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Development of Multi-Fingered Hand for Telepresence Based on Tactile Information

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In the bilateral teleoperator systems, transferring tactile information from a slave to a human operator is very important in order to improve the presence in the master side. The coiled nerve structure of the Meissner corpuscles can separately detect stretch and shear deformation of the skin that is caused by various frictional conditions. Based on this property, a biomimetic coiled tactile sensor involved in the non-uniform elastic skin has been developed in this study. In this paper, it is confirmed that this novel sensor can measure a friction coefficient just after the contact, a center of contact, and an incipient local slip. Furthermore, the lifting of the slippery tapered object by the pinch grip is dealt with as a precision task. In the experiment of teleoperation through the network, the human subject could adequately regulate the coordination between the grip force and the vertical lifting force by utilizing the frictional information from the tactile display.

Key Words: telerobotics, multi-fingered hand, tactile sensor and display, incipient local slip, telepresence

1. Introduction

In the field of tele-robotics, development of force-feedback type of bilateral control system had been actively carried out as a teleoperation device with high presence using master-slave [?]. The authors have developed the practical force-reflecting teleoperator through the Internet. In the experiments, the several kinds of tasks, such as pushing the wall, inserting the video cassette, and holding the raw egg, were performed with haptic senses [?].

In the future, it is required to improve technologies enhancing the difficulty level toward higher operation with multi-degree of freedom [?]. Yokokohji et al. [?] have implemented to build Lego with several grades of difficulty. In this study, the task to lift up the slippery tapered object is dealt with. Human being realizes various adaptable grasping by adjusting the grip force experientially based on the force and tactile information [?]. Johansson et al. [?] have investigated the movements of human beings to grasp the object and lift it up under various conditions (the weight of object, the frictional coefficient) and have elucidated the characteristics. It is required to enhance the telepresence based on tactile information in order to use such human skills as are operated directly in teleoperation practically [?].

In grasping the object and lifting it, while the grip force is augmented, it is transferred smoothly to lifting movement at a certain point. At this time, it should be taken into account that how the tactile sense is used. First, whether it is slippery or not is perceived at the early stage of the contact with the object. Then, after transferring to the lifting motion, the slip will be foreseen according to the situation [?]. In 1999, its sensing mechanism was put forward by Maeno [?] and Shinoda [?] respectively. From these researches, the frictional coefficient can be detected by utilizing the distribution pattern of the shear strain inside the finger. A certain stress component in an elastic body of the tactile sensor can indicate the frictional coefficient at the outset of touching.

In this study, the soft finger with a built-in tactile sensor and haptic display are proposed and the multi-fingered hand system for telepresence is developed. The adaptive operation will be possible if some haptic senses such as slipperiness or sliminess, in addition to hardness and softness, of the object can be obtained [?].

2. Master-Slave Type Multi-Fingered Hand System

2.1 Slave Multi-Fingered Hand

In this study, multi-fingered hand as shown in Fig.1 was developed. This slave hand is 350[mm] in length and 240[mm] in width, and it is one and a half the size of human hand. Compact actuators are installed in each joint. AC servo motor (rated output of 1.4[W]), harmonic drive gear (reduction gear ratio of 1/80), and optical encoder

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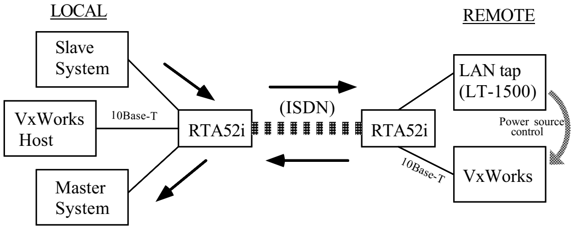
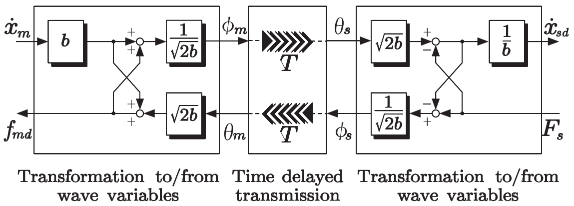
Fig. 1 Slave multi-fingered hand



(a) Network system through ISDN



(b) Transfer of wave variable

Fig. 2 Teleoperator system

(resolution of 128[P/R]) are built in this actuator, and it can drive finger joints directly.

In the experiments mentioned in section 4, the fingers are rearranged as shown in Fig.8. As seen from Fig.8, two fingers with 3 joints in the thumb and 3 in the index finger can realize the pinch movement on the 2D plane and can generate fingertip force of about 1.0[kgf]. Also, the linear slider with stroke of 300[mm] is combined with AC servo motor (100[W]) to move the hand up and down at the position of the wrist.

To measure the friction coefficient of the object and to display it to the operator through the tactile display are essential for the intuitive tele-grasping. Consequently, in this paper, the soft finger with tactile sensor and force-tactile display are described in section 3 and section 4 respectively.

2.2 Control System and Compensation of Time Delay

In this control system, real-time OS, VxWorks (Tornado) is adopted. The force-tactile display (master device) is connected to the target machine (MMX Pentium, 233[MHz]) for master, while the multi-fingered hand is connected to the target machine (MMX Pentium, 266[MHz]) for slave. In each computer, 16-bit A/D converter board, 12-bit D/A converter board, counter board, and so on are equipped. The computer (Pentium 4, 1.5[GHz]) is used as the host.

The network system is constructed as shown in Fig.2(a). ISDN is adopted as the communication channel. Though the slave should be normally placed at the remote site of 50[km] away from local site, it is set at the local site for the experimental reasons. Hence, the extra VxWorks machine at the remote site is utilized as the reflector of data transfer. ISDN router (RTA52i) establishes the PPP connection among the both site. Consequently, this network system can be functioned as a LAN with the exception of communication speed. Data communication between the master and the slave is executed at 512[Hz] via a UDP/IP connection.

One of most serious problem on the networked robotics is the unstable phenomenon caused by the time delay. Anderson and Spong ?) suggested a new communication architecture based on the scattering theory formalism to compensate for the time delay. Niemeyer and Slotine introduced a wave variable concept ?). The wave variable was utilized to characterize time delay systems and leading to a new configuration for force-reflecting teleoperation. In this study, these strategies are adopted. As shown in Fig.2(b), the wave variables generated by the velocity of master and the force of slave are transferred.

3. Soft Finger with Tactile Sensor

3.1 Skin and Mechanoreceptor

The slipperiness (frictional coefficient) can be identified by measuring the horizontal expansion and contraction (shear strain) along the surface of skin. Human being can perceive the frictional coefficients almost at the moment of contact by obtaining sufficient contact areas from the non-uniformity of the skin (the inner the softer) at the stage of grasping with small force ?). The mechanoreceptor that measures the shear strain of skin and perceives the frictional conditions is the Meissner corpuscles.

Nara et al. ?) investigated the roles of helical nerve axons of Meissner corpuscles. The coiled structure has a property of transforming of shear and stretch deformations of the elastic skin into stretch and shear deformations of the surface of the line of the coil. Thus, the transducers on the surface of the line of the coil can separately detect stretch and shear deformation of the elastic skin. Maeno et al. ?) found that the strain energy is concentrated at tactile receptor locations. And, they found

(a) Epidermis with fingerprint (silicone) (b) Dermis (silicone gel) (c) Bellows-type skin and coiled sensors

Fig. 3 Biomimetic soft finger with built-in tactile sensor

that the shape of the epidermal ridges/papillae influences the stress/strain distribution near the tactile receptors.

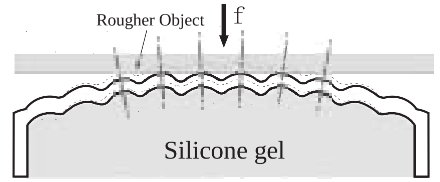
3.2 Sensor Structure and Detection Principle

Figure 3 shows the developed soft finger with a built-in tactile sensor. This soft finger has the curvature of 14[mm] and 34[mm] in the size of 20 × 30[mm]. First, taking account of the non-uniformity of the human skin, silicone rubber is used for the skin surface (epidermis) and silicone gel is used for the inside (dermis) (see Fig.3(a) and (b)). Also for the reason as mentioned later, the bellows-type structure with some dimples was formed on inside and outside of the skin 0.8[mm] thick (see Fig.3(c)). This fingertip unit is connected to the hand through a 6-axial force sensor (NANO5/4).

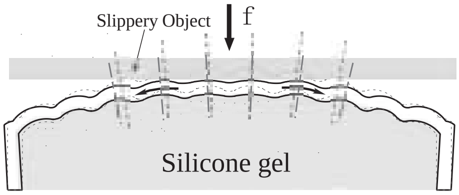
Next, from the spiral structure of the Meissner corpuscles, which is 150[μm] long and diameter of 40~70[μm], as shown in Fig.3(c), six coil springs (the length of 5[mm], the diameter of 2[mm]) with strain gauges are placed inside the soft finger as the tactile sensor. Also, the strain gauge is attached as shown in Fig.3(c) in order to measure the bend moment as the shear deformation of coil occurs.

The detection principle of developed tactile sensor is mentioned using Fig.4. When the frictional coefficient is large, since the convex section of bellows is stuck on the object, the horizontal stretch along the surface will be restricted (see Fig.4(a)). On the contrary, when the frictional coefficient is small, the horizontal stretch of silicone rubber will not be restricted (see Fig.4(b)).

For the increase of the internal pressure caused by the pressing motion of finger, 3D bellows-type structure changes into 2D plane structure as shown in Fig.4(b). In this study, it is considered that “bellows-type structure” is more important than the property of the stretch of the material itself in order to generate sensitive stretch of skin 7). As mentioned above, since the horizontal stretch of the epidermis generates depending on the friction with the object surface, the frictional coefficient can be estimated by measuring the shear strain of the coil installed inside.



(a) Rough object



(b) Slippery object

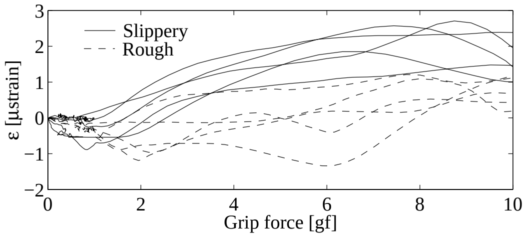
Fig. 4 Principle of detection of frictional conditions

3.3 Property Evaluation

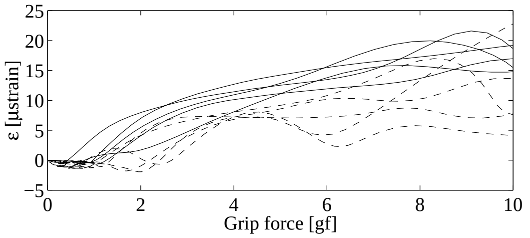
First, the basic property of the tactile sensor at the early stage of the contact starting to grasp is evaluated. The shear strain data ε obtained from the four gauges in Fig.3(c) are shown in Fig.5. The broken line represents the case when the frictional coefficient is large, and the solid line the case when the frictional coefficient is small (aluminum board with lotion on) . The grip force is denoted on the axis of abscissa.

As seen from the figure, the smaller the frictional coefficient is, the larger shear strain (absolute value) generates. Especially, the discrimination whether the object is rougher or more slippery is possible at the early stage when the grip force is small, and the frictional coefficient can be measured just after contact.

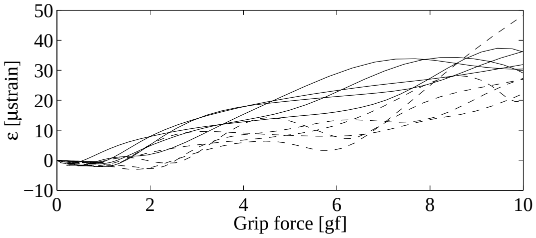
Figure 6 shows the variation of rate of shear strain $\dot{\varepsilon}$ from No.3 gauge and its spectrum analysis. As seen from Fig.6(a), the transition occurs gently in the case of low friction. On the other hand, in the case of high friction, the fluctuation caused by the stick-slip is observed. As seen from Fig.6(b), the significant frequency of stick-slip is about 5[Hz]. Consequently, the frictional condition can



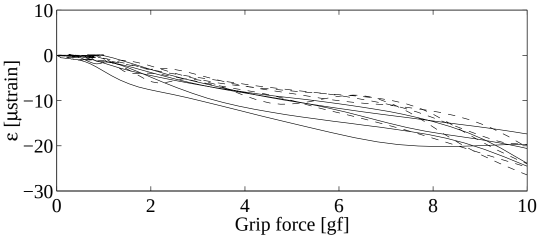
(a) Gauge no.2



(b) Gauge no.3



(c) Gauge no.4



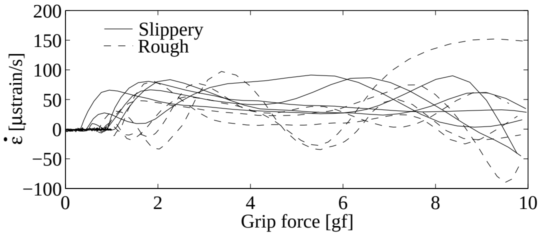
(d) Gauge no.5

Fig. 5 Variation of shear strain

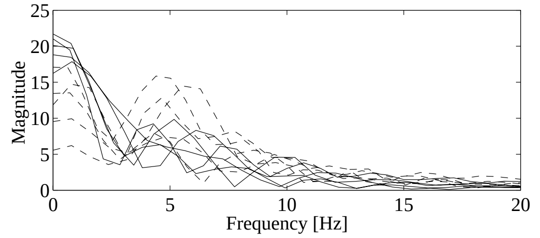
be estimated by this tactile information. And, this is consistent with the fact that the Meissner corpuscles responds to the rate of shear strain.

In the next experiment, the object is lifted up. After that the grip force is gradually decreased. Figure 7(a) shows the variation of shear strain ε from six gauges. Since the shear strain becomes zero at the center of contact, the center locates between No.3 and No.4 gauge. General speaking, it is difficult to detect the center of contact of soft finger. However, this tactile sensor can detect the frictional coefficient and the center of contact at once.

Figure 7(b) shows the variation of rate of shear strain $\dot{\varepsilon}$. As seen from this figure, the local slip propagates from the outside to the inside [7]. Finally, the object slips down. This tactile sensor can also foresee slip.

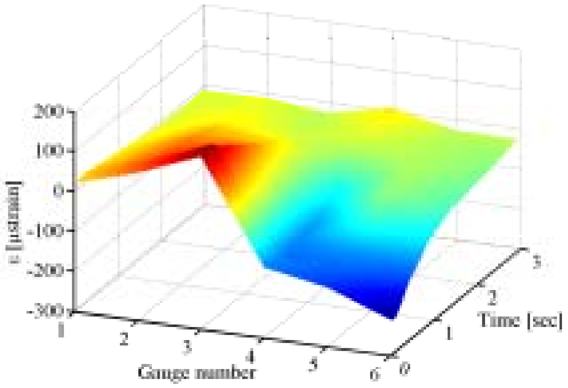


(a) Variation of strain rate

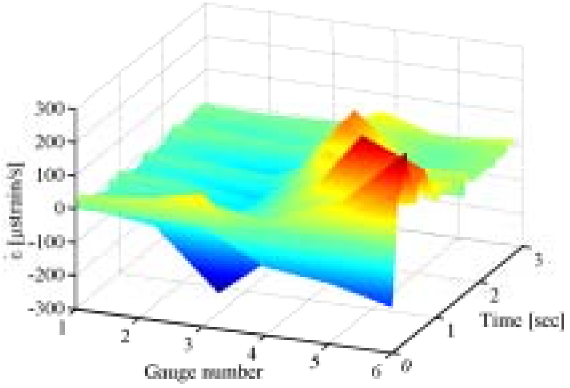


(b) Spectrum analysis

Fig. 6 Rate of shear strain



(a) Center of contact



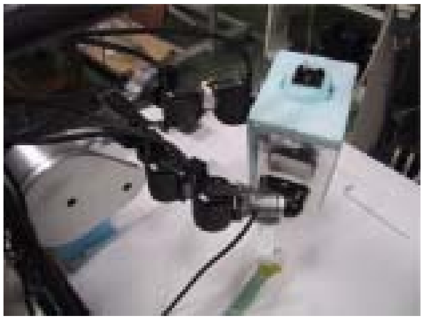
(b) Propagation of local slip

Fig. 7 Various detection

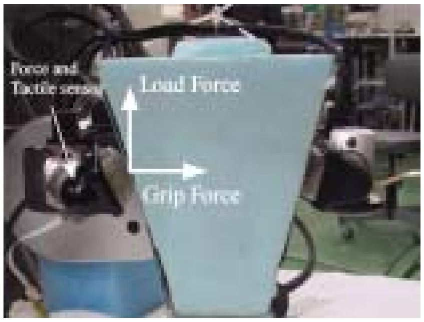
4. Multi-Fingered Hand for Telepresence

4.1 Tactile Oriented Task

In this study, it is considered to grasp and lift the tapered object as shown in Fig.8. The size of the object is 9[cm] and 3.5[cm] wide for upper and lower ends respectively, 15[cm] high, 6[cm] thick. The angle of taper



(a) Grasping condition



(b) Tapered object

Fig. 8 Experimental setup

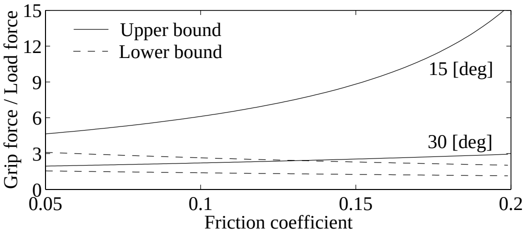
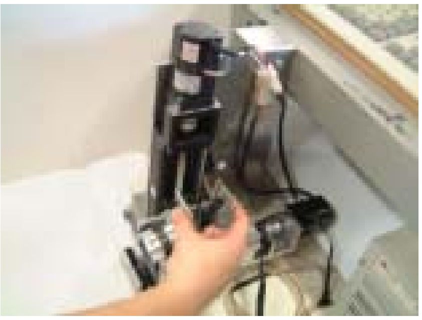
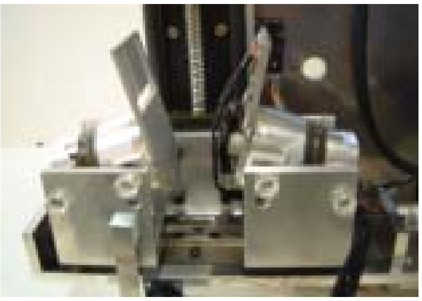


Fig. 9 Stability region for μ, γ



(a) Display system and grasping style (pinching)



(b) Close-up ultrasonic vibrator and force sensor

Fig. 10 Tactile and force display

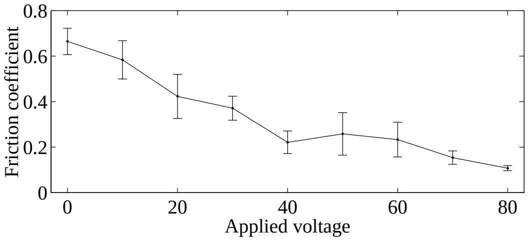


Fig. 11 Frictional coefficient

γ is 15[deg]. The object is made of styrene foam with an aluminum board on the surface, and by putting some weight on the object to 120[g] on order to set the center of the gravity low. Further, for the case when the frictional coefficient is small, lotion is put on the surface of the aluminum board.

Because the object is tapered, if the grip force is too large, the object slips upward. On the other hand, if the grip force is too small, the object is slipped down. Namely, as shown in Fig.9, this experimental task is that upper and lower bounds in addition to the rate of grip force and load force (vertical lifting force) exist. The axis of ordinate presents the rate of grip force and load force and the axis of abscissa the frictional coefficient μ. The upper bound is expressed as solid lines and the lower bound as broken lines. The lines are presented for the case that the angles of taper are 15[deg] and 30[deg] respectively. As seen from this figure, the smaller the frictional coefficient is, the narrower the stability region becomes and appropriate grasping adjustment is required. However, the range of the ratios of grip force and load force in which a human operator normally can apply is relatively large in the middle of the stability region.

4. 2 Tactile and Force Display

Given ultrasonic waves, the frictional coefficient reduces by the squeeze effect, between finger and oscillation surface, and the operator can feel as if touching something smooth and slippery [?]. The frictional coefficient can be controlled by regulating the amplitude.

Figure 10(a) shows the developed tactile and force display and grasping style (pinching). Two aluminum plates of 23×26×3[mm] on which the thumb and the index finger are placed display force and tactile sense simultaneously. This interface is customized for the experimental task described in section 4.1, so the aluminum plate is fixed a lean of 15[deg] as shown in Fig.10(b). These plates function as the force sensor, and they are connected directly to two ultrasonic vibrators mentioned later.

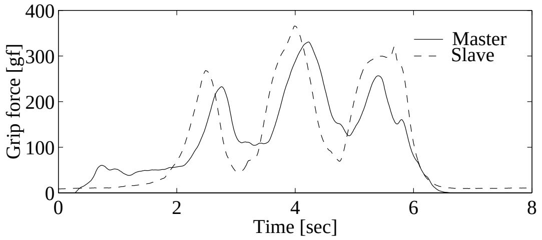


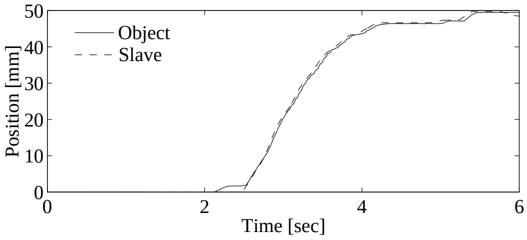
Fig. 12 Grasping without scattering

In order to display grip force and load force, the device has 2 degrees of freedom of horizontal and vertical. As to the vertical axis, the combination of linear guide (stroke of 100[mm], pitch of 6[mm]) and AC servo motor (50[W]) is adopted. On the other hand, as to the horizontal axis, the pinch movement (10 ↔ 80[mm]) is performed by driving right and left screw (pitch of 1[mm]) by AC servo motor (30[W]). The vertical and horizontal position resolutions are approximately 3.0[μm] and 0.5[μm] respectively.

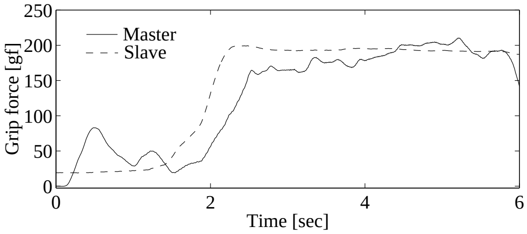
As shown in Fig.10(b), two ultrasonic vibrators ($\phi45 \times 54$[mm]) of resonance frequency of 40[KHz] were used as the source of oscillation, and they are driven by the power amplifier (10[MHz], 150[Vp-p]) through the high-speed D/A converter board with a built-in memory. Figure 11 shows the frictional coefficient and its standard deviation in the case of varying the applied voltage (40[KHz]). As seen from this figure, the frictional coefficient can be controlled within the range approximately from 0.1 to 0.7. Putting lotion on makes the aluminum board very slippery. In this study, the operator can feel as if touching slippery object with lotion on when the frictional coefficient of tactile display is set to 0.1 according to the tactile information obtained by the tactile sensor.

5. Experimental Result and Discussion

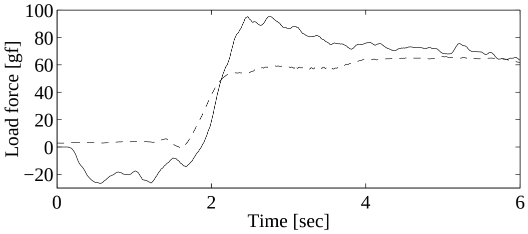
The experimenter instructs the subject to grasp and lift up the tapered object by leading the tactile and force information. At first, the experimental result without the compensation of time delay is shown in Fig.12. The lotion is not put on the surface, the frictional coefficient is large. The solid line denotes the operation force in the master side, and the broken line denotes the grip force of slave hand. The round-trip time delay was nearly 0.15[s]. As seen from this figure, the master-slave system was so unstable that the operator could not almost grasp.



(a) Position

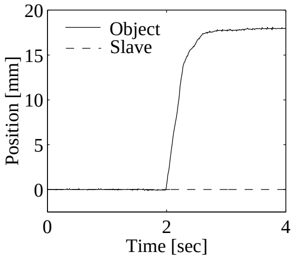


(b) Grip force

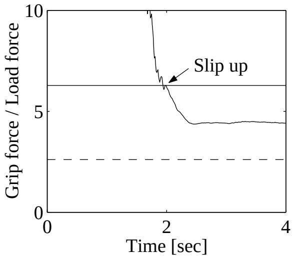


(c) Load force

Fig. 13 Grasping and lifting with tactile feedback

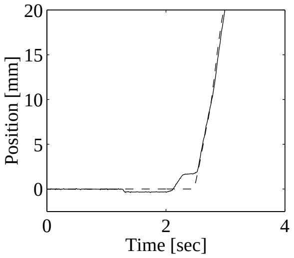


(a) Position

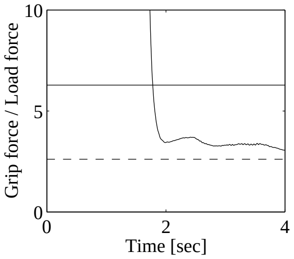


(b) Grip force/load force

Fig. 14 Without tactile feedback



(a) Position



(b) Grip force/load force

Fig. 15 With tactile feedback

Next, the teleoperation was executed under the compensation of time delay. In this experiment, the subject lifts the slippery object with lotion up to 5[cm] in about 2 seconds by the movement of the arm whose wrist is fixed. Figure 13 shows an example of results. Fig.13(a) represents the positions of the object and the fingertip of slave hand. And, Figs.13(b) and (c) represent the grip force and the load force, respectively. The solid line denotes the force in the master side, and the broken line denotes the force in the slave side. As seen from Fig.13(a), the object and the fingertip were on the same position, and no slip has occurred. As seen from Figs.13(b) and (c), the slippery tapered object can be stably lifted up the target position in 2 seconds under the slight vibration.

For comparison, the experimental results in the case without tactile feedback are shown in Fig.14. As seen from Fig.14(a), without feedback, the object slipped up before it was lifted. The values of upper bound and lower bound of the stability region become 6.3 and 2.6 respectively (see Fig.9) when μ is equal to 0.1, and are noted in Fig.14(b). Figure 14(b) shows the transition of the rate of grip force and load force. As seen from this figure, it notes that the grip force was excessive toward the load force at the slip-up point.

Figure 13 was rearranged as Fig.15. As seen from Fig.15(b), the rate of grip force and load force got in the stability region almost instantaneously, and achieved the stable and intuitive tele-grasping and lifting.

6. Conclusions

In this study, as teleoperation based on tactile sense, the task to grasp and lift up the slippery tapered object was discussed. The multi-fingered hand system for telepresence based on the tactile information was developed. The results of this study are summarized as follows:

(1) From a biomimetic viewpoint, the soft finger with the built-in compact tactile sensor was developed. Since the bellows-type silicone rubber skin is sensitively stretched depending on the frictional conditions, the slipperiness of the object can be estimated by measuring the shear strain by coil sensor.

(2) It was confirmed that the smaller the frictional coefficient is, the larger shear strain generates. By adopting non-uniform skin, the discrimination whether the object is rougher or more slippery was possible at the early stage when the grip force is small, and the frictional coefficient could be measured just after the contact.

(3) The developed tactile sensor can detect the center of contact on the soft finger and also foresee the whole slip by checking the local one.

(4) By the squeeze effect, the tactile information was displayed. Feeling of smooth and slippery could be obtained because the friction reduces. The frictional coefficient could be controlled in the range of 0.1-0.7.

(5) With the tactile feedback, the human operator could adequately regulate the coordination between the grip force and the vertical lifting force by utilizing the frictional information from the tactile display. Consequently, human skills (experience) could be successfully used in the intuitive teleoperation.

We will discuss displaying the real slippage of the object to the operator as a future work.

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References

1) A. Sano and H. Fujimoto: "New Evolution of Robotics to Network Society, " Systems, Control and Information, **44**–12, 710/715 (2000)
2) H. Fujimoto, A. Sano, and K. Okamoto: "Force-Reflecting Bilateral Teleoperation Through the Internet, " Journal of the Robotics Society of Japan, **18**–5, 713/720 (2000)
3) T. Oomichi, A. Maekawa, N. Kawauchi, and K. Ohnishi: "The Design of the Advanced Manipulator Applying under Harsh Condition -The Design Method of Multiple Sensory Bilateral Control for the Fingered Manipulator-, " Journal of the Robotics Society of Japan, **17**–5, 658/669 (1999)
4) Y. Yokokohji, Y. Iida, and T. Yoshikawa: ""Toy Problem "as the Benchmark Test for Teleoperation Systems, " Proc. of the 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems, 996/1001 (2000)
5) Y. Nakamura: "Control of Finger, " Journal of The Society of Instrument and Control Engineers, **30**–5, 395/399 (1991)
6) R.S. Johansson and G. Westling: "Roles of Glabrous Skin Receptors and Sensorimotor Memory in Automatic Control of Precision Grip When Lifting Rougher or More Slippery Objects, "Experimental Brain Research, **56**, 550/564 (1984)
7) B.B. Edin, R. Howe, G. Westling, and M. Cutkosky: "A Physiological Method for Relaying Frictional Information to a Human Teleoperator, " IEEE Transactions on Systems, Man, and Cybernetics, **23**–2, 427/432 (1993)
8) Y. Yamada: "Sensing Strategies before Grasping -Part 2 Detection of Slip and Static Friction Coefficient Used to Acquire Information on Surface Roughness, " Journal of the Robotics Society of Japan, **11**–7, 959/965 (1993)
9) S. Tei, T. Kawai, and T. Maeno: "Detection of Friction Coefficient using Strain Distribution of Semicircular Elastic Finger, "Proc. of JSME Annual Conference, (V), 235/236 (1999)
10) S. Sasaki, W.H. Sheong, K. Nakamura, and H. Shinoda: "Instantaneous Detection of the Friction Coefficient Using ARTC Tactile Sensor, "Proc. of SICE Annual Conference, 339/340 (1999)
11) Y. Iwamura: "Touch, "Igaku-Shoin Ltd. (2001)
12) R.J. Anderson and M.W. Spong: "Bilateral Control of Teleoperators with Time Delay," IEEE Transactions on Automatic Control, **34**–5, 494/501 (1989)
13) G. Niemeyer and J.J.E. Slotine: "Stable Adaptive Teleoperation, " IEEE Journal of Oceanic Engineering, **16**–1,

152/162 (1991)
14) H. Shinoda: "Intelligence in Human Skins, " Systems, Control and Information, **46**–1, 28/34 (2002)
15) T. Nara, T. Maeda, S. Ando, and S. Tachi: "A Theory of Skin's Orthogonal Deformation Detected by Mechanoreceptors, " Proc. of the Symposium on Biological and Physiological Engineering, 407/410 (2000)
16) T. Maeno, K. Kobayashi, and N. Yamazaki: "Relationship between Structure of Finger Tissue and Location of Tactile Receptors, " Transactions of the Japan Society of Mechanical Engineers (Part C), **59**–567, 881/888 (1997)
17) D. Yamada, T. Maeno, and Y. Yamada: "Design of Elastic Finger Having Distributed Tactile Sensors underneath Ridges of Finger Surface for Controlling Grasping Force, " Proc. of JSME Annual Conference on Robotics and Mechatronics, 1A1-C9 (2001)
18) T. Kawai, Y. Hirano, and T. Maeno: "Development of Strain Distribution Sensor Having Curved Surface for Grip Force Control, " Transactions of the Japan Society of Mechanical Engineers (Part C), **64**–627, 4264/4270 (1998)
19) T. Maeno, S. Hiromitsu, and T. Kawai: "Control of Grasping Force by Estimating Stick/Slip Distribution at the Contact Interface of an Elastic Finger Having Curved Surface, " Journal of the Robotics Society of Japan, **19**–1, 91/99 (2001)
20) T. Watanabe and S. Fukui: "Control of Tactile Surface-Roughness Sensation Using Ultrasonic Vibration, " Transactions of the Japan Society of Mechanical Engineers (Part C), **62**–596, 1329/1334 (1996)

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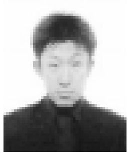
Kosuke Nishi



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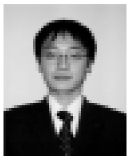
Hideki Miyanishi



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