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研究課題名（和文）3D printed elastomer gripper with integrated multifunctional wireless sensors

研究課題名（英文）3D printed elastomer gripper with integrated multifunctional wireless sensors

研究代表者
Ｚｈｕ　Ｍｉｎｇｚｈｕ（Zhu, Mingzhu）

立命館大学・立命館グローバル・イノベーション研究機構・研究員

研究者番号：５０８０６１８０

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研究成果の概要（和文）：第一に、統合されたひずみセンサを備えたエラストマー流体アクチュエータに基づいてソフトフィンガが設計され、指の本体はドラゴンスキンで作られ、ひずみセンサはカーボンナノチューブ複合材料で作られた。柔らかい指の剛性が低いと把持が不安定になったり失敗したりする可能性があるため、低速3Dプリント技術を使用して柔らかい指を直接プリントアウトしました。提案されたフィンガーは空気圧式アクチュエータと一体型ジャミングユニットを備えており、ロボットアームが高加速度で動いているときには、グリッパーの堅牢性を保証することができます。

研究成果の学術的意義や社会的意義
Development of controllable soft robotic gripper is important to achieving the real-life requirement of manipulating fragile and delicate objects with high accuracy. This research contains the design and fabrication of soft gripper that can be used in industrial pick-and-place tasks.

研究成果の概要（英文）：First, soft fingers were designed based on elastomer fluid actuators with integrated strain sensors. Finger body was made of Dragon skin and the strain sensors were made of carbon nanotubes composite. Finger deformation was controlled by regulation chamber pressure, and finger shape can be calculated through sensor's resistance change. Then multi-material 3D printing technique was used to directly print out the soft-bodied finger. Low stiffness of soft fingers can lead to unstable or even failed grasping, soft robotic gripper with variable stiffness was developed in response to this limitation. The proposed finger includes a pneumatic actuator and an integrated layer jamming unit. Grasping robustness of the proposed gripper can be guaranteed when the robotic arm is moving at high acceleration. Pressure sensors were integrated into the jamming layers to monitor the stiffness change of the finger.

研究分野：Robotics

キーワード：Soft gripper　3D printing

１．研究開始当初の背景

Soft robotics made of soft material with high degrees of freedom have attracted a lot of attention in recent years. The development of soft robotics has provided opportunities for adding soft grippers as part of hard bodied industrial robotic arms. Current soft finger based grippers can only perform simple tasks in open loop control without suitable sensors. Sensation plays a vital role in ensuring robots can achieve accurate motion as well as being able to adapt to changing environments. However, traditional rigid sensors are not able to fulfil the requirements of measuring the large deformation in soft gripper. In addition, rigid sensors might interfere the actuation or even break the soft material. Soft and compliant sensors are necessary to overcome the limitations of traditional sensors. Sensors made of conductive particles filled polymers (CPFP) have attracted a lot of attention due to good conductive performance with minimal effect on the intrinsic properties of the polymers. These sensors can achieve remarkable electrical, mechanical and sensing properties. Several techniques are employed to create the desired sensing geometry, such as lithographic, micro-channel modelling and coating. Assembling errors are unavoidable when integrate the sensor into soft body. With the increasing number of sensors, physical cable connections and mountings can lead to increase of the entire system size and cross talking. New fabrication method is required for developing soft robots with integrated multifunctional wireless sensors.

２．研究の目的

To develop a soft gripper for used in the industry, in addition to addressing hygiene issues the following requirements need to be met. Firstly, the gripper requires the ability to handle objects without damaging surfaces or tissue. Secondly, the gripper has to be flexible, light and low maintenance. Last but not least, the gripper must have the ability to ensure grasping robustness during high acceleration where a high reaction force may occur, leading to an unstable or even failed grasp. Considering the underlying soft material and compliant structure, a soft gripper with variable stiffness is needed to resist large reaction forces and ensure the stability of grasping. The purposes of this proposal are: (1) to develop light and small soft gripper with high accuracy by 3D printed elastomer, achieving an easy and effective actuator design and fabrication method; (2) to sense the gripper’ s shape and tip force for accurate manipulation through integrated sensors, which are highly sensitive to strain/pressure changes. As a result, the proposed research can achieve actuate manipulation of the fragile and delicate objects with real-time tracking and controlling of the soft finger’ s shape and tip force.

３．研究の方法

First, soft fingers were designed based on elastomer fluid actuators with integrated strain sensors. Finger body was made of Dragon skin and the strain sensors were made of carbon nanotubes composite. Finger deformation was controlled by regulation chamber pressure, and finger shape can be calculated through sensor's resistance change. MWNTs (Shenzhen Nanotech Port Co. Ltd., China. Length: >5 m, outer diameter: 7-15 nm, and purity: >97%) was used as a conductive phase in the structure obtained from the supplier without any further processing. Room temperature vulcanization silicone rubber (Dragon Skin 10, Smooth On, USA) was used as an insulating phase. 0.03wt% CNTs was added to isopropyl alcohol (IPA) and mechanically stirred at 120 rpm for half an hour to release agglomerated CNTs into IPA. The mixture was then sonicated for 3 hours in order to disperse CNTs well in the IPA. Fig. 1 shows the fabrication process of the sensor: (a) acrylic mould of the strain sensor; (b) the CNTs-IPA solution was bladed into the patterned acrylic mould to form a uniform thin CNTs film after the IPA was evaporated; (c) a layer of Dragon Skin of 1 mm was poured on the top of CNTs film and degassed for 4 hours until the Dragon Skin

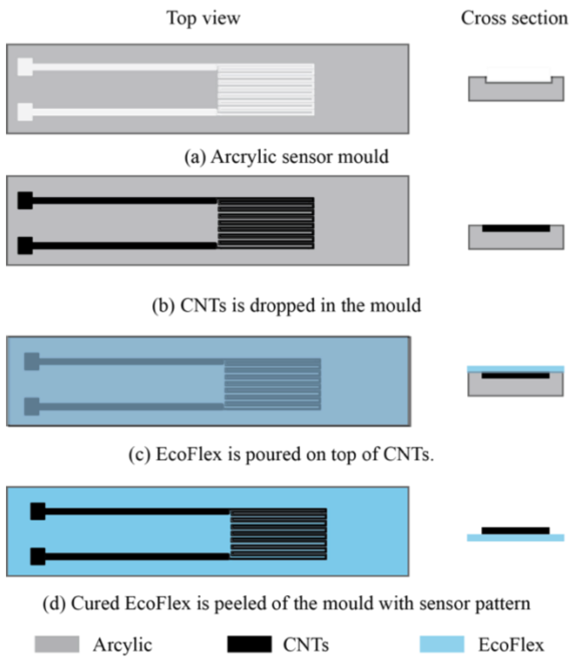

Fig. 1 Sensor fabrication process.

was fully cured; (d) the nanocomposite was successfully transferred to the Dragon Skin film surface by peeling off the Dragon Skin layer from the mould due to the strong interfacial adhesion between CNTs and Dragon Skin. Copper wires were attached to the ends of the connection wires by silver paste. Finally, the sensor was completed by pouring anther 1 mm same silicone onto the top of the nanocomposite film.

Fig. 2 (a) shows the illustration of the soft finger with integrated curvature sensor. There are 12 inflation chambers in total. The curvature sensor is located in the middle of the whole finger to detect the finger shape according to the average curvature. Image of the the strain sensor is shown in Fig. 2 (b). The geometry difference between the strain sensitive area and the connection wires can differentiate the resistance response to the strain. The soft finger is finished when both the finger body and the strain sensor are glued together by liquid Dragon Skin, as shown in Fig. 2 (c).

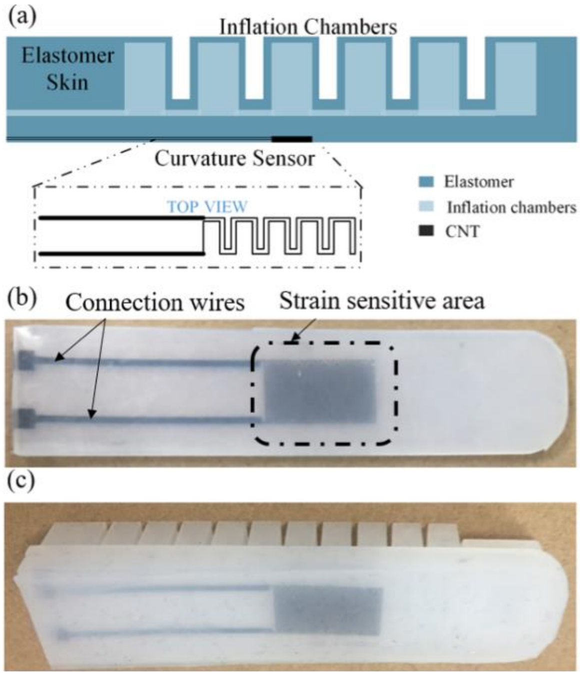

Fig. 2 Illustration of soft finger with integrated sensor.

Afterwards multi-material 3D printing technique was used to fabricate the soft-bodied finger to achieve similar actuator performance, small individual differences within an easy and fast fabrication process. Multi-material 3D printing was directly used to 3D printing the soft actuators with high complexity and functionality in a fast and easy fabrication process. It was found out that low stiffness of soft fingers can lead to unstable or even failed grasping. In order to response to this limitation, soft robotic gripper with variable stiffness was developed. Design of the soft finger is shown in Fig. 3. The main body of the soft finger has nine inflation chambers connected with the main air way (Fig. 3 (a)). The inflation chambers have a semi-circular shape with a radius of 10 mm, and the bottom strain limiting layer has a height of 7 mm. The chamber configuration allows the finger to bend in one direction only. Thus, the finger has 1 DoF, which can be described by the bending angle. The jamming chamber is located below the strain limiting layer with a wall thickness of 0.5 mm. Fig. 3 (b) shows the design of the pneumatic tubes and jamming layers. The outer sizes of the air inlet and outlet are 8 mm and 6 mm, respectively. They can easily be connected with pneumatic systems for pressurizing and

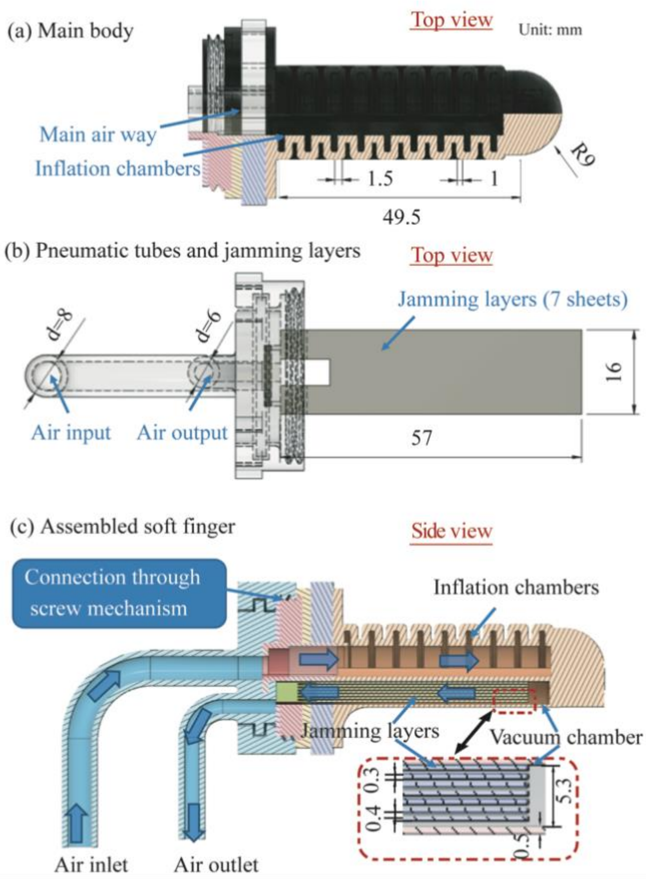

Fig. 3 Detailed design of the soft finger.

vacuuming. There are seven jamming sheets in total; each has a thickness of 0.3 mm with an interval gap of 0.4 mm. The dimensions of the jamming layers are based on empirical values. Optimization of the jamming unit design should be carried out in terms of dimensions, materials and surface profile, and this will be addressed in our future work. Fig. 3 (c) shows the section view of the assembled soft finger with two parts connected through the screw mechanism. The two air-ways are separated from each other to ensure the inflation of the chamber and vacuuming of the jamming layers are actuated independently.

Prototypes of the soft finger, with material hardness transfer from the soft-bodied actuator to the hard pneumatic tubing and layer jamming unit, are fully fabricated by one-step 3D printing. A multi-material 3D printer, Objet350Connex, is used to directly print out the whole finger without the need for an additional casting process. The printed soft finger has a complex inner geometry which integrates a small, light and flexible layer jamming unit. The fabrication process of the proposed soft finger by multi-material 3D printing requires four steps: (a) Soft finger design in CAD software. Components are saved as two parts for printing: (1) pneumatic tubes and jamming layers, and (2) soft finger and vacuum chamber. (b) Material selection and parts orientation adjustment in the printing environment. The material hardness distribution and printing orientation ensure actuator' strength and accuracy. (c) Supporting material is removed to form inflation chambers, vacuum chamber, jamming layers and air-ways.

The proposed finger can freely deform at low stiffness and maintain its grasping robustness at high stiffness during high acceleration. To demonstrate the effectiveness of the proposed design, the gripper is mounted on a robotic arm to evaluate its grasping robustness. Fig. 4 shows successful grasping with the layer jamming effect under high speed motion. In Fig. 4 (a) to (d), the robotic arm is moving with a maximum speed of 0.75 m/s and an acceleration of 2 m/s^2. The soft gripper was able to grasp the object and move it to the referenced position. The grasped object was held for 5 s after the movement stopped. All five grasps were successful in this set of experiments, a success rate of 100%. In Fig. 4 (e) to (h), the robotic arm is moving with a maximum speed of 1.5 m/s and an acceleration of 8 m/s^2, with 40 % successful grasping achieved. Typical speed and acceleration requirements for an arm robot are 2 m/s and 10m/s^2. In this study, the actual maximum speed and acceleration were 1.5 m/s and 8 m/s^2, similar to the typical values. With the integrated layer jamming unit, the ability of the soft gripper to resist a reaction force improved up to 4 times. Higher speed and acceleration can be achieved by a soft gripper with three or more fingers.

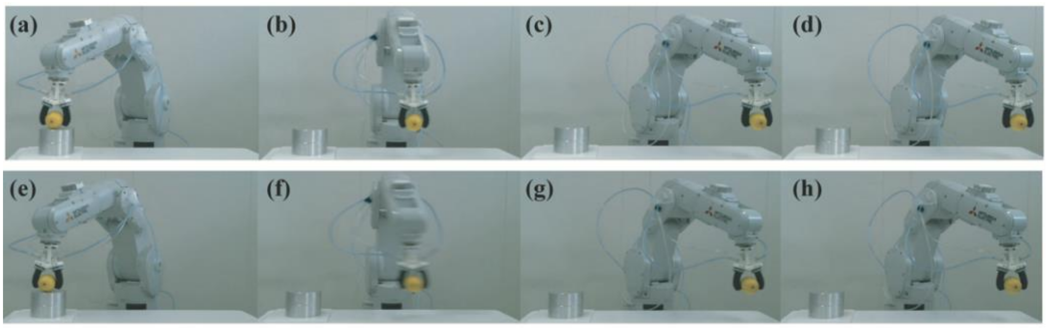

Fig.4 Gripper grasping robustness test with layer jamming effect.

４．研究成果

Development of controllable soft robotic gripper is important to achieving the real-life requirement of manipulating fragile and delicate objects with high accuracy. This research contains the exploration of design and fabrication of soft gripper which has the potential ability to be used in industrial pick-and-place tasks. Several soft grippers with different features were developed: soft fingers with nanocomposite-based sensors, soft fingers with layer jamming based stiffness variation unit. Multi-material 3D printing was used to directly print out variable stiffness soft finger to achieve a flexible, simple and fast design and fabrication process. This study also provides the general knowledge about using multi-material 3D printing for directly fabrication soft robotics with its hard accessories.

５．主な発表論文等

〔雑誌論文〕（計３件）

1. Mingzhu Zhu, Yoshiki Mori, Tatsuhiro Wakayama, Akira Wada, and Sadao Kawamura, A Fully Multi-Material Three-Dimensional Printed Soft Gripper with Variable Stiffness for Robust Grasping. Soft Robotics. 2019. doi: 10.1089/soro.2018.0112. [Epub ahead of print]
2. Mengying Xie, Kyohei Hisano, Mingzhu Zhu, Takuya Toyoshi, Min Pan, Shima Okada, Osamu Tsutsumi, Sadao Kawamura, and Chris Bowen, 2019. doi: 10.1002/admt.201800626. Flexible Multifunctional Sensors for Wearable and Robotic Applications. Advanced Materials Technologies, p.1800626.
3. Zhongkui Wang, Mingzhu Zhu, Sadao Kawamura, and Shinichi Hirai, 2017. doi:10.1186/s40638-017-0067-1. Comparison of different soft grippers for lunch box packaging. Robotics and biomimetics, 4(1), p.10.

〔学会発表〕(計４件)

1. Mingzhu Zhu, Yoshiki Mori, Mengying Xie, Akira Wada, and Sadao Kawamura, "A 3D printed Two DoF Soft Robotic Finger With Variable Stiffness." 12th France - Japan Congress, 10th Europe -Asia Congress on Mecatronics, 2018.
2. Mingzhu Zhu, "Multi-material 3D Printing for Soft Robotic Hand." Invited Workshop of Soft Robotic Actuators and Sensors, Mechatronics and Machine Vision in Practice (M2VIP), 25th International Conference. IEEE, 2018.
3. Mingzhu Zhu, Zhongkui Wang, Shinichi Hirai, and Sadao Kawamura,"Design and Fabrication of a Soft-bodied Gripper with Integrated Curvature Sensors." Mechatronics and Machine Vision in Practice (M2VIP), 2017 24th International Conference, IEEE, 2017.
4. Mingzhu Zhu, Mengying Xie, and Sadao Kawamura, "Design and Characterization of a Strain Sensor Array Based on Nanocomposite for a Soft Bodied Gripper." IEEE International Conference on Advanced Intelligent Mechatronics (AIM), IEEE, 2017.

〔図書〕(計１件)

1. Mengying Xie, Chris Bowen, Tom Pickford, Chaoying Wan, Mingzhu Zhu, et al. Springer Nature, " Achievements and perspectives of thermoelectric and hybrid energy harvesters for wearable electronics applications." 2019.pp:1-37.