Proceedings of the 2019 IEEE/SICE
International Symposium on System Integration
Paris, France, January 14-16, 2019

Inflatable Robotic Arm with Overlaid Plastic Sheet Structure

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Abstract— **An inflatable structure has been focused by several researchers in the field of soft robotics, owing to its features: flexible, lightweight and compactable. In particular, inflatable robotic arms have been expected to perform daily tasks near humans due to safe contact. To date, several inflatable robotic arms have been proposed, however, the number of robotic arms composed of only plastic materials is quite limited. In addition, the control performance of the robots has not been discussed sufficiently.**

This paper proposes a novel inflatable robotic arm composed of poly-laminated sheets and low-density polyethylene (LDPE) sheets. The combination of the two materials provides high-pressure resistance. Several advantages are also given: high torque, high control performance, and high load capacity. Moreover, both pressure and visual feedback controls are utilized to realize precise motion control. The end-effector of the robot is composed of pleated structures and grasps flexibly according to object shapes. The performance of the robot is finally described by some experiments.

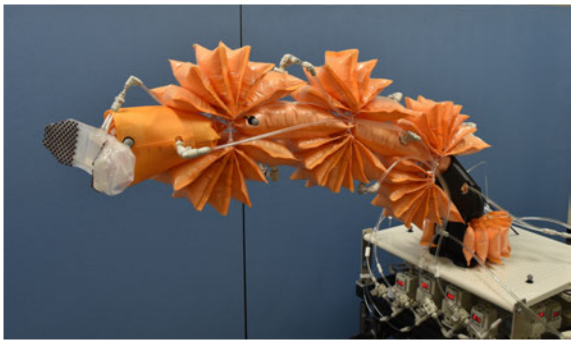

Fig. 1. Inflatable robotic arm

I. INTRODUCTION

Service robots have been expected to play a role in the society because of the lack of workforce in the welfare and nursing care fields. Safety is one of the most important factors for service robots to work in these fields since robots need to perform tasks near people and other various things. However, most of the conventional robotic arms have been mainly made of metal materials to realize high stiffness and precise control. It leads to risks of contacts with humans and things due to high rigidity and heavyweight. On the other hand, inflatable structures have been focused by some researchers in the field of soft robotics due to flexibility, lightweight and compactability. In particular, inflatable robotic arms have been expected to perform daily tasks near humans and things safely. These robots can be applied to a wide range of applications where safety, lightness and flexibility are required such as human support robots, drone, harvesting robots and mounting on space structures requiring compactness.

Several inflatable robotic systems have been developed so far. Sanan *et al.*. have been proposed a lightweight and flexible inflatable link for robotic arms. They make it possible to control the contact force at the tip of the link [1]. Viosembert *et al.* have focused on the inflatable structure which connects joints and links continuously [2]. The structure is quite light, therefore the constraint due to the weight is reduced. Ronghuai *et al.* have developed flexible inflatable robotic arms for telepresence robots [3]. The robot is capable of imitating human arms and realizing remote interaction. As mentioned above, several inflatable robotic arms have been proposed so far. However, most of conventional inflatable robotic arms partially consist of highly-rigid and heavy materials [4]–[7]. The number of robotic arms composed of only plastic materials is quite limited.

To date, we have focused on the inflatable structures and developed lightweight and flexible inflatable robotic arms using plastic materials for all components [8], [9]. The inflatable structures are made only of polyethylene material. The inflatable robot is driven by differential air pressures of the inflatable pneumatic actuators arranged on opposite sides of joints. The control method of this robot is visual feedback control using RGB cameras. In the previous researches, the performance of the robotic arm has been confirmed by some experiments of motion control, but it has some problems with the durability of the plastic material and the control method. The problem is that tensile strength and durability of the material are not high. In addition, the desired pressure is applied by feedforward control of pneumatic regulators in the control method, and pressure feedback control is not implemented since no pressure sensors are mounted on the robotic arm. It is therefore difficult to realize precise motion control.

This paper proposes a new inflatable robotic arm composed of poly-laminated sheets and LDPE. **Figure** 1 shows the proposed inflatable robotic arm. The combination of

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the two materials provides high durability and high-pressure resistance. Then, several advantages are also given: high torque, high control performance, and high load capacity. Moreover, both visual and pressure feedback controls are utilized to realize precise motion control using a motion capture system and pressure sensors. The end-effector of this robot is composed of pleated structures which deform and grasps flexibly according to object shape. The performance of the robot is finally described by some experiments of practical daily applications.

II. INFLATABLE ROBOTIC ARM

The proposed inflatable robotic arm consists of inflatable pneumatic bag actuators, inflatable links, a robotic gripper with a pleated structure as shown in **Figs.** 6 and 7. All parts consist of bags of poly-laminated sheets sandwiched between two LDPE sheets. Although the LDPE sheet is a popular material for an inflatable parts and has many advantages such as lightweight, softness, and safety, it is easy to break under high-pressure conditions. Therefore we attached the poly-laminated sheet with the LDPE sheet. The poly-laminated sheet has good characteristics such as high tensile strength and durability. Each link weights 50 g and the actuators weight from 90 g to 120 g depending on the number of bags. The total weight of the arm is only 340 g. In this paper, the detail of the manufacturing process of the components is shown below.

As shown in the conventional researches [8], [9], the tensile strength and durability of the inflatable robot made only of PE are not high. We have already tested some materials such as LDPE and high-density polyethylene (HDPE). However, these pressure resistance are about 60 kPa and 100 kPa respectively and are not adequate to realize the manipulation of daily things. In addition, the durability is not adequate for repetitive use. Therefore, a poly-laminated material is newly introduced in this research. Firstly, the making process of inflatable bags is described. Next, the details of the inflatable actuator and link are shown below.

A. Inflatable bag unit

A poly-laminated sheet is made by knitting LDPE fibers which are produced by slitting oriented LDPE film. The oriented LDPE film is manufactured by stretching LDPE film with commercial film stretching system which leads to align molecular direction in a specified direction. The tensile strength of poly-laminated sheet is quite high, but the seal performance is quite low. Thereby, the combination of poly-laminated sheet and LDPE sheet is appropriate and provides high durability and high-pressure resistance. The combination of the two materials gives high tensile strength and high seal performance. A poly-laminated sheet sandwiched by LDPE sheets is welded at once using heat sealer NL-303DH (Ishizaki electric mfg. Co., Ltd.) and a pneumatic cylinder CDG1BN63-200Z (SMC Co., Ltd.). By using these devices shown in **Fig.** 2, both welding temperature and pressing force are able to be controlled. In order to get the optimal temperature and pressing force to weld these materials, a number of experiments are conducted. In the experiments, a simple square airbag is welded. According to the experimental results, the optimal temperature, pressing force and welding time are determined to 125 °C, 1500 N and 60 s, respectively. Finally, the pressure resistance of the inflatable bag using two materials is 300 kPa. It is five times higher than the conventional one [8], [9].

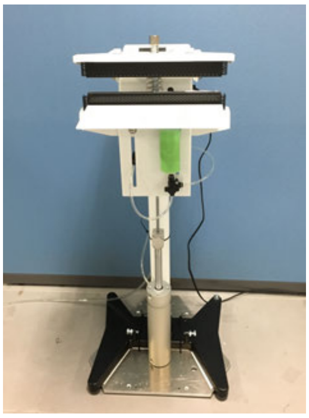

Fig. 2. Welding machine

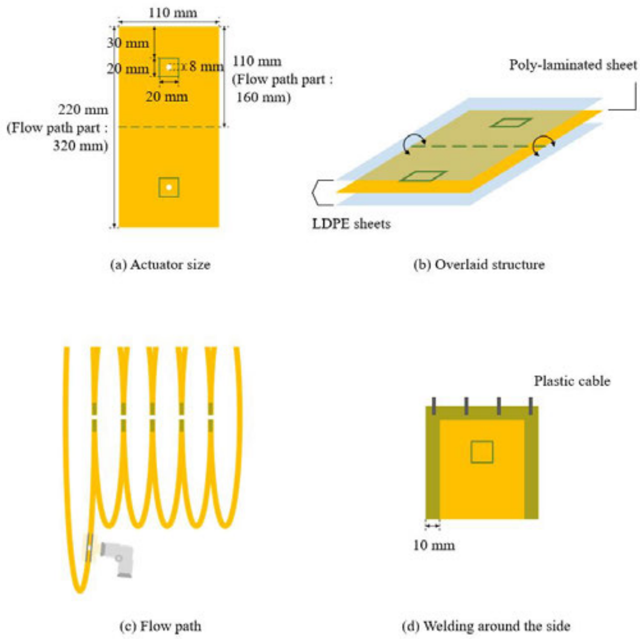

Fig. 3. Actuator structure

B. Inflatable links and actuators

Firstly, the manufacturing process of an inflatable actuator is introduced. An inflatable actuator is made by cutting the sheets to the size as shown in **Fig.** 3(a). Poly-laminated sheet and LDPE sheets are alternately overlaid as shown in Fig. 3(b). Next, the overlaid sheets are folded along the dotted line and from six to eight sheets are accumulated as shown in Fig. 3(c). In order to connect chambers, the centers of the sheets are welded and flow path holes are drilled. **Figure** 4 shows flow path parts. Then, a connector component is attached to

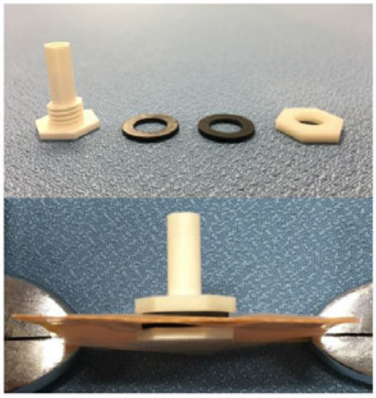

Fig. 4. Flow path

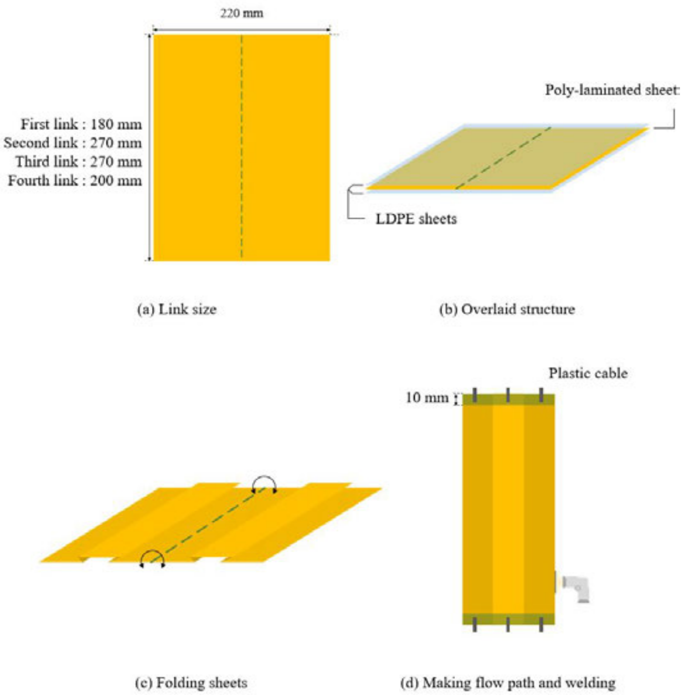

Fig. 5. Link structure

the large airbag to connect to an external air tube as shown in Fig. 4. After welding the surrounding sides, all airbags are connected with a plastic cable as shown in Fig. 3(d). Finally, two actuators are arranged antagonistically inside and outside of each joint. The joint torque to actuate the robotic arm is generated by inflating and deflating the actuators.

The making process of the inflatable link is almost the same as the inflatable actuator as shown in **Fig.** 5. In order to form a cylindrical link into a shape, all sheets are folded and welded as shown in Fig. 5(c). The links maintain rigidity by pressurizing in a cylindrical shape. **Figure** 6 shows a photo of links and actuators.

C. *Robotic gripper with pleats structure*

Pleated sheet structure is used for the robotic gripper and the pleated structure is a bag-like structure, where the back side of the gripper is folded as shown in **Fig.** 7. Different

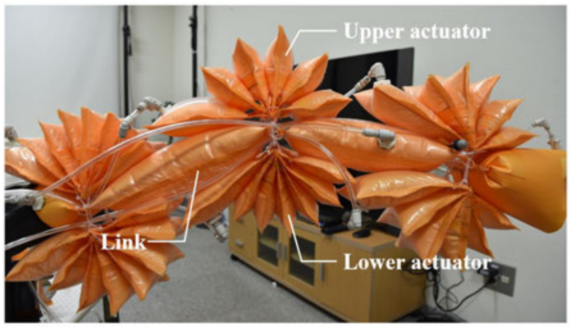

Fig. 6. Inflatable links and actuators

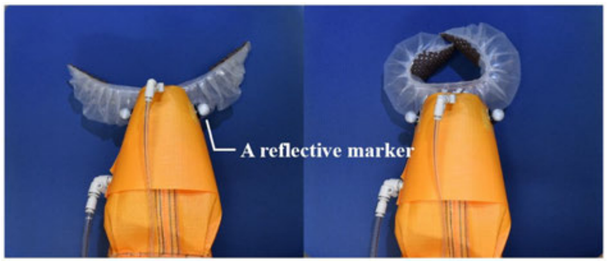

Fig. 7. Robotic gripper with pleated sheet structure

expansion ratio between the flat part and the folded part enables the gripper to grasp objects. The robotic gripper has a load capacity of approximately 700 g at least and deforms flexibly according to the target shape.

III. CONTROL METHODS

This section shows the control method of the proposed inflatable robotic arm. The robotic arm is controlled by both pressure and visual feedback controls. In conventional researches [8], [9], the inflatable robotic arm is controlled by only visual feedback control using RGB cameras. However, the control performance is depending on the calibration precision of the cameras. In addition, the pressure control of actuators has been based on feedforward control by just inputting desired pressure into pressure regulators. There always exist pressure errors due to time-delays and distance from regulators. It also decreases the performance of the robotic arm. Therefore, the motion capture system and the pressure feedback control system are newly introduced in this paper.

A. *Visual feedback control*

Figure 8 shows the configuration of the robot. This inflatable robot does not have any encoders on joints. The posture of the robotic arm is measured by means of the motion capture system Vero (Vicon Motion Systems Ltd). It is assumed that the gripper position and a target object are measured by the motion capture system. Each joint angle is estimated from the gripper position by inverse kinematics technique. For example, the position of the gripper is measured using optical markers attached to the objects as shown in Fig. 7.

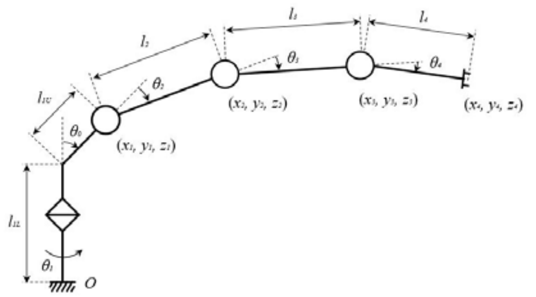

Fig. 8. DOF configuration of the inflatable robotic arm (In this research, θ_0 is constant value $45°$.)

The desired torque of each joint is then calculated by using a PID control method. The control method is given as follows:

$$\boldsymbol{\tau_v} = \boldsymbol{J}^T(\theta)\{K_{Pv}\boldsymbol{e}_v(t)+K_{Iv}\int\boldsymbol{e}_v(t)dt+K_{Dv}\frac{d}{dt}\boldsymbol{e}_v(t)\} \quad (1)$$

$$\boldsymbol{e}_v(t) = \boldsymbol{r}_t - \boldsymbol{r}, \quad (2)$$

where
$\boldsymbol{\tau_v} = (\tau_{v1}, \tau_{v2}, \tau_{v3}, \tau_{v4})^T$: Desired torque of visual feedback control
$\boldsymbol{J}^{3\times4}(\theta)$: Jacobian matrix
$\boldsymbol{r}_t = (x_t, y_t, z_t)^T$: Target gripper position
$\boldsymbol{r} = (x_4, y_4, z_4)^T$: Current gripper position
K_{Pv}, K_{Iv}, K_{Dv} : Proportional, integral and differential gain of visual feedback control.

Moreover, torques for gravity compensation are required. It is calculated as follows:

$$\tau_{g1} = 0 \quad (3)$$

$$\tau_{g2} = (m_2gl_{g2} + m_3gl_2 + m_4gl_2)S_{02} + (m_3gl_{g3} + m_4gl_3)S_{023}+(m_4gl_{g4})S_{0234} \quad (4)$$

$$\tau_{g3} = (m_3gl_{g3} + m_4gl_3)S_{023} + (m_4gl_{g4})S_{0234} \quad (5)$$

$$\tau_{g4} = (m_4gl_{g4})S_{0234} \quad (6)$$

where
$\boldsymbol{\tau}_g = (\tau_{g1}, \tau_{g2}, \tau_{g3}, \tau_{g4})^T$: Gravity compensation torque
m_2, m_3, m_4 : Total sum of the mass of each link and actuator
l_{g2}, l_{g3}, l_{g4} : Distance from joints to center of gravity of the link.

As a result, desired torques are calculated as

$$\boldsymbol{\tau} = \boldsymbol{\tau}_v + \boldsymbol{\tau}_g, \quad (7)$$

where
$\boldsymbol{\tau} = (\tau_1, \tau_2, \tau_3, \tau_4)^T$: Desired torque.

B. Pressure feedback control

The desired torques $\boldsymbol{\tau}$ are converted into pneumatic pressures using the torque-pressure conversion characteristics. These characteristics are obtained by some preliminary experiments. **Figure** 9 shows the result of experiments for torque-pressure characteristics. The relation between torques and pressures change depending on joint angles. The base pressure is applied to both upper and lower actuators beforehand to maintain a certain rigidity. The differential pressure is applied to the upper actuator and the lower actuator with different signs. We define the relationship between desired torque and target pressure as

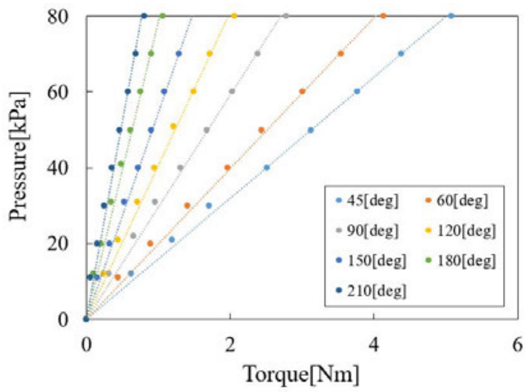

Fig. 9. The result of preliminary experiment for torque-pressure characteristics

$$\Delta\boldsymbol{P} = \pm\frac{1}{2}A(\theta)\boldsymbol{\tau} \quad (8)$$

$$\boldsymbol{P}_t = \boldsymbol{P}_b + \Delta\boldsymbol{P} \quad (9)$$

where
$\Delta\boldsymbol{P}$: Differential pressure
$\boldsymbol{A}(\theta)$: Transformation matrix obtained by Fig. 9
$\boldsymbol{P}_t$: Target pressure
$\boldsymbol{P}_b$: Base pressure.

After the conversion from torque to pressure, pressure feedback control is utilized. The feedback control not only makes precision of motion control higher than the conventional control method but also suppresses unstable behavior like hunting. As mentioned above, the current pressure values of actuators are measured by pressure sensors AP-33A (KEYENCE Co., Ltd.).

After denoising, target pressure are updated by the following equations:

$$\boldsymbol{P} = \boldsymbol{P}_t+K_{Pp}\boldsymbol{e}_p(t)+K_{Ip}\int\boldsymbol{e}_p(t)dt+K_{Dp}\frac{d}{dt}\boldsymbol{e}_p(t) \quad (10)$$

$$\boldsymbol{e}_p(t) = \boldsymbol{P}_t - \boldsymbol{P}_s \quad (11)$$

where
$\boldsymbol{P}$: Compensated target pressure
$\boldsymbol{P}_s$: Pressure acquired by a pressure sensor
K_{Pp}, K_{Ip}, K_{Dp} : Proportional, integral and differential gain of pressure feedback control.

Consequently, the whole control flow is shown in **Fig.** 10 by a block diagram.

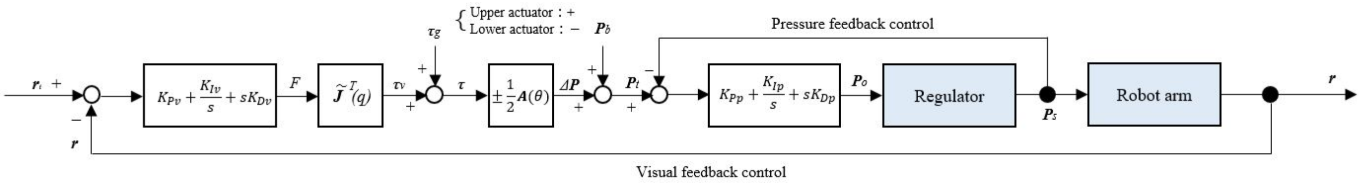

Fig. 10. Block diagram

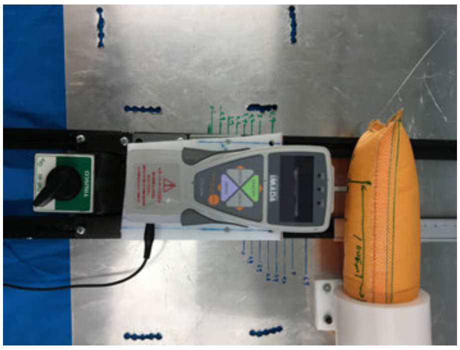

Fig. 11. Environment of inflatable link rigidity characteristic experiment

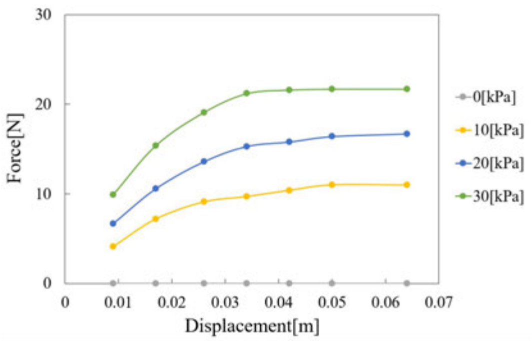

Fig. 12. The relationship between displacement of the link made only of LDPE and force at the steady state

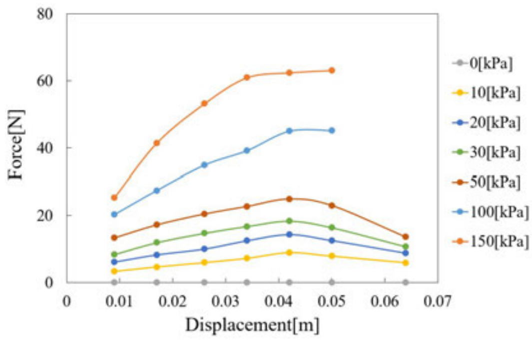

Fig. 13. The relationship between displacement of the link made of poly-laminated sheets and LDPE, and force at the steady state

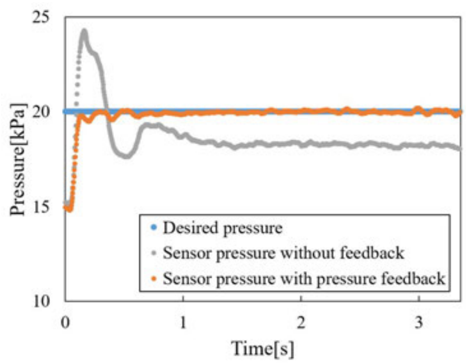

Fig. 14. Result of comparing the effect of pressure feedback control by step response of sensor pressure.

IV. EXPERIMENTS

A. Rigidity evaluation

Experiments to confirm the improvement with changing material are conducted. In this research, the rigidity characteristics of the inflatable link are focused on as one of the evaluation indices. **Figure** 11 shows the experimental environment. A digital force gauge ZTS-500N (Imada Co., Ltd.) is used to measure the rigidity of the link. The relationship between the displacement of the link and the force measured by the force gauge at the steady state is shown in **Figs.** 12 and 13. From these figures, it is confirmed that not only pressure resistance but also the rigidity of the link made of the proposed material are improved compared with conventional one.

B. Pressure feedback control

Next, the experiments to confirm the performance of the pressure feedback control are conducted. **Figure** 14 shows the transient responses of the pressure denoised by an IIR low-pass filter. In this figure, the target value is represented by a blue line. The orange line shows the transient response of pressure in the case where the pressure feedback control is utilized. The gray line shows the case without pressure feedback control. From the figure, the pressure measured by a pressure sensor converges to the target value. Furthermore, it is also confirmed hunting, an unstable behavior, is not observed by applying the feedback control during the experiments.

C. Visual feedback control

Finally, the experiment to confirm the performance of pressure and visual feedback control are conducted. In the experiment, the gripper position of the robot is controlled by the proposed method. **Figure** 15 shows the transient response of the deviation of the position of the gripper. In addition, **Fig.** 16 show the initial and final states of motion control of the visual feedback control experiment. As a result, it is confirmed that the position of the gripper converges to the desired value precisely.

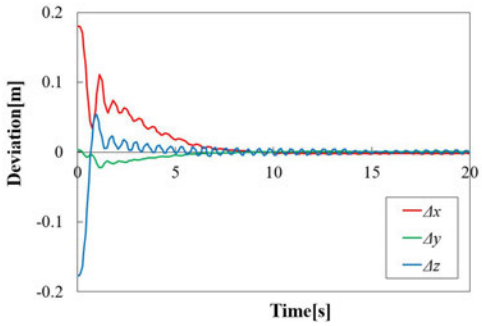

Fig. 15. Step response of visual feedback control

Fig. 16. Experimental environment of visual feedback control

V. CONCLUSIONS

This paper proposed an inflatable robotic arm made of LDPE and poly-laminated sheets. By using the combination of these two materials the pressure resistance performance, load capacity and working area of the inflatable robotic arm were improved. The manufacturing process of the robot were also described. Moreover, the control performance of the robot was improved by both visual and pressure feedback controllers. Finally, the control performance of the robot was confirmed by some experiments.

In future works, we will realize more practical daily applications using the proposed inflatable robot.

ACKNOWLEDGEMENTS

This research is supported by the Japan Society for the Promotion of Science Grant-in-Aid for Basic Research (B) (JP18H03764).

We would like to appreciate Kawamura laboratory researchers at Ritsumeikan University who have helped a lot in making the robotic arm.

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