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Proprioceptive Soft Pneumatic Gripper for Extreme Environments using Hybrid Optical Fibers

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Abstract—Soft pneumatic robotic grippers can be used to conduct a wide range of tasks in extreme environments as they are generally free of conductive or magnetic components. But the sensorization of these grippers can potentially make them unsuitable for such environments and lower their performance through the introduction of electronic components or conductive materials into their structure. This work introduces the design of a sensorized soft pneumatic gripper using hybrid optical fibers making use of rigid and hard segments to measure the bending deformation and the contact force at specific segments of the finger. Using rigid optical fibers, which has low optical loss, for optical signal transmission allows to place all electronic components outside and away from the gripper ensuring the structure of the gripper and its nearby components are non-conductive and non-magnetic. The utilization of rigid reinforcements on the soft pneumatic actuator also helps maintain the performance of the actuator close to existing non-sensorized soft pneumatic actuators. This sensorized actuator is then used in a proprioceptive soft robotic gripper capable of controlling its grasping force.

Index Terms—Soft Sensors and Actuators, Force and Tactile Sensing, Sensor-based Control, Soft Optical Fibers, Proprioceptive Soft Gripper, Hybrid Optical Fibers

I. Introduction

Soft robotic actuators made from rubbers or polymers have gained a lot of attention for their ability to adapt to their environment through their inherent compliance [1]. This compliance has gained significant interest for grasping where the compliance of the actuator can be used by the fingers to adapt their shape to the surface of the object and produce a well distributed force that is both gentle and secure [2]. In the case of pneumatic soft actuators, their rubber or polymeric bodies coupled with the use of air rather than electric or heat inputs make them ideally suited for operation in environments where the use of electric power or magnetic materials should be avoided [3]. This can include situations such as handling magnetic objects, operating inside strong magnetic fields, or operation in highly explosive environments. So, the sensorization of these grippers for such conditions requires the use of non-conductive and non-magnetic materials without obstructing their deformation [4].

Stretchable silicone with conductive fillers such as carbon powder or carbon nanotubes can be used to detect deformation of the silicone matrix based on the change of resistance of the conductive element caused by changes in thickness and length. This principle has been used to measure the linear deformations of McKibben actuators [5], compressions of the matrix to measure applied pressures [6], bending of the actuator in a PneuNet bending actuator [7], or even measurement of both the bending angle and pressure at specific points of a 3D printed pneumatic finger module [8]. Stretchable silicone materials can be replaced by conductive solutions such as saline solutions to measure the stretching of polymeric structures where the conductive solution is inserted in channels within the structure [9], which can also be used to measure the bending angle or pressure generated by soft pneumatic actuators [6], [10]. Liquid metals have higher conductivity than ionic liquids and have been used to measure the contraction deformation and force of McKibben actuators [11], [12], and the bending deformation of soft pneumatic grippers [13], [14]. However, measuring the change in resistance of the conductive material also requires applying electric currents which make this kind of actuator not well suited for extreme environments such as highly explosive environments, environments with electromagnetic radiations or for underwater applications where the medium can cause short-circuits.

Alternative sensing methods for measuring the change in resistance of conductive materials have been proposed to obtain actuators with similar sensing characteristics or possessing new sensing capabilities [15], [16]. Dielectric elastomers have been used to measure the change in capacitance of the material and can measure the linear deformation of McKibben actuators [17], bending actuators [18], [19], or for robotic skins capable of measuring contacts at a large number of points on a surface [20]. But these capacitance-based sensors also rely on the application of an electric current and have similar limitations as resistance-based sensors.

Another alternative has been to use acoustic signals where an acoustic source and a microphone is implemented in the system and the change in acoustic measurements is used to estimate changes in the system. A system comprised of a speaker and a microphone has been implemented in a soft pneumatic finger where contacts with the finger cause a measurable change in

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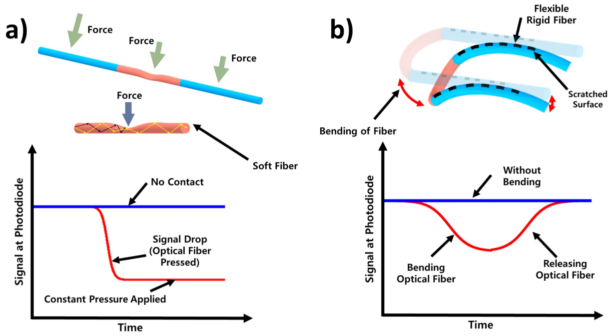

Figure 1. (a) Contact force sensing optical fiber; the soft part (shown in orange) of the hybrid fiber responds to external contact forces as the light intensity diminishes inside the fiber due to force exerted on the fiber, while the rigid part (shown in blue) of the hybrid fiber are used to easily transmit the signal without interference from outside forces. (b) The bending deformation sensing fiber has scratches on its outer surface such that bending of the fibers causes optical losses proportional to the bending deformation.

frequency response such that a single acoustic source can be used to measure the location of contact [21], [22] and the pneumatic pump itself has been used as the acoustic source to measure the location of contact on the pneumatic tube connected to a soft robotic hand [23]. However, acoustic sensing has not been demonstrated for measuring bending deformations and is highly susceptible to external disturbances. Also, either the acoustic source or the microphone should be located at the measurement point and require an electric current to be provided to this point.

An interesting solution for the sensorization of soft actuators is the use of optical fibers (can also be mentioned as waveguide which is a combination of soft optical fiber and cladding) where photocurrent variations are used to measure inputs [24]–[27]. These can be used to measure bending deformations of bending actuators or soft pneumatic actuators when being made with a flexible or stretchable waveguide [28]–[30], and can measure the fingertip force of a robotic hand or gripper [31]. These two types of sensors have been integrated into a single waveguide and used in an underwater gripper [32]. However, the two types of sensing are coupled and decoupling them involves implementing them on different fingers the pressure inside the actuator and both bending and tip forces of a soft pneumatic gripper [33]. However, the actuation performance of this last gripper proposed in [33] is not well demonstrated and could potentially be impeded by the large volume occupied by the optical waveguides. The use of such optical waveguide can help take the electronic components outside of the polymeric structure. But the high optical losses of soft waveguides along their length and due to undesired deformations means that their light sources and receptors should be kept at the base of the actuator. This makes this sensorization technique unsafe as electric currents are used close to the end effector. There is a need for a sensorization method for soft pneumatic actuators that allows to place all electronic components outside and away from the actuator such that they can be used in extreme environments.

This paper introduces the design for a proprioceptive soft pneumatic gripper for extreme environments making use of separate optical fiber sensors for bending and contact force sensing in the same actuator. This enables the decoupling of the two sensing signals and allows for measuring the contact force even in the deformed state and enables the feedback control of the force. The use of hybrid soft and rigid optical fibers also allows for measuring the multi-point contact forces at specific portions of the actuator. Rigid reinforcements are used for guiding the fibers during assembly and actuation while improving the actuation performance. First, the design of the sensorized actuator is introduced along with its characterization, then its implementation into a three-fingered proprioceptive soft pneumatic gripper is shown as well as its ability to measure the stiffness of objects of different size.

II. Design and Methods

A non-conductive and non-magnetic sensorized actuator would show a lot of potential for use in areas with extreme environmental conditions such as high conductivity areas, electromagnetically noisy areas, MRI (magnetic resonance imaging) operations, etc. Soft pneumatic actuators themselves meet these requirements as they are generally made from non-conductive and non-magnetic elastomers. However, the methods used to sensorize these actuators have made them electromagnetically conductive or required the use of an electric current inside the actuator.

A method for the implementation of optical fiber in a PneuNet actuator is introduced in this section using hybrid optical fibers alternating soft and rigid segments for measuring the bending deformation and contact forces. Rigid optical fibers are better at transmitting optical signals over long distances while soft optical fibers display more sensing responsiveness with respect to lateral deformations. Thus, the use of rigid optical fibers allows to place electrical components such as the light-emitting diode (LED) and the photodiode (PDE) far from the actuator while soft components can be used to measure deformations at specific points. As the optical fibers themselves are non-conductive and non-magnetic, this allows for the sensorized gripper to be entirely made from non-conductive and non-magnetic materials. The main elements of the proposed sensorized gripper are described below.

A. Contact force sensing optical fibers

Contact force sensing using optical fibers has generally used soft optical fibers which incur signal losses when stretched or compressed. However, the location of the contact along this soft optical fiber cannot be determined. Furthermore, soft optical fibers have more optical losses than rigid ones which limits their lengths. The proposed design uses hybrid optical fibers with soft and rigid segments which allow the use of soft segments to sense the compressive forces at specific points and

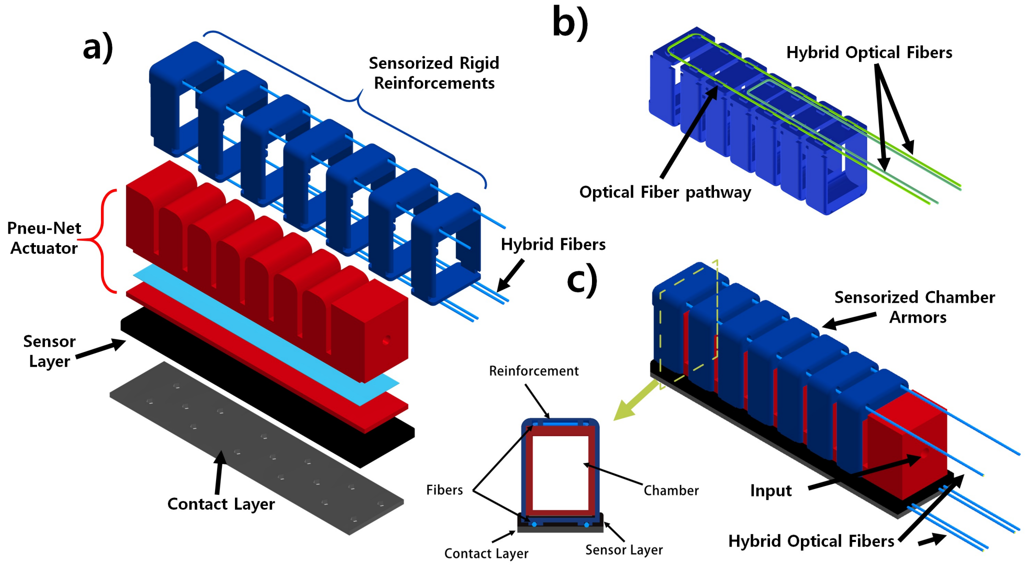

Figure 2. (a) Structure of the proposed sensorized soft pneumatic actuator, (b) layout of the contact force sensing hybrid optical fibers, and (c) assembled design of the sensozired soft pneumatic actuator where the upper fiber serves as a bending deformation sensor and the lower fibers are used for contact force sensing.

rigid segments to filter out deformations in the rest of the actuator and to transmit the optical signal over long distances without further optical losses, as shown in Fig. 1(a). This allows to sense contact forces at the desired location and for the electronic components to be placed outside of the actuator. Rigid contacts are also designed to be attached with the sensitive part of the hybrid fiber to transfer contact forced from the contact layer to the soft optical fiber.

B. Bending deformation sensing optical fibers

Unaltered optical fibers generally do not lose signal when slightly bent, so imperfections in the surface of optical fibers have generally been introduced using laser-based patterning of the fiber which allows the measurement of bending deformations [34]–[36]. However, this makes these fibers weak and results in mechanical failure over repeated use and low signal quality. In this work, we used a sharp edge cutter to scratch the outer surface of the fibers. By scratching the surface, the optical radiation hitting these spots loses its angle of refraction resulting in a loss of optical signal which is proportional to the bending angle of the fiber. Fig. 1 (b) shows how bending and unbending affects the optical signal. As the optical fiber needs to sharply bend at the fingertip, this segment is replaced by a soft optical fiber which allows it to be easily bent at the required angle.

C. PneuNet with rigid reinforcements

The actuator itself is a basic PneuNet soft pneumatic actuator design with multiple pneumatic chambers as shown in Fig. 2 (a). Rigid reinforcements are added that encapsulate each of the pneumatic chamber of the actuator. The rigid reinforcements have holes in their upper portion which serves as a guide for the bending angle sensing optical fibers in which they can easily slide while bending as the actuator itself bends. This does not allows these fibers to stretch even as the distance between pneumatic chambers increases. The bottom of the rigid reinforcements is also used as a guide when installing the contact force sensing optical fibers during manufacturing, as shown in Fig. 2 (b). The configuration of the entire actuator and of the location of the optical fibers within the rigid reinforcements is shown in Fig. 2 (c).

III. Fabrication

The proposed sensorized non-conductive actuator is fabricated using mostly conventional soft lithography processes. The main actuator is a PneuNet actuator with eight chambers containing three layers each: the PneuNet chamber layer including an inextensible strain-limiting fabric and rigid reinforcements, the sensor layer containing the hybrid fibers for contact force sensing, and the contact layer which is a patterned softer layer used as the layer interacting with the environment. The PneuNet was fabricated by a standard two-step molding process and was made from Dragon Skin 30 (Smooth-On). The rigid reinforcements were printed from PLA (Polylactic Acid filament) using a 3D printer (Ultimaker 5S), and each pneumatic chamber was incapsulated in these rigid reinforcements by inserting them over the actuator as shown in Fig. 3.

Both soft and rigid optical fibers are commercially available with the soft optical fiber being a urethane-based elastic tendon and the rigid optical fiber being acrylic based, and all fibers are cut to the appropriate lengths for both the bending angle sensor and the contact force sensor. The rigid optical fibers used for measuring the bending deformation were scratched on the surface using a cutting tool with each scratch having a length of 5mm and being approximately 5 mm

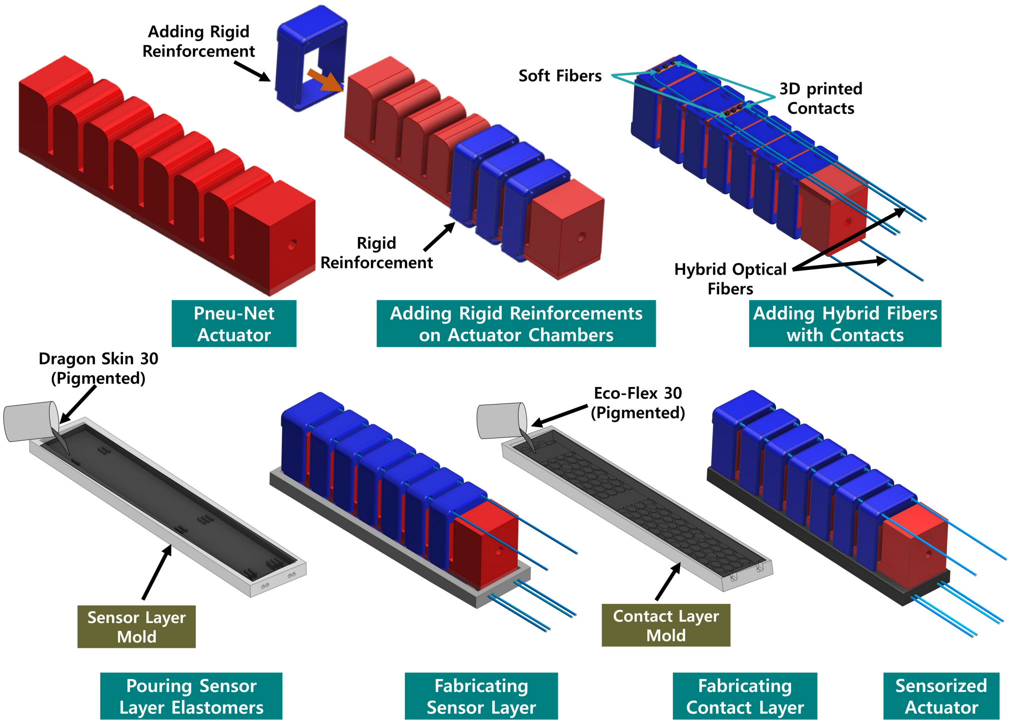

Figure 3. Complete fabrication process of the proposed actuator.

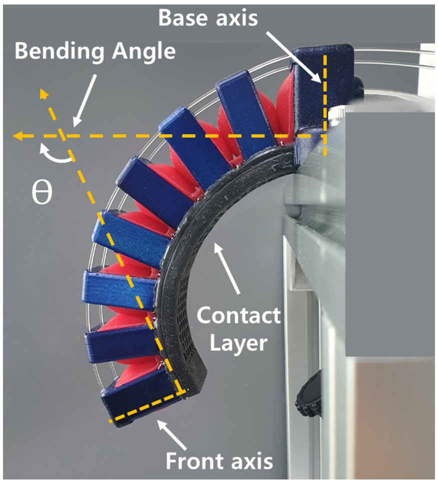

Figure 4. The prototype of the sensorized PneuNet actuator with 3D printed reinforcements and hybrid optical fibers. The figure shows the bending angle measurement method for the proposed actuator.

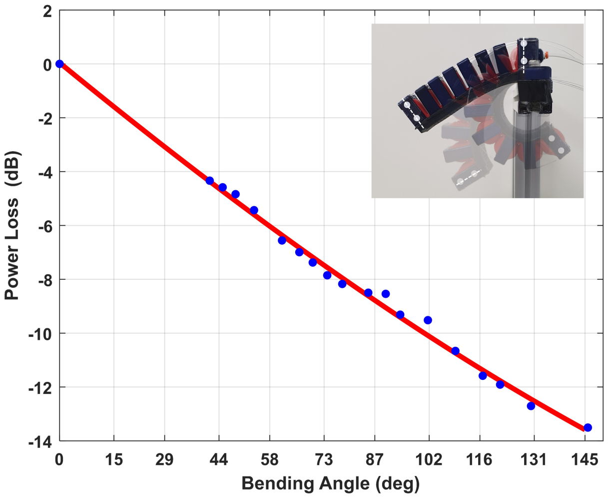

Figure 5. Power loss in the optical fiber versus the bending angle. The graph shows the power loss in dB against the bending angle in degrees.

apart before being inserted through the routing holes within the rigid reinforcements. These scratches allow the fiber to have light transmissibility losses as the fiber is bent. The ends of the rigid optical fibers are glued to the ends of the soft optical fibers using an elastomeric glue (Loctite, 401) which securely attaches them while allowing for light to travel between the fibers. The contact force sensing optical fibers were attached to the rigid reinforcements using small clips located on the reinforcements. Next, the sensor layer is fabricated by placing the PneuNet with the contact force sensing optical fibers face down into a mold in which pigmented Dragon Skin 30 is poured and cured. As the soft optical fibers are susceptible to interference by external light sources, black silicone pigments are added into the elastomer during mixing. This assembly is then inserted into another mold containing pigmented EcoFlex 00-30 (Smooth-On) to form the contact layer. The prototype of the actuator after fabrication is shown in Fig. 4.

IV. Results

A. Bending Actuation Performance

The addition of sensors into a soft pneumatic actuator generally influences their bending actuation performance in terms of bending deformation and bending force. In this case, the addition of the hybrid fibers increases the rigidity to the actuator which could

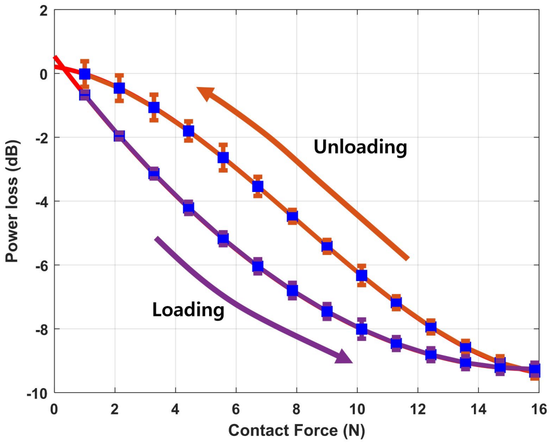

Figure 6. Power loss in the contact sensing layer versus the the contact force.

hinder the actuator during its pressurization while the addition of rigid reinforcements should increase its bending capabilities versus an actuator made entirely from polymers. Two actuators were built where one is the proposed actuator with optical fibers and rigid reinforcements and the other one, called the base actuator, does not contain optical fibers or rigid reinforcements. Both actuators were able to reach its maximum bending deformation which occurs when the tip of the actuator touches the underside of the actuator, but the proposed actuator reached this deformation at $59 \sim 62$ kPa and the base actuator reached this deformation at $54 \sim 56$ kPa.

Blocked force tests were then performed on both actuators. The proposed actuator was capable of a blocked force of 10 N with a constraint to keep it from deforming upwards, and without this constraint the actuator was capable of a blocked force exceeding 5 N using a pressure of 80 kPa in each cases. Due to overinflation, the pressure within the base actuator was limited to 40 kPa, and it was capable of an unconstrained blocked force of 1.2 N while the proposed actuator was capable of an unconstrained blocked force of 1.8 N at a similar pressure without the use of a constraint to prevent the upward deformation of the actuator. These results show that the performance of the proposed sensorized actuator is similar to comparable non-sensorized soft pneumatic actuators in terms of bending performance. This good performance is due to the design of the actuator which minimizes the effect of the optical fibers on the performance of the actuator and due to the rigid reinforcements which guide the inflation of the PneuNet and limit the inflation of the lateral walls.

B. Bending Sensing Characteristics

The first experiment consists of verifying the capability of the actuator to measure the bending angle of the actuator using the optical loss of the scratched optical fibers passing through the upper portions of the rigid reinforcements of the actuator. The actuator was attached horizontally to a rigid base setup and its bending angle, $\boldsymbol{\theta}$, was measured as shown in Fig. 4. The actuator pressure was provided by a pneumatic pump and its pressure was controlled using a pneumatic regulator (ITV-1030, SMC pneumatics). The pressure ranges are applied such that the actuator bends up to the maximum desired angle. The angles were measured using a camera and an on-screen program which measures the angle between two vectors measured using stickers applied on the actuator. The signal from the photodetector is first amplified and then filtered using a low pass filter. This filtered signal was then sampled at 10 KHz frequency and the average value over 100 samples is used for the reference bending angle of the actuator. The comparison of the measured power loss versus bending characteristics of the actuator as shown in Fig. 5 where the point at 0 bending angle is obtained by manually supporting the actuator in the horizontal position. This graph shows the bending angle characteristics curve for the actuator with a 3rd order polynomial fit of the data points acquired through experiments. The measured signal shows that, combined with the filtering of the signal from the photodetector, the power loss from the optical fiber can be used to precisely measure the bending angle of the actuator. A potential limitation of this method is that uneven deformations of the actuator that could occur due to things such as obstacles cannot be predicted, but it could be used to determine when and the bending angle at which contact is made.

C. Contact Sensing Layer Characteristics

The second experiment is to characterize the ability of the actuator to measure contact force at the contact force sensing segments of the actuator through the compression of the soft optical fibers which increase their power loss. For this experiment, the actuator is placed upside down on a flat base to support the actuator. A contact force measurement tool is then used to exert and measure a force on the contact sensing point of the actuator contact surface. This tool contains a loadcell (BONGSHIN, model cbms-5) with a 3D printed contact which is used to simulate contact. Due to the structural stability of the armors covering the chamber, the actuator does not deform under forces that are normal to its contact layer. The relationship between the contact force and the power loss of the optical fiber is shown in Fig. 6. This curve shows a nonlinear response with slight hysteresis which can either be modeled or approximated as a single curve with less accuracy. It is to be noted here that the contact force was applied normal to the rigid tip that was attached on top of the soft fiber. It was found through these experiments that, as in other force measuring instruments, the location of the application of the force significantly affects the results. An improved design for the 3D printed contacts could perhaps resolve this issue and will be addressed in future works.

To further investigate the capability of the proposed contact sensing layer we tested it during its interaction with objects having very low stiffness (see attached

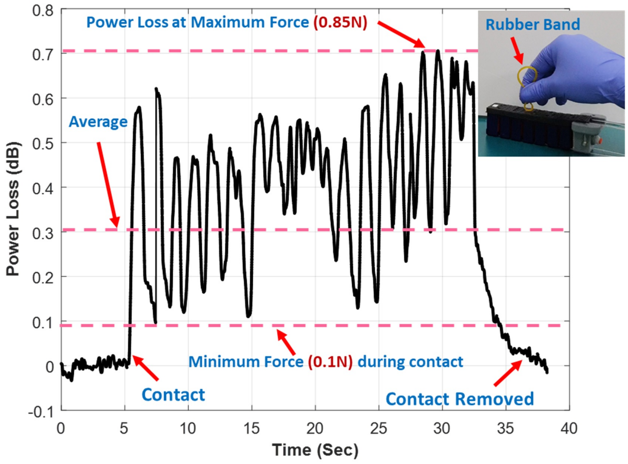

Figure 7. Response of the contact sensing layer during continued repetitive application of a small force created by the low stiffness of a rubber band.

video). One of these tests includes a rubber band which was pushed against the middle contact tip of the actuator as shown in Fig. 7. During this experiment, the rubber band was held such that the rubber forms a loop which deforms when pushed against the actuator. The force is gradually applied and repeated with different magnitudes to verify the repeatability and the sensitivity of the contact sensing layer. A minimum force of 0.1 N and a maximum force of 0.85 N were measured during this experiment, and the sensor was very responsive to changes in forces. This demonstrates the high capability of this contact sensor integrated into the proposed sensorized soft pneumatic actuator.

D. Coupling between Sensors

Pressurization of the actuator causes it to bend as the PneuNet chambers are expanded, which results in the deformation of all components of the actuator. When this occurs, the optical fibers used to measure the bending angle are deformed and their signal are consequently affected, but a slight deformation will also occur in the contact layer which will also cause optical power losses in the contact sensing optical fibers. This is due to the fibers having to compress slightly to conform to the slight compression of the sensing layer. This will be characterized and compensated by adjusting the optical losses of the contact sensing waveguides as a function of the optical losses of the bending sensing optical fibers as these can slide freely and are not affected by the contact forces. The power losses of both optical fibers were plotted during actuation without any blocked forces as shown in Fig. 8. It can be seen that the optical power losses in the contact force sensing optical fibers are significantly smaller than for the bending sensing optical fibers, but that this power loss is still significant in terms of measuring the contact force. Thus, this power loss will be compensated during the calculation of the contact force. It would be possible to come up with designs that allow the rigid fibers of the contact force sensing waveguide to slide more freely during the deformation, but this could generate additional nonlinearities between the contraction and relaxation motions.

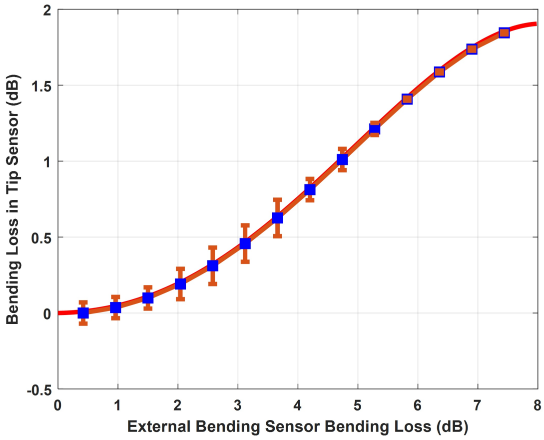

Figure 8. Coupling between the power losses of the bending sensing layer and the contact sensing layer.

V. Proprioceptive Soft Gripper

A. Stiffness Sensing

A three-fingered proprioceptive gripper is manufactured using the proposed sensorized actuators, as shown in Fig. 9(a). As with other soft pneumatic grippers, the gripper is capable of grasping a wide range of objects with different weights and its general grasping evaluation will be omitted for brevity. The gripper was tested during its interaction with objects of different stiffness to explore the possibility of the gripper being able to detect the stiffness of the object during interaction. This ability has several obvious advantages such as facilitated control, haptic interactions, shape identification, and object stiffness analysis. The gripper was tested for grasping a (double-layered) paper cup with the pressure being increased to about 75 kPa, maintained for 5 seconds and lowered back to 35 kPa (as shown in Fig. 9 (b)). A second paper cup was inserted into the already grasped cup and the pressure was increased to 75 kPa, maintained for about 3 seconds, and decreased back to 38 kPa. A third paper cup was inserted into the second one and the pressure was increased again to 75 kPa, maintained for about 5 seconds, and decreased back to 40 kPa. The signal from the tip sensor was acquired during these experiments, and the power loss relative to the initial baseline signal as shown in Fig. 9 (c). The different amount of loss level indicates the effect of the stiffness of the object under grasping and the steady signal shows the relative stability of the signal throughout this experiments. These results show that the proposed gripper could be used to predict the stiffness of the object. To evaluate gripper under extreme condition, it was tested under magnetic field. The three cups were grasped and then the grasping force was changed while changing the magnetic field around the gripper. As expected, no changes were observed under these conditions (see attached video).

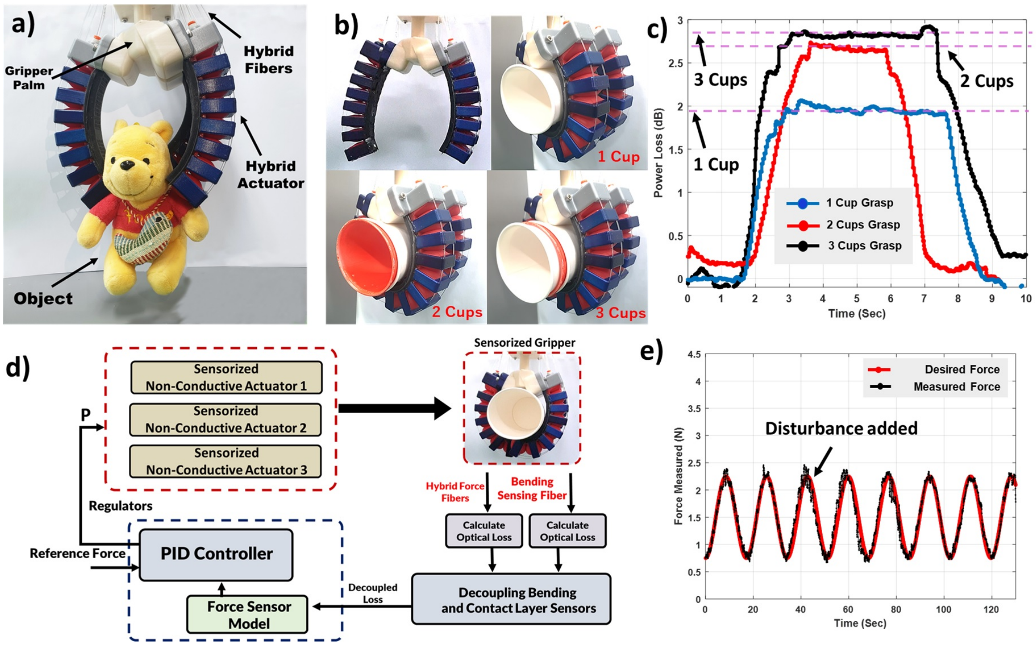

Figure 9. (a) The sensorized non-conductive gripper integrated with hybrid optical fibers, b) the proposed gripper grasping different number of paper cups (c) the corresponding power loss response. (d) Control loop for the grasping force control and (e) grasping force control when grasping three paper cups and disturbance rejection results as two paper cups are suddenly removed.

B. Control of Grasping Force

The use of sensors within a soft gripper can be used to control the behavior of the actuator. In particular, force control is of the utmost importance to interact in a desired manner with objects. Here, the grasping force control of the actuator was conducted using the signals from both the bending and contact force sensors at a sampling frequency of 1 kHz as there is a slight coupling between the two signals. These signals are then used to calculate the power loss compared to their initial baseline powers. This power loss is then passed through a decoupling routine which uses the coupling model obtained previously. This decoupled optical loss is used to calculate the force of the sensing layer, and this calculated force is then passed to a PID control routine to control the force exerted by the actuators. The overall control loop as shown in Fig. 9 (d). This was tested by having the gripper apply a force following a sinuosial input onto three paper cups, and after a few cycles suddenly remove two paper cups to change the stiffness of the objects as shown in Fig. 9 (e). These results indicate good tracking performance from the actuator and, due to the robustness of the PID control for the gripper, the ability to reject disturbances (see attached video).

VI. Conclusions

This paper introduces the design for a proprioceptive soft pneumatic gripper for extreme environments making use of separate optical fiber sensors for bending and grasping force sensing. This enables the decoupling of these sensing signals and to measure the contact force even in the deformed state. This was helped by the use of hybrid rigid and soft optical fibers which can sense the contact force at specific points and enabled the control of the contact force in the deformed state using a simple PID controller. The use of these hybrid optical fibers also allowed all electronic components to be placed outside of the gripper and for the sensorized gripper itself to be free of electric and magnetic components. Rigid reinforcements were used to position the optical fibers and to prevent out-of-plane deformations of the polymeric PneuNet which maintained the high actuation performance of the actuator which is comparable to non-sensorized soft pneumatic grippers. As such, this soft pneumatic gripper has a high potential for application in environments with extreme conditions such as high conductivity areas, electromagnetically noisy areas, MRI operations, etc.

Some hysteresis could be observed in the fibers due to the non-linear characteristics of the soft optical fiber components and some coupling between the bending angle and contact force sensors. This can cause issues when precise forces and displacements are required, but the sensing performance of the gripper as demonstrated is sufficient for most applications as it can detect touch and adjust its grasping force to a reasonable degree of accuracy. Another potential limitation is that the bending angle sensing mechanism cannot obtain the exact deformation of the structure and the estimated shape may be significantly different from the real shape during blocked deformations. The proposed proprioceptive gripper demonstrates a way to sensorize soft robotic components that does not add magnetic or conductive components within their structure and without influencing their performance, which is a useful combination of characteristics. In future work we intend to increase the distance at which electronic components are placed and, to use the proposed sensorized gripper concept for medical applications, to improve the accuracy of the sensing, and to stabilize the performance of the gripper. We also intend to use similar concepts for sensorizing entire robotic arms.

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