PAPER

Tiny Feel: A New Miniature Tactile Module Using Elastic and Electromagnetic Force for Mobile Devices

Tae-Heon YANG[†], **Sang-Youn KIM**[††], **Wayne J. BOOK**[†††], ***Nonmembers, and*** **Dong-Soo KWON**[†a)], ***Member***

SUMMARY For tactile feedback in mobile devices, the size and the power consumption of tactile modules are the dominant factors. Thus, vibration motors have been widely used in mobile devices to provide tactile sensation. However, the vibration motor cannot sufficiently generate a great amount of tactile sensation because the magnitude and the frequency of the vibration motor are coupled. For the generation of a wide variety of tactile sensations, this paper presents a new tactile actuator that incorporates a solenoid, a permanent magnet and an elastic spring. The feedback force in this actuator is generated by elastic and electromagnetic force. This paper also proposes a tiny tactile module with the proposed actuators. To construct a tiny tactile module, the contactor gap of the module is minimized without decreasing the contactor stroke, the output force, and the working frequency. The elastic springs of the actuators are separated into several layers to minimize the contactor gap without decreasing the performance of the tactile module. Experiments were conducted to investigate each contactor output force as well as the frequency response of the proposed tactile module. Each contactor of the tactile module can generate enough output force to stimulate human mechanoreceptors. As the contactors are actuated in a wide range of frequency, the proposed tactile module can generate various tactile sensations. Moreover, the size of the proposed tactile module is small enough to be embedded it into a mobile device, and its power consumption is low. Therefore, the proposed tactile actuator and module have good potential in many interactive mobile devices.
key words: *tactile actuator, miniature actuator, solenoid, tactile display, haptics*

1. Introduction

Currently, to increase the size of a visual display unit, the mechanical keypad has been replaced by a touch screen. While visual information is the most dominant sensory input for perceiving an object, haptic information coupled with visual information increases the sense of reality. Especially in mobile devices, haptic feedback is regarded as one of the dominant factors for increasing the degree of realism or immersion because the size of the visual display unit in these devices typically does not adequately provide users with realistic and exciting sensations. A user can communicate and/or interact with a mobile device efficiently by adding haptic information to auditory and visual information.

Manuscript received August 12, 2009.
Manuscript revised March 12, 2010.
[†]The authors are with the Department of Mechanical Engineering, KAIST, Daejeon, 305–701, Republic of Korea.
[††]The author is with the Department of Computer Science & Engineering, Korea University of Technology and Education, Cheonan, 330–708, Korea.
[†††]The author is with the Department of Mechanical Engineering, Georgia Institute of Technology, Atlanta, 30332, the United States.
a) E-mail: kwonds@kaist.ac.kr
DOI: 10.1587/transinf.E93.D.2233

Many haptic actuators that directly provide force or distributed pressure are too bulky to be inserted into a mobile device. Therefore, for mobile devices, haptic researchers have focused on stimulating the skin of users. There are four major mechanoreceptors (the Meissner corpuscle, Merkel's disk, the Ruffini ending, and the Pacinian corpuscle) in human glabrous skin. Merkel's disk responds to quasi-static deformations of the skin such as force or displacement in the frequency range of 0.4 Hz to 3 Hz [1]. It plays an important role in detecting spatial structures in a static contact, such as detecting an edge or a bar. The Ruffini ending responds to buzz-like sensations in the frequency range of 100 Hz to 500 Hz [1]. The Meissner corpuscle, which is activated in the frequency range of 2 Hz to 40 Hz, detects dynamic deformations of the skin such as the sensation of a flutter [1]. The Pacinian corpuscle, which is activated in the frequency range of 40 Hz to 500 Hz, detects acceleration or vibration [1]. A vibrotactile signal is useful for stimulating human skin in mobile devices, because vibrotactile motors have already been applied in many commercial mobile devices.

There have been many instances of fruitful research works using vibration motors as a media for delivering haptic information to users. A. Chang et al. developed a mobile system (ComTouch) for providing vibrotactile feedback coupled with auditory information [2]. The ComTouch system allows rich communication among users by converting hand pressure into vibrational intensity. I. Oakley et al. developed a hardware platform in which a user provides a command to a device with a motion sensor [3]. In their system, a user senses vibrotactile feedback according to scrolling and/or tilting motion. Immersion Corporation developed the VibTonz® system that generates vibrotactile sensation [4]. Although the VibTonz® system presents a favorable method to increase the quality of communication, current commercial vibration motors cannot sufficiently express the robust haptic feedback offered by the VibTonz® system. Commercial eccentric motors generate vibration using an electromagnetic and centrifugal force. As an unbalanced mass in the eccentric motor rotates while interacting with a permanent magnet, the intensity of the vibration is coupled with the frequency, and the respond rate to stimulate the finger of the user is slow. Therefore, the use of the eccentric motor limits the ability to discriminate diverse vibrotactile sensation.

To generate a variety of tactile sensations, researchers have focused on developing new haptic actuators. Samsung Electro-Mechanics developed a new linear vibration motor to improve the response rate [5]. Y.Y. Mizukami and H. Sawada proposed a muscle wire actuator using an SMA (a shape-memory alloy) [6]. The muscle wire actuator was well designed with consideration given to the size, the working frequency and the power consumption. However, since the actuator generates only vibrotactile sensation for stimulating Pacinian corpuscles, it can hardly create detailed texture in a small-scale shape. In order to overcome this limitation, several research works have been made to develop pin-array type tactile actuating systems that can selectively stimulate human mechanoreceptors. I. Poupyrev et al. embedded piezo-actuators into mobile devices [7]. To increase the stroke of piezo-actuator, M. Wagner et al. developed a helically wound PZT ceramic actuator, helimorph [8]. Since these actuators can actuate over a broad bandwidth, these actuators can convey various tactile sensations such as the clicking of a button, the surfing of menus, and exploration of a rough surface.

Although the haptic sensation by vibrotactile actuators improves usability and/or immersion in mobile devices, the vibrotactile actuators scarcely generate a detailed texture and/or a small scale shape. In order to overcome this limitation, several attempts have been made to develop pin-array type tactile actuating systems that can selectively stimulate human mechanoreceptors. C.R. Wagner et al. developed a tactile actuation system that used servo motors to operate a mechanical pin-array device [9]. Q. Wang and V. Hayward developed a pin-array type tactile transducer system that generates a relatively large lateral skin deformation by adjusting the cantilever mechanics [10]. S.Y. Kim et al. developed a compact pin-array type of a tactile display unit using piezoelectric bimorphs and attached it to a PHANToMTM haptic device [11]. Moreover, they presented an area-based haptic rendering method which provides kinesthetic and the tactile sensation to human operators. K.U. Kyung and J.S. Park developed a miniature pin-array tactile module with ultrasonic linear actuators and a pen-like tactile display (Ubi-pen) using a module [12]. In their system, nine ultrasonic linear actuators are arranged to provide texture and vibration. R. Velazquez et al. presented a pin-array tactile actuating system with an SMA (shape memory alloy) coil and a permanent magnet [13].

Despite the fruitful research in the development of various pin-array tactile modules, it remains difficult to embed them into mobile devices due to their size and large power consumption. In the consideration of size and power consumption, a haptic switch [14] using electroactive polymers was developed for a small-size device. However, it is not easy to generate a variety of tactile sensation with the haptic switch because its maximum working frequency is not fast enough to stimulate Pacinian corpuscles. For mobile devices, a tactile module should be designed that takes into account the small size, low power consumption, low weight, and performance measures (pin stroke, output force, and working frequency) of these devices. For haptic feedback in mobile devices, this paper presents a new miniature tactile actuator that consumes a low amount of power. Moreover, this paper suggests a tiny tactile module using the proposed tactile actuators.

2. Design of a New Miniature Tactile Actuator

The objective of this work is to develop a tactile module which can create a variety of tactile sensation. In order to provide various tactile sensations, human's mechanoreceptors need to be selectively stimulated. Every mechanoreceptor except Ruffini ending has own operating frequency as mentioned in Introduction. For example, only Merkel's disk is activated in the range of low frequency (0~3 Hz) stimulation. To stimulate mechanoreceptors selectively, a tactile actuator should be designed in the consideration with 'wide operating frequency range'. Among many types of actuators, we decided to use a solenoid actuator. The reason is that it creates enough force and stroke to stimulate human skin and generates a wide enough frequency bandwidth to convey abundant tactile sensation. Moreover, a solenoid actuator can be easily redesigned for various structures and miniaturized. Therefore, many attempts have been made to develop pin-array tactile displays with solenoid actuators [15]–[17]. However, it remains a challenge to reduce the size of a tactile display with an array of solenoids without decreasing the magnitude of the stimulating force. The reason is that the actuating force of a solenoid depends considerably on its size. In this section, we present a new solenoid type actuator which is small enough to construct a miniature tactile module.

2.1 Design Process of a New Miniature Tactile Actuator

To ensure high performance with a miniature actuator, it is desirable to combine more than two types of energy mechanically. For example, centrifugal force by an eccentric mass and the repulsive force between a solenoid and a permanent magnet can be combined to construct a commercial coin-type vibration motor that can generate strong vibration. The piezoelectric force and the inertial force are combined to develop the ultrasonic miniature linear motor known as "TULA", which can generate a large stroke [18].

For tactile feedback in mobile devices, a tactile actuator should generate enough force to stimulate human skin, should be actuated in a wide frequency range, should be small enough to be inserted into mobile devices, and should be designed to consume low power. To minimize the diameter of the solenoid actuator, a small push/pull type of solenoid actuator with a solenoid core and an external permanent magnet was chosen. However, a small solenoid does not generate enough force to push out a permanent magnet. Therefore, an elastic spring was added to provide additional elastic return feedback force. That is, the elastic return force of the elastic spring and the electromagnetic force between the solenoid and the permanent magnet were combined. Figure 1 shows the proposed tactile actuator that incorporates a push-pull type solenoid and an elastic spring.

The proposed actuator consists of an elastic spring, a contactor, a permanent magnet, and a solenoid. The contactor is adhered to the center of the elastic spring and the permanent magnet is attached to the end of the contactor. The solenoid is placed with a tiny gap for the permanent magnet.

2.2 Driving Principle of the Proposed Tactile Actuator

Figure 2 shows the driving principle of the proposed tactile actuator. As the core of the solenoid is made of a steel alloy, the permanent magnet connected to the elastic spring is attracted to the tip of the solenoid steel core, causing the elastic spring to deform in the initial state. The deformation of the elastic spring generates elastic return force. When electric current flows into the solenoid, repulsive force between the solenoid and the permanent magnet is generated. Due to the elastic return force and the electromagnetic repulsive force, the contactor rises up strongly and stimulates the finger pad of the human operator. As the permanent magnet is weakly attached to the steel core due to the elastic return force, the impulse current input only needs to generate strong and fast returning actuation. The electromagnetic repulsive force between the permanent magnet and the solenoid only plays a role in detaching the permanent magnet from the solenoid. Therefore, the proposed tactile actuator consumes considerably low power while producing a high level of performance (output force, working frequency and response rate).

The human's absolute threshold (activation force) for a fingertip is determined as a function of frequency, contactor's area, and etc. In the case where we used a contactor whose radius is about 0.35 mm, the human's absolute threshold becomes nearly 20 dB μm at low frequency (about 0~3 Hz) [28], [36]. The contactor's radius of our system (0.25 mm) is similar as that of [28], [36]. Thus, we decided to determine the maximum stroke of the proposed tactile actuator as 200 μm, twice as the human's absolute threshold, to strongly stimulate the human's finger tip. By considering the maximum stroke (200 μm), the gaps between each permanent magnet and solenoid part were determined.

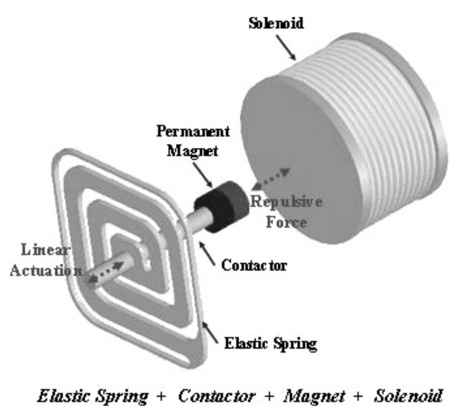

Fig. 1 Design of new tactile actuator.

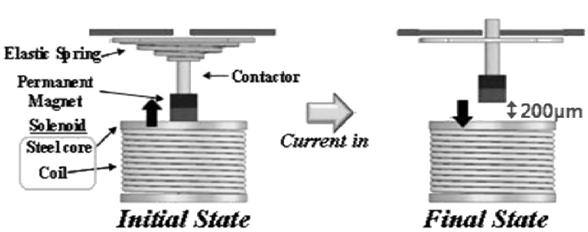

Fig. 2 Driving principle of the proposed actuator.

3. Design of a Miniature Tactile Module

In Fig. 2, the stimulating force and the contactor stroke of the proposed tactile actuator are shown to be proportional to the width and the thickness of the elastic spring. As the width and the thickness of the elastic spring increase, the elastic return force and the contactor stroke become larger. Therefore, it becomes necessary to increase the width and the thickness of the elastic spring for better performance. However, if the size of the elastic spring becomes larger, the gap between a contactor and its neighbor, which should be as close as possible for better tactile sensation, increases. Hence, to increase the size of each elastic spring without increasing the contactor gap, a multilayer structure was adopted, as shown in Fig. 3.

Figure 3 shows the assembly method of the nine actuators with the multilayered elastic springs. In Fig. 3, contactor 2, which is attached to elastic spring 2 of the second elastic plate, moves up and down while passing through a gap between elastic springs 1 and 3 in the first elastic plate and also transiting through the third and fourth elastic plates. Contactor 5 fixed to elastic spring 5 of the first elastic plate and moves up and down while passing through the second, third and fourth elastic plates. Likewise, each contactor moves through the different elastic springs and the plates. While this assembling method enlarges the size of the elastic springs, the contactor gap is minimized.

Figure 4 shows the disassembled structure of the pro-

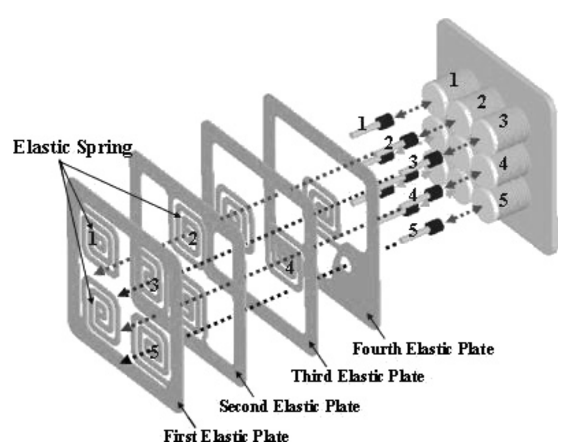

Fig. 3 Structure of the multilayered elastic spring and assembling procedure of tactile actuators.

posed miniature tactile module. The tactile module consists of a touch plate, four different elastic plates (plates with elastic springs), five spacers, nine contactors with permanent magnet separators and a solenoid part (the array of solenoids and the solenoid holder). The touch plate is the part where a human operator places a finger on it to feel the tactile sensation. It is important to remove or to minimize the maldistribution of the gaps between the permanent magnet and the solenoid, because the force generation of each actuator is determined by the gap. In order to minimize the gap and to remove interference with the other elastic springs in different layers, the spacers were inserted among elastic plates. Each contactor with a permanent magnet is grasped by the center hole of the corresponding elastic spring in the elastic plate. The separators enable the contactors to actuate vertically, as this action eliminates the interaction among the magnets. The solenoids are arranged by the solenoid holder and generate electromagnetic repulsive force due to the interaction with the permanent magnets [19].

The Pacinian corpuscle is a highly sensitive mechanoreceptor over 100 Hz [20]. The length of the Pacinian corpuscle is 3∼4 mm in an adult finger [21], [22]. The longest vertical axis and the transverse axis of the diameter of the Pacinian corpuscle are 3.5 mm and 4.84 mm, respectively [23]. The contactors' gap of the proposed tactile module is determined by considering the size of the Pacinian corpuscle, because the Pacinian corpuscle is most sensitive among the mechanoreceptors. The contactors' gap should be smaller than the distance between the Pacinian corpuscle and its neighbor. In this paper, considering the size of the Pacinian corpuscle, the contactor gap of the proposed tactile module was set to 3 mm. The distance from the center of a contactor to that of its neighbor was defined as the contactors gap.

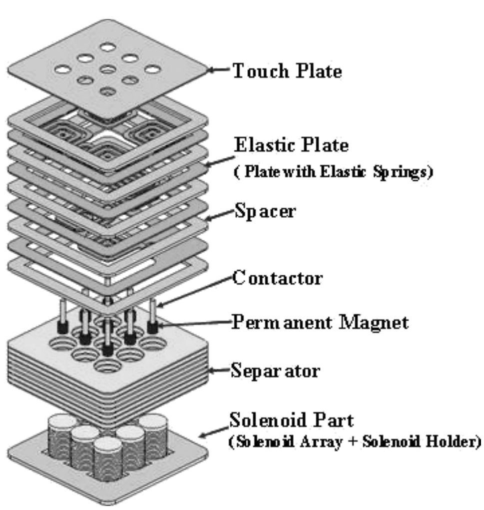

Fig. 4 Disassembled structure of new miniature tactile module.

4. Fabrication of the Proposed Tactile Module

4.1 Design and Fabrication of Elastic Spring Parts

Figure 5 shows the simulation result and the displacement-force graph of the elastic spring. From this result, the width of the beam of the elastic spring was set to 0.5 mm, and the thickness of the elastic spring was set to 0.15 mm. This spring is elastically deformed up to 200 μm under 5 mN loads. The lager the gap between the permanent magnet and the solenoid becomes, the larger elastic return force is generated as shown in displacement-force graph in Fig. 5.

As discussed in Sect. 2.2, elastic springs were included to increase the repulsive force. A 3D analysis tool (COSMOSXpress) was used to simulate the elastic spring. The material chosen was SUS 304 because it is light and it has good elastic characteristic. The size of the elastic spring was set to 4.5 × 4.5 mm considering the contactor gap and the multi-array structure. The material for the contactor was chosen as an SK stainless steel, because it is light, antirust, and easy to manufacture.

Four different elastic plates were manufactured by a commercial machine (wire-cutting), as shown in Fig. 6 (b). The first elastic plate has four elastic springs, the fourth plate has one elastic spring, and the others have two springs, as shown in Fig. 6 (a). Each elastic spring grasps the corresponding contactor. The permanent magnet is attached to the end of the contactor, as shown in Fig. 6 (c). The proposed nine pin-array tactile module using multi-layered structure can be expanded up to 37 pin-array module [24].

To assemble the elastic spring and the contactor, we made a hole in the center of the spring as shown in Fig. 7. The maximum tolerance of the hole is smaller than the minimum tolerance of the contactor. Hence, the interference fit

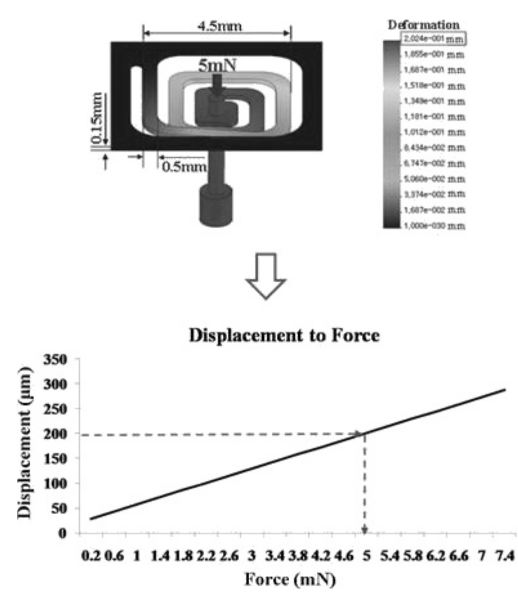

Fig. 5 Simulation result and displacement-force graph of an elastic spring.

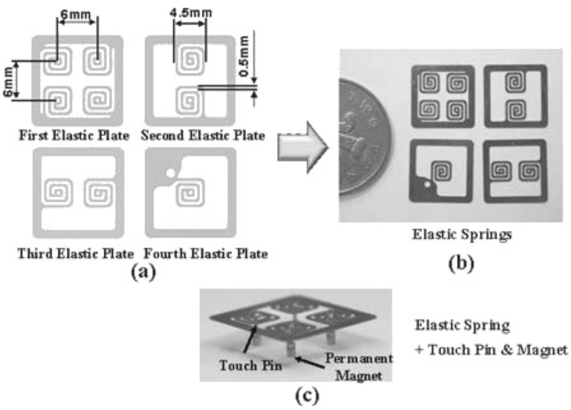

Fig. 6 Disassembled structure of new miniature tactile module.

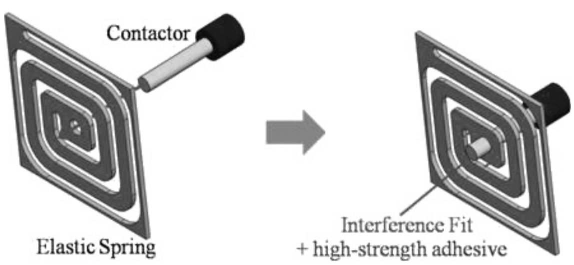

Fig. 7 Assembling process of the elastic spring and the contactor.

occurs between the hole and the contactor. After the interference fit, the contactor is fixed by an adhesive in the hole of the spring.

4.2 Design and Fabrication of Solenoid Parts

Elastic return force is generated when each elastic spring is stretched due to the attractive force between the magnet connected to an elastic spring and the solenoid steel core. If the sum of the elastic returning force and the electromagnetic repulsive force is larger than that of the attractive force, the contactor with the magnet moves upwards to stimulate a finger tip (See Fig. 2). The elastic return force is approximately 5 mN when the actuator is maximally stretched (0.2 mm), and the attractive force was measured as nearly 7 mN. Therefore, the electromagnetic repulsive force should be larger than approximately 2 mN to push out the permanent magnet.

$$F_m = \frac{B_i^2 \times A_g}{2 \times \mu_0} \tag{1}$$

$$B_i = \frac{\phi}{A_i} \tag{2}$$

$$\phi = \frac{N \times 1}{R_m} \tag{3}$$

$$R_{m_i} = \frac{L_i}{\mu_i \times A_i} \tag{4}$$

F_m = Magnetic Force
μ_0 = Magnetic Permeability of Air

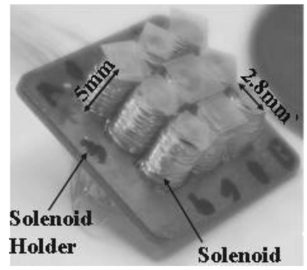

Fig. 8 Array of nine-miniature solenoids.

A_g = Cross Section Area generating Magnetic Force
B_i = Magnetic Flux Destiny
ϕ = Magnetic Flux
N = Wiring Number
I = Current in Coil
R_{m_i} = Magnetic Reluctance
μ_i = Magnetic Permeability
A_i = Cross Section Area
L_i = Length of Material passing through Magnetic Flux

Generally, a solenoid can be expressed by Eqs. (1), (2), (3), and (4). The electromagnetic force (1) is derived from Eqs. (2), (3) and (4). A permanent magnet is attached to the end of a corresponding contactor which is adhered to an elastic spring. As this permanent magnet interacts with the corresponding solenoid, the diameter of the solenoid has to be smaller than the gap (3 mm) between a contactor and the gap of its neighbor contactor. In the proposed system, the diameter of each solenoid was fixed as 2.8 mm as shown in Fig. 8. Consequently, through these four equations, the height of the solenoid was determined to be 5 mm. Based on these parameters, the miniature solenoids were manufactured with array of nine-solenoids.

4.3 Fabrication of the Proposed Tactile Module

Figure 9 shows a new miniature pin-array tactile module with the proposed tactile actuators. The total size of the proposed tactile module is 15 mm × 15 mm × 8.5 mm and its weight is only 8 g. The contactor gap is 3.0 mm and its diameter is 0.5 mm. Each actuator can be independently actuated with a stroke of 0.2 mm and with a wide working frequency range. We found other commercial braille pin array-type display and summarized in Table 1 [25]–[27]. The volume of the proposed display per one pin is considerably smaller than that of others per one pin.

The proposed tactile module consisting of nine tactile actuators consumes considerably low power. For a case in which 5 V of input is applied to the module, when only one actuator moves at 1 Hz, its power consumption is 0.16 W. When actuating at 340 Hz, the power consumption is 0.39 W (5 V input). In addition, the response time of the proposed actuator is on the order of milliseconds.

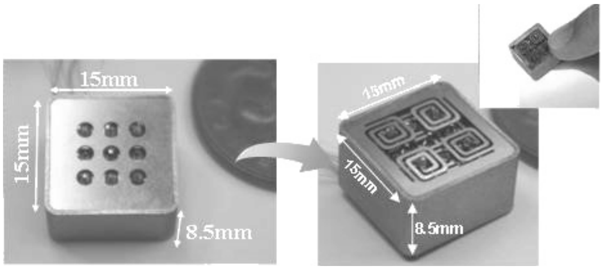

Fig. 9 Developed pin-array tactile module.

Table 1 The comparison among the proposed tactile module and other braille displays.

Parameter /Device	Tiny Feel	Sync Braille	Refreshable Braille Displays	PAC Mate Portable Braille Display
Number of Pins	9Pins	32 Cells (32X8= 256Pins)	40Cells (40X8= 320Pins)	40Cells (40X8= 320Pins)
Size of Devices	15mm X 15mm X 8.5mm	260mm X 85mm X 20mm	13.2"w X 13.5"d X 1"h	4.8"X 12.5"X 1.53 "
Volume	1912 mm^3	$4.4x10^5$ mm^3	$2.9x10^6$ mm^3	$1.5x10^6$ mm^3
Volume of One Pin	382 mm^3	13750 mm^3	72500 mm^3	37500 mm^3

5. Performance of the Proposed Miniature Tactile Module

A hardware control system was constructed to evaluate the performance of the proposed tactile module. The proposed tactile module is controlled by an AVR microprocessor. A control signal generated by the microprocessor (AVR128) is transferred to each actuator through a current amplifier (ULN2803). Figure 10 shows the control circuit that is used to operate the proposed tactile module. To convey a wide variety of tactile sensations, a tactile module should provide enough force to stimulate human mechanoreceptors and has to be operated over a wide range of frequency (0~300 Hz). The performance of the developed tactile module was evaluated by measuring two characteristics: 1) the exerting force via a load cell, 2) the frequency response through a vibrometer.

5.1 Exerting Force Measurement

As the proposed tactile module is a miniature and low-power system, it may produce too small an output force to stimulate human skin [1]. Therefore, the output force was measured to determine whether it is larger than the activation. The human vibrotactile threshold has the highest value, nearly 40 μm, for a static stimulus [28]. The mechanical impedance of the skin to normal displacement at the finger pad is 0.09 mN/μm [29]. Therefore, the activation threshold (3.6 mN) to stimulate the mechanoreceptor can be computed by multiplying the vibrotactile threshold (40 μm) and the mechanical impedance (0.09 mN/ μm).

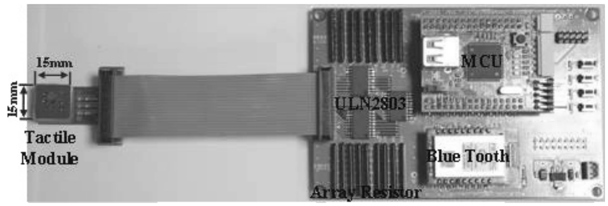

Fig. 10 Controller for the developed pin-array tactile module.

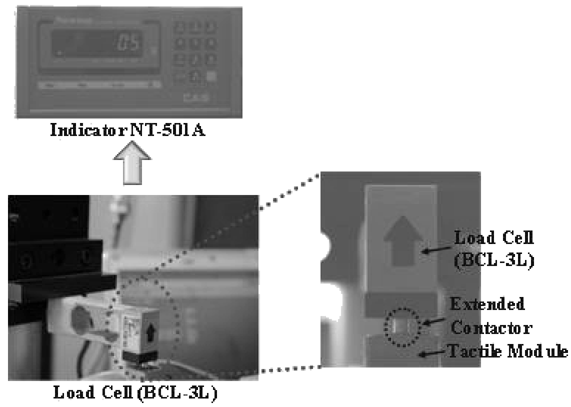

Fig. 11 Measurement of tactile module's exerting force.

Figure 11 shows the measurement system as used here to investigate the contactor output force. A load cell (BCL-3L) was placed on the proposed tactile module through its extended contactor. The indicator (NT-501A) displays the force when the contactor of the tactile module hits the extended contactor. The force was measured six times and the average of these measurements was used. The measured output force of the contactor was 5 mN, which is larger than the activation threshold (3.6 mN). This result shows that each contactor provides enough force to stimulate a human mechanoreceptor.

5.2 Frequency Response

There are four major mechanoreceptors (the Meissner corpuscle, Merkel's disk, the Ruffini ending, and the Pacinian corpuscle) in human glabrous skin, as described in Sect. 1 [1]. As each mechanoreceptor has its own working frequency in the range of 0 Hz to 300 Hz, the frequency bandwidth is the dominant factor in the stimulation of skin. Therefore, the amplitude of the proposed tactile actuator was measured as a function of the vibration frequency.

Figure 12 shows a schematic diagram of the measurement system used for the frequency response. The amplitude of the proposed tactile actuator was measured by a

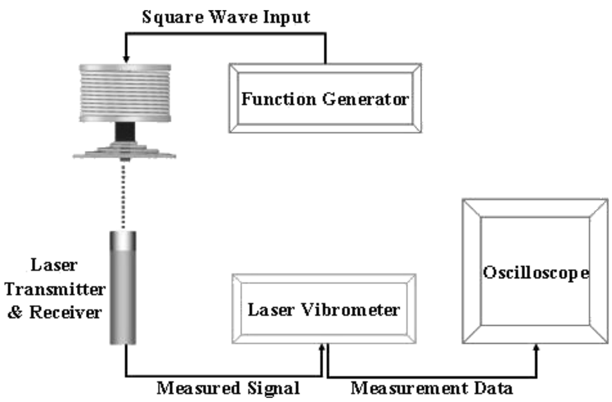

Fig. 12 Schematic measurement system for frequency response.

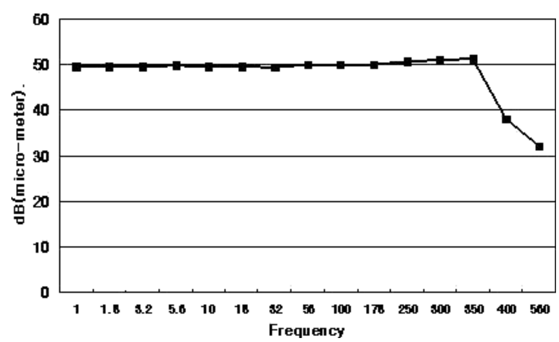

Fig. 13 Frequency response of the proposed tactile actuator.

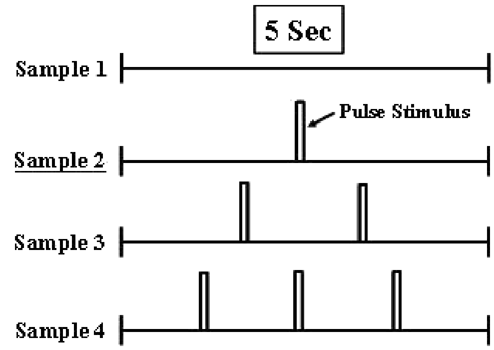

Fig. 14 Four experimental samples containing the different presentations of stimuli.

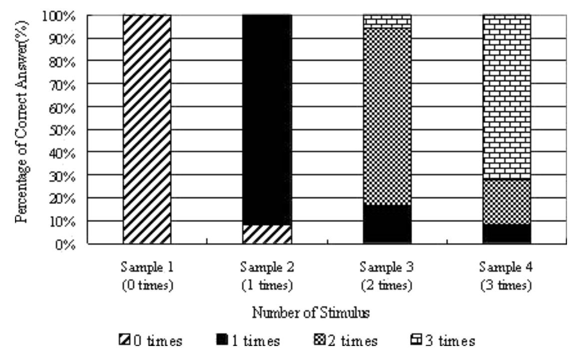

Fig. 15 Mean percentage of correct answers in identifying the number of stimuli presented for each sample.

Laser Doppler Vibrometer (LDV). In this experiment, the amplitude was measured when a square wave input was provided to the developed tactile actuator.

Figure 13 shows the result of the measured amplitude of the proposed tactile actuator according to the frequency. The stroke (200 μm) of the proposed actuator is enough to stimulate the human's mechanoreceptors. So, we limited the stroke up to 200 μm. For this reason, when the proposed actuator vibrates in the resonance frequency, the stroke of the actuator does not have any overshot. Therefore, the resonance has no critical affects on the proposed actuator under the frequency range of 0 to 340 Hz. The sensitivity of human's mechanoreceptors reaches the peak around 250 Hz, and then it starts to decrease after the frequency [1]. Thus, the working range of the tactile actuator (0 Hz~340 Hz) is enough to stimulate all mechanoreceptors without the resonance effect.

6. Experimental Result and Evaluation

Two different experiments were performed. Six subjects participated in this experiment; five were male and one was female. All were between 24 and 30 years old. All subjects were right-handed and they did not have any tactile abnormalities. Subjects were asked to place their index finger on a surface where tactile contactors were protruding. These experiments were conducted under the condition of passive touch. There was no pilot test with the tactile module. External noise was blocked by earplugs during the experiments.

6.1 Experiment I: Perceiving One Pin Stimulation

An experiment was performed to investigate whether the proposed tactile module generates enough force to stimulate human skin. Only one contactor located in the center was actuated during the experiment. In each test, the subjects were asked to gently place their index finger on the tactile module. We performed each test for 5 seconds because mechanoreceptors start to paralyze after around 7 sec tactile stimuli [30]. Four samples were prepared for this test, as illustrated in Fig. 14. There was no pulse in sample 1, and one pulse in sample 2. Samples 3 and 4 had two and three pulses, respectively. Each pulse input was presented to the subjects during the same interval (five seconds). Four samples were randomly displayed six times; hence, the subjects were required to answer 24 times. First, the subjects experienced a randomly selected sample for five seconds. Afterward, the subjects rested for three seconds to recover their tactile sense and checked their answers [31], [32]. They then continued the experiment. A four-alternative forced-choice (4AFC) method was adopted, and the subjects were instructed to select how many pulses were provided for each sample.

Figure 15 shows the mean percentage of correct answers when subjects attempted to identified the number of stimuli presentations as each sample was presented to them.

The results are summarized in Table 2. The average percentage of correct answer was 91.7 % when sample 2 was provided to the subject, 77.8 % for sample 3, and 72.2 % for sample 4. The lowest percentage of correct answer was 72.2 % in the four-alternative forced-choice (4AFC) method. Let us consider the case where subjects marked the answer sheet randomly. In this case, the probability for 72 % of correct answer is about 5 %. So, we can conclude that subjects were able to identify the number of presented stimuli reliably. This result shows that the subjects were able to identify the number of presented stimuli presentations reliably. This shows that subjects can perceive each stimulus by a contactor. Therefore, each contactor provides enough force to stimulate the human finger pad.

6.2 Experiment II: Nine-Contactor Actuating for Providing Tactile Sensation

An experiment was performed to investigate whether the proposed tactile module can convey a variety of tactile sensation to users. All nine contactors were actuated during the experiment. The subjects experienced five different frequencies (2 Hz, 5 Hz, 25 Hz, 100 Hz, and 250 Hz) six times with same displacement. A seven-alternative forced-choice (7AFC) method was adopted [30], [33]. In the 7AFC method, it was rated 7 score if the perceived stimuli is strongest and 1 score if it is weakest. The period of each stimulus was about 7 seconds and the subjects responded within 10 seconds.

Table 2 Mean percentage of answers in identifying the number of presented stimuli.

Stimulus \ Answer	Sample 1 (0 times)	Sample 2 (1 times)	Sample 3 (2 times)	Sample 4 (3 times)
0 times	100.0	8.3	0.0	0.0
1 times	0.0	91.7	16.7	8.3
2 times	0.0	0.0	77.8	19.4
3 times	0.0	0.0	5.6	72.2

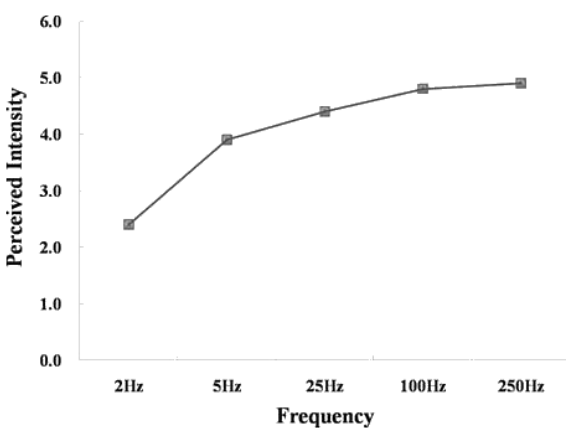

Fig. 16 Perceived intensity as a function of frequency of vibration using the proposed tactile module.

Generally, as the frequency of vibration increases, vibrotactile threshold become lower in a palm and a finger [28], [35]. That is, as the frequency of vibration with same displacement rises, perceived intensity goes up. Figure 16 shows the experimental result. In the proposed tactile module, as the frequency of vibration increases, perceived intensity is intensified. Therefore, the proposed module can be used to stimulate tactile sensation.

7. Conclusion

Although a pin-array module is a powerful structure for generating tactile sensation, it is not easy to embed this type of module into a mobile device due to its size and its high level of power consumption. This study proposed a miniature and low-power tactile actuator that provides enough working frequency, output force and amplitude to stimulate mechanoreceptors. The proposed actuator consists of an elastic spring, a contactor, a permanent magnet, and a solenoid. The contactor is attached to the center of an elastic spring which generates elastic return force. The permanent magnet is attached to the end of the contactor, and it interacts with the corresponding solenoid. The proposed tactile actuators were arranged and modularized to construct a miniature tactile module. The contactor gap, the dominant factor for providing tactile sensation, was minimized by adopting a multilayered structure that did not decrease the performance level. The developed tactile module is small and consumes a low amount of power. Therefore, the proposed tactile module can be embedded into mobile devices. If the proposed tactile actuator and the tactile module are incorporated into a mobile device, users will be provided with immersive and realistic sensations while interacting with their mobile devices.

Acknowledgments

This research was supported by the ‘SMEs Technology Innovation Program.’ This work was also supported by Grant No. R01-2007-000-20977-0 from the Basic Research Program of the Korea Science & Engineering Foundation.

References

[1] R.S. Johansson and A.B. Vallbo, “Tactile sensibility in the human hand: Relative and absolute densities of four types of mechanoreceptive units in glabrous skin,” J. Physiology, vol.286, pp.283–300, 1979.
[2] A. Chang, S. O’Modhrain, R. Jacob, E. Gunther, and H. Ishii, “ComTouch: Design of a vibrotactile communication device,” ACM Designing Interactive Systems Conf., pp.312–320, 2002.
[3] I. Oakley and S. O’Modhrain, “Tilt to scroll: Evaluating a motion based vibrotactile mobile interface,” Proc. 1st Joint Eurohaptics Conf. and Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems, pp.40–49, Pisa, Italy, March 2005.
[4] http://www.immersion.com/products/touchsense-tactile-feedback/4000-series/index.html
[5] S.D. Kweon, I.O. Park, Y.H. Son, J. Choi, and H.Y. Oh, US PATENT

no.7,358,633 B2, Linear vibration motor using resonance frequency, Assignee Samsung Electro-Mechanics Co., Ltd.

[6] Y. Mizukami and H. Sawada, "Tactile information transmission by apparent movement phenomenon using shape-memory alloy device," Int. Conf. on Disability, Virtual Reality and Associated Technologies, pp.133–140, Esbjerg, Denmark, 2006.

[7] I. Poupyrev, S. Maruyama, and J. Rekimoto, "Ambient touch: Designing tactile interfaces for handheld devices," UIST'02, Paris, France, Oct. 2002.

[8] M. Wagner, A. Roosen, H. Oostra, R. Hoppener, and M. De Moya, "Novel low voltage piezoactuators for high displacements," J. Electroceramics, vol.14, no.3, pp.231–238, 2005.

[9] C.R. Wagner, S.J. Lederman, and R.D. Howe, "Design and performance of a tactile shape display using RC servomotors," Electronic Journal of Haptics Research, Haptics-e, vol.3, no.4, pp.1–6, 2004.

[10] Q. Wang and V. Hayward, "Compact, portable, modular, high-performance, distributed tactile transducer device based on lateral skin deformation," 2006 Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems IEEE VR, pp.67–72, Arlington, VA, March 2006.

[11] S.Y. Kim, K.U. Kyung, J. Park, and D.S. Kwon, "Real-time area-based haptic rendering and the augmented tactile display device for a palpation simulator," Advanced Robotics, vol.21, no.9, pp.961–981, 2007.

[12] K.U. Kyung, J.Y. Lee, and J.S. Park, "Haptic stylus and empirical studies on braille, button, and texture display," J. Biomedicine and Biotechnology, vol 2008, pp.1–11, 2008.

[13] R.Velázquez, E. Pissaloux, M. Hafez, and J. Szewczyk, "A low-cost highly-portable tactile display based on shape memory alloy micro-actuators," VECIMS 2005—IEEE International Conf. on Virtual Environments, Human-Computer Interfaces and Measurement Systems, Giardini Naxos, Italy, July 2005.

[14] http://www.eamex.co.jp/denshi_hp/english/touchPanel_e.htm

[15] S.F. Frisken-Gibson, P. Bach-Y-Rita, W.J. Tompkins, and J.G. Webster, "A 64-solenoid, four-level fingertip search display for the blind," IEEE Trans. Biomed. Eng., vol.BME-34, no.12, pp.963–965, 1987.

[16] T. Fukuda, H. Morita, F. Arai, H. Ishihara, and H. Matsuura, "Micro resonator using electromagnetic actuator for tactile display," Int. Symp. on Micromechatronics and Human Science, Nagoya, Japan, Oct. 1997.

[17] M.B. Khoudja, M. Hafez, J.M. Alexandre, A. Kheddar, and V. Moreau, "VITAL: A new low-cost vibro-tactile display system," Proc. 2004 IEEE International Conf. on Robotics & Automation, New Orleans. LA, USA, April 2004.

[18] http://www.piezo-tech.com

[19] T.-H. Yang, S.Y. Kim, C.H. Kim, D.-S. Kwon, and W.J. Book, "Development of a miniature pin-array tactile module using elastic and electromagnetic force for mobile devices," World Haptics 2009, Salt Lake City, UT, USA, March 2009.

[20] A.J. Brisben, S. Hsiao, and K.O. Johnson, "Detection of vibration transmitted through an object grasped in the hand," J. Neurophysiol, vol.81, pp.1548–1558, 1999.

[21] R.T. Verrillo, "Psychophysics of vibrotactile stimulation," J. Acoust. Soc. Am., vol.77, no.1, pp.225–232, 1985.

[22] N. Cauna and G. Mannan, "The structure of human digital pacinian corpuscles (corpuscula lamellosa) and its functional significance," J. Anat., vol 92, pp.1–25, 1985.

[23] B. Stark, T. Carlstedt, R.G. Hallin, and M. Risling, "Distribution of human pacinian corpuscle in the hand," J. Hand Surgery, vol.23B, no.3, pp.370–372, 1998.

[24] T.-H. Yang, S.Y. Kim, and D.-S. Kwon, "Design of new micro actuator for tactile display," Proc. 17th World Congress The International Federation of Automatic Control, pp.14693–14698, Seoul, Korea, July 2008.

[25] http://www.himskorea.co.kr

[26] http://www.deafblind.com/display.html

[27] http://www.freedomscientific.com

[28] K.U. Kyung, M.S. Ahn, D.S. Kwon, and M.A. Srinivasan, "Perceptual and biomechanical frequency response of human skin: Implication for design of tactile displays," Proc. 1st Joint Eurohaptics Conf. and Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Pisa, Italy, March 2005.

[29] J. Biggs and M.A. Srinivasan, "Tangential versus normal displacements of skin: Relative effectiveness for producing tactile sensations," Proc. 10th Symp. On Haptic Interfaces for Virtual Environment and Teleoperator Systems, Orlando, Florida, March 2002.

[30] K.U. Kyung, Development of a Broadband Tactile Display and Role of Vibration in the Tactual Perception, Ph.D Dissertation, KAIST, 2006.

[31] S.J. Bensmaia, Y.Y. Leung, S.S. Hsiao, and K.O. Johnson, "Vibratory adaptation of cutaneous mechanoreceptive afferents," J. Neurophysiol, vol.94, pp.3023–3036, 2005.

[32] Y.Y. Leung, S.J. Bensmaia, S.S. Hsiao, and K.O. Johnson, "Time-course of vibratory adaptation and recovery in cutaneous mechanoreceptive afferents," J. Neurophysiol, vol.94, no.5, pp.3037–3045, Nov. 2005.

[33] S.C. Kim, K.U. Kyung, and J.H. Sohn, "An evaluation of human sensibility on perceived texture under variation of vibrotactile stimuli using a tactile display system," Proc. 14th Symp. on Haptic Interfaces for Virtual Environment and Teleoperator Systems, Washington D.C., USA, 2006.

[34] R.T. Verrillo, "A duplex mechanism of mechanoreception," Proc. First International Symposium on the Skin Sense, D.R. Kenshalo, ed., pp.139–159, Thomas, Springfield, Illinois, 1968.

[35] K.-U. Kyung, S.-C. Kim, and D.-S. Kwon, "Texture display mouse: Vibrotactile pattern and roughness display," IEEE/ASME Trans. Mechatronics, vol.12, no.3, pp.356–360, 2007.

[36] K.-U. Kyung, M.S. Ahn, D.-S. Kwon, and M.A. Srinivasan, "A compact planar distributed tactile display and effects of frequency on texture judgment," Advanced Robotics, vol.20, no.5, pp.563–580, 2006.

Tae-Heon Yang received the B.S. degree in Mechanical Engineering from Yonsei University, Seoul, Korea, in 2006, and the M.S. degree in Mechanical Engineering from Korea Advanced Institute of Science and Technology (KAIST), Daejeon, Korea, in 2008. He is currently working towards the Ph.D. Degree in the Human–Robot Interaction Research Center, KAIST. His research interests include haptics (Micro-tactile Actuator, tactile display and haptic interface design) and human–computer interface.

Sang-Youn Kim received the B.S. degree from Korea University, Seoul, Korea and an M.S.E (1996) and a Ph.D. (2004) in mechanical engineering at Korea Advanced Institute of Science and Technology (KAIST). He was a researcher in Virtual Reality Research Center in 2002. From 2004 to 2005, he was a researcher at Human Welfare Robot System Research Center. In 2005, he was a research staff member at Samsung Advanced Institute of Technology (SAIT). He is currently an assistant professor of internet-media engineering at Korea University of Technology and Education. His current research interests include Human-Computer Interaction, 3D object modeling, Virtual Reality, and Haptics (haptic rendering, tactile display).

Wayne J. Book (F'96) was born in San Angelo, TX, in 1946. He received the B.S.M.E. degree from the University of Texas at Austin in 1969 and the M.S. and Ph.D. degrees in mechanical engineering from the Massachusetts Institute of Technology, Cambridge, in 1971 and 1974, respectively. He has been on the faculty of Mechanical Engineering at the Georgia Institute of Technology, Atlanta, since 1974 and was promoted to Professor in 1986. In 2001, he was named HUSCO/Ramirez Distinguished Professor in fluid power and motion control. He teaches courses in system dynamics, controls, robotics, and manufacturing systems. His research includes the design, dynamics, and control of high-speed, lightweight motion systems, which is an area in which he has published numerous papers and is internationally recognized. He holds several patents on robotics related inventions. He is the immediate past Senior Technical Editor of the ASME Journal of Dynamic Systems and Measurement and Control. Dr. Book is a member of the management committee of the ASME-IEEE TRANSACTIONS ON MECHATRONICS and active in the administration of the ASME Dynamic Systems and Control Division, the IEEE Robotics and Automation Society, and the American Automatic Control Council. He was General Chairman of the 1993 IEEE International Robotics and Automation Conference. He was the founding director of Georgia Tech's multidisciplinary Computer Integrated Manufacturing Systems (CIMS) Program from 1983 to 1988 and the leader of the CIMS team that won the Society of Manufacturing Engineer's University LEAD award. He is a Fellow of the American Society of Mechanical Engineers as well as the Institute of Electrical and Electronics Engineers and received Georgia Tech's award for Outstanding Faculty Leadership for development of Graduate Research Assistants in 1987.

Dong-Soo Kwon received the B.S. degree in mechanical engineering from the Seoul National University, Korea in 1980, the M.S. degree in mechanical engineering from Korea Advanced Institute of Science and Technology (KAIST), Seoul, Korea in 1982 and the Ph.D. degree in mechanical engineering from Georgia Institute of Technology, Atlanta, Georgia, USA, in 1991. From 1991 to 1995, he was a research staff at Oak Ridge National Laboratory. He is currently a Professor of mechanical engineering and the director of Human-Robot Interaction Research Center at KAIST, Daejon, Korea. His current research interests include human-robot/computer interaction, telerobotics, medical robots, and haptics. He is a member of IEEE, KSME and ICASE.