Soft flexible gripper design, characterization and application

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Abstract. This paper presents a design concept of soft flexible gripper dedicated for delicate objects manipulation. Traditional grippers are composed of rigid components and consist of finite number of discrete joints. The more joints they have the better they can adapt for the specific object. However, manipulating with fragile objects still requires precise control and some kind of measurement as well. In this paper the Authors propose soft flexible gripper that is able to adapt for the manipulated object shape without any additional computational effort nor any sensors. The gripper is made only of flexible materials such as rubber and silicone. Since the gripper lacks of any discrete joints and is actuated through smooth deformation of its body, it can take very complex shapes and thus easily adapt to the surface of grasped object. The mechanism is based on soft pneumatic actuators developed by the authors and its configuration can be easily redesigned in order to extend its application for special purposes. In this paper the design and experimental characterization of the gripper prototypes is presented. Possible applications are discussed.

Keywords: robotics, soft manipulator, gripper, grasping, artificial muscle

1 Introduction

One of the most fundamental challenges in robotics is object grasping. Conventional grippers and graspers are expensive and sometimes unsuitable for tasks where the manipulated object weight, its shape or the environment are uncertain. Moreover, manipulating delicate objects with a traditional rigid gripper requires sophisticated sensing and high precision that might not always be easily provided. Rigid grippers designed to handle fragile objects are often complex or can handle only specified type of items. One of the possible solutions is replacement of the gripper by a soft device that can passively adapt to the object and to the environment. For that reason, soft robotics has been extensively investigated by scientists, and many different kinds of soft mechanical structures has been proposed [1][2][3]. Soft robots offer high flexibility, adapt to the external conditions and interact more safely with human than any rigid machine. In this paper we present a soft flexible gripper that is able to manipulate with fragile objects and adapt to unstructured shapes. In the following sections design, manufacturing process and the gripper capabilities are presented. Then, possible applications are discussed. In general two issues are discussed when characterizing robotic grippers: ability to fixture object (often called grasping), and task of manipulating object with fingers [4]. In this paper we will focus on grasping only.

2 Design of the gripper

2.1 Finger construction

A crucial element of the gripper are fingers. The fingers are derived from artificial muscles technology developed first in late 1950 [5][6], principle of their operation is, however, significantly different from the initial muscles technology. An actuator based on the similar principle our fingers are, was first described in 1991 and called flexible micro-actuator [2]. The most important difference between artificial muscle and the actuator described in this paper is that the force exerted by actuator and the one generated by muscle have opposite directions. In our design each finger is a cylinder made of silicone with a pressure actuated chamber aligned with its central axis, Fig. 1. Two kinds of silicone are used - EcoFlex 0050 for softer and SmoothSil 950 for stiffer parts. The actuation chamber (c) is made of the softer material and reinforced with tight helix (e) (made of polyester thread) in order to limit radial expansion of the finger [7]. The inner fingers' side (f) is made of the stiffer silicone and formed in a bellow shape (g) in order to increase grasping capabilities. For the outer side of the finger (a) the softer silicone is used, so that the pressure application results in bending (j) as the inner part of the finger elongates less than the outer one. The tip (d) and the bottom (h) of the finger are sealed with the stiffer silicone. An actuation fluid is provided via small rubber pipes connected to the actuation chamber at the base of each finger.

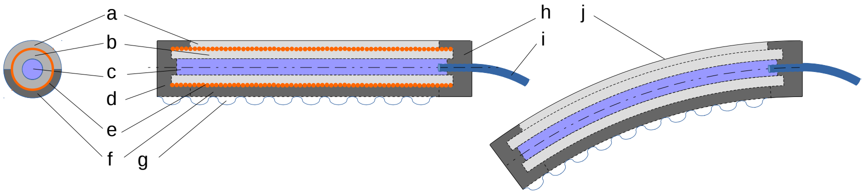
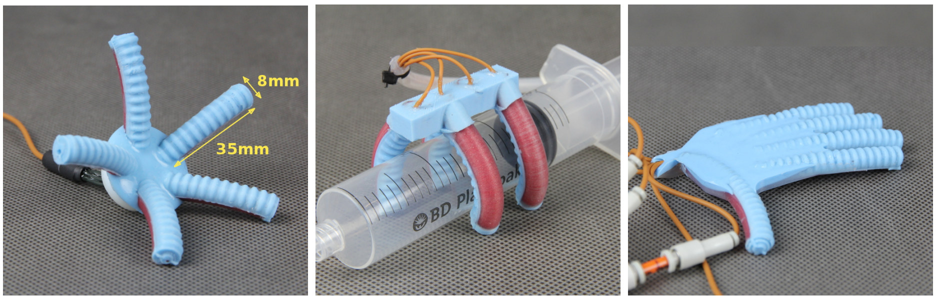


Fig. 1: Single finger design. a - outer silicone layer, b - actuation chamber wall, c - actuation chamber, d - finger's tip, e - reinforcement, f - inner layer, g - bellow shaped surface, h - finger's base, i - pressure cable, j - actuated finger. Light and dark grey colour corresponds with soft and stiff silicone, respectively.

2.2 Gripper construction

The gripper consists of a number of fingers. In particular, every single finger can be considered as a gripper as it can coil around the object and grasp it. The fingers can be arranged symmetrically or asymmetrically, actuated in groups or working independently each other. Fingers are bound to the gripper body with the same silicon type that is used for the inner finger side. In this paper we present few patterns of the fingers arrangements, however, due to simple design the setup can be very easily rearranged and adapted for a specific application. Exemplary arrangements are presented in Fig. 2.

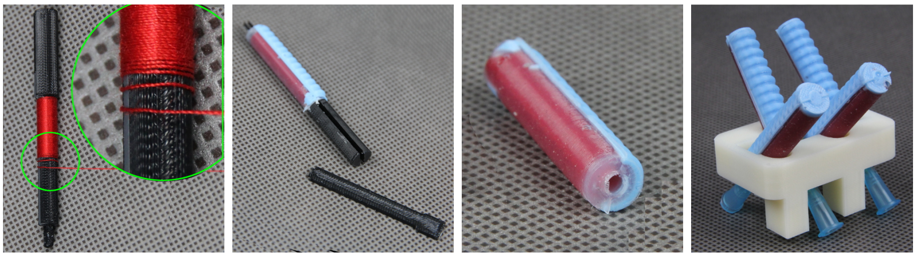


(a) (b) (c)

Fig. 2: Example grippers with different fingers arrangements: (a) with axial and (b) linear symmetry, (c) human hand inspired.

3 Manufacturing

The manufacturing process consists of several steps. The fingers are prepared first. For each finger special cylindrical chamber rod with removable core is prepared. Next, the rods are tightly braided using a low-diameter polyester thread, Fig. 3a. Then, the chamber reinforcement prepared in this way is covered with silicone layer separately - the soft outer part and the inner harder one. After the silicone cures, the rods are removed by first removing their cores, Fig 3b. Removing whole rod at once would cause high friction between the rod and the finger structure and result in finger damage. Next the actuation chamber wall is created by pouring the soft silicone inside the finger reinforcement and inserting dedicated rod of smaller diameter than the previous one, Fig. 3c. Last step of finger manufacturing is sealing its tip with the hard silicone. Once the fingers are ready, they are bound together in the final mould that forms the gripper body, Fig. 3d.



(a) (b) (c) (d)

Fig. 3: Manufacturing steps: (a) chamber reinforcement preparation, (b) rod removal (core goes first), (c) inner chamber wall moulding, (d) final moulding.

4 Characterization

The described gripper has been tested in terms of geometry and generated forces, partially covering possible characterization [8][9]. The force generated by the single finger depending on its length and the overall gripper capabilities were examined. The bending angle of the finger as a function of pressure was determined and compared with proposed mathematical model.

4.1 Single finger bending

Mathematical description The pressure applied into the actuation chamber results in a force acting in a cross-section of the finger. Considering the cross-section perpendicular to the finger neutral axis, the force is perpendicular to the cross-section plane. Its value is proportional to the pressure and the chamber cross-section area. As the Young modulus of the materials used in the finger construction differs at the cross-section, the bending neutral axis is shifted towards the inner finger part, Fig. 4.

Since the activation camber is aligned with the finger geometrical centre axis, the pressure applied results in the force that is not aligned with the bending neutral axis. That leads to a bending moment in the cross-section. The cross-section geometry does not change along the finger and due to the Pascal's law, force acting in all the cross-sections has the same value. Thus the bending moment along the finger is constant. The bending moment around neutral axis resulting from pressure can be expressed as (1). The P states for pressure value, d corresponds with the distance of the neutral bending axis from cross-section's geometrical centre that is a point of internal force acting, A states for the actuation chamber cross-section area and equals $\pi(r_3)^2$.

$$M = PdA \tag{1}$$

The neutral axis position can be obtained from the assumption that tensions for pure bending compensates on both sides of that axis. In such case the tension at the point (x, y) is expressed by (2),

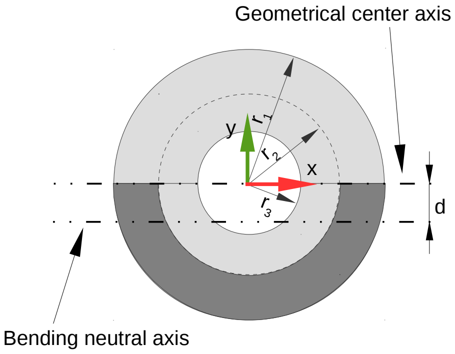


Fig. 4: Finger cross-section. Light grey and dark grey colours correspond with soft and stiff silicone, respectively.

$$\sigma(x,y) = E(x,y)\frac{x-d}{\rho} \tag{2}$$

where $E(x,y)$ states for the Young's modulus of the material used at (x,y) and ρ states for the curvature radius of the neutral plane at the cross-section . Hence, the neutral axis position d can be obtained from equilibrium condition (3) [10].

$$\iint\limits_{xy} \sigma(x,y)dxdy = 0 \tag{3}$$

Since the ρ value is a constant the equation can be rewritten as (4).

$$\iint\limits_{xy} E(x,y)(x-d)dxdy = 0 \tag{4}$$

Then the curvature radius ρ for a certain bending moment M can be derived from (5),

$$\rho_M = \frac{\sum^n E_n I_n}{M} \tag{5}$$

where E_n and I_n states for Young modulus and moment of inertia in respect to neutral bending axis of the cross-section $n^t h$ component, respectively. Once the position of the neutral bending axis is determined the moments of inertia can be obtained using parallel axis theorem.

The pressure applied into the actuation chamber causes not only bending, but elongation as well. The change of length can be derived from Hooke's law (6),

$$\Delta l = \frac{l_0 F}{\sum^n E_n A_n} \tag{6}$$

where l_0 represents rest finger length, E_n and A_n states for the area and Young modulus of the relevant cross-section component, respectively. F is stretching force that equals to pressure value multiplied by an activation chamber cross-section area. Hence, the overall bending angle can be expressed by the (7).

$$\alpha = \frac{l_0 + \Delta l}{\rho_M} \tag{7}$$

Thus the bending angle for a specific finger length is a quadratic function of the pressure.

Experiment The finger bending angle as a function of pressure has been measured. Due to limited data regarding material's Young modulus and not very precise manufacturing process (3D printed moulds, manual moulding, etc.) obtaining parameter values to compare the results with theoretical model is not easy. However, the second order polynomial fit presents good approximation of the gathered data, thus the principle of the model seems to be in force. The length of an active finger part was 20mm and the pressure range was 0-0.6 bars. The empirical data is presented in Fig. 5.

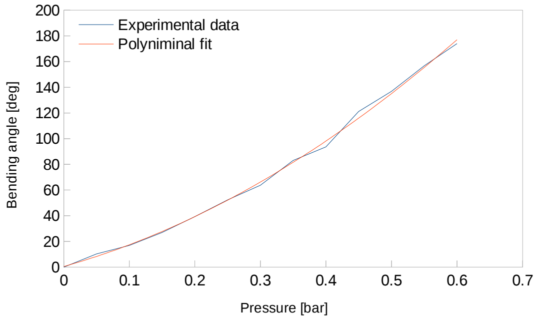
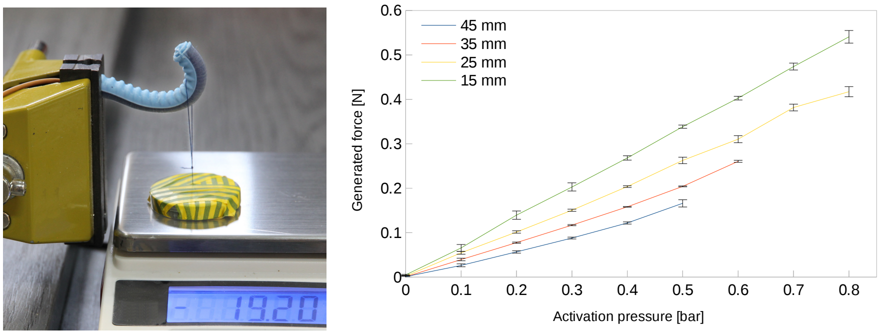


Fig. 5: Bending as a function of pressure.

4.2 Force generated by a single finger

The finger capabilities in terms of generated force values has been examined. The finger was mounted horizontally and the force has been measured as a function of pressure. The point at which the force has been measured was constant in space. For the measurement precise scale was used. The weight exceeded the finger capabilities, thus its position on the scales was stable during the experiment. The measurement setup and the results of the experiment are presented in Fig. 6



(a) (b)

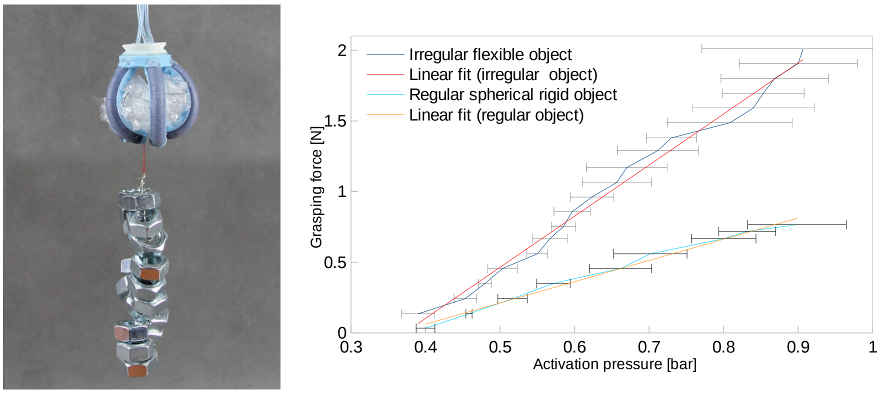
Fig. 6: Finger capabilities examination: (a) experimental setup, (b) force generated by fingers measured for different length fingers.

4.3 Grasping capabilities

Single finger gripper would have very limited application capabilities. In this section the performance of a grasper composed of five fingers is presented. Two manipulated objects of different kinds were tested. The force of the grasp was obtained for each object for various actuation pressures. The experiment was performed by grasping the object of known weight with the maximal available pressure and reducing the pressure until the object was dropped. Due to high variation of the results the experiment was repeated 6 times for each weight value. The tested use case is presented in Fig 8a. The performance for irregular soft object and for spherical rigid one is presented in Fig. 8b

5 Usage scenario discussion

There are many potential applications of flexible graspers in various scenarios. One of the examples is dealing with soft, flexible or delicate materials, in industries like apparel or shoe manufacturing [11]. Soft robots can enable us to make exoskeletons or wearable protetics, and provide more unobtrusive way to interface with human body [12]. Another intensively investigated application in recent years is friut picking that require caution due to objects fragility [13][14]. Higly demanding potential usage scenario is forensic evidences collection [15]. Since

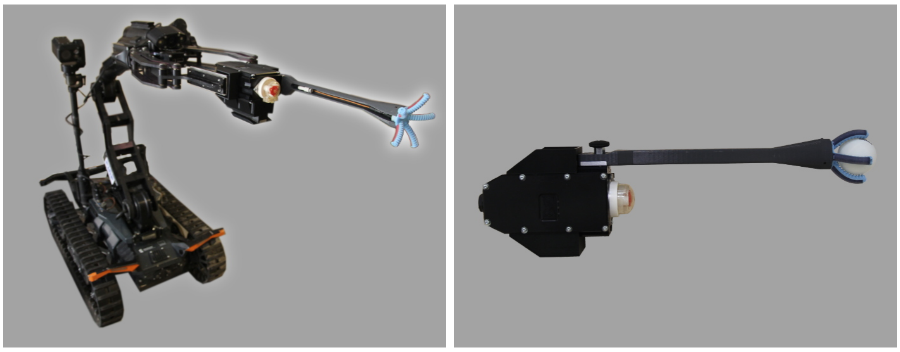


(a) (b)

Fig. 7: Grasper capabilities examination: (a) experimental setup, (b) grasping force comparison.

the evidences may be fragile and of irregular or unexpected shapes they may be difficult to grasp using conventional gripper. Experience of PIAP's experts gained from working in this field in cooperation with crime scene investigators concludes that such a soft grippers may be very useful for remote physical crime evidence gathering. One of the PIAP's robots equipped with the soft gripper is presented in Fig. 8. Generally handling fragile objects (fruits, human body, forensic evidences), in very different situations and usages can become domain dominated by soft robots [16], especially soft grippers such as the one described in this paper.

In the Fig. 9 few example handled objects are presented.



(a) (b)

Fig. 8: Mobile security robot equipped with the soft gripper: (a) the robot, (b) the device designed to actuate the soft gripper and to be carried by robot.

Fig. 9: Examples of grasped objects.

6 Summary

Traditional grippers are very widely utilized devices. However in some cases, the usage of rigid tools is problematic due to their stiffness. Soft and flexible graspers and grippers demonstrate great potential in such cases. Their adaptation capabilities and soft contact make them safe and adequate for fragile object manipulation. Due to their safety properties, soft grippers and grasper are extensively considered as a substitution for rigid devices in the human-present environments. Moreover, the passive adapting skills make it possible to use soft devices in uncertain environments and for unstructured object manipulation without any additional control effort. In many cases there is no need to use any sensing to realise a task, since the gripper flexibility successfully compensates all the object irregularities.

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