WCMNM
2021

Metal Bellows Structure for Micro Device Sensing

Bilal Ahmed Mir[1], Tohru Sasaki[1], Atsushi Murakami[1], Akane Muranaka[1], Mami Iwasaki[1],
Noriyasu Oguma[1], Shinichiro Sugawara[1], Kenji Terabayashi[1] and Kuniaki Dohda[2]

[1] *University of Toyama*
[2] *Northwestern University*

Abstract

Micro force sensors are of utmost importance for a variety of the latest-of biomedical devices that require micro-manipulative operations with high precision and accuracy. Unfortunately, the measurement of accuracy of miniaturized sensors decreases as they become smaller. Traditional sensing systems, such as piezoelectric sensors, are also not adequate for numerous sensing applications because they also show decrease in detection output when scaled down. However, a micro force sensor using a hydraulic drive mechanism can obtain a large output even when the size is remarkably reduced. By observing the pressure change in the water feeder, the external force applied to the end effector can be measured. The system uses the Pascal principle to measure small forces acting on the end-effector. Conventional systems use a nitrile rubber bellows for the end-effector, but this system measures small forces acting on the end-effector. Since rubber bellows possess low rigidity, it deformed significantly. However, the rubber bellows deformed not only in the axial direction but also in other directions. Therefore, the rubber bellows did not deform linearly, and the device could not be controlled accurately. To overcome this challenge, we developed a new microdevice in which the metal bellows are made of very thin metal using electroforming technique. The preliminary results show that the metal based bellows are low in stiffness and linearly expand and contract, which allows the bellows to expand at small forces and provides high sensitivity to pressure changes. In this report, we report on the development of a new micro-device made of metal bellows structure and the results of the evaluation of its measurement accuracy and durability.

Keywords: Hydraulically driven, forceps, micro sensor

1. Introduction

Accurate and careful procedures generally require support from microrobotic systems. For example, many microsurgical and minimally invasive operations, such as surgical operations, have been made possible by the use of robots [1-5]. Manipulators used for such careful work are required to have high kinaesthetic sensitivity [6], but they do not always have a sensing function. Unfortunately, the measurement accuracy of miniaturized sensors decreases with decreasing size. In addition, the proportional output of common force sensors, such as piezoelectric sensors, also tend to decrease with miniaturization. To solve this problem, a microsensor with a hydraulic drive mechanism was developed [7, 8]. In future, a microrobot will be able to perform palpation. As shown in Figure 2, mechanical properties such as hardness and viscosity change due to pathological changes in the organism [9]. The developed system uses Pascal's principle to measure the small forces acting on the end-effector. The force acting on the end-effector is calculated by determining the change in the internal pressure of the end-effector [10,11]. Conventionally, nitrile rubber bellows are commonly used as the end-effector or micro forcep. The rubber bellows are generally less rigid and therefore they get deformed easily. Deformation in the rubber bellows takes place not only in the axial direction, but also in other directions. Therefore, the rubber bellows do not deform in a straight line and the control of the device cannot be assumed as accurate. To overcome this challenging issue, we developed a new microdevice in which the metal bellows are made of very thin metal using electroforming method. The metal bellows are less rigid and can expand and contract in a linear fashion, which allows the bellows to expand with small forces and is highly sensitive to pressure changes.

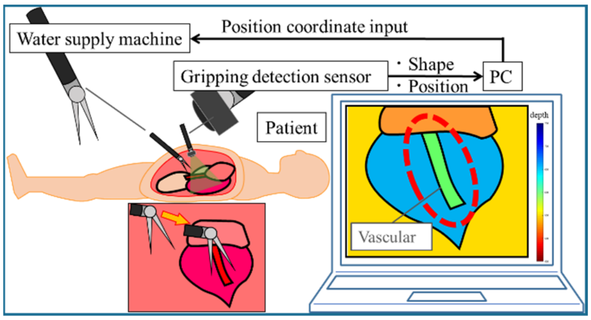

Fig. 1. Concept of micro surgery system.

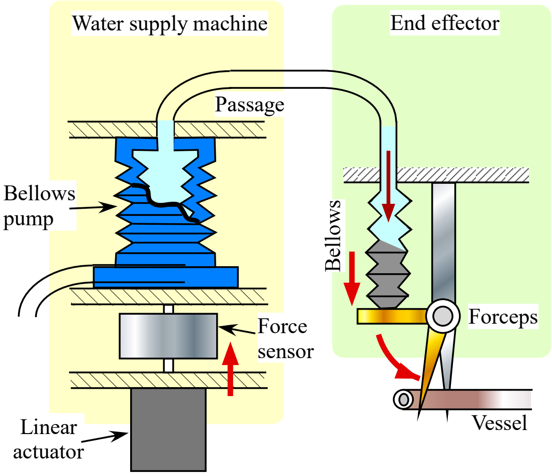

Fig. 2. Model of the hydraulic-driven mechanism.

2. Mechanism of force measurement

Figure 2 is a model of a hydraulic drive mechanism located inside a water supply machine, featuring a sensor, an end-effector. The end-effector is a micro forcep using a bellows tube structure. The bellows pump of the water supply machine moves when water is supplied to the bellows tube of the end-effector. When an external force acts on the tip of the end-effector, the pressure inside the bellows pump of the water feeder changes. This change in pressure can be clearly observed and the external force can be measured. The external force is amplified by Pascal's Theorem, i.e., the ratio of the cross-sectional area of the end-effector tip (bellows tube) to the cross-sectional area of the bellows pump of the water feeder. A stepper motor with a built-in ground ball screw is used as linear actuator. The linear actuator moves precisely by controlling the pulse.

The manufacturing process of the bellows pump structure of the water feeder is shown in Figure 3, which is made of steel (SUS316L). Thin metal sheets were welded together to form a low-rigidity bellows structure. Compared to other processing methods, the welding method can be fabricated mechanisms with higher material elongation rates. The finished bellows possess low stiffness and excellent pressure resistance capability. The outer diameter of the bellows is 18 mm and the valley diameter is 8 mm. The spring constant of the bellows is 16 N/mm. The range of motion is ±5 mm. The resolution of the water supply is 0.17 μl delivered by a metal bellows pump.

The control of the hydraulic drive mechanism is shown in Figure 4. As can be seen in Figure 4,the linear actuator moved the bellows pump structure of the water feeder according to the position command issued by the computer, and the bellows pump supplied water to the bellows pipe of the end-effector.

3. Improvement of end effector

3.1. Micro cylinder

In order to reduce the size of the micro cylinder, a micro cylinder structure was firstly developed as an end-effector. A prototype of the micro cylinder is shown in Figure 5. A prototype micro cylinder with an inner diameter of 1.6 mm was made. The surface roughness of the rods of all the cylinders was manufactured with Ra 1.6. but the inside of the cylinder was not machined. The clearance between the cylinder and the pistons was small.

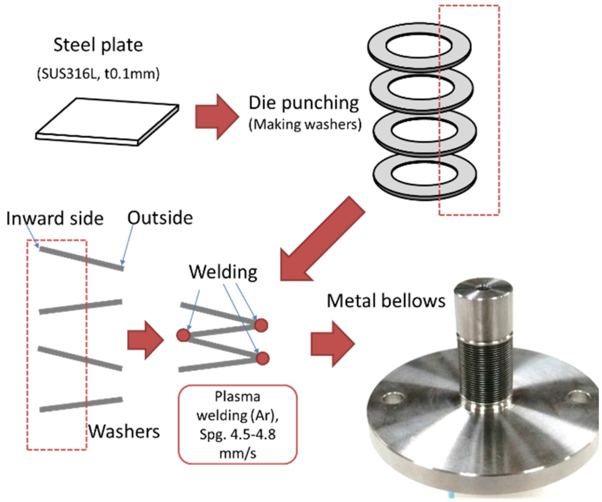

Fig. 3. Production of the metal bellows.

3.2. Nitrile rubber bellows

The forceps, which are end-effectors with a hydraulic drive mechanism, are made from micro bearings and bellows tubes. One side of the forceps rotates with the expansion and contraction of the bellows tube to hold an object. Conventional forceps used a bellows made of nitrile rubber (Figure 6). Due to its low rigidity, the amount of deformation is larger. However, the bellows deforms in other directions as well as in the axial direction. The bellows did not deform in a straight line and the control of the forceps was not accurate.

3.3. Metal bellows structure

A new metal bellows structure was used for the forceps model. The metal bellows is shown in Figure 7. The metal bellows is made of nickel using electroforming process. The manufacturing process of the metal bellows is shown in Figure 8. The mandrel (aluminum) is formed by CNC machining. A thin layer of metal was built on the mandrel and the mandrel was chemically removed after electroforming. Compared to

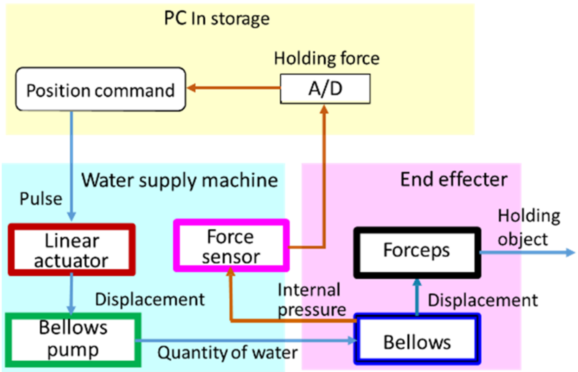

Fig. 4. Control system of the mechanism.

Fig. 5. Prototypes of micro cylinder.

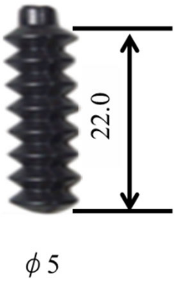

Fig. 6. A nitrile rubber bellows

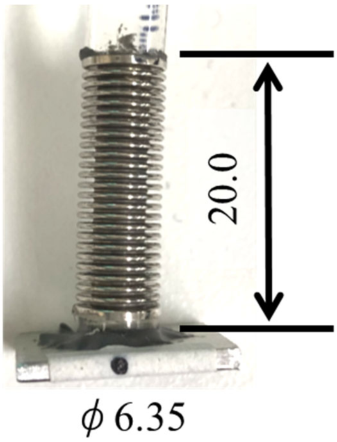

Fig. 7. Metal bellows structure.

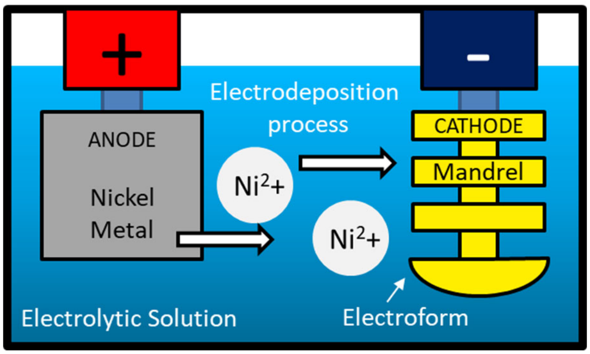

Fig. 8. Production of the metal bellows
(Servometer MW Industries, Inc.).

other processing methods, electroforming is very robust but lightweight. Electroforming is particularly effective when extreme tolerances and complex geometries are required. This process can produce thin sheet bellows, and the manufactured bellows retain their non-axial stiffness, reducing their axial stiffness. The outer diameter of the metal bellows is 6.35 mm and the inner diameter is 3.81 mm. The spring constant of the bellows is 4.14 N/mm and the range of motion is 0.81 mm. The improvement process of the end-effector is shown in Figure 9.

4. Measurement using metal bellows

4.1 Pressure drop when holding the forceps

In order to achieve high precision in hydraulic drives, the internal pressure drop and hysteresis must be controlled. These parameters were confirmed using a new experimental setup. A liner actuator was used to move the metal and rubber bellows to 125-750 μm and stop them for 60 seconds. They then returned to their original state. The internal pressure of the bellows was measured during this interval. A comparison of the changes in internal pressure between the metal and rubber bellows is shown in Figure 10 when the liner actuator was stopped. It can be seen that the drop in internal pressure is smaller for the metal bellows than for the rubber bellows. When the liner actuator was stopped after 750 μm of elongation of the metal and rubber bellows, the internal pressure drop for the metal bellows was 3.0% and the internal pressure drop for the rubber bellows was 11.0%. These results show that the metal bellows are more accurate than the rubber bellows.

4.2. Measurement of attach experiment

The force sensing device was identified. A metal bellows, an end-effector, was attached to the object for measuring the reaction force. Figure 11 shows the attachment experiment with the PVA gel. Three types of experimental objects were used in the experiment: a PVA gel mixed with borax, clear starch and water. Three types of gels of different hardness were prepared by varying the water content. Water at 0.085 ml / 2.72 μl/s was supplied to the metal bellows from the liner actuator. Data sampling for internal pressure measurement was 62.5 ms and the tip of the bellows was taken at 29.97 FPS to measure the object displacement. An LED was also illuminated to indicate the start time of the bellows extension. Figure 12 shows the reaction force of the PVA gel with the metal bellows. The device was able to accurately represent the target hardness difference. These results demonstrate that we were able to achieve high accuracy of the device with the metal bellows.

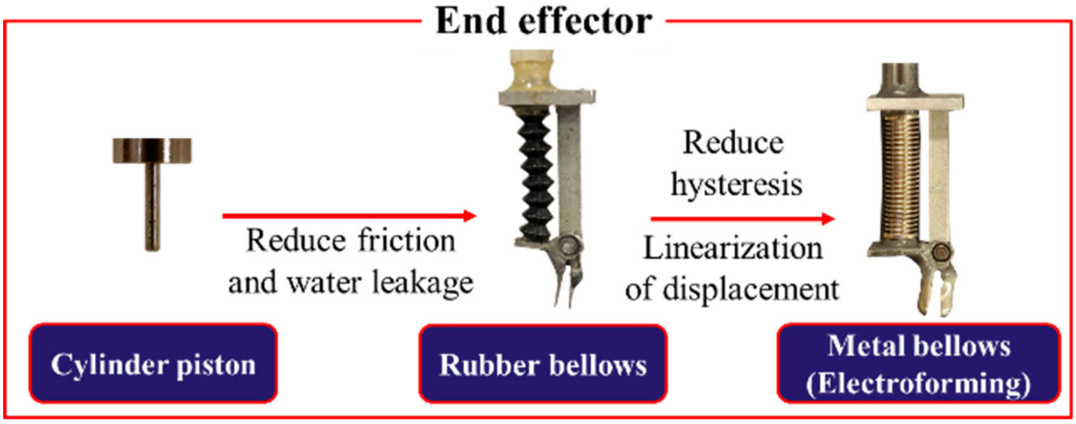

Fig. 9. Improved process of end effector.

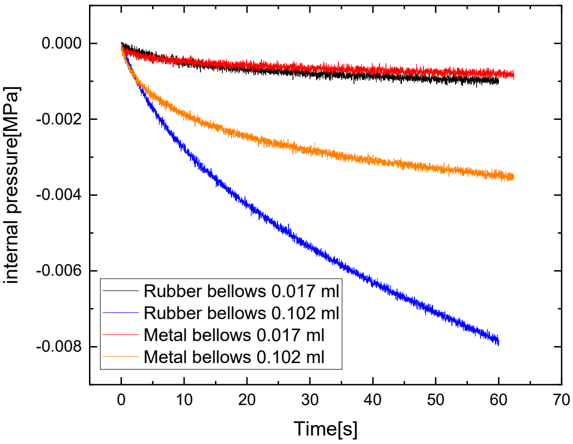

Fig. 10. Comparison between the metal bellows and the rubber bellows.

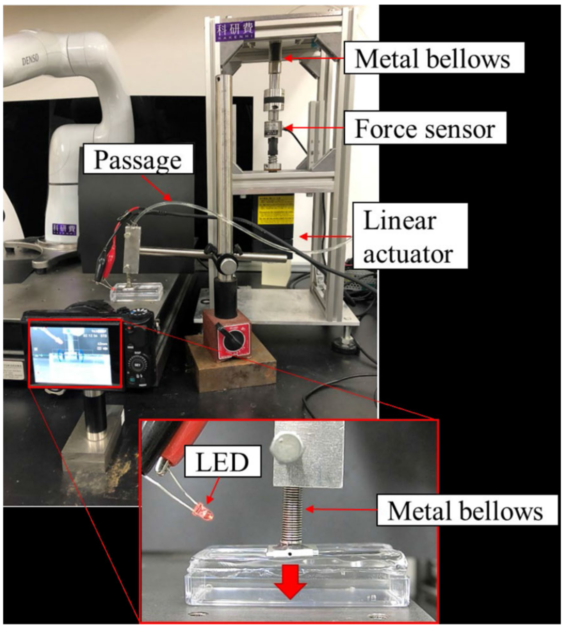

Fig. 11. Attach experiment using PVA gel.

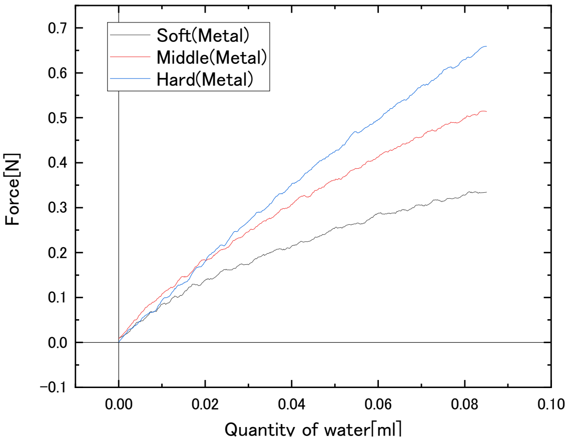

Fig. **12**. Reaction force of PVA gel using the metal bellows.

5. Conclusions

A system using metal bellows as an end-effector was proposed to measure the reaction force of an object with high accuracy. Conventional systems use nitrile rubber bellows as end-effectors. The rubber bellows are less rigid and therefore they deform significantly. Rubber bellows deform not only in the axial direction, but also in other directions. Therefore, we developed a new micro device using metal bellows. The device with metal bellows has a 3.0% lower internal pressure and improved accuracy than the rubber bellows. The device with metal bellows was able to accurately represent the difference in hardness of the three types of PAV gels.

Acknowledgements

This work was supported by JSPS KAKENHI Grant Number 19K04308.

References

[1] M. T. Gettman et al., “Robotic-assisted laparoscopic partial nephrectomy: Technique and initial clinical experience with DaVinci robotic system”, Urology, 2004, 64,5, pp. 914–918.

[2] Hongo, K. et al., “Microsurgery-assisting Robotics (NeuRobot): Current Status and Future Perspective”, Japanese Journal of Neurosurgery, 2011, 20, 4, pp. 270–274.

[3] Kobatashi, E. et al., “Development of Naviot for Minimally Invasive Surgery”, Journal of Robotics Society of Japan, 2005, 23, 2, pp. 168–171.

[4] Fujie M. et al., “Development of a multi-DOF brain retract manipulator for minimally invasive surgery : Third report –Development of a total model for clinical application”, Journal of Japan society of computer aided surgery, 2002, 4, 3, pp.255-256.

[5] Hockstein, NG. et al., Robotic microlaryngeal surgery: A technical feasibility study using the daVinci surgical robot and an airway mannequin, LARYNGOSCOP, 2005, 115, pp.780–785.

[6] Garg A. et al., “Tumor localization using automated palpation with gaussian process adaptive sampling”, IEEE international conference on automation science and engineering, 2016, pp.194-200.

[7] Sasaki, T. et al., “Hydraulically driven joint for a force feedback manipulator”, Precision Engineering, 2017, 47, pp. 445–451.

[8] Ikuta, K. et al., “Study on Hydraulically Driven Active Catheter for Safe Operation”, Trans. of the JSME(c), 2010, 76, 766, pp. 1553–1559.

[9] Kawata, Y. et al., Measurement of blood vessel characteristics for disease detection based on cone-beam CT images, IEEE Transactions on Nuclear Science, 1996, 43, 6, pp. 3348-3354.

[10] Sasaki, T. et al., “Improving accuracy of hydraulic-driven forceps”, Proceedings of the 16th international conference of the European society for precision engineering and nanotechnology, 2016, p.2.07.

[11] Sasaki, T. et al., “Force measurement of blood vessel gripping by hydraulic-driven forceps”, 2017, Procedia CIRP (3rd CIRP Conference on BioManufacturing),2017, 65, pp.84-87.