PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

Experimental evaluation of a miniature haptic actuator based on electrorheological fluids

Alex J. Mazursky , Jeong-Hoi Koo, Tae-Heon Yang

Alex J. Mazursky , Jeong-Hoi Koo, Tae-Heon Yang, "Experimental evaluation of a miniature haptic actuator based on electrorheological fluids," Proc. SPIE 10595, Active and Passive Smart Structures and Integrated Systems XII, 105951M (15 March 2018); doi: 10.1117/12.2300982

SPIE.

Event: SPIE Smart Structures and Materials + Nondestructive Evaluation and Health Monitoring, 2018, Denver, Colorado, United States

Experimental evaluation of a miniature haptic actuator based on electrorheological fluid

Alex J. Mazursky[a], Jeong-Hoi Koo[a*], Tae-Heon Yang[b]
[a]Dept. of Mechanical and Manufacturing Engineering, Miami University, Oxford, OH, USA 45056
[b]School of Electrical Engineering, Korea National University of Transportation, Chungju-si, Chungbuk, Republic of Korea

ABSTRACT

Haptic feedback is desired for numerous applications including simulators, teleoperations, entertainment and more. While many devices today feature vibrotactile feedback, most do not provide kinesthetic feedback. To address the need for both vibrotactile and kinesthetic feedback, this study investigates the use of electrorheological (ER) fluids for their tunable viscosity under electrical stimulation. A prototype device containing ER fluid was designed and fabricated. The device operates based on pressure-driven flow of the fluid between charged plates due to user interaction with the touch contact surface. The prototype was tested using a dynamic mechanical analyzer to measure the actuator's resistive force with respect to indentation depth for a range of applied voltages and frequencies. The results indicate that increasing the applied voltage causes an increase in the force produced by the actuator. Varying the supplied signal over a range of voltages and frequencies can convey a range of force and vibrational feedback. This range is sufficient to transmit distinct haptic sensations to human operators and demonstrates the design's capability to transmit remote or virtual touch feedback conditions.

Keywords: haptic actuator, electrorheological fluids, haptics, kinaesthetic, tactile

1. INTRODUCTION

In recent years, the rising implementation of haptic technology has transformed how we interact with electronic devices and digital information. Haptic technology conveys information to the user through touch sensations, offering a more engaging and realistic user experience. In addition to visual and auditory sensations, being able to touch, feel and manipulate objects in an environment, whether real or virtual, offers a greater sense of immersion in that environment.[1] Previous studies have shown that enhancing user immersion through haptic feedback results in improved user performance of typical tasks on devices.[2,3] The benefits of integrating haptic feedback have been realized across a wide range of applications, including medical training simulators, teleoperation and entertainment.[4-6]

For a device to provide complete haptic feedback, it must be capable of producing both tactile and kinesthetic sensations. Kinesthetic feedback is felt in one's joint and muscle nerves and provides information about position and movement. Tactile feedback consists of the sensations felt at the surface of one's skin and just underneath it. When sensing an object, humans may rub it to feel its texture and roughness (tactile sensation) and press it to feel its resistance and elasticity (kinesthetic sensation). Therefore, both sensations must be present to completely observe an object through touch.[1]

Though many devices today incorporate vibrotactile feedback, most neglect to integrate kinesthetic feedback due to size constraints. Many of the kinesthetic devices proposed in current research are based upon alternating current/direct current (AC/DC) motors to create force feedback sensations.[7-9] Despite developments toward AC/DC motor-based kinesthetic actuators, they cannot be easily implemented into small-scale devices, such as mobile handhelds, due to their size and power requirements. Additionally, active-controlled motors tend to have instability problems, which can be a significant roadblock for certain applications.[10,11]

*koo@miamioh.edu; phone +1-513-529-0723

Active and Passive Smart Structures and Integrated Systems XII, edited by Alper Erturk, Jae-Hung Han,
Proc. of SPIE Vol. 10595, 105951M · © 2018 SPIE · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2300982

To address this issue, researchers have proposed 'smart materials' to actuate the haptic sensations instead of traditional motors. Smart materials are designed to have variable properties dependent upon external stimuli, such as temperature, stress, magnetic or electric fields and more. Jansen *et al.* utilized a pouch containing magnetorheological (MR) fluid and an electromagnet array to produce haptic sensations over the pouch's flexible surface, deemed the "Mudpad."[12] The electromagnet array controlled the smart fluid's viscosity, and therefore, the kinesthetic and vibrotactile feedback observed when interacting with the "Mudpad." However, reducing the size of the "Mudpad" design for use in handheld applications may prove difficult due to its electromagnet coils. Beyond "Mudpad", Yang *et al*. (2010) introduced a miniature tunable stiffness display based on MR fluids, validating the feasibility of using MR fluid in smaller kinesthetic devices.[13] In a subsequent study, Yang *et al.* (2012) applied MR fluid in a miniature (10 x 10 x 12 mm) haptic button capable of producing a wide range of kinesthetic and vibrotactile feedback.[14] However, basing an actuator around MR fluid requires complex circuitry and manufacturing.

Analogous to MR fluid, electrorheological (ER) fluid's viscosity is reversibly tunable in response to electric fields.[15] Similarly, ER fluid features response times in the order of milliseconds, low power consumption and has few issues with stability.[16-18] Though MR fluid is capable of producing a larger range of yield stresses, ER fluid may prove advantageous in some haptic applications due to simple electrical control design, as only two electrodes are needed compared to a "bulky" solenoid coil for MR devices. With a miniature design in mind, it is also possible to improve upon the device fabrication.

The goal of this paper is to fabricate an ER fluid-based actuator and validate its ability to convey both tactile and kinesthetic sensations. The actuator contains ER fluid, which provides the variable resistive force to the button's kinesthetic interface. By supplying voltage signals to electric field plates housed within the actuator, the device's force feedback is controlled. Introducing a frequency into the applied voltage results in oscillations in the kinesthetic response to produce a vibrotactile response. Therefore, the proposed ER fluid-based device is capable of producing haptic feedback. Section 2 describes the working principle and design process of the proposed ER fluid-based actuator. Section 3 then details the experimental methods performed to evaluate the actuator's effectiveness and analyzes the results.

2. DESIGN AND FABRICATION

2.1 Working principle and design considerations

Figure 1 depicts the cross-section and working principle of the proposed haptic actuator. The body of the actuator is cylindrical and contains two concentric electrodes separated by a gap of 1 mm. The internal volume of the body is filled completely with ER fluid and is sealed within the body by a nonconductive, silicone rubber layer. The seal doubles as the elastic contact interface of the haptic actuator. By indenting the membrane interface, ER fluid is pushed through the gap between the electrodes and up into a reciprocating reservoir to compensate for the change in volume. Therefore, the device operates based on pressure-driven flow mode. When the pressure on the contact surface is removed, the fluid flows back from the reservoir and the device returns to its initial state. The actuator has been designed to operate at a maximum stroke of 1 mm.

When a voltage is supplied to the plates, the ER fluid in the gap forms a network of fibers along the field lines. The resultant change in viscosity produces a yield stress due to flow mode in relation to the voltage input and contributes to the kinesthetic force experienced by the user when indenting the membrane. Therefore, the total force feedback felt by the user can be represented by the relation:

$$F_{total} = F_{0V} + F_{ER} \tag{1}$$

where F_{total}: total force (N); F_{0V}: resistive force in off state; F_{ER}: force due to the ER effect. Rearranging the terms allows isolation of the force due to the ER effect:

$$F_{ER} = F_{total} - F_{0V} \tag{2}$$

By providing an alternating signal to the electrodes, the viscosity of the fluid fluctuates in response and provides a time-dependent force to the user indicative of vibrational feedback.

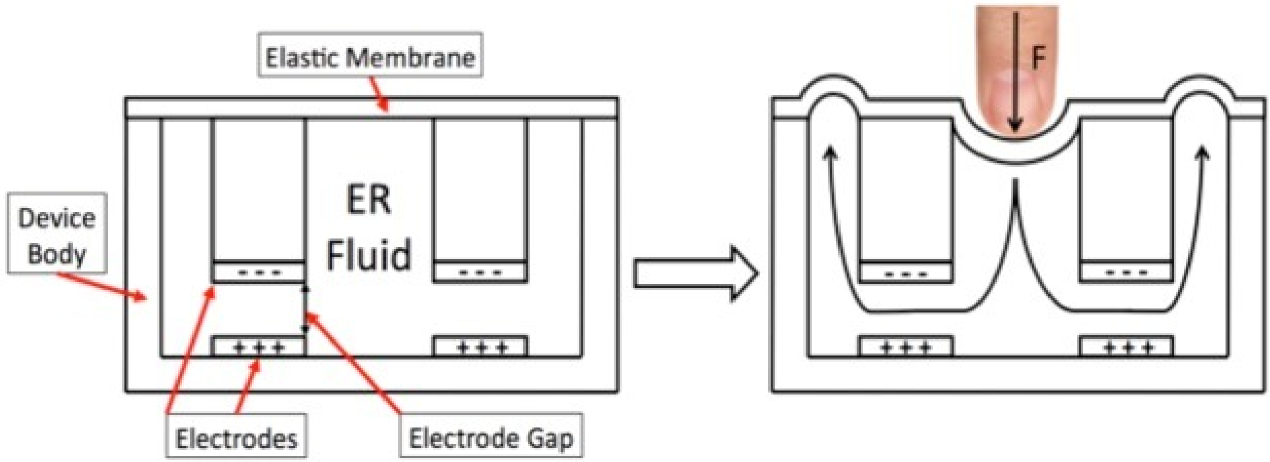

Figure 1. Diagram of the actuator's design features, flow mode under pressure and simple volume change compensation.

2.2 Fabrication of haptic actuator

The schematic view of the haptic actuator is shown below in Figure 2. The two-piece, plastic housing contains the concentric electrode rings and ER fluid. The lower and upper electrodes are attached to the negative and positive halves of the housing, respectively, and are separated by a fixed, 1 mm gap. Conductive leads connect to the electrodes and are fed out through the side of the device to receive input voltage signals. The two halves of the housing are sealed by a groove fit. The actuator's volume is then filled with ER fluid and a thin silicone rubber membrane is placed over the top half of the device. The membrane is compressed against the upper surface of the positive housing by tightening the cover with nylon screws. The membrane therefore doubles as a seal and the actuator's contact surface. The assembled device measures 42 mm in diameter and 14.5 mm thick.

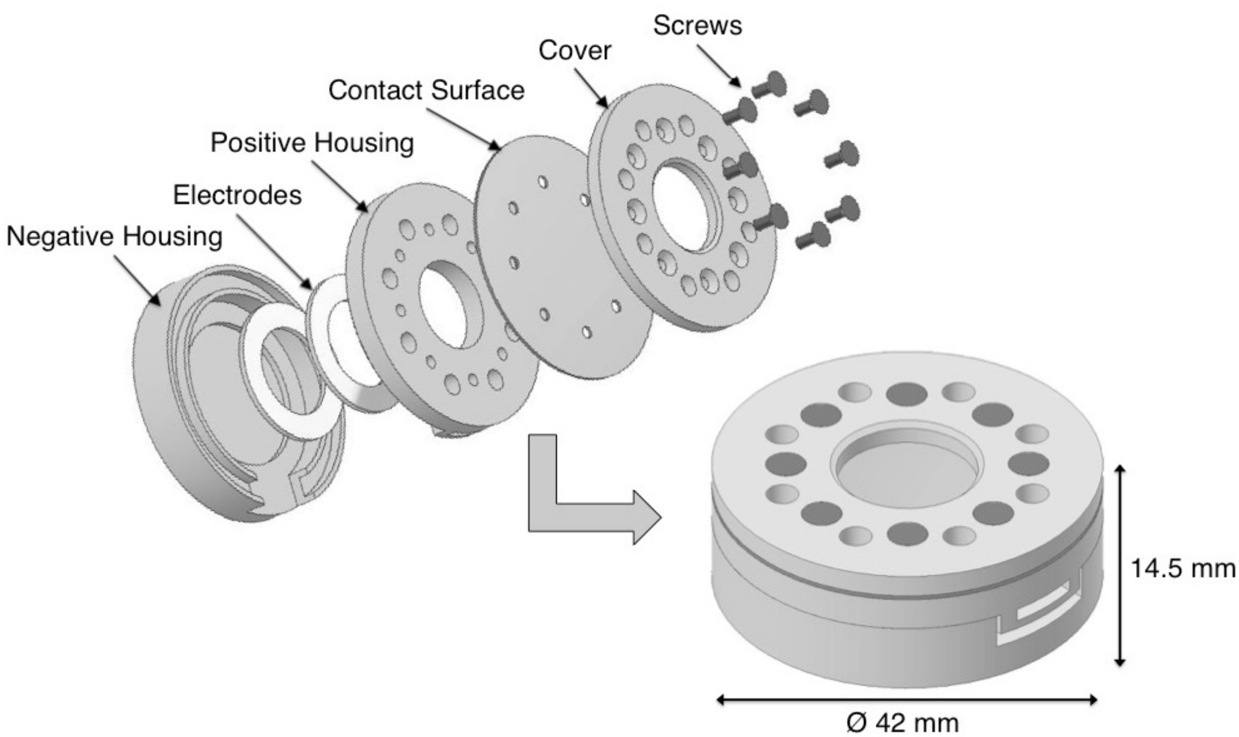

Figure 2. Schematic view of the proposed haptic button.

3. EXPERIMENTAL EVALUATION

To evaluate the haptic performance of the device prototype, mechanical analysis was conducted using a dynamic mechanical analyzer (RSA3, TA Instruments), as seen in Figure 3. This experimentation measured the total resistive force with respect to indentation depth over the button's stroke of up to 1 mm. The performance was evaluated under different input voltage and frequency conditions using a tool similar in size to a human finger. This testing was performed with giant ER fluid inside the device, which produces greater yield stresses than conventional fluid.[19] Subsections 3.1 and 3.2 detail the kinesthetic and vibrotactile performance of the actuator, respectively.

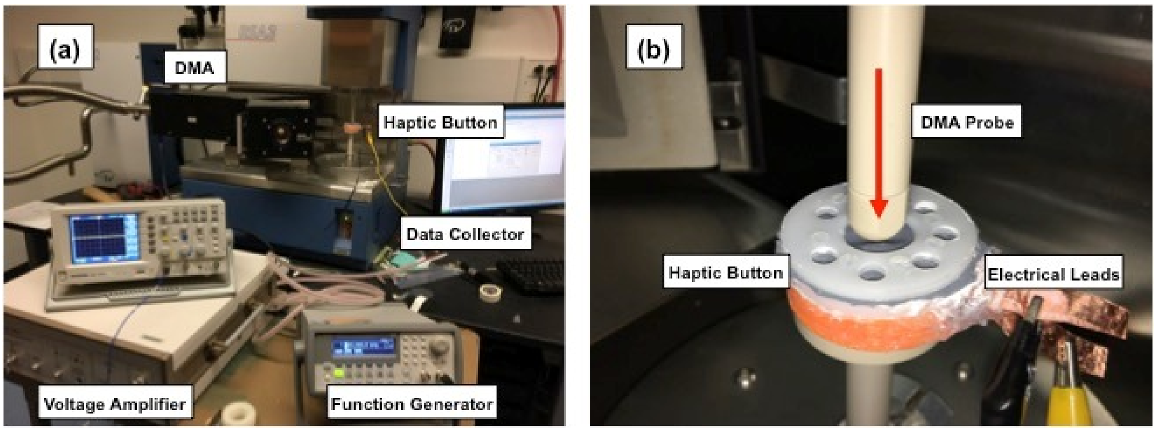

Figure 3. (a) Experimental setup to measure the generated force of the haptic button with respect to applied voltage and indentation depth and (b) a closer inspection of the indentation probe and button position.

3.1 Kinesthetic response

Figure 4 shows the variation of the measured resistive force with respect to the pressed depth (varied from 0 mm to 1 mm) and the applied voltage across the 1 mm electrode gap (0 V/mm, 1 kV/mm, 2 kV/mm, and 3 kV/mm) at a pressing velocity of 1 mm/s. As shown in the figure, the resistive force increases as the input voltage and the pressed depth increase. The off-state resistive force at the maximum depth was measured to be about 1.4 N, and the maximum resistive force produced was found to be about 2.3 N with 3 kV supplied. It should be noted that a thin layer of air is trapped inside the device during assembly, causing an inevitable, small gap between the contact surface and fluid. Hence, when the actuator is indented at small depths, the stiffness of the membrane alone contributes to the total force. At larger strokes, the force due to the ER effect is present.

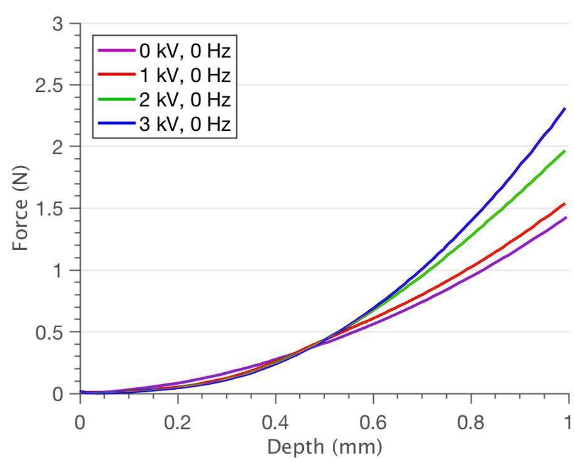

Figure 4. Results of the experimental measurement of the kinesthetic actuator: measured force vs. pressed depth (stroke length) with varying input voltage magnitudes.

3.2 Tactile response

Under direct current, the actuator operates kinesthetically, as no oscillations are produced in the response. To demonstrate a vibrotactile response, sinusoidal and square wave functions were applied at maximum voltage (3 kV/mm) and 3 Hz frequencies and the force vs. depth responses were observed, shown below in Figure 5. From the resultant plot, it is evident that the actuator conveys vibrational feedback when excited with a harmonic voltage. The square waveform resulted in greater amplitudes of vibration than the sinusoidal waveform due to its instantaneous nature. As a consequence of the fluctuating signal, greater amplitudes of vibration corresponded to reduced force at maximum depth. It should also be noted that the observed frequency is twice that of the applied frequency due to the absolute behavior of the resistive force.

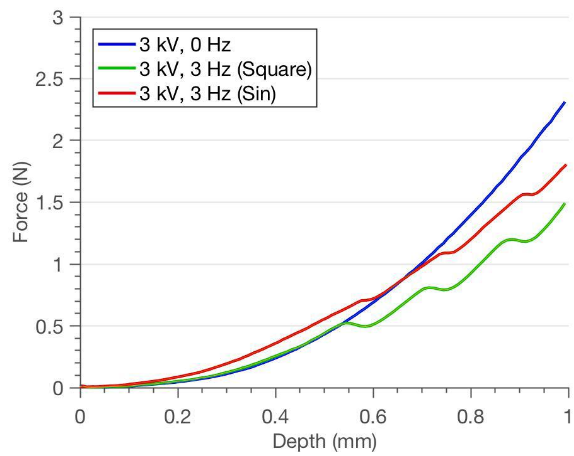

Figure 5. Results of the experimental measurement of the haptic actuator: measured force vs. pressed depth with varying input waveforms.

In post-processing, it is possible to extract the force due to the ER effect from the kinesthetic response by removing the response in the off-state to demonstrate the vibrotactile behavior of the actuator, shown in Equation 2. Figure 6a was produced to examine the effect of varying frequency of a sinusoidal input on the force due to the ER effect. Similarly, Figure 6b was produced using square wave inputs. The ER effect due to square wave excitation increased with depth due to longer times at absolute maximum voltages compared to the sinusoidal wave. The troughs in the force plots correspond to the sign change in the applied signal, whereas the peaks correspond to the absolute maximum voltages. For the sinusoidal wave, a 1 Hz frequency produced the greatest force due to the ER effect of about 0.25 N. The highest frequency tested, 10 Hz, led to the smallest amplitude of vibration of about 0.05 N. This analysis yields that as frequency increases, the amplitude of the force due to the ER effect decreases. Additionally, greater voltage amplitudes resulted in higher forces due to the ER effect, as shown in Figure 6b.

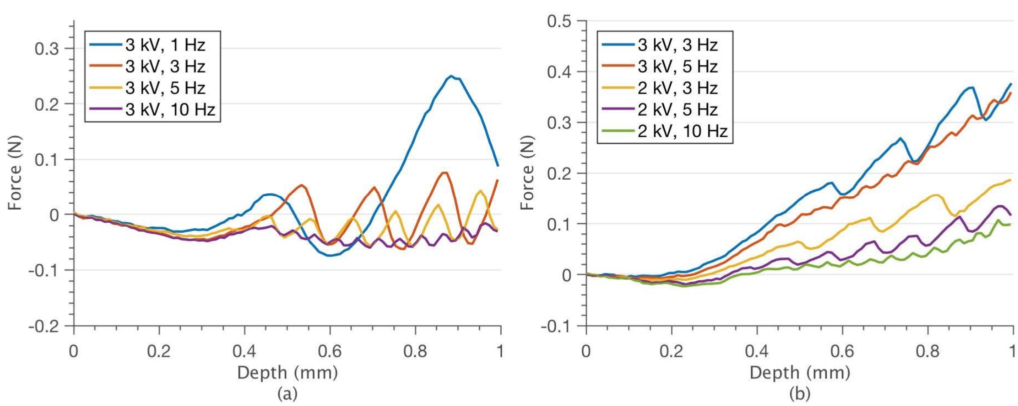

Figure 6. (a) Force due to the ER effect vs. pressed depth for sinusoidal waveform inputs and (b) for square waveform inputs.

4. CONCLUSIONS

This article has proposed a new miniature haptic actuator based on ER fluids. An elastic contact surface was used to drive fluid between fixed electrodes to produce a range of kinesthetic and vibrotactile feedbacks. After constructing a prototype actuator, the device's behavior was characterized experimentally with a dynamic mechanical analyzer under different input voltages and frequencies. The results demonstrate that the resistive force increases as the indented depth and the input voltage increase. Additionally, the device is capable of producing vibrational feedback. Hence, this study validated that the proposed ER fluid–based haptic device can be used to provide haptic feedback in button-type applications. This work has potential to be implemented in a larger haptic display that can convey localized touch feedback over a continuous surface by using an array of electrodes.

ACKNOWLEDGEMENTS

This work was partially supported by the "Undergraduate Research Award" funded by the Office of Research for Undergraduates at Miami University and by the Ohio Space Grant Consortium. This work was also partially supported by the Korea Institute of Oriental Medicine (Grant no. K18022) funded by the Korean government.

REFERENCES

[1] Srinivasan, M., Basdogan, C., "Haptics in virtual environments: taxonomy, research status, and challenges," Comput. & Graphics 21(4), 393-404 (1997).

[2] Hoggan, E., Brewster, S.A., Johnston, J., "Investigating the effectiveness of tactile feedback for mobile touchscreens," Proc. of CHI ACM, 1573-1582 (2008).

[3] Poupyrev, I., Maruyama, S., and Rekimoto, J., "Ambient touch: designing tactile interfaces for handheld devices," Proc. of UIST ACM, 51-60 (2002).

[4] Coles, T., Meglan, D., John, N., "The role of haptics in medical training simulators: A survey of the state of the art," IEEE Transactions on Haptics 4(1), 51-66 (2010).

[5] Park, J., Khatib, O., "A haptic teleoperation approach based on contact force control," The Int. J. of Robotics Research 25(5-6), 575-591 (2006).

[6] Laycock, S.D., Day, A.M., "Recent developments and applications of haptic devices," Computer Graphics Forum 22(2), 117-132 (2003).

[7] Song, A., Morris, D., Colgate, J.E., "Haptic telemanipulation of soft environment without direct force feedback," Proc. of the 2005 IEEE International Conference on Information Acquisition, 21-25 (2005).

[8] Bianchi, M., Scilingo, E.P., Serio, A., et al. "A new softness display based on bi-elastic fabric," Proc. of the third joint eurohaptics conference and symposium on haptic interfaces for virtual environment and teleoperator systems, 382-383 (2009).

[9] Fujita, K., Ohmori, H., "A new softness display interface by dynamic fingertip contact area control," Proc. of the 5th World Multiconference on Systemics, Cybernetics and Informatics, 78-82 (2000).

[10] Adams, R.J., Moreyra, M.R., Hannaford B., "Stability and performance of haptic displays: theory and experiments," Proc. of ASME international mechanical engineering congress and exhibition, 227–234 (1998).

[11] An, J., Kwon, D.S., "Stability and performance of haptic interfaces with active/passive actuators-theory and experiments," The Int. J. of Robotics Research 25(11), 1121–1136 (2006).

[12] Jansen, Y., Karrer, T., Borchers, J., "MudPad: Localized tactile feedback on touch surfaces," Proc. of UIST, 385-386 (2010).

[13] Yang, T.H., Kwon, H.J., Lee, S.S., et al., "Development of a miniature tunable stiffness display using MR fluids for haptic application," Sensors and Actuators A: Physical 163, 180–190 (2010).

[14] Yang, T.H., Koo, J.H., Kim, S.Y., Kyung, K.U., Kwon, K.S., "Application of magnetorheological fluids for a miniature haptic button: Experimental evaluation," Journal of Intelligent Material Systems and Structures 23(9), 1025-1031 (2012).

[15] Whittle, M., Bullough, W. A., "The structure of smart fluids," Nature 358, 373–373 (1992).

[16] Whittle, M., Atkin, R.J., Bullough, W.A., “Dynamics of an electrorheological valve,” Int. J. of Modern Physics B 10(23-24), 2933–2950 (1996).
[17] Bullough, W.A., Johnson A.R., Hosseini-Sianaki, A., Makin, J., Firoozian, R., “The electro-rheological clutch: design, performance characteristics and operation,” Proc. Inst. Mech. Eng. 207, 87–95 (1993).
[18] Han, S.S., Choi, S.B., Cheong C.C., “Position control of X–Y table mechanism using electro-rheological clutches,” Mech. Mach. Theory 35, 1563–77 (2000).
[19] Wen, W., Huang, X., Yang, S., Lu, K., Sheng, P., “The giant electrorheological effect in suspensions of nanoparticles,” Nature Materials 2, 727-730 (2003).