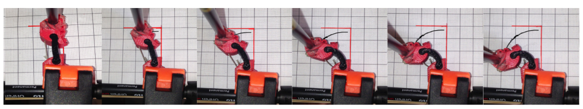

Figure 5. Experimental setup for recording the bending angle of the tested specimen.

Two specific parameters were considered in this experimental setup:

$$E = E(p_1; p_2);$$

where p_1, indicates the printing pattern and p_2 indicates the infill density percentage. The following printing patterns were considered

- $p1;1$: Rectilinear;
- $p1;2$: Line;
- $p1;3$: Concentric;
- $p1;4$: Honeycomb;
- $p1;5$: Hilbert Curve;
- $p1;6$: Archimedean Chords;
- $p1;7$: Octagram Spirals.

The following infill density percentages were considered

- $p2;1$: 20%;
- $p2;2$: 40%;
- $p2;3$: 60%;
- $p2;4$: 80%.

Some results of the tests are summarized in Fig. 6, reporting joint equivalent stiffness as a function of the applied force, for different values of the infill density percentage and printing patterns. It is evident that both the parameters have a clear effect on the overall stiffness, influencing both its value and its behavior.

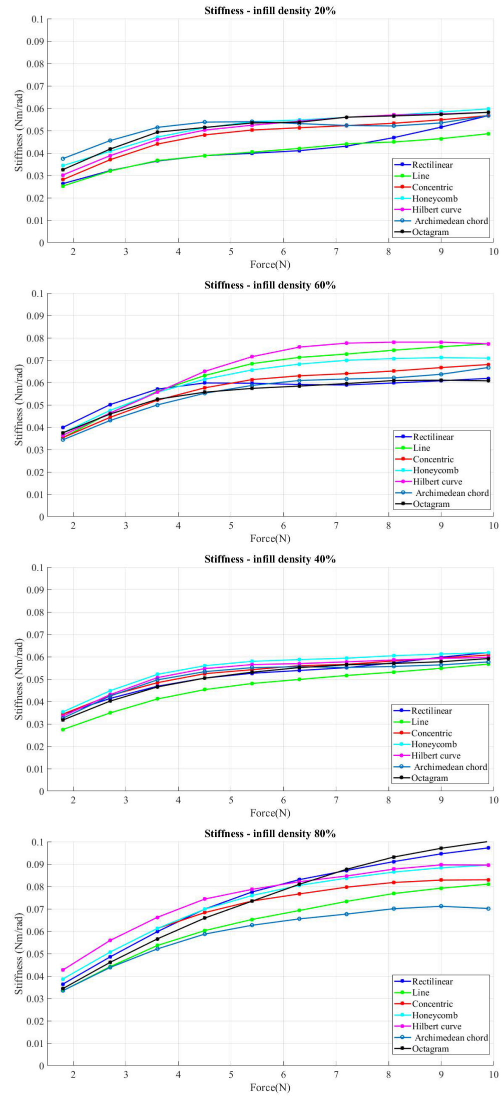

Figure 6. Stiffness variation due to different pattern types while keeping the same infill density

Conclusions

Exploiting additive manufacturing technologies and material properties in underactuated compliant mechanical structures can be a strategic solution for the design of simple, highly adaptable and robust robotic hands that can be effectively employed in industrial and service applications. However, to fully utilize this potential, there is the need to investigate and analyze the different printing possibilities and usage of tools effectively. In this paper, we present a preliminary study aimed at defining a systematic tool for the design of passive joints in underactuated modular hands.

We have analytically and numerically analysed how the different infill density percentage affects the overall joint stiffness. To consider the role of other parameters, as for instance the printing pattern, we set up some experimental tests. In particular in the tests we investigated different combination of infill density percentage and printing patterns. Results shows that the mechanical behavior of the joint depends on both these parameters. Methods for numerically simulate different printing patterns, through FEM simulation will be one of the topic of our future studies.

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