Proceedings of the 2001 IEEE
International Conference on Robotics & Automation
Seoul, Korea • May 21-26, 2001

Proposal of A SkilMate Finger for EVA Gloves

YAMADA, Yoji, MORIZONO, Tetsuya, SATO, Shuji,
SHIMOHIRA, Takahiro, UMETANI, Yoji
Toyota Technological Institute,
2-12-1, Hisakata, Tempaku, Nagoya 468-8511, Japan
yamada@toyota-ti.ac.jp

YOSHIDA, Tetsuji, AOKI, Shigeru
Shimizu Corporation,
3-4-17, Etsunakashima, Koto-ku, Tokyo 135-8530, Japan

Abstract

It has been pointed out that the hard structure of an EVA glove deteriorates e±ciency of tasks in the space environment. We also found a claim that an EVA glove did not allow an astronaut to acquire contact information at the ¯ngertips. In the study, we proposed a SkilMate Hand for space EVA gloves which has both a tactile media and a power assist devices. We locate SkilMate in a wider framework of wearable intelligent machines which assist in a®ording such working surroundings that they can exhibit their skills in spite of their necessity for wearing special suits typically in hazardous environments. The paper focuses on the development of a ¯nger system of a SkilMate Hand, and begins with determination of the design guidelines through analyses from an interview with an astronaut. To improve the task e±ciency, we manufacture a power assist device which compensates the bending moment exerted at a human ¯nger joint utilizing an ultrasonic motor. We show the structure and the control strategy of the motor drives. To overcome the second problem of tactile insensibleness, we produce a tactile media device which is composed of a slip sensor element on the outer side and a vibrotactile display element on the inner side of a SkilMate Hand. Transduction characteristics of both pressure sensitive conductive rubber and piezo-rubber are experimentally examined in the low temperature region. Finally, piezo-rubber is chosen to be used as a slip sensing transducer. Such a proposal of a wearable intelligent machine as that of a SkilMate with its concept has not been o®ered, and moreover, the technical argument about temperature dependence of tactile sensing performance has not been intensively made so far in the ¯eld of robotics.

1 Introduction

Experts need to wear special suits to protect themselves under hazardous environments. Consequently, they cannot exhibit the skills that they are inherently equipped or have acquired in their long experience. To overcome the problem we have proposed to attach wearable intelligent machines to heavy working suits taking aim at recovering the skills that the experts should be able to display. We conceptually referred to this category of intelligent machines as SkilMate[1].

One of the typical environments where we need to apply such a SkilMate technology is space. A number of EVAs (extravehicular activities) so far have proved that various tasks in space require the skills of astronauts who need to wear spacesuits to protect themselves from such hazardous conditions as vacuum, high/low temperature, micrometeoroids, and so on. Obviously, a spacesuit has some disadvantages from the viewpoint of EVA task e±ciency which originates in the heavy-armed structure for the protection capabilities. Hand fatigue is one of the major concerns, and several studies on the development of power-assisted space suit gloves have been already reported.

One of the earliest research and development was conducted by Main et al.[2]. They not only proposed to provide a power assist mechanism to help the astronaut overcome the inherent sti®ness of the glove, but also explored what kind of pneumatic actuator design enabled to produce su±cient magnitude of bending force for four independent MP (metacarpophalangeal) joints even when a space

0-7803-6475-9/01/$10.00

suit was pressurized. Later, Sorenson et al. [3] made a more practical approach in which the integrated design strategy of both a space suit glove and power assist hardware and software were described. The strategy was characterized by that the inherent closing torque about the MP mobility joint when the glove was pressurized was compensated by applying a tension along a spectra cable run on the exterior of the glove and connected to a power assist DC motor. They reported initial test results of the prototype system and concluded that their development was promising. More recently, Shields et al. (the same group as [2] with Prof. Strauss) reported extensive work on the development of another anthropomorphic hand exoskeleton system for assisting MP and IP (interphalangeal) joints of the pointing through the index ¯ngers[4]. The system consists of three ¯ngers driven by DC motors in which the third assists both a ring and an index human ¯ngers, and the authors stress the importance of kinematically designing the mechanical system to have the appropriate instant centers which coincide with the centers of rotation of the wearer's ¯nger joints.

How to simplify the power assist mechanism is discussed in every report because of the limited space of EVA gloves. Moreover, there is a further question of whether power assistance is only required from the viewpoint of enhancing EVA task e±ciency. For clarifying these problems of the EVA gloves that are developed and used under current technology, we made an interview with a Japanese astronaut who is an EVA specialist, The tasks for which he used his hands and the corresponding hand movements were analyzed in detail and through this interview, we identi¯ed the problems on EVA gloves. They were not only that they caused hand fatigue but also that they deteriorated tactile sensation at the wearer's ¯ngertips. We have proposed an initial solution of a SkilMate to a power assistance of a space suit[1]. However, support for displaying contact information is missing in the initial development and the use of pneumatic actuators for power assistance is less practical in space from the viewpoint of the power supply equipment, safety, and so on.

The study is directed to the development of a SkilMate Hand for an EVA glove which is considered to be the most important part to be improved in a space suit. The paper focuses on determining the design guidelines of the SkilMate Hand, and manufacture of a power assist device for an MP joint of a SkilMate Finger with its position control based schemes, and examination of contact force transducers in the extremely high/low temperature region. Such a proposal of a wearable intelligent machine as that of a SkilMate with its concept has not been o®ered, and moreover, the technical argument about temperature dependence of tactile sensing performance has not been intensively made so far in the ¯eld of robotics.

2 Design guidelines

In addition to the basic design policy described in the introduction, we set design guidelines concerning both devices of power assist and tactile media for developing a SkilMate Hand.

An EVA glove consists of 3 layers; a bladder, a restraint, and a thermal micrometeoroid protection garmament (TMP) layers[5]. The intermediate restraint layer limits the volume of the inner bladder layer which is expanded due to the ballooning e®ect. Tightly covering the bladder layer with mesh resins excluding the volume around ¯ngertips causes resistive movements especially at MP joints of a wearer. This motivates such a development as a power-assisted EVA glove for the wearer's MP joints[3]. Moreover, it is also revealed from our interview with the astronaut that he is more likely to use the major three ¯ngers, thumb, pointing and middle ¯ngers, than the remaining ring and little ¯ngers. The reason behind this tendency is that the two ¯ngers are not used so frequently as the major three ¯ngers are because the two ¯ngers are usually kept retained in order not to cause too much fatigue preparing for such kind of complex tasks that are composed of more than one sub-task where the use of the two ¯ngers are indispensable. For example, the task for hooking a terminal ga® of a tether is composed of not only the hooking motion utilizing the three major ¯ngers but a very important push-button motion which can be conducted only by using the ring and the little ¯ngers at the same time.

From the above consideration, we determined the design direction of the proposed device as power-assisting the wearer's thumb, pointing and middle ¯ngers. In detail, the joints to be assisted are the MP joints of the pointing and middle ¯ngers for their °exion and extension movements, and the CM (carpometacarpal) joint of the thumb for its opposition movements to the little ¯nger.

It is desirable, on the other hand, that contact information at EVA glove ¯ngertips be transmitted to the wearer as some tactile sensation. It is true that an astronaut does not conduct ¯rm grasp in most situations, i.e. he/she tends to hold objects as light as possible, and even a simple touch sensation is very helpful. Moreover, there came out an evident claim that the astronaut often needed to con¯rm his object grasp by his observation in the eyes when he tried holding and rotating eg. a disc-shaped switch. Therefore, it is also very important to transmit slip information, which requires installation of both object slip detecting and slip sensation displaying functions on an SMF. This is a unique approach to integrating a tactile sensor and a display in marked contrast to the pioneer work on transmitting vibratory information for inspection, exploration, and manipulation tasks in teleoperation [6].

3 Power assist device of a SkilMate Finger

In the paper, we focus on the development of a ¯nger system of the SkilMate Hand, which we refer to as an SMF (SkilMate Finger).

3.1 Structure of the power assist device

The proposed structure of the power assist device part of the SMF is shown in Figure 1. The device consists of both an inner and an outer components which correspond to a master and a slave ones respectively in a unilateral control system.

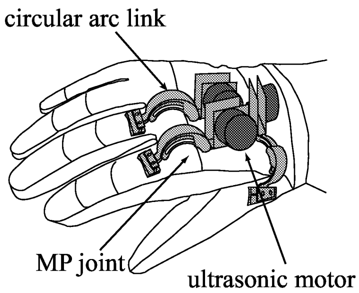

Figure 1: Proposal of a SkilMate Hand for space-suits

The inner component by which the MP joint angle of the wearer's ¯nger (eg. the pointing ¯nger) is detected consists of a very small optical encoder(Alpha Giken Co., 012-125BIIT, 12 mm £ 12 mm £ 25.5 mm) and a spiral leaf spring. A steel wire one end of which is attached to the spring is tightened and ¯xed at two di®erent points from each other across the dorsal MP joint of the wearer's ¯nger. The wire is extended as the distance between the two ¯xed points gets longer in a °exion movement of the MP joint. The spring constant measured when the wire is pulled against the restoring force of the spiral leaf spring is at most 0.3 N/mm which is negligible for the wearer to move his/her MP joint. The spring reels up the wire in the MP joint extension movement. Figure 2 is the photograph of the inner component. Face fastener tapes are used as attachments.

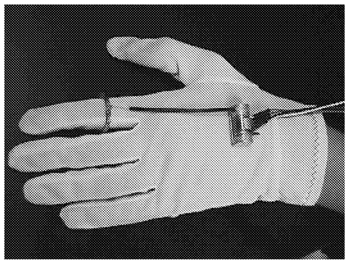

Figure 2: Photograph of the inner component

The actuator used in the outer component is a small ultrasonic motor that is promising to be used in space[7]. The joint structure of the outer component has a circular arc with 15:5 mm radius as is shown in Figure 3. It is covered by another coaxial outer circular arc link with 17:5 mm radius which slides along the arc by using a steel belt driven (pushed and pulled) by the ultrasonic motor. The circular arc covers the wearer's MP joint so that the displacement of the center of rotation of the wearer's MP joint is taken into account.

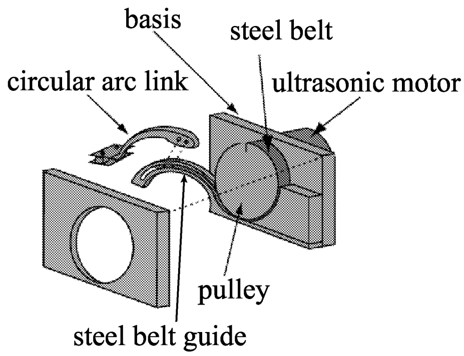

Figure 3: Joint structure of the ¯xture covering the wearer's MP joint to have a coaxial center with the joint rotation

Figure 4 is the photograph of illustrating structure of the outer component with an ultrasonic motor. It also has an optical encoder to detect the rotary angle of the motor, and the size of the motor is 30 mm in radius with 25 mm in height. The maximum output torque of the ultrasonic motor (Shinsei Industry Co., MODEL USR30-S3) currently mounted on the setup is on the order of 10^{i1} Nm. It is to be replaced with another type the maximum toque of which is nearly 10 times higher[12].

Figure 4: Experimental result of the ultrasonic motor position control

3.2 Control of the assist device

The coaxial circular arc sliding motion of the outer component is controlled basically in a position control mode, i.e. the joint angle of the coaxial circular arc link is controlled to match that of the wearer's MP joint. Figure 5 is a sample of the experimental results for demonstrating the position control scheme. The motion response is fast enough to drive the mechanism.

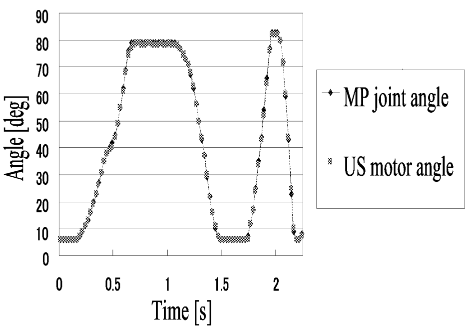

Figure 5: Experimental result of position control

We also prepare another control mode called phase-lock control mode to ¯x the angular position of the joint sub-mechanism taking the advantage of the high holding torque of the ultrasonic motor into condition. Hand fatigue is considered to originate partially in the situation where the astronaut needs to maintain his/her the con¯guration of ¯rm grasp for holding grip of some tools making resistance to the bending torque of the original EVA glove to recover to the initial (natural) ¯nger con¯guration. The ultrasonic motor is controlled to hold the position stably when the detected MP joint angle on the master side deviates within a small amount of threshold value ¢μ_M for a certain interval $T_{¢\mu_M}$. The phase-lock control mode is canceled when the MP joint angle deviates more than ±L while the motor is locked, which corresponds to the torque required for the astronaut to move his/her MP joint.

Figure 6 shows the experimental result of demonstrating the normal operation in the phase-lock control mode. It is seen that the angle of the joint mechanism follows the referential angle of the wearer's MP joint. On the other hand, the rotary motion of the motor is commanded to stop after $T_{¢\mu_M}$ of the stable output data from the wearer's MP joint angle. The motor is commanded to restart rotating when the angular difference ¢μ between the wearer's MP joint and the joint of the outer component exceeds ¢μ_M (which is set to 5 deg: in our experiment).

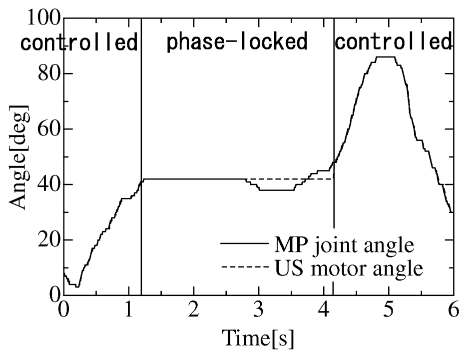

Figure 6: Position data in the position-controlled phase and the locked phase

4 Tactile media device

As was previously stated in section 2, it is helpful to provide an EVA glove with such a tactile media device, a set of both a tactile sensor and a display element, as to transmit tactile information from the outer surface of the glove to the inner, wearer's bare ¯nger pad.

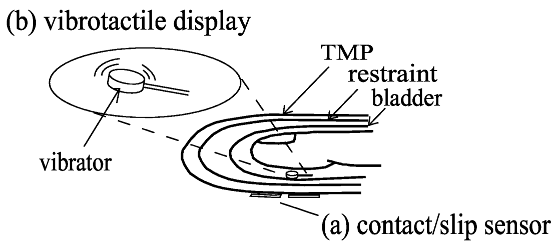

Figure 7: Tactile media device

Figure 7 illustrates the structure of the tactile media device to be incorporated in the SMF. We propose to attach a tactile sensor element to the outer surface of the TMP layer and a tactile display element on the inner surface of the bladder layer at around the SMF ¯nger pad. The outputs from the tactile sensor element are binary-coded by setting up certain thresholds to the outputs so the sensors function as having touch sensing capability. It is well known that displaying vibrotactile sensation in a manner of sensation substitution is the most sensible in various kinds of tactile sensation[8]. In the following subsections, we describe the details on the tactile media device: Main issue is on the temperature dependence of the tactile sensing function especially in the lower temperature region below zero for space use, because hardening of the sensor materials becomes a serious problem in the region far below zero in contrast to high temperature region.

4.1 Tactile sensing performance in the low temperature region

4.1.1 Selection of transducers

It is desirable to use rubber-based functional materials with a contact force transduction capability because they are sturdy and yet have high potential for ¯tting the curved surface of EVA glove ¯ngertips. We selected two kinds of rubber-based transducers from which analog contact force signals can be generated; pressure sensitive conductive rubber (abbreviated as PSCR. Yokohama Image System Co.[9]) and piezo rubber (abbreviated as PR. NGK Spark Plug Co.[10]).

It is anticipated that the transduction performance of the PSCR theoretically deteriorates in the lower temperature region because the quench hardening e®ect causes less change in strain and thus resistance in the thickness direction because the resistance is a function of normal strain.

On the other hand, PR is expected to function even in the low temperature region because the transducing mechanism is caused by a change in not stain but stress of a PR sheet in the thickness direction. A PR sheet is made by mixing the powder of piezo material into a silicone rubber layer in the molding stage and the layer is held between two electrode layers made of silver. The stress exerted in the rubber layer when it is loaded induces a certain amount of electric charges by the piezoelectric e®ect. Since we detect not charges themselves but current which is dependent on the stress rate applied to the PR sheet (similar to PVDF ¯lm transducers[11]), we can easily obtain dynamic contact force information such as slip by detecting the amount of charge generation.

4.1.2 Experimental setup for examining the transduction characteristics

Figure 8 overviews the experimental setup for examining the transduction characteristics of the 2 kinds of transducers especially in the low temperature region. The setup is composed of a Dry Ice-ethanol-bath and a transducer sheet of either PSCR or PR followed by their respective primary detecting circuit. Mixing ethanol with Dry Ice (carbon dioxide snow) cools the inside of the bath in which the transducer sheet is inserted down to ¡70 ℃. The primary detecting circuit of the PSCR transducer is a bridge circuit in which two resistors out of four are PSCR sheets: one for balancing the temperature-dependent change in resistance of the other. The bridge circuit is exposed to the atmosphere for acquiring pressure information. The differential voltage from the bridge circuit is properly ampli¯ed at the secondary circuit which is located outside of the container. In the case of PR, only the transducer sheet is set inside the bath. The sheet is 1:2 mm thick and pectinate with 1 mm pitch. The detecting circuit located outside of the bath is primarily a di®erential OP ampli¯er which is followed by a 2nd order Butterworth low pass ¯lter of 10 Hz cut-o® frequency.

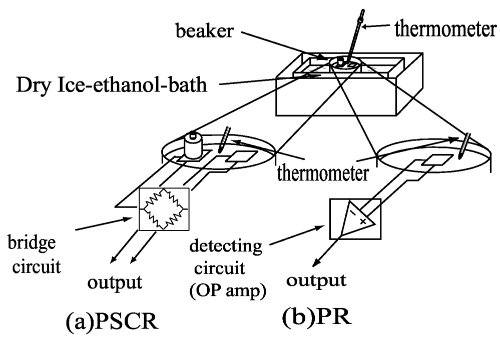

Figure 8: Experimental setup for examining contact force transduction characteristics in the low temperature region for (a)PSCR (pressure senstive conductive rubber) and (b)PR(piezo-rubber)

4.1.3 Experimental results

The temperature dependence of the PSCR transduction performance is shown in Figure 9 where both cases of 1N-load/no-load are applied on the

PSCR transducer. The left rising characteristics of the output voltage in the lower temperature region come from the slight di®erence of resistance of the two PSCR sheets (one for pressure detection and the other for temperature compensation). It should be noted that it is quite di±cult to produce many pairs of PSCR sheets while making two resistance values in each pair precisely coincide with each other. We can also see some hysteresis in the cool-down, warm-up cycle of the experiment. The hardening e®ect of the PSCR sheet is examined to appear at around ¡60 ℃.

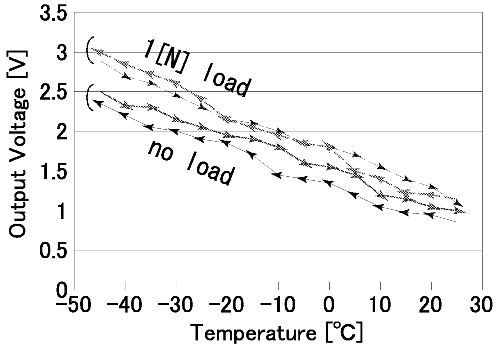

Figure 9: Temperature-dependent characteristics mainly in low-temperature region (PSCR)

The output signals of the PR transducer circuit are depicted in Figure 10(a) in which the temperature was kept at 25 ℃, and (b) at ¡45 ℃. The experimental condition was that an object (insulated force sensor probe with 12mm edge) was slid on the transducer sheet surface approximately from 2 s to 5 s in the graph. Meanwhile, a constant normal force of 1 N is applied. The experimental result shows that the PR transducer is capable of detecting contact/slip phases even at ¡45 ℃ because one can easily determine the threshold for isolating them.

The results of the above two experiments lead us to conclude that PR transducers are more promising for us to use because:

1) In the PSCR case, it is hard to su±ciently compensate the deviation of the bridge circuit output which depends on the temperature.

2)Slip information is very important in practice and a PR transducer normally operates at ¡45 ℃.

4.2 Slip sensation display

The contact/slip signal detected from the PR transducer element which is mounted on the outer surface of an SMF is processed by a peak holding circuit to generate a binary coded contact/slip phase. This triggers a small DC motor vibrator

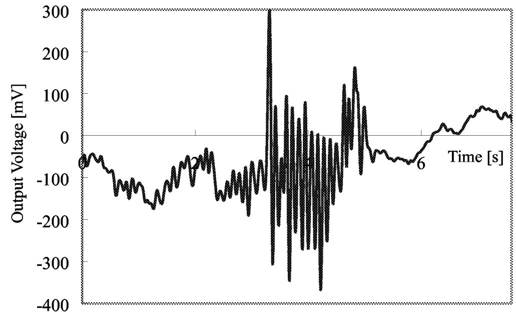

Figure 10: (a)Output signal of the PR transducer circuit when operated at 25 ℃.

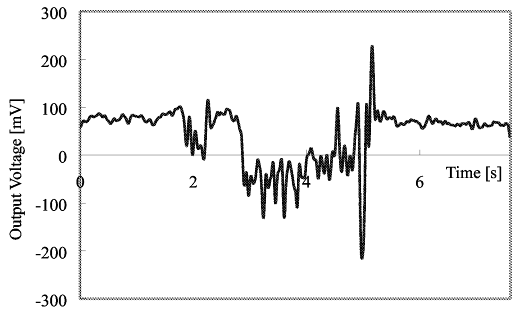

Figure 11: (b)Output signal of the PR transducer circuit when operated at -45 ℃.

which is attached in turn to the inner surface of the bladder.

5 Conclusion

In the study, we proposed a SkilMate Hand for space EVA gloves which has both power assist and tactile media devices. The paper focuses on the development of a ¯nger system of the SkilMate Hand, and is summarized in the following three items.

(1) We determined the design policy for developing the SkilMate Hand taking into account both the opinions from an astronaut and the structure of the current EVA gloves. It was desirable that a power assist device be mounted on TM joint of the thumb and MP joints of both the pointing and middle ¯ngers. The design policy also involved installation of a tactile media device for acquiring contact/slip information at EVA glove ¯ngertips.

(2) Following the above policy, we ¯rstly manufactured a power assist device for an MP joint movement which covers the wearer's dorsal joint from outside of the EVA glove and has the coaxial center of rotation with the joint axis.

The device was driven by a small ultrasonic motor which was controlled under both position control and phase-locked control modes.

(3) Secondly, the development process of the tactile media device was described, in which the applicability of the two kinds of contact force transducers was examined in the low temperature region below zero was examined. We decided to use a piezo rubber transducer which could generate slip signals even in the temperature region down to ¡45 ℃, while the other pressure sensitive conductive rubber was hardened. Finally, the normal operation of the tactile media device, from the contact/slip detection signal to displaying vibrotactile sensation using a small DC-motor vibrator, was experimentally con¯rmed.

The ongoing work includes redesign of the Skil-Mate Fingers for applying them to ¯tting the individual thumb, pointing ¯nger and middle ¯ngers and replacement of the ultrasonic motors with higher torque. It is interesting as future work to examine the ¯nal setup in the simulated space environment taking the drastical and cyclic change in the temperature into consideration, in addition to the di®erence of the atomospheric pressure between inner and outer sides of an EVA glove [13]. This attempt will also supply to us the practical information on the lowest temperature which we need to deal with, while we limited it to ¡45 ℃ in the study.

Acknowledgment

The authors are grateful to the Astronaut Dr. Doi at NASDA for his helpful advice in the beginning stage of the study. The research has been fully supported by NEDO(New Energy and Industrial Technology Development Organization) under METI and partly by High-tech Research Center project under MECSST, Japan.

References

[1] Y. Umetani, Y. Yamada, T. Morizono, T. Yoshida, S. Aoki, \Skil Mate", Wearable Exoskeleton Robot, Proc. of IEEE Int. Conf. on SMC, Tokyo, pp.984{988, 1999

[2] John A. Main, S. W. Peterson, A. M. Strauss, A Prototype Power Assist EVA Glove, Publ. Soc. Automot. Eng., sp{872 , pp.85{93, 1991

[3] E.A. Sorenson, R. M. Sanner, R. D. Howard, D. L. Akin, Development of a Power-Assisted Space Suite Glove Joint, SAE Tech. Pap. Ser. (Soc. Automot. Eng.) SAE{972323, pp.7{12, 1997

[4] B. L. Shields, J. A. Main, S. W. Peterson, A. M. Strauss, An Anthropomorphic Hand Exoskeleton to Prevent Astronaut Hand Fatigue During Extravehicular Activities, IEEE Trans. on Systems, Man, and Cybernetics, Vol. 27, No. 5, pp.668{673, 1997

[5] David A.Nice, Development of the Hermes EVA Space Suit Glove, SAE Tech. Pap. Ser. (Soc. Automot. Eng.), pp.826{846, 1992

[6] D. A. Kontarinis, R. D. Howe, Tactile Display of Vibratory Information in Teleoperation and Virtual Environments, PRESENCE, 1995

[7] Yoseph Bar-Cohen, Xiaoqi Bao, and Willem Grandia, Rotary Ultrasonic Motors Actuated by Traveling Flexural Waves, Proc. of SPIE's 6th Annual Int. Symp. on Smart Structures and Materials, Newport CA, No.3668{63, pp.1{7, 1999

[8] R. T. Verrillo, Psychophysics of vibrotactile stimulation, J. of Acoustic Society of America, Vol.77, pp.225{232, 1985

[9] Yokohama Image System Co., Pressure Sensitive conductive Rubber, http://www.y-i-s.co.jp/CSAEnglish.htm,

[10] NGK Spark Plug Co. Ltd., NTK Technical Ceramics Division, NTK Piezo-Rubber, Piezoelectric Flexible Composite

[11] Howe, R. D., Cutkosky, M. R., Dynamic Tactile Sensing: Perception of Fine Surface Features with Stress Rate Sensing IEEE Trans. on Robotics and Automation, Vol.9, No.2, pp. 140{151, 1993

[12] T.Nagaya, H. Mukai, T. Yamamoto, Development of High Power Ultrasonic Automobile Motor Element, Proc. of the Annual Meeting of Society of Automotive Engineers of Japan, No.76{9939992, pp.1-2, 1999

[13] E.A. Sorenson, R. M. Sanner, C. U. Ranniger, Experimental Testing of a Power-Assisted Space Suite Glove Joint, Proc. of IEEE Int. Conf. on Systems, Man, and Cybernetics, Vol. 3, pp.2619{2625, 1997