A Hybrid Gripper with Soft Material and Rigid Structures

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Abstract—Various robotic grippers have been developed over the past several decades for robotic manipulators. Especially, the soft grippers based on the soft pneumatic actuator (SPAs) have been studied actively, since it offers more pliable bending motion, inherent compliance, and a simple morphological structure. However, few studies have focused on simultaneously improving the fingertip force and actuation speed within the specified design parameters. In this study, we developed a hybrid gripper that incorporates both soft and rigid components to improve the fingertip force and actuation speed simultaneously based on three design principles: 1) the degree of bending is proportional to the ratio of the rigid structure; 2) a concave chamber design is preferred for large longitudinal strain; and 3) a round shape between soft and rigid materials increases the fingertip force. The suggested principles were verified using the finite element methods (FEMs). Then, the improved performance of the hybrid gripper was verified experimentally and compared with the performance of a conventional SPAs. The ability of the hybrid gripper to grasp different objects was evaluated and was applied in a teleoperated system.

Index Terms—Soft Material Robotics, Grippers and Other End-Effectors, Flexible Robots

I. INTRODUCTION

RECENTLY, the limitations of rigid gripper due to the necessity of additional linkages, complicated controls, and so on, have been overcome by the soft gripper [1]. Especially, the soft grippers based on soft pneumatic actuators (SPAs), which offer better compliance, and a higher degree of freedom than the rigid robot, have been actively developed [2]–[9]. Due to the inherent compliance of soft materials, complicated controls and additional structures are not needed with soft grippers, as the proper selection of materials of various stiffness allows for simple control. Furthermore, soft grippers with SPAs are constructed from low-cost and readily-available elastomers.

SPAs with a variety of forms and operating pressures, including granular jamming, and fiber-reinforced SPAs have been suggested; however, their practical application as a robotic gripper has been limited by a small fingertip force and slow actuation speed. A large pneumatic compressor can be used to address these issues, but the size of the whole system would be increased [2], [6]. The granular jamming gripper, for example, uses granular components, which are jammed in the soft chamber under vacuum pressure [7]. As a large vacuum pump is required for granular jamming, the pneumatic system required would inevitably be bulky. General SPAs with operating pressures in the range of 0-80 kPa have a slow actuation speed and low fingertip forces [5], [6] have difficulties with the limited actuation speed and fingertip forces. To increase the actuation speed, a fast-pneumatic network (fast-PneuNet) comprising a series of soft chambers and channels has been suggested [2]. However, the resulting fingertip force is low (< 1.5 N) [2]–[4]. Improved fingertip force actuation has been achieved with fiber or fabric reinforcement [8]–[10]. Since a large pneumatic pump with pressures of 350 kPa is needed, the entire system is inevitably bulky. Also, the actuation speed is relatively slow as large volume changes are required for the bending. Above all, few studies have attempted to enhance the actuation speed and fingertip force simultaneously.

Integrating different actuating mechanisms [11]–[13] or materials have also been tried as hybrid actuators [14], [15]. However, we are not focused on the integrating different actuating source, but incorporating the soft material and rigid structures. Rigid materials were usually used to increase the stiffness of the soft structures [14]. For example, rigid structures were used to reinforce the soft chambers, inspired by the lobster [15]. However, the degrees of freedom may be
limited depending on the rigid structures, which may reduce the compliance as the main advantages of SPAs, and may not focus on enhancing the actuation speed and fingertip force simultaneously.

Thus, in this paper, we developed a hybrid gripper that incorporates both soft material and rigid parts to overcome the drawbacks of the conventional SPAs without reducing the compliances (Fig. 1). The rigid structures are inserted into a fast PneuNet, hereafter referred to as the hybrid PneuNet, as the grippers, which have improved fingertip force, and increased actuation speed. The main contributions of this paper are as follows: 1) design methodology for a hybrid PneuNet, 2) experimental verification of the hybrid gripper, 3) a practical application as a simple and compact pneumatic system for teleoperations.

II. DESIGN PRINCIPLES FOR THE HYBRID GRIPPER

The bending motion of a SPA is controlled by differential strain effects between the inextensible layers and soft chambers, as shown in Fig. 2a. The nature of this motion is manipulated by the geometries and material properties of the chambers. The governing equations for bending motion of the SPA are as follows:

\[ L = (1 + \epsilon_{cham})L_0 \]

\[ \theta_{spa} = \frac{L}{h' + R} = \frac{(1 + \epsilon_{cham})L_0}{h' + R} \]  

where \( L_0 \) and \( L \) is the initial and longitudinally elongated length of the actuator, \( \epsilon_{cham} \) is the longitudinal strain of the chamber, \( \theta_{spa} \) is the bending angle of the SPAs, and \( h' \) is the height where maximum longitudinal strain occurs. \( R \) is the radius of the bent SPAs, which decreases during the bending motion.

According to (1), the bending angle, \( \theta_{spa} \) is proportional to the longitudinal strain of the chamber. Thus, the longitudinal strain of the chamber, which induces actuation of longitudinally elongated SPAs, should be increased for improved bending motion. The hybrid PneuNet, which has a rigid structure between soft chambers, increases the elongated length of the SPAs. Furthermore, the force transmission is improved since the damping ratio is decreased with placing the rigid structures, which increases the force transmissibility [16].

The working principle for bending motion of hybrid PneuNet were shown in Fig. 2(b). The basic concept of the bending motion is similar to the previously developed SPAs, but the existence of rigid structures should be considered. The design principles were derived from the concepts in Fig. 2(b) and the governing equation of the hybrid PneuNet is expressed as follows:

\[ L = n_{rigid}L_{rigid} + n_{cham}(L_{cham} + \Delta L_{cham}) \]

\[ \theta_h = \frac{L}{h' + R} = \frac{n_{rigid}L_{rigid} + n_{cham}(L_{cham} + \Delta L_{cham})}{h' + R} \]  

where \( n_{rigid} \) and \( n_{cham} \) are the numbers of specific rigid structure and the chamber, respectively, and \( L_{rigid} \) represents the length of the rigid structure. \( L_{cham} \) and \( \Delta L_{cham} \) represent the initial and longitudinally elongation of the chamber at the contact height between the rigid and soft materials, respectively. \( \theta_h \) is the bending angle of the hybrid PneuNet. The contact height \( h' \), was assumed to be constant during inflation. From (2), the bending motion is mainly induced by the longitudinal strain of the soft chamber and the length of the rigid structures.

The fingertip force of the hybrid PneuNet, which is exerted normal to the ground, is based on the simplified model shown in Fig. 2. Given that the soft chambers and rigid structures are positioned in an alternating sequence along the actuator length, and that the length of the strain limiting layer remains constant, the simplified linkage forms a rotating joint. The fingertip force, normal to the ground, is the sum of the bending moments of the individual linkages; the governing equation is as follows:

\[ F_{tip} = \sum_{i=1}^{n} \frac{M_i}{L_0} = \sum_{i=1}^{n} \frac{M_i}{l_i \cos \theta_i} \]
where $n$ is the number of simplified linkage with the soft chamber and rigid structure, $M_i$ is the bending moment of the $i^{th}$ linkage, and $L_0$ is the initial longitudinal length of the hybrid PneuNet. $F_i$ is the force exerted on the $i^{th}$ linkage for the bending moment. The resultant force at the tip position ($F_{\text{total}}$), which can be decomposed into the fingertip force $F_{\text{tip}}$ and the friction force at the tip position $F_f$, in equilibrium with the friction on the ground. During inflation, the length of the moment arm, expressed in terms of the angle ($\theta_i$) and length for each linkage ($l_i$) depends on the postures of the hybrid PneuNet. It was assumed that the length of the moment arm does not change. From the (3), a stronger fingertip force requires a larger total bending moment of each linkage ($M_i$).

Based on the analysis results described above, we focused on the following design principles for the enhancements of the hybrid PneuNet: 1) increasing the rigid structure length via rigid structure ratio, 2) increasing the longitudinal strain of the soft chamber by manipulating the chamber shape, and 3) applying a round edge design between the soft and rigid materials to enhance fingertip force. Finite element method (FEM) simulations based on the hyperelastic Mooney-Rivlin model [17] were carried out to verify these design factors under various linear pressure loading conditions.

### A. Rigid Structure’s Ratio

The first design principle is based on manipulating the length of the rigid structures according to (2). The improved longitudinal elongation of the hybrid PneuNet with increased length of the rigid structures leads to a large bending motion. To discuss the length of the rigid structures quantitatively, the ratio of the rigid structures, $\gamma_{\text{rigid}}$, with respect to the soft chambers is defined as follows:

$$\gamma_{\text{rigid}} = \frac{n_{\text{rigid}}L_{\text{rigid}}}{L_0} = \frac{L_0 - n_{\text{cham}}L_{\text{cham}}}{L_0} \quad (4)$$

where $\gamma_{\text{rigid}}$ is constrained from the longitudinal length of the chambers at the contact height, $L_{\text{cham}}$, which is limited by the fabrication technique. Generally, the soft chambers, fabricated with three-dimensional (3D) printed molds, have at least a 2 mm wall thickness to provide durability of the molds and soft chambers. As such, the minimum length of the soft chamber and the rigid structure were set as 6 mm and 1 mm, respectively. The size ($138 \times 23 \times 21 \text{ mm}^3$), and number of soft chambers ($n_{\text{cham}} = 9$) of the hybrid PneuNet were determined considering the conventional SPAs of the soft
By rearranging (4) and adding the ratio of the rigid structures, $\gamma_{\text{rigid}}$, the longitudinally elongated length of the actuator can be expressed as follows:

$$\theta_h = \frac{\gamma_{\text{rigid}} L_0 + n_{\text{cham}} (1 + \varepsilon_{\text{cham}}) L_{\text{cham}}}{h' + R}$$

Note that the bending angle is increased by $\gamma_{\text{rigid}}$ and $L_{\text{cham}}$ is inversely proportional to $\gamma_{\text{rigid}}$. However, the longitudinal strain is increased by $\gamma_{\text{rigid}}$ under the boundary condition, since the stiffness at top of the chamber is increased depending on the reduced $L_{\text{cham}}$. Consequently, the strain of the chamber occurs more longitudinally, not in a radial direction.

FEM simulations were conducted to verify the first design principle and the simulation was performed for a chamber with a plain shape. In Fig. 3, the bending angles of the hybrid PneuNet were compared with the simple plain shape; up to 50 kPa, $\gamma_{\text{rigid}}$ was set as 0.06, 0.31, and 0.61, respectively. The bending angle increased with $\gamma_{\text{rigid}}$ in agreement with the expectation that the hybrid PneuNet with a larger ratio should have more bending motion.

**B. Chamber Shape**

The cross-sectional shape of the chamber is another key design factor to enhance the bending angle under the same pressure. As shown in (2), manipulating the elongation of the soft chamber, which is also expressed as the longitudinal strain ($\varepsilon_{\text{cham}}$), increases the bending angle with increased $L$. The longitudinal strain of the material is proportional to the strain energy of the chamber [18]. The strain energy is affected by the energy dissipation of the chamber, specifically the chamber’s shape. In a comparison of various chamber designs, three types of shape, plain, convex, and concave, were evaluated in terms of resulting longitudinal strain. The cross-sectional shape of the chambers are illustrated in Fig. 4(a).

The tension of the soft chamber around the center, describing the elastic behavior, is depicted by the red arrows in Fig. 4(a). The resultant vector at the center of the height, $T_{\text{soft}}$ (red arrows in Fig. 4(a)) acts against chamber inflation. The applied pressure ($F_{\text{load}}$), depicted as black arrows in Fig. 4(a), exerts normal to the chamber’s inner wall. The resultant vectors of $T_{\text{soft}}$ and the $F_{\text{load}}$, depicted as blue arrows, cause accumulation difference of the strain energy of the soft chamber at the mid-height. For example, since the resultant vectors are headed to the mid-height of the chamber, the more strain energy is accumulated for the concave chamber,
comparing with the convex chamber. On the other hand, the less strain energy is accumulated with the mid-height of convex chamber, since the resultant vector left out of the mid-height. Thus, the differentiated accumulated strain energy due to the chamber shape induces the different longitudinal strain and the concave chamber would have more longitudinal strain.

For verification, the strain energies for each chamber shape at mid-height were compared, as shown in Fig. 4(b) up to 30 kPa. The concave chamber had the largest strain energy, followed by the plain and convex chambers up to 30 kPa. The concave shape also had the largest longitudinal elongation, ε_{cham}, as shown in Fig. 4(c), which means the concave-shaped chamber offered the largest bending angle under the same loading pressure.

C. Round Edge

The third design principle, i.e., the use of a round edge between soft and rigid materials of the hybrid PneuNet (Fig. 5(a)), was applied to increase the fingertip force. Assuming a chamber with a plain shape, a round-edge between the soft chambers increases the contact area and guides the longitudinal elongation between the chambers and rigid parts with enhanced force transmission (Fig. 5(a)). In a simplified model, in which the interaction between soft and rigid structures is considered as a simple linkage (Fig. 2(c)), the bending moment can be expressed as follows:

\[ M_i = l_i \sin \theta_i F_{i,x} + l_i \cos \theta_i F_{i,y} \]

\[ = l_i \sin \theta_i \int \sigma_{i,x} \, dA_{yz} + l_i \cos \theta_i \int \sigma_{i,y} \, dA_{xz} \quad (6) \]

where \( \sigma_i \) and \( dA \) are the stress, and contact area between the soft and rigid structure, respectively. \( \sigma_{i,x} \) and \( \sigma_{i,y} \) represent the decomposed stresses from \( \sigma_i \) in \( x \) and \( y \) directions. \( F_{i,x} \) and \( F_{i,y} \) are decomposed into \( x \) and \( y \) directional forces as shown in Fig. 2(c). \( dA \) is also decomposed into the contact area projected onto the \( yz \) and \( xz \) planes. The decoupled force components can be expressed as the integral forms of the decoupled stresses and contact areas. Thus, the fingertip force can be manipulated by varying the bending moment between soft and rigid materials.

The proposed round edge design is shown in Fig. 5(a)-(c). Assuming that the entire system volume remains the same and that the rigid structure does not protrude from the soft chambers, the bending moment of each linkage increases with the round edge configuration. The additional bending moment exerted by the round edges between the soft chambers and rigid structures is given by the following:

\[ M_{i,\text{top}} = \int \sigma_{i,y,e} \, dA_{xz} \]

\[ F_{\text{tip},RE} = \sum_{i=1}^{n} \frac{M_i,RE}{l_i \cos \theta_i} = \sum_{i=1}^{n} \frac{M_i + M_{i,\text{top}}}{l_i \cos \theta_i} \quad (7) \]

where \( M_{i,\text{top}} \) is the additional bending moment of each linkage with the round edge design. \( F_{\text{tip},RE} \) and \( M_i,RE \) represent the fingertip force and \( i^{th} \) bending moment for each linkage of the hybrid PneuNet with round edge design. \( \sigma_{i,y,e} \) and \( \sigma_{i,x,e} \) decomposed from \( \sigma_i \) in \( y \) and \( z \) direction, represent the additional stresses, exerted at round edges (Fig. 5(b) and (c)). From (7), \( \sigma_{i,y,e} \) creates an additional bending moment \( M_{i,\text{top}} \), which increases the fingertip force with the round edge \( F_{\text{tip},RE} \). Given that the \( z \) directional stress at the edge, \( \sigma_{i,z,e} \), is applied symmetrically in Fig. 5(c), it does not affect the additional bending moment term but instead guides the longitudinal expansion of each chamber. To verify the suggested theoretical principle, the fingertip force of the hybrid PneuNet was simulated up to 40 kPa, with and without the round edges (Fig. 5(d)). The fingertip force was enhanced by the round edge design, and its gap was increased as the applied pressure was increased.

III. EXPERIMENT VERIFICATION

A. Fabrication of the Hybrid PneuNet

The three design principles based on the simulation results were combined simultaneously for the hybrid PneuNet with the maximized ratio of the rigid structures \( \gamma_{\text{rigid}} = 0.61 \), the concave chamber shape with the maximum radius, and round edge design.

The detailed configuration of the hybrid PneuNet is illustrated in Fig. 6. Dragonskin 30A (Dragonskin 30A, Smooth-On [19]) was used as the soft material, manufactured by 3D printed molds. To accommodate the required concave chamber shape, 3D printed molds were divided into several parts. The rigid structures (ABS-P430, Stratasys [20]), manufactured via 3D printer, were inserted into punched holes and sealed with the silicone. Readily available plastic film was used as an inextensible layer. The top and bottom layer shown in Fig. 6, were combined monolithically with a commercial silicone adhesive. The teflon tube was inserted to supply air to the chambers. For the increased grasping ability, a nail was fabricated with Dragonskin 10A and attached to the tip of the hybrid PneuNet; a bumpy shape was added to the bottom layer to enhance friction. Finally, the fabricated hybrid PneuNet was assembled into the hybrid gripper as shown in Fig. 1.
Fig. 7: Actuation speed comparison experiment: (a) fast PneuNet ($137 \times 25 \times 20 \text{mm}^3$) [2], (b) fiber-reinforced SPAs ($136 \times 26 \times 20 \text{mm}^3$) [8], (c) measurement of the volume change during the bending motion, (d) comparison for the normalized volume change.

B. Actuation Speed Comparison

Experiments were performed to evaluate the actuation speed and fingertip force of the single hybrid PneuNet. The proposed hybrid PneuNet demonstrated enhanced bending speed. As the actuation speed is affected by the specification of the fluidic pumps, the volume change was measured for the actuation speed comparison at 180 deg of bending. The conventional SPAs including the fast PneuNet (Fig. 7(a)) and fiber-reinforced SPA (Fig. 7(b)) were compared with the developed hybrid PneuNet [2], [8]. To avoid inaccurate measurements due to compressible air, incompressible water was used to inflate the chambers, as illustrated in Fig. 7(c).

Fig. 7(c) shows the volume change measurements, performed manually 10 times in water. The mean values of the fast PneuNet, fiber-reinforced SPA, and hybrid PneuNet were 9.0, 4.0, and 2.2 mL, respectively. The measured volume change after bending motion was normalized with respect to the initial volume. The initial volumes were calculated based on the mold parameters: 23.6, 8.5, and 8.3 mL for fast PneuNet, fiber-reinforced SPA, and hybrid PneuNet, respectively; the normalized volume change of each actuator, which are calculated as $\frac{V_f}{V_0}$, were 0.382, 0.471, and 0.275, respectively. The developed hybrid PneuNet had the smallest normalized volume change, followed by the fast PneuNet and fiber-reinforced SPA. Thus, the actuation speed of the hybrid PneuNet improved 1.3 times compared with the fast PneuNet, irrespective of the capabilities of the attached electrical pump.

C. Fingertip Force Comparison

The fingertip force of the hybrid PneuNet was compared to that of the fast-PneuNet and fiber-reinforced SPA. The SPAs, including the hybrid PneuNet, were attached to a mounting platform. The fingertip normal force was measured using a force/torque (F/T) sensor (ATI Gamma; ATI [21]), as depicted in Fig. 8(a). Given that the general operating pressure range of SPAs is about 0-80 kPa, the three SPAs were compared up to 80 kPa. A commercial dispenser (Performus III; Nordson EFD [22]) was used to inflate the pneumatic chambers.

The hybrid PneuNet exerted about 1.5-2 times greater fingertip force compared with the other SPAs, as shown in Fig. 8b. At 80 kPa, the measured fingertip force of the fast PneuNet, fiber-reinforced SPA, and hybrid PneuNet were 1.28 N, 0.68 N, and 2.56 N, respectively. Thus, the hybrid PneuNet showed the better performance in exerting the fingertip force due to the interaction between the soft and rigid structures with increased force transmission rate.

D. Lifting force measurement

The maximum lifting force was also measured for the developed hybrid gripper with the hybrid PneuNets. The lifting force of the gripper indicates the maximum lifting weight for grasping objects. The experimental setup for lifting force measurements is shown in Fig. 9(a). A spherical dummy object was grasped by the hybrid gripper, and the gripper was moved upward manually at a slow speed (about 10 mm/s) until it failed to grasp under different pressure (20, 40, 60, and 80 kPa). The lifting force and displacement of the hybrid gripper were measured with the F/T sensor and a motion capture system (Prime 17, Optitrack [23]).
Fig. 9: Lifting force measurement: (a) Experimental setup for measuring the displacement and the lifting force with the motion capture system and F/T sensor, (b) lifting force of the developed hybrid gripper depending on the different operating pressure.

Fig. 9(b) shows the lifting weight as a function of operating pressure. The displacement when the gripper released the object increased in proportion to the applied pressure. Due to the increased friction between the surface of the gripper and the object, the displacement of the gripper showed the perturbation (Fig. 9(b)). The maximum lifting force was about 28.7 N, which showed an enhanced lifting force under similar pressure loadings [3], [10].

IV. APPLICATION

A. Grasping objects test

We evaluated the ability of the hybrid gripper to grasp various objects. The various weight and size of objects were grasped (Fig. 10) below 80 kPa pressure. Compared with previously developed grippers, the hybrid gripper grasped heavy objects such as a heat gun and the duct tape with increased bending speed; notably, the operating pressure conditions were similar to those used in previous studies [3], [24]. The hybrid gripper was able to grasp different objects with the increased fingertip force without the need for complicated control algorithms. It was verified that different objects with large weights were grasped with simple inflation of the hybrid grippers, compared with the mechanisms used in conventional SPA grippers [3], [7], [24].

B. Application for the teleoperation system

We tested the developed hybrid gripper with a teleoperation system; these systems require light and compact components for mobility. The hybrid gripper uses a small pneumatic component with low pressure and flow rate to exert a large lifting force. Thus, the hybrid gripper offers high actuation speeds without the need for a bulky pump motor or complex any complicated control algorithms for actuation. The pneumatic system for the hybrid gripper (Fig. 11(a)) consisted of two pneumatic pumps (DAP-370A) connected in parallel to enhance the flow rate, as well as a pressure sensor and solenoid valves to inflate the hybrid gripper.

As shown in Fig. 11(b)-(d), several objects were grasped with the teleoperated hybrid gripper and moved into the basket. The teleoperation system, which uses a robot arm with seven degrees of freedom, was operated by the motion of the operator. The motion was measured with a wearable sensor system and finger motion measurement system [25]. An institutional review board (IRB) approved for human operation (UNISTIRB-17-28-A approved). The baskets containing objects, which weighed in 1.25 kg, were carried by the gripper. A detailed demonstration is shown in a supplementary video.

V. CONCLUSION

The hybrid gripper, which was assembled with the hybrid PneuNet, was developed to achieve enhanced fingertip force and fast actuation speed based on three design principles: 1) the degree of bending is proportional to the ratio of the rigid structure, 2) a concave chamber design is preferred for large longitudinal strain, and 3) a round edge shape between soft and rigid materials increases the fingertip force of the hybrid PneuNet. FEM simulations were conducted to verify these design principles independently. Based on our simulation results, we constructed a hybrid gripper with the design...
principles via the 3D printed molds. With the hybrid design, the fingertip force increased 1.5-2 times and the actuation speed increased 1.3 times compared with those of conventional SPAs. The developed hybrid gripper design included a compact pneumatic system with the solenoid valves and the pressure sensor. As it has low operating pressures (<100 kPa), a large compressor with high flow rate was not needed to achieve a large grasping force or fast actuation, making it applicable to teleoperated systems without any complicated control algorithms.

REFERENCES


Fig. 11: Application of the hybrid gripper for teleoperation system: (a) compact pneumatic system, grasping (b) the tape (200 g), (c) the bowl (300 g), (d) the box (150 g), (e) the baskets containing all objects (1.3 kg)