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# **Robot design and operating principles**

* 1. **Actuator design**

Generally, PneuNet (pneumatic network) actuators are elastomers embedded with a series of parallel chambers and channels as a repeated component which enables various soft actuation movements, originally developed by [1] at Harvard. The structure of the soft actuator is modified by applying pressure in the chambers, forcing it to expand in the regions of less thickness and stiffness.

In this design we embedded a series of cuboidal shaped chambers over the elastomer with extensible top layer and inextensible but flexible bottom layer as represented in FIGURE 3(b). The extensible top layer is made to have gaps between the interior walls of the chambers, all chambers are designed to have thinner inner walls and higher surface area proving to have reduced change in volume required for complete actuation as mentioned at [2]. The basic principle of actuation in this design is when a fluidic pressure (either air or liquid) is applied through the chambers of the PneuNet, the thinner chamber walls start to expand and increase in volume as represented in FIGURE 2(c) creating a difference in the compliance of extensible (top) and inextensible (bottom) layers and due to this the actuator bends towards the inextensible (bottom) layer as represented in FIGURE 2(b). For multiple applications, various movements can be implemented in this soft actuator by modifying the material, distribution, configuration and size of the embedded pneumatic network. One such example has been demonstrated by [1].

A diagram of a machine

Description automatically generated

**Figure 1:** (a) Cross sectional view of the soft Pneunet actuator, which shows inner chambers with thinner side walls and central channel connecting every chamber from [3]. (b) Illustration of the soft Pneunet actuator when fully actuated, having all its chambers expanded resulting in a curved motion from [3]. (c) Illustration of the soft Pneunet chamber expanding along the thinner walls due to air pressure from the central channel from [3].

A hand holding a white plastic object with copper strips

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**Figure 2:** (a) Picture of the manufactured soft Pneunet actuator, which has a length of 105.55mm and width of 31.25mm embedded with the capacitive sensor on its back and attached with a tubing for applying air pressure along the central channel. (b) The manufactured soft Pneunet actuator bent to a certain extent, displaying the extensible top layer and inextensible bottom layer.

**3.2 Sensing principle,**

The sensing principle here involves electrostatic theory, which states that the capacitance between two conducting surfaces is inversely proportional to the distance between them. This theory is used to measure the curvature data of the actuator by attaching a capacitor module at the smooth surface of the actuator, partially embedded inside the silicon as in [4]. The design of the capacitive sensor was referred from [5] which allows it to be deformable when curvature stretch is applied by the flexible actuator surface. It is fabricated from copper strip that is cut into comb-like structure by following the instructions from [6] with a wide base sheet at the end as shown in FIGURE 5(a). When curvature stretch is imposed, the distance between each tooth is going to vary as shown in FIGURE 4(c), hence varying the capacitance value.

The fabricated sensor is integrated in the soft actuator at its inextensible layer as shown in FIGURE 5(b). When actuating the PneuNet, the varying capacitance values are related to the stretch of the bending surface by the equation (1) from [5]. The capacitance values recorded by the sensor are then related to the input pressure values to calculate the resultant position data. This information is then given to the microcontroller to analyze the behavior and decide the next action necessary, enabling a closed loop function.

**Figure 3:** (a) Illustration of top view of the design of the capacitive sensor with comb-like structure used to measure the position data of the actuator taken from [5]. (b) Side view of the capacitive sensor design taken from [5]. (c) Illustration of the curved state of the flexible surface along with the capacitive sensor coupled with it showing the change in distance between adjacent teeth taken from [5].

**A diagram of a computer

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**Figure 4:** (a) Picture of the fabricated capacitive sensor with single row of multiple teeth like design. (b) Picture of the fabricated capacitive sensor attached to the inextensible based of the fabricated soft PneuNet actuator, with one side exposed to the surface.

**A close up of a device

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**3.3 Modelling,**

One of the major aspects of soft actuation is creating a model of its movements, which helps in better understanding of its behavior and there are various methods for the same as mentioned in [7]. This paper focuses on two general models, which included the curvature of the actuator as a function of pressure input (Model1) and capacitive sensor output as a function of pressure input (Model2).

**Model 1**

Based on Euler-Bernoulli Beam Theory, the relationship between the curvature (k) of the bending surface and the internal pressure (P) applied to the actuator can be formed as shown in equation (4). The beam theory states that the curvature (k) can be expressed in terms of bending moment (M) and flexural rigidity (EI) as shown in equation (2). This is proceeded with an assumption of considering the inextensible layer as a flexible beam as in [7] and having constant curvature behavior. Bending moment can be expressed as force responsible for the bending times the distance (d) at which it is acting, here the force responsible for bending can be expressed as the pressure (P) inside the actuator times the effective area (A) of the pressurized chambers and this is represented in equation (3). Using equation (2) and equation (3) we can conclude to equation (4) which relates the pressure applied to the actuator with the curvature of the actuator.

**Model 2**

From equation (1) we got the relationship between the stretch () and the capacitance value () after bending. Building upon the same equation from [5], it is obtained that ratio of further change in capacitance value from initial value () by initial capacitance value () can be represented as a function of curvature angle (), this is represented in equation (5).

By basic geometry we can relate curvature angle () with curvature (k) by , where is the length of the section of continuous teeth arrangement. By using this relation and equation (4) and substituting in equation (5) we get the relationship between the increased capacitance as function of the internal pressure applied to the actuator, this is represented in equation (6).

Table 1 List of symbols

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| **Symbols** | **Description** |
| k | Curvature of actuator |
| M | Bending Moment |
| E | Young’s Modulus |
| I | Bending Moment of Inertia |
| A | Effective area of actuator chambers |
| d | Distance from axis where pressure is applied |
| P | Internal Pressure applied to the actuator |
|  | Initial Capacitance before bending |
|  | Capacitance after bending action |
|  | Parameter to account for inhomogeneity constrains due to sensor coupling on the holding surface |
| G | Distance between 2 adjacent teeth |
| G | Gap between the central axis and the sensor surface |
|  | Curvature angle/ Bending angle |
|  | Length of the section of continuous teeth arrangement |

* 1. **Fabrication**

Fabrication of PneuNets using varying materials shows different behaviors when actuated. For the above-mentioned PneuNet we choose Dragon Skin 20 silicone rubber compound [8]. To start with the process, both parts of the Dragon skin 20 bottles as shown in FIGURE 4(b) were shaken vigorously for about 30 seconds. Equal parts of elastomer were poured into a plastic cup measuring up to 25 grams for each part (5% error acceptable) using a weighing machine which is depicted in FIGURE 4(c). Once both parts were poured, it was then put in the mixer along with a cup holder to mix both parts well without inducing air bubbles in the elastomer mixture. The total weight of the elastomer plus the plastic cup and the mixer cup holder were measured to set the counterweight in the mixer using a dial. After mixing the elastomer, it was then poured in the base mold and the top layer mold, quickly and gently so as not to get any air bubbles in them. We can use various types of molds for different actuator designs and varying motions [9]. A popsicle stick was A collage of several blue and white objects

Description automatically generatedthen used to wipe out excessive elastomer on the top layer mold using the doctor blading method as shown in FIGURE 4(g). The molds with the elastomer were let to set for a while as these materials have the property to distribute themselves evenly given some time. As the next step, both the molds were placed in the vacuum chamber as shown in FIGURE 4(h) and a negative pressure of about 22 Pascals were applied for about 10 minutes. This step is important as it brings all the bigger bubbles to the surface which makes it easier to pop it. After the required time, the outlet pipe was then released very slowly so as not to shake the molds and for the wear and tear of the pressure gauge in the long run. After removing the molds from the vacuum chamber, the fabricated capacitive sensor (along with its backing) was then placed inside the elastomer in the base mold and was pressed down using a popsicle stick until it was settled in the bottom as shown in FIGURE 4(d), these setups were left to cure for about 4 to 5 hours. Once the elastomers were completely cured it was removed carefully from their molds and its structures looked as shown in FIGURE 4(e)(f). To combine both the parts of the actuator, a smaller portion of the elastomer was prepared and applied on the smooth side of the base of the actuator, it was then evenly spread across the surface area of the base making a thin layer of uncured elastomer. The top layer was then placed gently over the bottom layer, where the uncured elastomer acted as a glue to bond both the parts. In this part it is important to make sure that the top layer isn’t pressed too hard so that the elastomer slides into the central channel of the actuator blocking the path. The central channel of the actuator is the path that connects all the chambers and facilitates the expansion of the walls of the chamber uniformly when pressure is applied. Once the entire actuator was let to cure, using an iron rod a hole was pierced in a particular angle as shown in FIGURE 4(i) to reach the central channel [3]. It is important to make sure the iron rod doesn’t puncture the chamber leading to fluidic leak. Finally, a tube was inserted into the hole enabling the expansion of the chamber walls when applying pressure through the tube. It can be observed that the bottom layer of the actuator is inextensible but flexible as it is a sheet of elastomer, whereas the top layer of the actuator is extensible due to the chamber design, facilitating expansion of the top layer. Hence, when both the structures are combined, the actuator performs a bending motion when pressure is applied as represented in FIGURE 2(a).

Figure :***(a)*** *Lab setup for the fabrication of the soft PneuNet actuator.* ***(b)*** *Dragon Skin 20 Silicon Rubber Compound both part A and part B.* ***(c)*** *Weighing scale along with the plastic cup used for mixing part A and part B of Dragon Skin 20.* ***(d)*** *Capacitive sensor placed in the elastomer in the base mold and pressed down to settle at the bottom of the mold.*

***(e)*** *The base of the actuator removed from the base mold, top view.* ***(f)*** *The base of the actuator removed from the base, bottom view along with the backing on the sensor.* ***(g)*** *Top layer mold filled with elastomer after applying doctor blading method.* ***(h)****Vacuum Chamber used for bringing air bubbles to the surface to pop and clear it.*

***(i)*** *Illustration of the correct angle of piercing of iron rod through the fabricated actuator* [3].

# Reference

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