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A miniature magneto-rheological actuator with an impedance sensing mechanism for haptic applications

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Abstract
This article presents a miniature haptic actuator (or haptic button) based on magneto-rheological fluids, designed to convey realistic and vivid haptic sensations to users in small electronic devices. The haptic sensation, which is generated in the form of resistive force, should vary according to the stroke of the actuator (or the pressed depth of its plunger). Thus, a sensing method for gauging the stroke should be integrated into the proposed magneto-rheological actuator to demonstrate real-world haptic applications. To determine the pressed depth of the magneto-rheological actuator, this article proposes an impedance sensing mechanism. The proposed sensing method measures the impedance change of the solenoid coil built in the actuator in the form of voltages to estimate the pressed depth. A control system was constructed to evaluate the simultaneous sensing and actuating performance of the proposed. The results show that the sensitivity of the proposed sensing method is sufficient to regulate the output resistive force over the small stroke range of the actuator. The results further show that the controller with the proposed sensing method enables users to measure the displacement of the plunger and concurrently generate resistive forces to convey haptic sensations to users without additional sensors.

Keywords
Impedance sensing, miniature magneto-rheological actuator, magneto-rheological fluids, haptics

Introduction

In handheld devices, haptic feedbacks can make interaction between the devices and users more vivid and fruitful. Generally, users rub (tactile) and press (kinesthetic) target objects when they try to perceive those objects (Srinivasan and LaMotte, 1996). Therefore, to convey a more realistic and vivid haptic sensation, both kinesthetic and tactile information should be presented to users. While miniature tactile actuators have been widely studied, only a few researchers have studied the use of kinesthetic devices to convey kinesthetic sensations (Kwon et al., 2006; Yang et al., 2011). Most of the kinesthetic devices proposed so far have adopted commercial alternating current (AC)/direct current (DC) motors to generate various kinesthetic sensations (Bianchi et al., 2009; Fujita and Ohmori, 2001; Iwata et al., 2002; Song et al., 2005). However, it is difficult to incorporate these devices into small electronic products because they primarily use AC/DC motor–based actuation mechanisms, which increases the size and the power consumption of kinesthetic devices. Moreover, active-controlled motors tend to have instability problems, which can be a significant road block for certain applications (Adams et al., 1998; An, 2005; Colgate et al., 1993).

Alternative to motors and other active-type actuators, some researchers applied smart materials toward miniature kinesthetic display applications. Blake and Gurocak (2009) proposed a miniature magneto-rheological (MR) brake for a haptic glove application. Even though the MR brake generates enough torque for haptic feedback, the size of the MR brake (diameter

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of 25 mm and height of 15 mm) may not be suitable for handheld device applications. Jansen et al. (2010) developed "MudPad," which consists of an array of electromagnets and MR fluid pouch. Although the "MudPad" can convey haptic sensation over a continuous surface using the MR fluid pouch, miniaturizing the overall structure to fit in small electronic devices seems a challenging task. Yang et al. (2010) proposed a miniature tunable stiffness display using MR fluids. While the device demonstrated a feasibility of using MR fluids for a miniature kinesthetic device, its size (24 mm × 24 mm × 15mm) is still large for handheld devices. Yang et al. (2012) also developed a miniature haptic button actuator using MR fluids. Using mixed mode (shear and flow mode) of MR fluids, the size of a cylinder-shaped button actuator (Φ 10 mm × 12 mm) was further miniaturized with better performance.

In order to demonstrate real-world haptic applications using the proposed miniature MR actuator, the haptic sensation, which is generated in the form of resistive force, should vary according to the user's pressed depth of the actuator. However, it is quite challenging to incorporate additional sensors into miniature haptic actuators to measure the displacement or the stroke of the actuators. Hence, this article proposes an impedance sensing mechanism that enables simultaneous calculation of the stroke position and generation of the actuation force. In other words, the haptic actuator with this impedance sensing method gauges the pressed depth of the actuator without extra sensors and conveys resistive force to users based on the position of the stroke of the actuator. Thus, the proposed sensing method will help advance the haptic actuators to be used for real-world applications.

The next section explains the design and the working principle of the proposed miniature MR actuator. After explaining the concept of impedance sensing mechanism based on the MR actuator, the experimental setup, which consists of microcontroller and signal processors, and control method, is described. Finally, analysis and discussion of experimental results conclude the article.

A miniature MR actuator and impedance sensing mechanism

Design and working principle of miniature MR actuator

The schematic view of the miniature MR actuator is shown in Figure 1(a). The housing with a yoke contains a solenoid, a cone-shaped plunger, an elastic spring, and MR fluids. The solenoid coil is attached to the bottom of the housing surrounding the yoke, and the plunger is placed inside the solenoid coil. A housing spacer and a housing cover are mounted to the top of the housing, and the contact plate is fixed to the upper end of the plunger. The elastic spring is placed between the housing cover and the contact plate, and it provides an elastic restoring force to bring the contact plate to its initial position upon removing the input current and releasing the actuator. Since the housing with the inclined yoke, the cone-shaped plunger, and the housing cover is made by a ferromagnetic material, those parts guide magnetic fields generated from the solenoid coil, creating a closed magnetic circuit. The housing contains MR fluids, and the fluids flow through the gaps between the yoke and the plunger.

When a user presses the MR actuator, MR fluids flow upward from the inclined gap between the yoke and the plunger. Once an input current is applied to the solenoid coil, MR fluids build up particle chains in the inclined gap, producing resistive forces. The proposed miniature MR actuator was designed to integrate multiple operating modes of MR fluids for maximizing the resistive force in a given size of the actuator. The force contributed by the squeeze mode exponentially

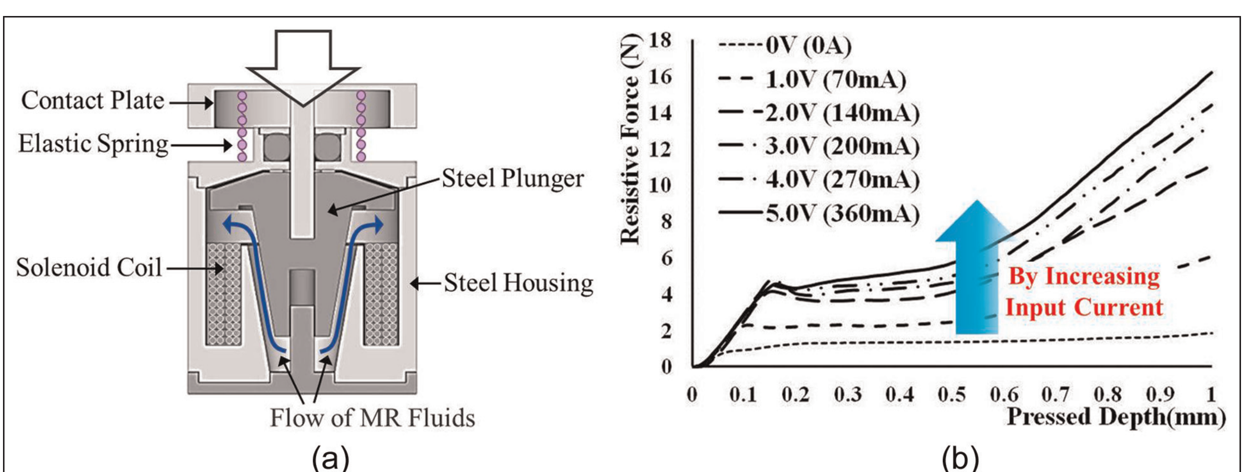

Figure 1. (a) Cross-sectional view and characteristics of the miniature MR actuator and (b) force profiles with varying input currents. MR: magneto-rheological.

decreases when the gap distance between the plunger and the housing in the actuator increases. Thus, the cone-shaped plunger design was employed to compensate dramatic decrease of the squeeze mode force. Moreover, the cone-shaped design allowed further reducing the height of the actuator as compared with an equivalent MR actuator with a cylindrical-shaped plunger design. For the current study, a prototype cylindrical-shaped actuator (diameter of 10 mm and height of 14 mm) was constructed, and its stroke is 1.0 mm. While detailed design and experimental results of the prototype actuator can be found in the study by Yang (2012), Figure 1(b) is included to briefly explain the actuation performance of the prototype actuator. As shown in Figure 1(b), the resistive force increases as the input current increases over the entire stroke (1 mm). It further shows that the maximum resistive force ranges from around 1.5 N (at 0 V or no input current) to 16.2 N (at 5 V, 360 mA) for the case of 1 mm compression (the button actuator is fully pressed down). These forces are sufficiently large to convey button click sensations to humans. Moreover, based on the just noticeable difference criteria or human's differential threshold of force changes, the miniature MR actuator is capable of generating various kinesthetic sensations (or resistive force) within the small stroke (Yang, 2012). The primary objective of the current article is to develop a control method that concurrently calculates the pressed depth or the stroke of the actuator and determines an input current in accordance with the pressed depth to convey a desired force to human operators, which is essential for practical haptic applications.

Impedance sensing mechanism

In order to demonstrate a real-world haptic application with the proposed actuator, a haptic rendering technique (haptic interface) should be applied by coupling the hardware (i.e. haptic actuator) with the computer software. For this haptic implementation, a control system with efficient actuating and sensing method should be designed. In other words, to control the output actuation (or resistive) force of the MR actuator based on input motions (i.e. the speed and position of the actuator stroke), a sensing scheme should be integrated into the developed actuator. To this end, the impedance change due to inductance changes of the solenoid coil in the proposed actuator was measured in the form of voltage, as shown in Figure 2(a). This figure compares the voltage signals between the initial state (not pressed) and the final state where the button is fully pressed down. When a user presses the contact plate of the proposed actuator, the gap between the plunger and the housing becomes reduced. The decrease of the gap causes to increase the magnetic permeability (μ) of the actuator, and this raises the inductance (L) of the solenoid coil in the actuator. The increase of the inductance

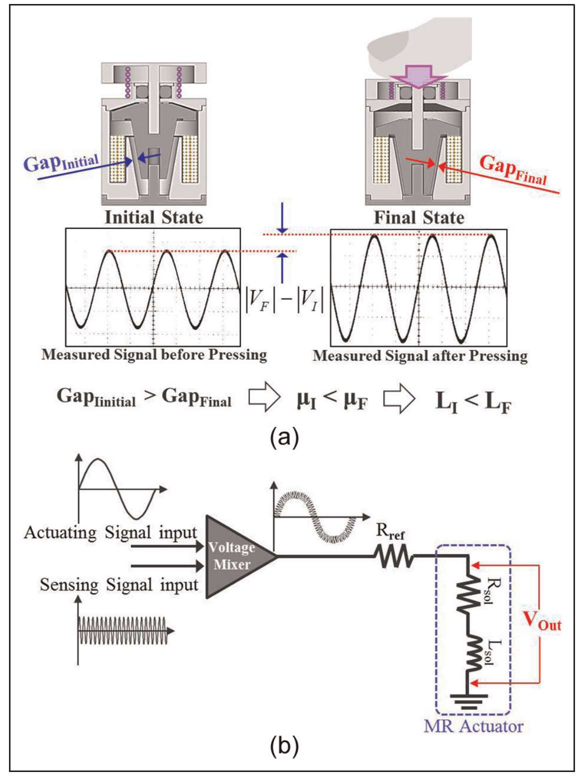

Figure 2. Impedance sensing method for measuring pressed depth of MR actuator: (a) impedance measuring principle and (b) system model.
MR: magneto-rheological.

raises the output voltage, as shown in Figure 2(a). An alternating voltage with frequency, ω, is applied to the solenoid coil for creating varying magnetic fields.

Figure 2(b) shows a conceptual circuit diagram for the proposed control method for concurrent sensing and actuation of the MR actuator. As shown in Figure 2(b), two distinctly different signals (high-frequency and low-frequency sine signals) are used as input voltage signals to realize simultaneous actuation and sensing of the proposed MR actuator. The low-frequency signal with high amplitudes is used to regulate the output actuation force, and the high-frequency signal is used to gauge the impedance change of the MR actuator owing to inductance changes for sensing of the pressed depth of the MR actuator (or sensing the stroke of the actuator). The high-frequency sensing signal does not activate the MR fluids because the bandwidth of the actuator is quite lower. Thus, it can be added or mixed with the low-frequency actuation input signal. After the mixed signals pass through a reference resistor, the low-frequency signal actuates the proposed actuator. The solenoid in the MR actuator can be modeled as a mixture of a resistor and an inductor, R_{sol} and L_{sol}. The sensing signal output, V_{Out}, is measured at a point between the reference resistor and the MR actuator, as shown in Figure 2(b). To extract the sensing signal from the mixed signals, a band-pass filter was used,

Table 1. Parameters for equations (1) and (2).

	Parameters	Value
Sine wave frequency for varying magnetic fields	ω	Variable
Sine wave input	V_{Source}	$\lvert V\rvert \times \sin \omega$ V
Impedance of solenoid coil	Z_{sol}	$R_{sol} + \omega L_{sol}\, i$
Reference resistance	R_{ref}	12 Ω
Resistance of solenoid coil	R_{sol}	14 Ω
Inductance of solenoid coil	L_{sol}	$\mu N^2 A/\ell$
Number of turns	N	396 turns
Area of solenoid coil	A	40.72 mm^2
Height of solenoid coil	ℓ	4.6 mm
Magnetic permeability	μ	Variable

which is further described with a control block diagram in a later section. As a reference, a mixed signal approach was used to control electro-active polymers (Jung et al., 2008).

Performance evaluation of impedance sensing mechanism

Simulation analysis

The peak value of the output voltage is gauged to estimate the pressed depth of the MR actuator. As explained earlier, when a user presses the actuator, the peak output voltage increases due to changes in inductance. The output voltage signal (V_{Output}) can be modeled using the expression in equation (1). Thus, the magnitude of the measured voltage signal due to inductance changes ($|V_{Output}|$) can be expressed, as shown in equation (2). In equation (2), V_{Source} is a sine wave input with high frequency (ω) for sensing function. R_{ref} is a reference resistor against the impedance of the MR actuator. The solenoid embedded in the MR actuator is modeled as R_{sol} and L_{sol}. Note that the output voltage is a function of input frequency (ω) and magnetic permeability (μ). Table 1 summarized the parameters for equations (1) and (2). To optimally design the solenoid coil of the MR actuator for generating maximum output resistive force, the parameters of the coil were designed through numerous simulations using the values shown in Table 1 (Yang, 2012)

$$V_{Output} = \frac{Z_{sol}}{R_{ref} + Z_{sol}} V_{Source} \tag{1}$$

$$|V_{Output}| = \frac{\sqrt{R_{sol}^2 + (\omega L_{sol})^2}}{\sqrt{(R_{ref} + R_{sol})^2 + (\omega L_{sol})^2}} |V_{Source}| = \frac{\sqrt{R_{sol}^2 + \left(\frac{\mu N^2 A}{\ell}\right)^2}}{\sqrt{(R_{ref} + R_{sol})^2 + \left(\frac{\mu N^2 A}{\ell}\right)^2}} |V_{Source}|$$

To evaluate the sensing capability of the proposed impedance sensing method, a series of simulations were performed using the values in Table 1 and varying key parameters, such as the input frequency (ω). The simulation results for the transfer function of the proposed impedance sensing method are shown in Figure 3. Figure 3(a) shows the magnitude changes of the output voltage signal with respect to the change of the pressed depth and the input frequency. Figure 3(b) and (c) shows the amplified output voltage signals by differential amplifiers. The differential amplification, which is the multiplication of amplifying ratio and the difference between the final value and the current value, is implemented using an op-amp in electric circuits in order to magnify small sensor signals obtained from the impedance sensing method. Figure 3(b) shows the voltage signals that are amplified once by the differential amplifier, and Figure 3(c) shows the voltage signals that are amplified twice by the differential amplifier. The twice amplified voltage signals range from 0.4 to 3 V, and they are mapped over the stroke of the actuator (i.e. 0.0–1.0 mm) to estimate the pressed depth of the button actuator. As shown in Figure 3(c), a sine wave input of 300 Hz creates the largest voltage range, up to around 2.6 V. Since the average threshold for compliance of a human finger is 22% (Jones and Hunter, 1990; Tan et al., 1995), users can differentiate around five steps of the pressed depth in the proposed actuator within the 1.0 mm stroke range. Because the voltage measurement range (2.6 V) is sufficiently large to gauge more than five steps of the pressed depth, the measured stroke by the impedance sensing method can be reliably used as a sensing signal. Therefore, based on these simulation results, the actuating signal with a low frequency and the sensing signal with 300 Hz are mixed by the voltage multiplier, and the mixed signals are applied to the proposed actuator to experimentally evaluate the performance of the proposed method.

Experimental setup

In order to demonstrate haptic applications of the proposed MR actuator, a haptic rendering technique should be applied by coupling the actuator with the computer software. For this haptic implementation, a control system with the impedance sensing method was designed and evaluated. Figure 4 shows a block diagram for the control system. A microcontroller (ARM Cortex LM8962) was programmed to generate two sine wave signals, which have a low-frequency signal for actuating and a high-frequency signal with small amplitude for sensing. While the signals passing through the voltage multiplier, the signals are mixed and applied to the proposed actuator. The high-frequency signal is extracted by the band-pass filter for sensing the pressed depth. The peak voltage difference of the extracted

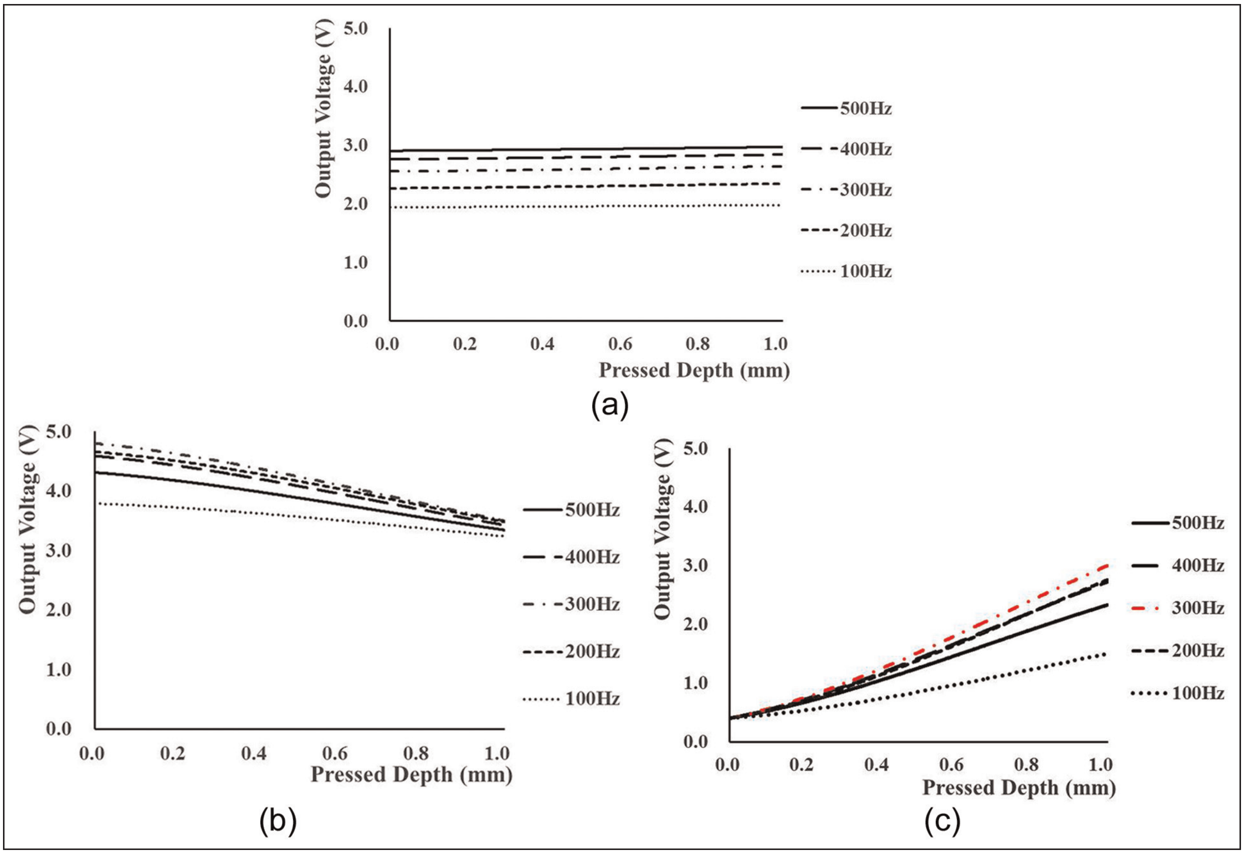

Figure 3. Performance results for the transfer function of the proposed impedance sensing mechanism: (a) output voltage signal created from the MR actuator, (b) once amplified voltage signal by the differential amplifier, and (c) twice amplified voltage signal by the differential amplifier.
MR: magneto-rheological.

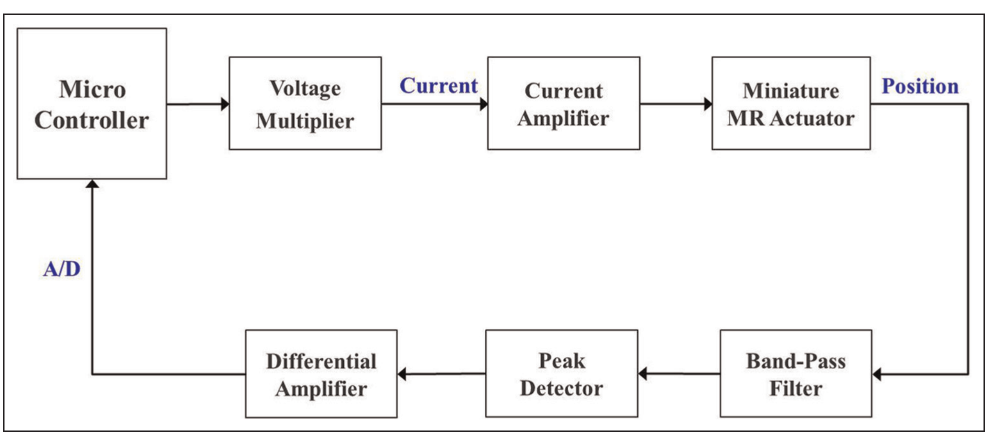

Figure 4. Control block diagram for actuating and sensing of the MR actuator.
A/D: analog-to-digital; MR: magneto-rheological.

sensing signal was obtained by the peak detector. It was then amplified by two difference amplifiers, as depicted in Figure 4. Therefore, the acquired signal is processed with a band-pass filter, a peak detector, and a difference amplifier to obtain a clear analog voltage signal. The analog voltage signal is collected to analog-to-digital (A/D) port of the microcontroller and converted to position (pressed depth). The microcontroller generates different sine wave signals for actuating the proposed actuator according to the pressed depth.

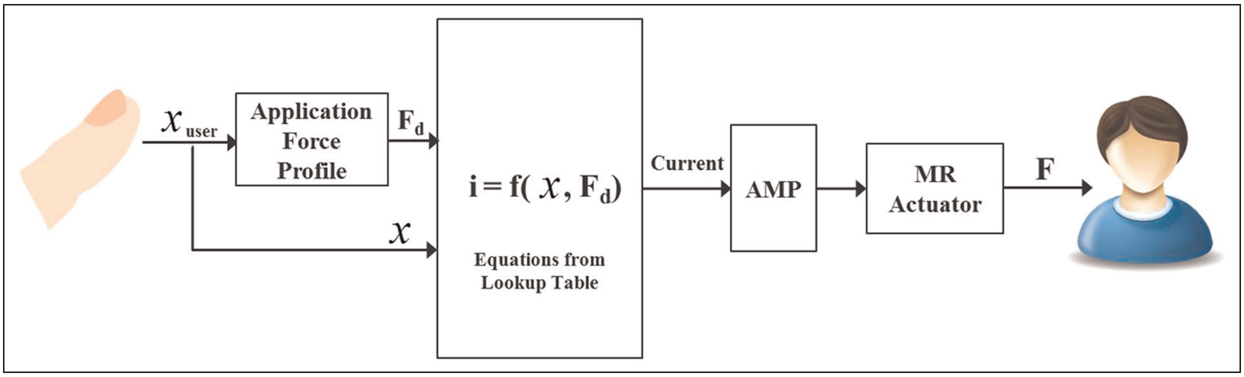

Figure 5. Control system for the MR actuator.
MR: magneto-rheological; AMP: amplifier.

The entire control system for conveying various resistive forces to users in accordance with the measured pressed depth is shown in Figure 5. When a user presses the proposed MR actuator, the collected pressed depth data by gauging impedance changes are converted into the desired force, F_d, from a predetermined application force profiles. The measured pressed depth and the desired force are inserted into the force–current equations constructed from experimental evaluations. From the force–current equations, a desired current signal is calculated. This current signal is applied to the MR actuator for generating resistive force or vibration. The specification of the proposed control system is as follows:

- Sampling rate of impedance sensing: 1.5 kHz;
- Resistive force is regenerated according to every stroke change of 0.05 mm;
- Force range of the MR actuator: 1.3–5 N;
- Maximum pressed depth of the MR actuator: 1 mm.

Experimental results

The proposed MR actuator can generate programmable force according to the pressed depth using the proposed control scheme. A precision load cell was used to measure the resistive force created from the proposed MR actuator according to user's press, as shown in Figure 6(a). Figure 6(b) shows a sample profile of the desired force, which was predetermined with respect to the pressed depth. The force profile was converted into a current signal profile, and this current profile was applied into the proposed MR actuator. The measured resistive force from the precision load cell was collected with respect to time, as shown in Figure 6(c). Note that the slope of the measured force profile is quite similar to that of the desired force. The measured pressed depth was accumulated by the proposed impedance sensing method, as shown in Figure 6(d). The pressed depth was gradually increased according to the gradual increase of the resistive force. As the desired resistive force suddenly drops around the 0.65 mm pressed depth (see Figure 6(b)), the gauged pressed depth was also dramatically increased up to the limitation, 1 mm. Hence, the results show that the proposed impedance sensing mechanism reliably gauges the user's pressed depth, and the designed control system works properly to produce the desired force according to the measured pressed depth.

Conclusion

This article has presented a new impedance sensing method to control the desired actuation force of the miniature MR actuator according to the stroke of the actuator. To realize actuating and sensing simultaneously with the proposed actuator, the proposed impedance sensing method uses mixed signals, which have a low-frequency signal for actuating and a high-frequency signal with small amplitude for sensing. The magnitude of the sensing signal due to impedance changes is gauged to estimate the users' pressed depth. The simulation results show that the proposed impedance sensing method can reliably differentiate more than five steps of the pressed depth within the 1 mm stoke of the actuator by satisfying the average threshold for compliance of human fingers. For evaluating the sensing performances combined by actuating function, the control hardware was constructed, consisting of a microcontroller, a current amplifier, and signal processors. The experimental results show that the prototype haptic actuator was able to produce a desired resistive force profile for users according to its pressed depth. From the results, the control system using the impedance sensing method can reliably provide various force profiles with respect to the gauged pressed depth. In summary, this study has proposed a new method for measuring the stroke of the miniature MR actuator, and it paved the way for the miniature MR actuator to be applied in

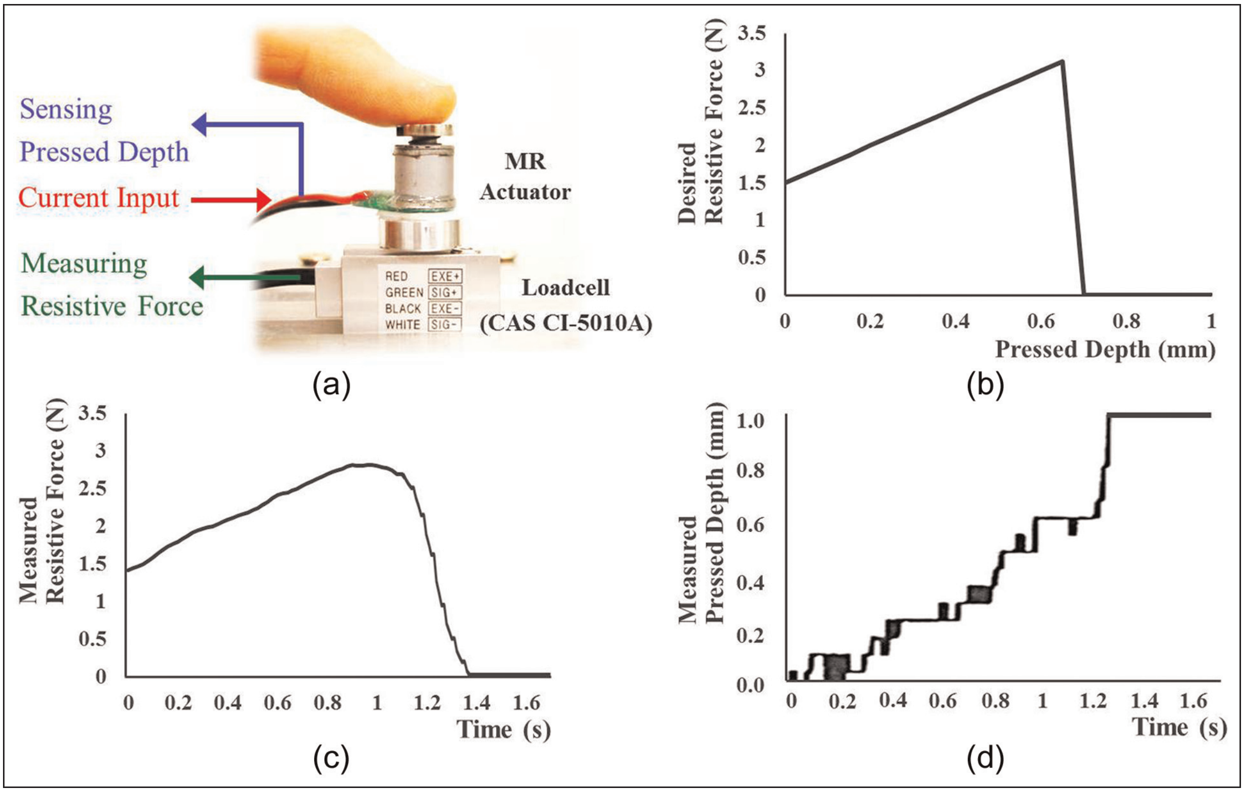

Figure 6. Experimental results for feedback control of the MR actuator: (a) experimental setup for measuring the resistive force and the pressed depth, (b) desired resistive force, (c) measured resistive force, and (d) measured pressed depth.
MR: magneto-rheological.

real-world haptic applications, such as game interfaces, mobile phones, and so on.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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