Soft Pneumatic Sensing Chambers for Robotic Grasping

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Abstract. This work presents the concept and prototyping of a tactile sensing system to enhance robots' exteroception. The proposed solution comprises soft tactile sensing elements, which are 3D-printed as monolithic structures. With a geometry inspired by human fingertips, these elements can sense contact both on the fingertip pulp and on the distal free edge, and Force Sensitive Resistors are integrated under their surface. Thus, this system mimics the human sense of touch, providing localized and global information on contact, and it can adjust its stiffness to grasp objects of different nature. Finally, preliminary results showing the system capabilities are presented.

Keywords: Tactile Sensing, Robot Exteroception, Compliant Grasping

1 Introduction

Manipulation of fragile and delicate objects is a major concern in various contexts, such as precision agriculture, medical care, and industry. In recent times, grippers integrating soft elements have emerged as a solution to the problem of object manipulation, due to their intrinsic ability to adapt and interact safely with unstructured environments. These soft elements functionally resemble the fingertips of the human hand, and they often integrate sensing chambers filled with fluid (either compressible or incompressible) [1,2,3], that deform under contact with an object. Tawk et al. [4] defined them Soft Pneumatic Sensing Chambers (SPSC), which are usually fabricated as low-cost 3D-printed soft membranes. Various types of tactile sensors, such as capacitive, piezoresistive, piezoelectric, and vision-based tactile sensors, can be integrated into soft fingertips to collect further information about contact points and object properties, e.g. size and shape [5]. Moreover, the active adjustment of the gripper's stiffness allows grasping both fragile and rigid objects, thus increasing dexterity.

Integrating all the aforementioned features in a system that mimics the human sense of touch is still a significant challenge. Hughes et al. [6] sensorized a soft gripper by means of latex-made SPSCs. Kuppuswamy et al. [7] have employed the same material to create *soft-bubble* fingertips to be mounted on rigid manipulators, where monitoring the internal pattern of the SPSC during gripping is used for in-hand pose estimation and object classification. Another camera-based sensing unit has been proposed by Su et al. [8], who sensed a silicon made PneuNet gripper by means of a soft inflatable palm with internal markers. Finally, Wang et al. [9] have made a rigid-soft gripper where two (or more) soft inflatable bladders are mounted on a rigid cylindrical structure.

Despite such research works, limitations still exist. SPSCs do, in fact, have a nearly spherical geometry, except in cases where the membrane is flat (rectangular or circular) and is deformed as a result of pressurization; and there is no analysis of the effect of geometry on the stiffness and sensitivity of the system. In addition to the need for a variable stiffness interface, there are also stringent requirements for lightness, compactness, and simplicity of the integrated system. In the case of robotic grasping, there is a need for a compact sensing system, which does not compromise the transportable payload and workspace of the manipulator, but at the same time increases its sensing capabilities.

This work advances what was presented by the authors in [10]. Specifically, a new SPSC-based, variable stiffness tactile sensing system is herein described. The effect of both the geometry of the SPSC and the set-up parameters of the sensing system are discussed, particularly focusing on the stiffness and sensitivity of the sensing unit. Finally, some applications are presented, to demonstrate the capabilities of the sensing system mounted on a commercial robotic manipulator.

2 SPSC Modeling

In this section, the stiffness and the sensitivity of the SPSC will be defined, and the parameter that affect those quantities will be identified.

To this end, the system depicted in Fig. 1 will be considered. It consists of a deformable sensing chamber which is deformed under contact with an infinitely rigid planar object. The static contact force F is a function of the contact depth y_s:

$$F(y_\mathrm{s}) = F_\mathrm{s}(y_\mathrm{s}) + (P(y_\mathrm{s}) - P_\mathrm{atm})A(y_\mathrm{s}) \quad (1)$$

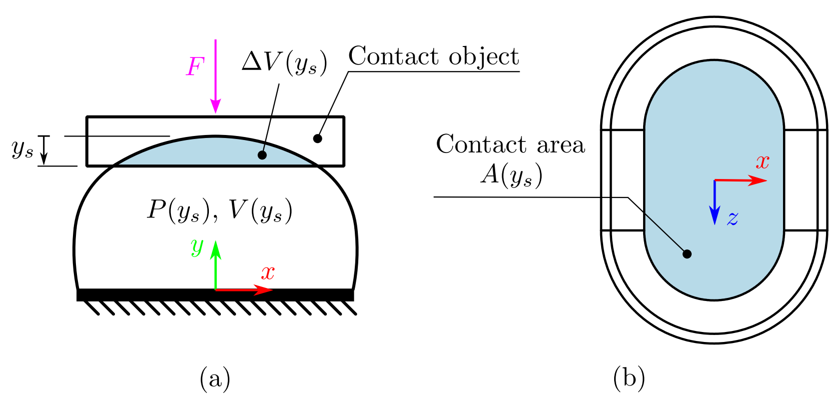

Fig. 1. Representation of the contact between the SPSC and an infinitely rigid planar object. (a) Identification of the chamber volume change $\Delta V(y_\mathrm{s})$. (b) Identification of the contact area $A(y_\mathrm{s})$.

where $F_s(y_s)$ is the structural elastic force of the membrane, $P(y_s)$ is the absolute pressure inside the chamber, P_{atm} is the atmospheric pressure, and $A(y_s)$ is the contact area. The function $P(y_s)$ is given by the polytropic transformation law for gases:

$$P(y_s) = P_i \left(\frac{V_i}{V(y_s)} \right)^n \tag{2}$$

where $V(y_s)$ is the volume of the chamber, n is the polytropic index, and $P_i = P(y_s = 0)$ and $V_i = V(y_s = 0)$ are, respectively, the pressure and volume in the chamber prior to contact. Finally, the stiffness of the SPSC is derived as:

$$k(y_s) = \frac{dF}{dy_s} = k_s(y_s) + p(y_s)\frac{dA}{dy_s} + A(y_s)\frac{dP}{dy_s} \tag{3}$$

where $k_s(y_s)$ is the structural stiffness of the membrane, and $p(y_s) = P(y_s) - P_{atm}$ is the gauge pressure in the chamber. Equation 3 can be reworked as follows:

$$k(y_s) = k_s(y_s) + p(y_s)\frac{dA}{dy_s} - \frac{n\,P(y_s)A(y_s)}{V(y_s)}\frac{dV}{dy_s} \tag{4}$$

to show that the stiffness of the SPSC depends on the membrane material, as well as on geometric parameters (chamber volume, contact area change, volume change) and set-up parameters (initial pressure in the chamber).

As regards the sensitivity of the SPSC, it is defined as:

$$\frac{dP}{dy_s} = -\frac{n\,P(y_s)}{V(y_s)}\frac{dV}{dy_s} \tag{5}$$

and it depends on both geometric parameters, i.e. chamber volume and its first-order derivative, and set-up parameters.

3 Implementation of SPSCs as Tactile Sensing System

This section presents the use of an SPSC in a tactile sensing system that enables a robotic manipulator to execute complex tasks, such as recognizing object properties, monitoring grasp, and detecting surfaces.

The functional architecture of the proposed system, here named PneuTact.Q, is depicted in Fig. 2. It consists of two independent SPSCs, one on the fingertip pulp and one on the distal free edge. These chambers are filled with pressurized fluid, and they are connected to an auxiliary electro-pneumatic system, which is mounted on the gripper. For each finger, the auxiliary electro-pneumatic system comprises a reservoir, which can be either isolated or connected to the fingertip pulp chamber by means of a digital valve, two check valves, and two pressure transducers (one for the fingertip pulp chamber and one for the free edge chamber). It must be noted that the check valves allow for retaining pressure inside the two chambers, so that, after an initial setup phase, the system can be operated without being continuously connected to a compressor.

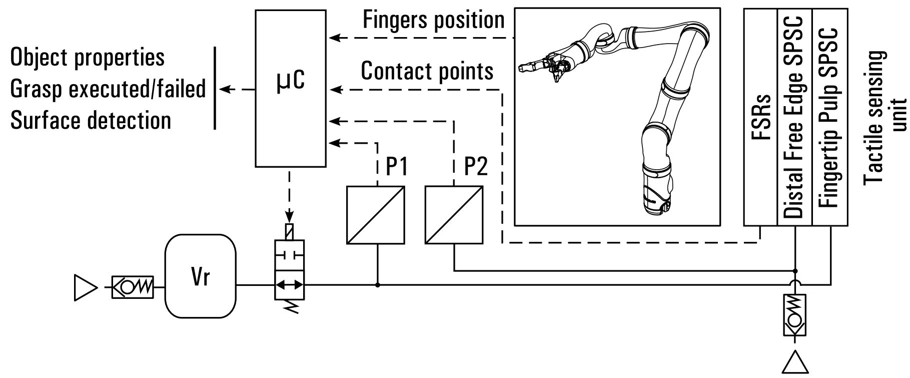

Fig. 2. Functional scheme of the proposed tactile sensing system. The electro-pneumatic system is replicated for each finger of the manipulator.

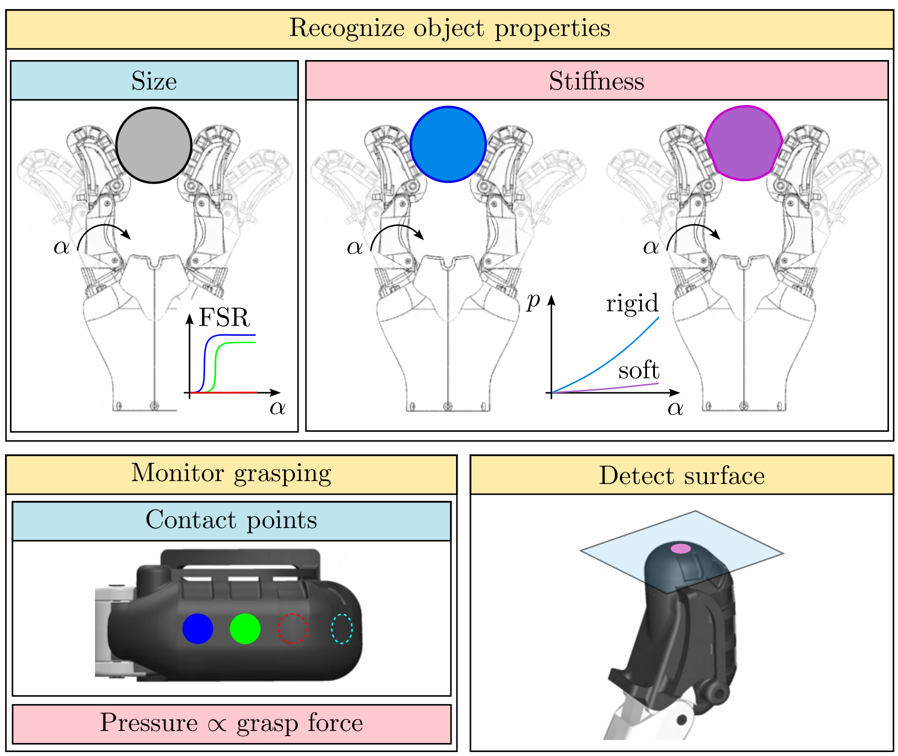

Fig. 3. The functionalities enabled by PneuTact.Q.

The digital valve allows control of the volume of fluid that undergoes deformation inside the fingertip pulp chamber. This chamber, which has a small volume, can be either isolated or connected to the reservoir, which is roughly eight times bigger than the SPSC volume. In the former case, the fingertip will be stiff, while in the latter it will be softer. To simplify the system, no stiffness regulation is possible for the free edge chamber.

FSRs provide localized information on contact, while the pressure in the sensing chambers gives global information on the deformation of the tactile sensing element. Moreover, FSRs are useful for precisely detecting contact with very soft objects. Indeed, in such a case the pressure change is not significant, as the sensing chamber undergoes a limited deformation.

The exteroceptive capabilities of the solution are summarized in Fig. 3. FSRs are mainly implemented to detect the first contact with the grasped object. Data from FSRs, combined with the gripper finger position, can thus provide an estimation on the object size. Once the object comes in contact with the SPSCs, internal pressure data are useful to estimate the object stiffness, meaning that the lower the pressure slope, the lower the object stiffness. Contact distribution data from FSRs can also be exploited to detect the slippage of the object, or, referring to the free edge FSRs, for surface detection.

4 Prototyping and Testing

The resulting PneuTact.Q prototype is visible in Fig. 4(a). It has been designed as an add-on for the two-finger gripper of the Kinova Gen2 7DoF commercial manipulator. The detail of the tactile sensing unit can be seen in Fig. 4(b). It is a monolithic, entirely soft element, which fits on the fingers of the gripper. The FSRs can be easily integrated into pockets realized on the surface, three on the fingertip pulp and two on the free edge.

SPSCs have been 3D-printed with an SLA printer (Formlabs Form 3B+), using both Formlabs Elastic 50A and Silicone 40A resins. The distinction between the two can be found not only in Shore hardness, but also in durability and cost: as a matter of fact, Silicone, while more durable, is associated with a higher cost. The reservoirs and the supports for fixing the electro-pneumatic system to the gripper have been printed with an FDM printer (Ultimaker S5), using Tough PLA.

The FSRs have a circular active area with a diameter of 5.6 mm (model FSR05BE, by Ohmite), and a force range of up to 5 kg. The voltage divider circuit for the FSRs reading has a 100 kΩ resistor. Finally, the pressure transducers used have a full-scale range of 100 kPa (gauge) and an accuracy of 0.25% (model ELVH-015G-HAND-C-NAA5, by Amphenol All Sensors).

Additional quantitative details of the PneuTact.Q prototype are listed in Table 1. It is worth noticing that the sensitivity is not linear and, as observed in [10], theoretical and experimental pressure values in the SPSC tend to diverge at higher contact depths. For these reasons, the reported sensitivity, calculated according to Eq. 5, has been mediated over the interval $0 \leq y_s \leq 2$ mm, which is a critical range to recognize object properties and in which the model is accurate.

A few of the functionalities discussed in Fig. 3 have been tested in grasping tasks. Figure 5 shows the raw data collected from the sensing unit when grasping a hard cylindrical object: as can be seen, the FSRs effectively provide information on contact points, and the system is sensitive enough to detect small deformations of the fingertip pulp chamber. Similar conclusions can be derived when using the free edge of the sensing unit for detecting contact with a surface (Fig. 6).

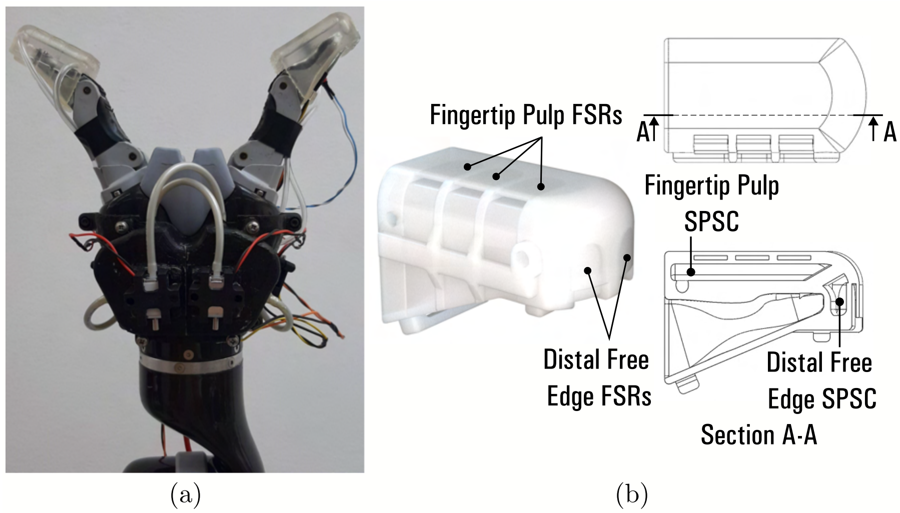

Fig. 4. (a) The PneuTact.Q prototype mounted on the Kinova Gen2 manipulator. SPSCs are made by Elastic 50A resin by Formlabs. (b) Detail of the tactile sensing unit implementing two distinct SPSCs and Force Sensing Resistors (FSRs).

Table 1. Quantitative details of the sensing system depicted in Fig. 4.

System weight		0.23 kg
Set-up gauge pressure		10 ÷ 30 kPa
Maximum contact depth	Fingertip Pulp SPSC	4 mm
	Distal Free Edge SPSC	4 mm
Volume	Fingertip Pulp SPSC	5 mL
	Distal Free Edge SPSC	1 mL
	Auxiliary reservoir	40 mL
Mean sensitivity[1]	Fingertip Pulp SPSC	1 kPa/mm (low stiffness) 8 kPa/mm (high stiffness)
	Distal Free Edge SPSC	22 kPa/mm

[1]Calculated according to Eq. 5, assuming $p_i = 20$ kPa (gauge) and $n = 1$, and mediated over the interval $0 \leq y_s \leq 2$ mm.

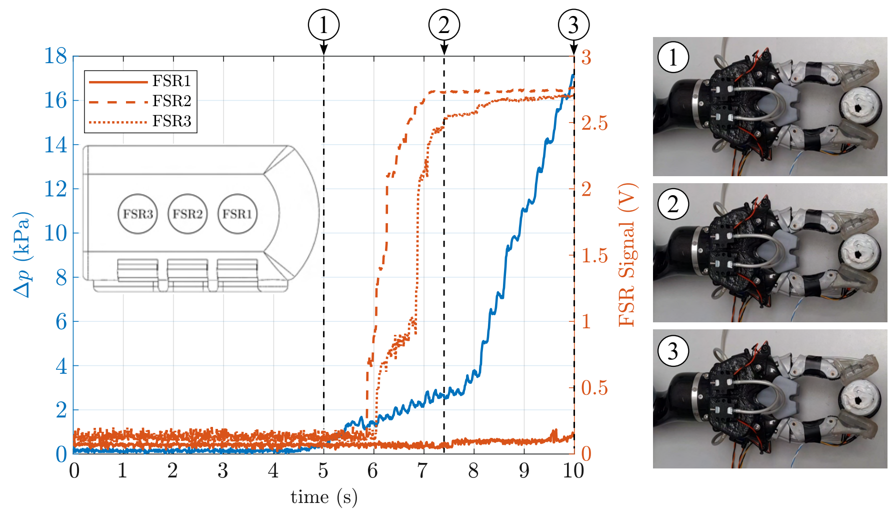

Fig. 5. Evaluation of tactile sensing capability when grasping a hard cylindrical object: first contact with the object (①), object recognition (②), grasping firmly the object (③). Only the signals acquired from one sensorized unit are shown. SPSCs were isolated from the reservoirs to maximize the sensitivity. $p(y_s = 0) = 20$ kPa (gauge).

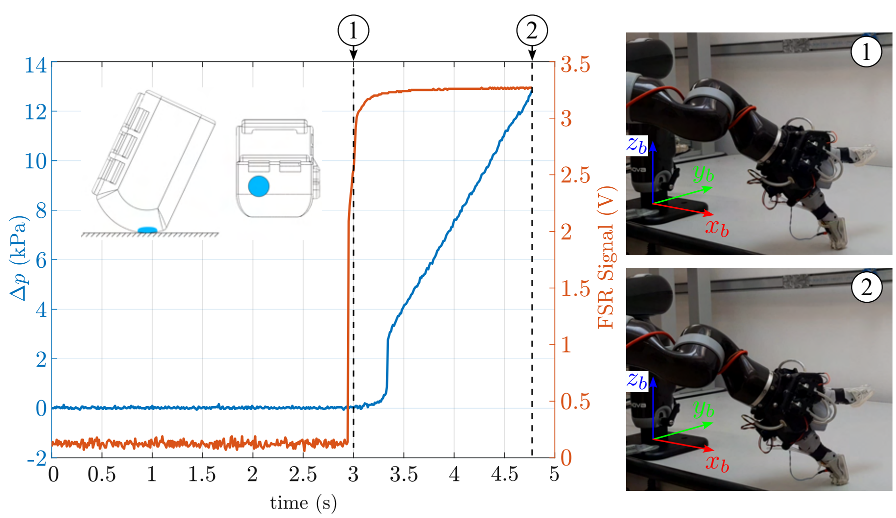

Fig. 6. Evaluation of tactile sensing capability using the distal free edge SPSC. The manipulator successfully detects the contact with the surface of the table thanks to the FSR sensor (①). Then, it applies an increasing force perpendicular to the surface, i.e. along z_b axis, as shown by pressure change (②). The pressure change in the chamber and only one of the two FSR signals are reported. $p(y_s = 0) = 20$ kPa (gauge).

5 Conclusions

This work presented a tactile sensing system that provides an artificial sense of touch to robotic manipulators. A 3D-printed monolithic tactile sensing unit, sensorized both on the fingertip pulp and on the distal free edge, has been introduced. An auxiliary electro-pneumatic system allows the switch between two different levels of stiffness, depending on the object to be grasped. The preliminary testing of the system shows promising results in terms of capability of localizing contact points, detecting grasping and recognizing surfaces. Future work will firstly focus on the experimental characterization of the manufactured SPSCs, both in terms of static characteristic and reliability. Moreover, further research will focus on the development of a sensor fusion algorithm to extract object properties, such as size and stiffness, from the raw contact information, and the implementation of data-based grasping control algorithm.

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