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Haptic Feedback of Real Soft Objects with Haptic Device Using Flexible Sheet

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Abstract— **A haptic device using flexible sheet is developed. This device elongates a rubber sheet with four servo motors in parallel. Controlling their motor angles varies softness of the sheet: stretched sheet feels hard, and loose sheet feels soft. Hence a user can feel different softness of virtual objects when he pushes the sheet directly with his finger. We apply this device to haptic feedback of real soft objects. The system consists of the haptic device and a robot with a pressure sensing device. This sensing device is a rubber hemisphere filled with air. The internal pressure is measured when the hemisphere is pressed against an object. First a user pushes the center of the sheet. The movement of the side edge of the sheet is observed with a close-up camera, and the user's pushing pressure on the sheet is estimated. Next the robot pushes a target object so that its pushing pressure on the object, which is measured with the pressure sensing device, may coincide with the user's pushing pressure on the sheet. At the same time, the softness of the object is estimated from the measured pushing pressure on the object and the indentation of the object, which is given by the robot's movement. Then the haptic device controls the motor angles so that the sheet's softness may be equal to the object's softness. The system repeats this process in real time. In this way the user feels the same softness as the real object by pushing the sheet. As an experimental result, the developed haptic device can imitate softness of a real stuffed doll.**

I. Introduction

Presenting haptic sense to users when they touch virtual objects is important in some virtual reality applications. Devices for presenting virtual haptic sense are called haptic devices[1-10]. One of medical applications of haptic devices will be a training simulator of palpation[11]. A haptic device simulates haptic sense in palpation and presents it to trainees; they experience virtual palpation through the haptic device. Another application is palpation from remote place: telepalpation[12,13]. A robot is placed at a patient's side. A doctor in a hospital operates this robot and performs palpation of the patient. At the same time the robot measures the reaction force or some haptic sense of the patient and returns them to the doctor through the haptic device. Virtual palpation and telepalpation require that doctors can feel like touching real patients. They can touch virtual or remote patients' bodies directly with hands or fingers, and the hands or fingers can move unrestrained. The objects to be presented are human bodies, which are soft and flexible.

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In our previous studies[14,15], we already proposed a haptic device using flexible sheet such as rubber, aiming at presenting haptic sense of soft objects such as human bodies and organs. This device varies softness of the sheet by controlling tension applied to the sheet: stretched sheet feels hard, and loose sheet feels soft. Hence a user can feel different softness of virtual objects when he pushes the sheet directly with his finger. Because he does not wear the device, finger movement is not restrained.

In the present study we develop a revised haptic device which elongates a rubber sheet with four servo motors in parallel. The device applies tension to the sheet by controlling the motor angles, thus varying the sheet's softness. We apply this device to haptic feedback of real soft objects; possible future application is telepalpation. The system consists of the haptic device and a robot with a pressure sensing device which is newly developed. This sensing device is a rubber hemisphere filled with air. The internal pressure is measured when the hemisphere is pressed against an object. We call relationship between pushing pressure and indentation "pressure-indentation curve". We beforehand measure the pressure-indentation curves at the center of the sheet for different motor angles. First a user pushes the center of the sheet. The movement of the side edge of the sheet is observed with a close-up camera, and the user's pushing pressure on the sheet is estimated. The relationship between the side edge movement and the pushing pressure is also measured beforehand. Next the robot pushes a target object so that its pushing pressure on the object, which is measured with the pressure sensing device, may coincide with the user's pushing pressure on the sheet. From the measured pushing pressure on the sheet and the indentation of the object, which is given by the robot's movement, we choose the most fitting pressure-indentation curve of the sheet among the curves for different motor angles. The haptic device controls the actual motor angles to the desired motor angle corresponding to this curve. As a result the sheet imitates the object's softness. The system repeats this process in real time. In this way the user feels the same softness as the object by pushing the sheet.

Section II explains the revised haptic device. Section III proposes a method of haptic feedback of real soft objects with this device. Section IV describes some measured properties of the haptic device and an experiment of haptic feedback of a real stuffed doll. Section V presents conclusions.

II. Haptic Device Using Flexible Sheet

A. Principle of Varying Sheet's Softness

Figure 1 shows principle of varying softness of a flexible sheet such as rubber. Controlling tension of the sheet varies

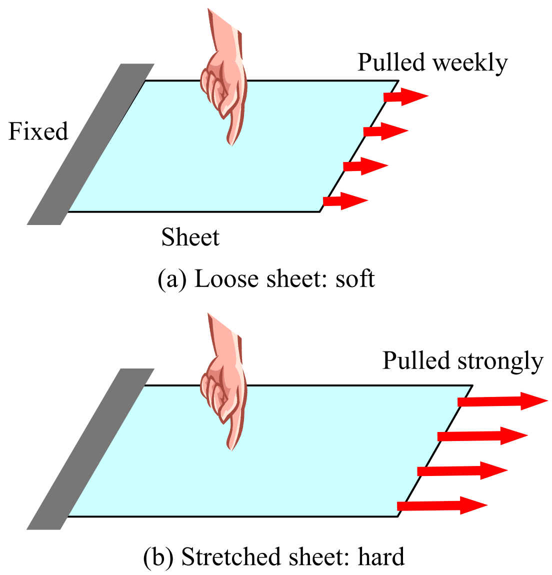

Figure 1: Principle of varying softness of flexible sheet by tension control

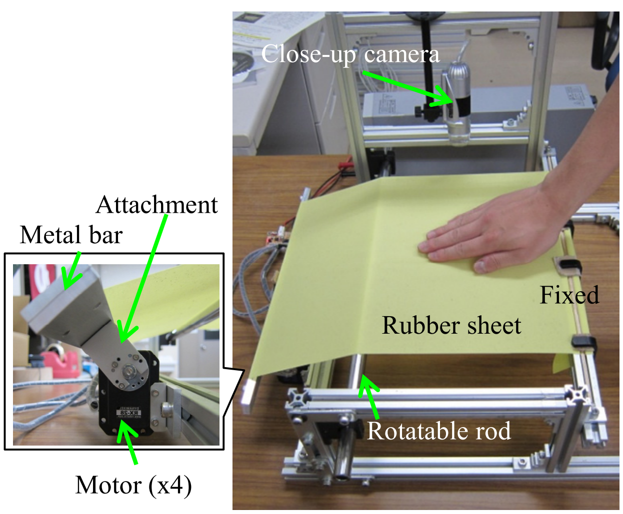

Figure 2: Developed haptic device using flexible sheet

the sheet's softness in normal direction: stretched sheet feels hard, and loose sheet feels soft. Hence a user can feel different softness of virtual objects when he pushes the sheet directly with his finger. If the tension is controlled so that the sheet's softness may be equal to softness of a target object, the user feels like pushing the target object. Tension can be applied to the sheet simply by pulling its edges using position-controlled actuators.

B. Developed Device

Based on this idea we develop a haptic device which elongates a rubber sheet with four servo motors in parallel. Figure 2 shows the developed device. Figure 3 illustrates the side view of its mechanism. The size of the yellow silicon rubber sheet is 300[mm] x 245[mm] x 0.5[mm]. One edge of the sheet is fixed on the base. The other edge is wound round a metal bar. The metal bar is fixed to the output shafts of four

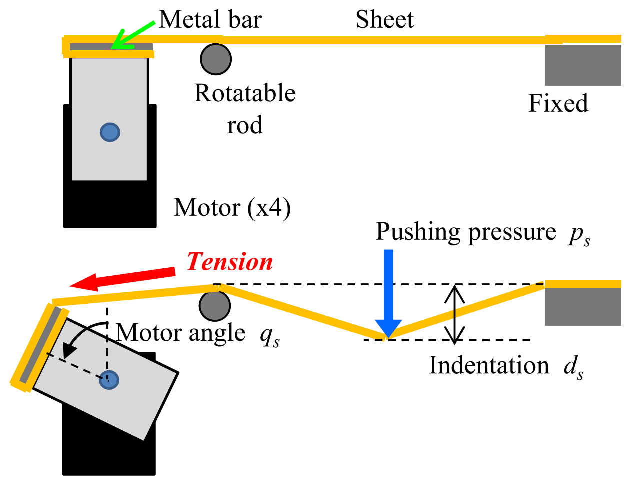

Figure 3: Side view of mechanism of device

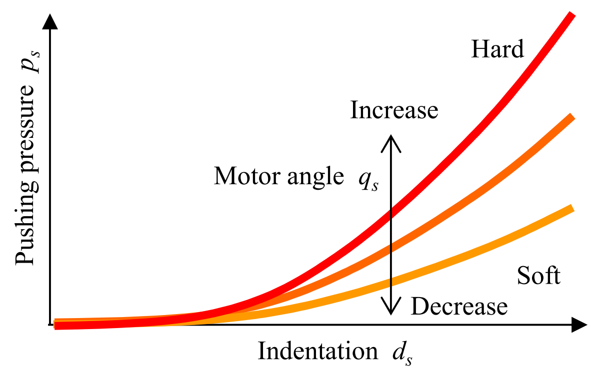

Figure 4: Pressure-indentation curves of haptic device using flexible sheet

servo motors placed in parallel through the attachments. The motor angles of all motors are the same. They pull the sheet together and apply tension to the sheet. The rotatable rod keeps the height of the sheet constant, regardless of the motor angles. We use four small servo motors in parallel instead of one powerful motor; that makes the device compact. The used servo motor is smart actuator module ROBOTIS Dynamixel RX-28. This module contains a servo motor, a reduction gear, a control unit and a communication interface in a compact package. If the reference motor angle (which is after reduction) is commanded through RS-485, the control unit controls the motor angle by local position feedback control. The resolution of the motor angle is 0.29[deg]. The maximum holding torque is about 37.7[kgfcm] for power supply voltage 16[V]. The modules are connected to a main computer DELL PRECISION T3400 (CPU: Inter Core2 Duo, 2.99[GHz]) with wired RS-485. The reference motor angles are commanded at baud rate 1[Mbps] from the computer to the modules.

Pushing pressure p_s, indentation d_s, and motor angle q_s are defined in Figure 3. If the motor angle increases, the sheet becomes stretched and hard. If the motor angle decreases, the sheet becomes loose and soft. Accordingly the device can vary the sheet's softness by controlling the motor angle. Figure 4 illustrates the pressure-indentation curves at the center of the sheet for different motor angles.

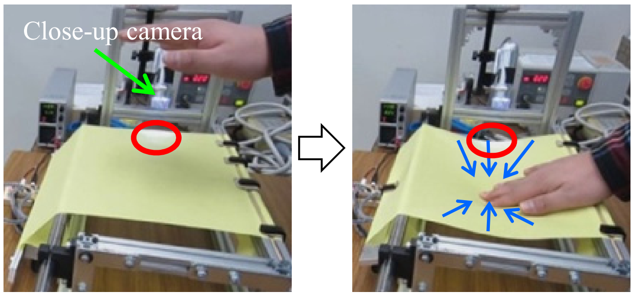

Figure 5: Side edge of sheet moves when center of sheet is pushed

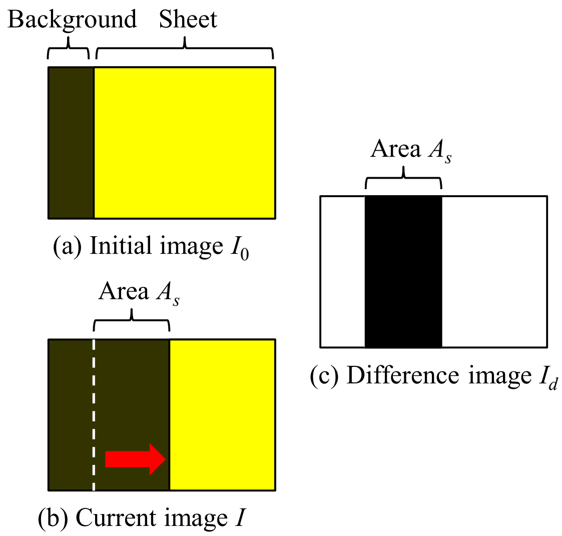

Figure 6: Measurement of side edge movement of sheet

$$p_s = f(d_s, q_s) \tag{1}$$

We measure these curves beforehand. How to measure them will be explained in Section III.B.

C. Features

1) This haptic device is suitable for presenting haptic sense of soft objects such as human bodies and organs.

2) The device varies softness of a flexible sheet by controlling its tension.

3) Position-controlled actuators simply pull the sheet to apply tension to the sheet.

4) Users can feel like pushing virtual objects directly with their fingers.

5) Users can stroke virtual objects.

6) Because users do not wear the device, the motion of their fingers along the sheet or in free space is not restrained.

7) The range of softness to be presented is limited by the size and material of the sheet.

8) The device does not generate different softness by location of the sheet.

D. Estimation of Pushing Pressure on Sheet

For haptic feedback of real soft objects, we must measure the pushing pressure p_s or indentation d_s when a user pushes the center of the sheet. Attaching a pressure sensor to the user's fingertip may restrain free motion of the fingertip. Placing a proximity sensor under the center of the sheet may limits the maximum indentation. This is because the fingertip may touch the sensor when it pushes the sheet deeply.

As shown in Figure 5, when the center of the sheet is pushed, its side edge is drawn to the center. We propose a method of estimating the indentation d_s of the sheet by observing this side edge movement.

A close-up camera with white LEDs (DigiScope, 2.0[Mpixel], Klein & Ross Int'l Co., Ltd.) is placed above the side edge of the yellow sheet. The background of the sheet seen from the camera is dark brown, which is clearly distinguishable from the sheet by image binarization. Figure 6 shows the process of measuring the side edge movement.

1) We set the device to initial state: the motor angle q_s is set to initial value when the sheet is mostly loose, and the sheet is not pushed (the indentation d_s = 0). As shown in Figure 6(a), we take the initial image I_0 in grayscale with the camera beforehand.

2) When the motor angle is changed or the center of the sheet is pushed, the side edge moves to the center. As shown in Figure 6(b), we take the current image I in grayscale.

3) We make the difference image I_d between the initial image I_0 and the current image I. When the side edge moves, the area A_s shown in Figure 6(b) changes from the sheet to the background seen from the camera. The left side of the area A_s remains the background, and the right side remains the sheet. Because the background color is quite different from the sheet's color, the area with larger difference than a threshold in the difference image I_d is the area A_s. Figure 6(c) shows the difference image I_d, where the black area is the area A_s. The size of the area A_s corresponds to the side edge movement.

As shown in Figure 7, the side edge of the sheet moves both when the sheet is pushed (red arrow) and when the sheet is elongated (light blue arrow). Thus the side edge movement (the area A_s) depends on the indentation d_s and the motor angle q_s. Figure 8 illustrates the relationships between the area A_s and the indentation d_s for different motor angles q_s.

$$d_s = g(A_s, q_s) \tag{2}$$

We also measure these relationships beforehand. How to measure them will be explained in Section III.B.

Now we can estimate the indentation d_s of the sheet from the commanded motor angle q_s and the measured side edge movement (the area A_s) using premeasured Equation (2) (Figure 8). We can also estimate the pushing pressure p_s on the sheet from the commanded motor angle q_s and the estimated indentation d_s using premeasured Equation (1) (Figure 4).

This method can detect minute indentation using a close-up camera. The resolution and the range of measurement

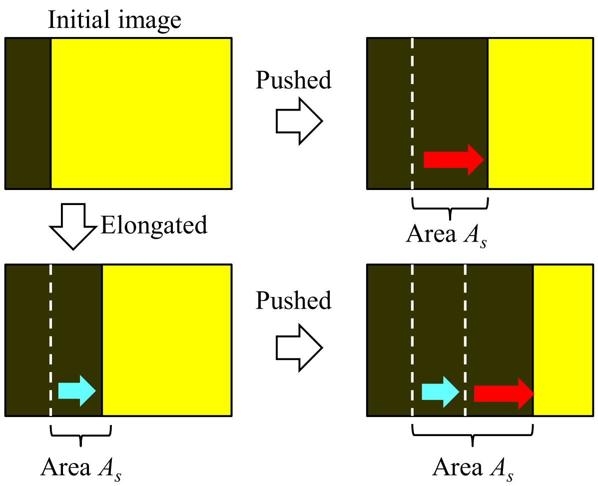

Figure 7: Side edge movement when sheet is pushed and when sheet is elongated

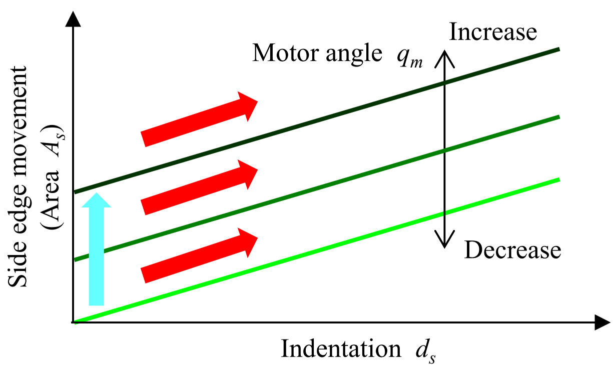

Figure 8: Relationship among side edge movement, indentation and motor angle

can be adjusted by changing the distance between the camera and the sheet.

III. Haptic Feedback of Real Soft Objects with Haptic Device Using Flexible Sheet

A. Robot and Pressure Sensing Device

We use a 6-DOF robot with a pressure sensing device to push real soft objects. The used robot is RV-1A by Mitsubishi Electric Corporation. The indentation d_r of an object is given by the robot's movement.

The pressure sensing device measures the robot's pushing pressure p_r on the object. Figure 9 shows the pressure sensing device which is newly developed. This sensing device is a rubber hemisphere filled with air. The radius of the hemisphere is 37.5[mm]. The internal pressure is measured with a pressure sensor ADP5121 by Panasonic Corporation. The output of this sensor is voltage proportional to the internal pressure, which is converted to digital code with an A/D converter of 10[bit]. Figure 10 shows the robot with the pressure sensing device. When the hemisphere is pressed against an object, the internal pressure increases.

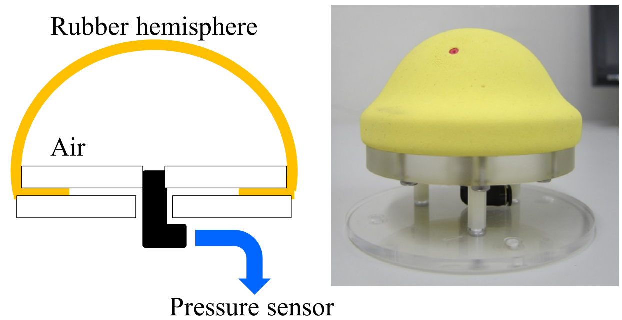

Figure 9: Pressure sensing device

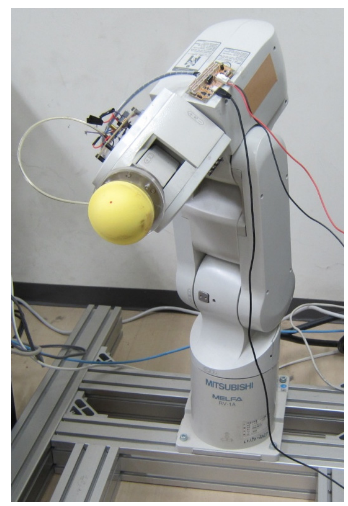

Figure 10: Robot and pressure sensing device

B. Measurement in Advance

As described in the previous sections, we must measure the pressure-indentation curves, Equation (1), and the relationships between the side edge movement and the indentation, Equation (2), for different motor angles. We use the robot shown in Figure 10 to measure them.

The haptic device is placed under the robot. The motor angle q_s is set to a certain value. The robot goes down at constant intervals and pushes the center of the sheet. The indentation d_s is given by the robot's movement. The pushing pressure p_s is measured with the pressure sensing device. The side edge movement (the area A_s) is measured with the close-up camera. The above process is repeated for different motor angles. Overall softness of the haptic device is measured, including servo stiffness of the motors.

C. Process of Haptic Feedback

The system consists of the haptic device shown in Figure 2 and the robot with the pressure sensing device shown in Figure 10. The motor angle q_s is set to initial value. Then the system repeats the following process in real time for haptic feedback (Figure 11):

1) A user pushes the center of the sheet.

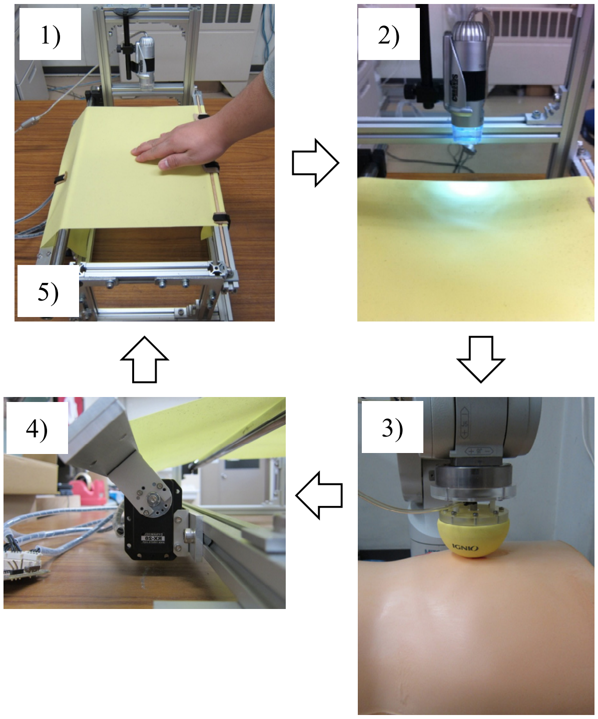

Figure 11: Process of haptic feedback of real soft object using developed system

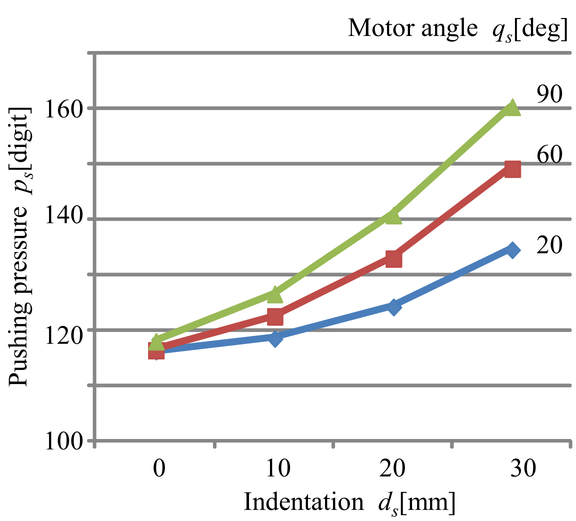

Figure 12: Measured pressure-indentation curves of developed haptic device

2) The side edge movement (the area A_s) of the sheet is measured with the close-up camera. The user's pushing pressure p_s on the sheet is estimated from the motor angle q_s and the area A_s, as explained in Section II.*D*.

3) The robot's pushing pressure p_r on a target object is measured with the pressure sensing device. The robot is controlled so that its pushing pressure p_r on the object may coincide with the user's pushing pressure p_s on the sheet. The control law is

$$\Delta d_r = K_p(p_s - p_r) \tag{3}$$

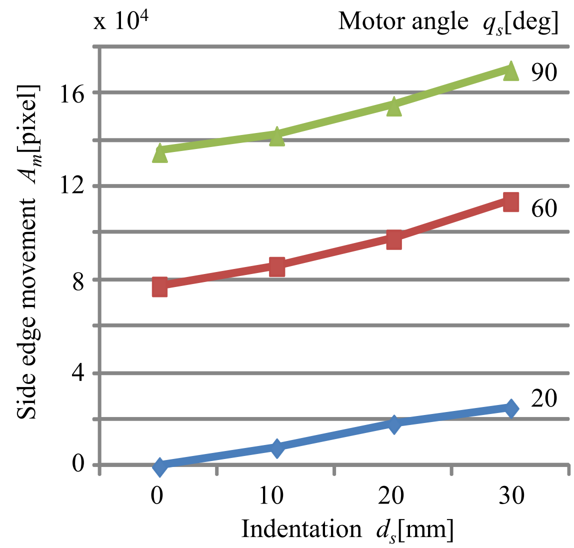

Figure 13: Relationship between side edge movement and indentation of developed haptic device

where Δd_r is the increment of the robot's movement, and K_p is feedback gain. The robot's movement gives the indentation d_r of the object. As a result the robot pushes the object with the same pressure as the user.

4) From the pushing pressure p_r and the indentation d_r of the object, we choose the most fitting pressure-indentation curve of the sheet from the premeasured curves (Figure 4). The motor angle q_s corresponding this curve is given by

$$q_s = f^{-1}(p_r, d_r) \tag{4}$$

It is commanded to the motors. As a result the sheet imitates the object's softness.

5) The user feels the same softness as the target object by pushing the sheet.

IV. Experiments

A. Pressure-Indentation Curves of Sheet

Figure 12 shows the measured pressure-indentation curves at the center of the sheet for different motor angles q_s: 20, 60 and 90[deg]. The horizontal axis is the indentation d_s, and the vertical axis is the pushing pressure p_s, which is expressed by the digital code after A/D conversion. We define the indentation d_s = 0[mm] when the pressure sensing device slightly touches the sheet. The robot presses the sensing device onto the sheet. From this graph the curve depends on the motor angle. Accordingly the sheet can generate different softness by controlling the motor angle.

B. Relationship between Side Edge Movement and Indentation of Sheet

Figure 13 shows the measured relationships between the side edge movement A_s and the indentation d_s of the sheet for different motor angles q_s: 20, 60 and 90[deg]. From this graph

Figure 14: Scene of experiment on haptic feedback of stuffed doll with developed haptic device

the relationship depends on the motor angle. The side edge moves almost linearly with the indentation.

C. Haptic Feedback of Real Stuffed Doll

We perform an experiment of haptic feedback of softness of a real stuffed doll. Figure 14 shows the scene of the experiment. A user pushes the center of the sheet, and the robot pushes the doll.

Figure 15 summarizes the experimental results. The horizontal axis is count of control loop corresponding to time.

Figure 15(a) is the side edge movement A_s of the sheet. Figure 15(d) is the motor angle q_s. As the user pushes the sheet more deeply, the side edge movement increases. The side edge also moves when the sheet is elongated. The side edge movement greatly increases when the motor angle changes.

Figure 15(b) shows the user's pushing pressure p_s on the sheet (blue) and the robot's pushing pressure p_r on the doll (red) which is measured with the pressure sensing device. The user's pushing pressure p_s is estimated from the side edge movement A_s and the motor angle q_s. Hence the pressure p_s instantaneously fluctuates when the motor angle q_s changes. This fluctuation is not intended by the user. The robot's pushing pressure p_r is controlled smoothly. Thus the robot can push the doll with the pressure as intended by the user.

Figure 15(c) is the indentation d_r of the doll, which is given by the robot's movement. Figure 15(d) is the motor angle q_s for the sheet to imitate the measured softness of the doll. From Figure 15(c) and (d), as the doll is pushed more strongly (thus more deeply), the motor angle increases. It means that the doll becomes harder as it is pushed more deeply.

Figure 15(e) shows the robot's pushing pressure p_r on the doll (blue) and the pushing pressure $\tilde{p}_s$ to be presented by the sheet (red). The latter is calculated from the indentation d_r of the doll and the motor angle q_s by

$$\tilde{p}_s = f(d_r, q_s) \tag{5}$$

This pressure $\tilde{p}_s$ is the pressure to be presented by the sheet when the sheet is pushed the same indentation d_r as the doll. If the sheet completely imitates the doll's softness, the red line agrees with the blue line. From this graph the haptic device can imitate the doll's softness except when the doll is pushed deeply. When the doll is pushed deeply, the motor angle becomes the maximum 90[deg]; the sheet is most stretched and hardest. But the red line is less than blue line. It means that the doll is harder than the softness which can be generated by the sheet.

V. Conclusion

A haptic device which elongates a rubber sheet with four servo motors in parallel is developed. Controlling their motor angles varies the sheet's softness. A user can feel variable softness when he pushes the sheet directly with his finger. We apply this device to haptic feedback of real soft objects. A user pushes the sheet. Then a robot pushes a real object with the same pressure as the user's pushing pressure on the sheet. The object's softness is estimated from the measured pushing pressure and indentation of the object. The haptic device controls the motor angles so that the sheet's softness may be equal to the object's softness. As a result the user feels the same softness as the real object by pushing the sheet. As an experimental result, the developed haptic device can imitate softness of a real stuffed doll.

In future work we will apply this device to medical fields; for example, telepalpation of abdomen. In abdominal palpation, a doctor pushes several points on an abdomen with his hand. He pushes one point and moves his hand to another point. Our haptic device can present haptic sense of pushing each point to the doctor. Needless to say, softness can be different by pushing points. Hence telepalpation of abdomen requires a method of moving the robot from one pushing point to another point along the convex shape of the abdomen. Furthermore our device can present a kind of softness at a time; it is impossible to present haptic sense of lumps under skin. We already proposed a method of combining air jet with flexible sheet to present virtual lumps[9]. We will add this method to our telepalpation system.

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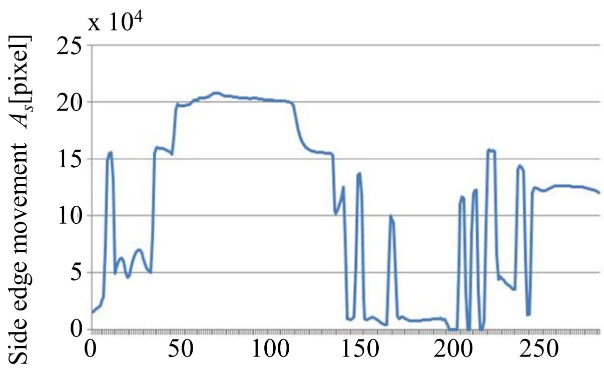
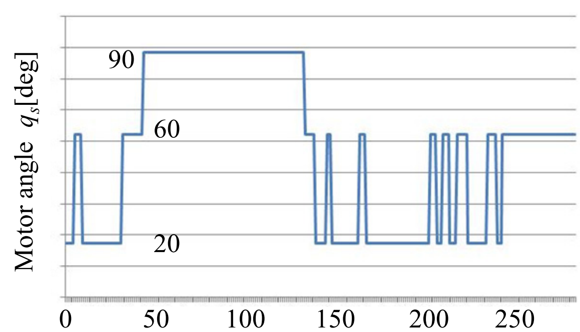
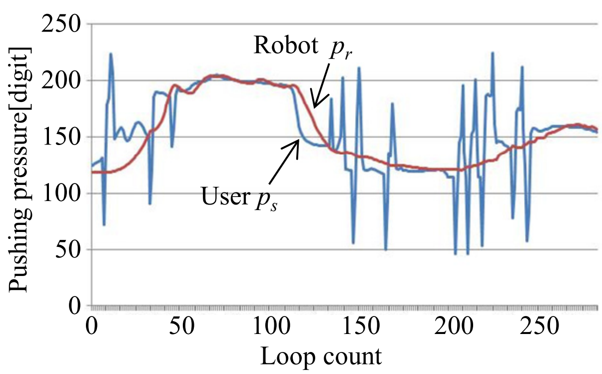


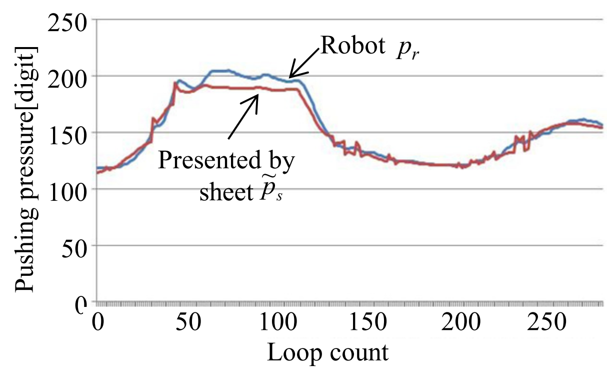
(a) Side edge movement of sheet



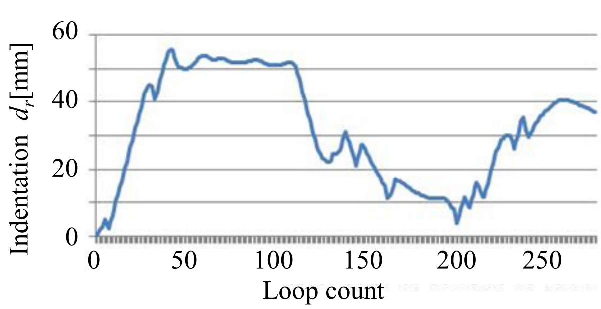
(d) Motor angle



(b) Pushing pressure



(e) Pushing pressure to be presented by sheet



(c) Indentation of doll

Figure 15: Experimental results of experiment on haptic feedback of stuffed doll using developed haptic device