



Article Development of a Tactile Actuator with Non-Contact and Trans-Object Characteristics Using a Time-Varying Magnetic Field

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Abstract: A non-contact tactile stimulation system using a time-varying magnetic field was developed. The system comprises a control unit, power unit, output unit, and actuator. The control unit adjusts stimulation parameters, particularly the signal intensity and frequency. The power unit produces high voltages for generating the magnetic field, whereas the output unit transmits the energy generated according to the signal from the control unit to the actuator. A spiral coil actuator generates the magnetic field. To validate the effectiveness of the system, preliminary experiments on 10 male adults without neurological disorders (23.2 ± 3.05 years) were conducted. Magnetic field stimuli were presented to the right palm of the subjects at three different frequencies (10, 30, and 50 Hz), and corresponding electroencephalogram (EEG) signals were measured simultaneously. Event-related potential (ERP) analysis showed that N100 and P300 components were identified in somatosensory areas. Subjective evaluations revealed that feelings such as "tingling," "trembling," "tapping," and "percussing" were induced. Moreover, as the stimulus frequency changes, differences may occur in induced feeling. The system uses a time-varying magnetic field, which not only induces tactile stimulation without contact but also has trans-object characteristics that can present tactile sensations, even when there is an obstacle between an actuator and skin.

Keywords: tactile actuator; non-contact; trans-object; time-varying magnetic field

1. Introduction

Virtual reality (VR) and augmented reality (AR) systems are increasingly used in games, entertainment, education, and media [1–5]. Moreover, technologies for improving the interaction between these systems and users, and for enhancing realism and immersion are being actively developed. Visual and auditory stimuli, which provide humans with the most information from the external environment, require high-resolution real-time image processing and adaptive sound design to enhance user interaction [4,6,7]. To achieve even greater realism in AR and VR environments, haptics technologies have been adopted to present tactile information, in addition to visual and auditory information [5,8,9]. Most haptic technologies utilize contact methods by which the tactile stimulation is transmitted only when the actuator remains in physical contact with the skin [10,11]. However, contact methods have various disadvantages, such as introducing discomfort and inconvenience caused by wearing the device. Moreover, inconsistent or inappropriate tactile sensations can be induced depending on contact conditions [12–14].

Non-contact tactile stimulation devices have been developed, such as those that use focused ultrasound [15,16] or compressed air [17]. However, ultrasound-based methods require multiple ultrasound modules for focusing, and high frequency noise is continuously produced owing to interference generated by the multiple ultrasound transducers [16].



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). While compressed-air methods do not generate continuous noise, the air compressor intermittently generates a very loud noise in proportion to the number of tactile transmissions. In particular, for methods involving air, the spatial resolution varies with the distance and a cold sensation is also additionally generated [17,18]. Non-contact tactile stimulation methods using lasers have also been developed. This method radiates a pulsed laser onto the skin and the human body perceives tactile sensations from the stress waves generated by the thermoelastic effect [19,20]. Because of the optical characteristics of the laser, it has the advantages of a very high time-resolution, very high spatial resolution, and very large working distances [20]. As such, laser-based techniques can provide a high degree of freedom with few restrictions to human movement in VR or AR environments. However, laser-based techniques are very expensive and require a delicate optical setup and meticulous alignment. Moreover, it can be difficult to present the same tactile sensation to different skin tones, and care must be taken to avoid optical damage for users. Furthermore, all of these non-contact tactile stimulation methods have the same disadvantage of poor or impossible tactile transmission when there is a large obstacle between the actuator and the skin. In addition, if even a small impurity exists on the actuator or the skin, a different sensation may be presented from the one intended. As such, while technologies for non-contact tactile stimulation have been developed based on various mechanisms for user convenience, they have numerous inherent limitations that must be overcome before they can be utilized in products. In addition, researchers must also explore the development of new non-contact technologies based on fundamentally different mechanisms.

This study aims to develop a technique that addresses the common limitations of current non-contact technologies in which obstacles between the actuator and skin prevent or distort tactile stimulation. This study uses the electric field induced by a time-varying magnetic field for a tactile stimulation system with trans-object capabilities, i.e., a non-contact technique that can activate the mechanoreceptors of the skin while being unaffected by obstacles. In addition, this study conducts a preliminary human experiment to verify whether the proposed technique can induce tactile sensations.

2. Materials and Methods

2.1. System Configuration

Figure 1 shows the overall configuration of the time-varying magnetic field-based tactile stimulator. The system comprises four parts: a control unit, power unit, output unit, and actuator (spiral coil).



Figure 1. Overall configuration of the tactile stimulator based on a time-varying magnetic field (TSTM).

The control unit uses the AVR series ATMEGA128A microcontroller (Microchip, USA) as the main controller for the entire system. This controller is a general-purpose low-power 8-bit microprocessor with an operating voltage of 4.5 V to 5.5 V; it has eight 10-bit analog-to-digital converters (ADCs), serial communications, two each of 8-bit and 16-bit timers/counters, and an operating speed of up to 16 MHz. Moreover, it can interface with

various circuits related to control operations through 53 general-purpose input/output (GPIO) ports.

The system induces various tactile sensations by changing the frequency and intensity of the time-varying magnetic field. To this end, the stimulus frequency can be changed in five steps at 10-Hz increments from 0 to 50 Hz using the 16-bit timer/counter of the microcontroller. This signal is delivered to the output unit and used as a trigger signal to operate the spiral coil actuator. The stimulus intensity is proportional to the magnitude of the output unit capacitor charge. The charge voltage magnitude has five levels and can be adjusted using a voltage comparator located in the power unit and a digital potentiometer AD5290 (Analog Devices, Norwood, MA, USA). Using a character liquid crystal display (CLCD) and four button switches on the control unit, the output stimulus frequency and intensity can be controlled and monitored. Electroencephalogram (EEG) signals from subjects were recorded to objectively verify whether tactile stimulations based on the time-varying magnetic field generated from this system can induce actual tactile sensations in humans. To synchronize the timing of stimulus presentation and the acquisition of EEG signals, a sync signal of +5 V with a pulse width of 1 ms is delivered to the EEG measurement device simultaneously with the stimulus output.

The power unit receives +24 V DC from an external power supply and generates a high voltage of at least 1100 V to 1400 V to generate the magnetic field required to induce the tactile sensation. For this purpose, a switched-mode power supply (SMPS) which is widely used for pulsed discharge circuit [21] was fabricated with a flyback topology, and a UC3845 current mode PWM controller (Texas Instruments, USA) was used for step-up. The step-up high-voltage energy is stored in a high-voltage discharge capacitor DMF-200207K (Daedong Capacitor Co., Ltd., Seongnam-si, Korea) with a rated voltage of 2000 V and capacitance of 70 μ F. The charge voltage is monitored through the resistor voltage divider and this signal is fed to the power unit comparator. This signal is compared with the AD5290 output signal that is controlled by the microcontroller, and the SMPS is turned on and off accordingly to control the charging voltage.

The output unit transfers the energy stored in the capacitor to the coil over a short period of time using a silicon-controlled rectifier (SCR), and a magnetic field is formed by the current flowing through the coil. Trigger signals generated by the control unit are transmitted to the SCR gate via the gate driver MC33152 (ON Semiconductor, Phoenix, AZ, USA). When the SCR is turned on, under maximum discharge conditions, 1200 V is generated and approximately 1300 A flows through the coil. A ST300S18 (International Rectifier Corp., El Segundo, CA, USA) SCR with a repetitive peak voltage of 1800 V and a surge on-state current of short-time duration up to 8000 A was used.

The actuator that generates the magnetic field was a coil composed of a wire wound in a spiral around a rectangular copper wire (The conductivity is 5.96×107 S/m). The spiral shape is easy to manufacture and the shape and size of the generated magnetic field can be calculated from well known Equations (1)–(3). In addition, the number of coil windings and the magnitude of voltage and current were determined according to the target tactile presentation distance and the specifications of the electric parts used for hardware production. The resulting coil is a simple structure 12.8 cm in diameter and 9 mm thick. The magnetic field generated from the coil can be determined using

$$B = \frac{\mu_0}{4\pi} I \int \frac{dl \times \hat{r}}{r^2} \tag{1}$$

where *B* is the generated magnetic field, μ_0 is the permeability in free space, *I* is the electric current, *dl* is the vector along the coil path, \hat{r} is the unit vector, and *r* is the distance of an arbitrary point from the coil in normal direction. Therefore, the magnitude of the magnetic field is proportional to the amplitude of the current flowing through the coil and decreases farther away from the coil.

2.2. Tactile Stimulation Mechanism

All activities and functions of the human body are controlled by electrical or chemical reactions. These reactions are caused by the regulatory mechanism for maintaining homeostasis in the body and artificially inducing the same or similar reactions outside the body can cause similar effects.

When a physical stimulus such as an external vibration or pressure activates mechanoreceptors in the skin, an action potential is generated. This electrical signal is transmitted to the brain and perceived as a tactile sensation. In this regard, tactile perception could be elicited if the mechanoreceptors can be activated without direct physical stimulation. An example of this is to use electrodes to apply a current directly to the skin, stimulating the nerves and muscles around the mechanoreceptors; this can deform or stimulate the mechanoreceptors and induce a tactile effect [22–24]. In other words, the tactile sensation is induced by electrical stimulation.

However, the method proposed in this study does not involve direct contact electrical stimuli, but rather indirect non-contact electric stimuli induced by a magnetic field. That is, when a current is applied to the coil spaced from the skin over a short time, a time-varying magnetic field is formed around the coil, and when the hand and the magnetic field are mutually coupled, an electric field (*E*) is induced on the mechanoreceptors of the skin as

$$\nabla \times E = -\frac{\partial B}{\partial t}.$$
(2)

Similar to the electrical stimulus described above, the stimulus provided by this induced electric field can act on the nerves and muscles around the mechanoreceptors, which can induce tactile sensations. Figure 2 shows the overall schematic diagram for the tactile sensation induced by TSTM.



Figure 2. Schematic of the diagram for tactile sensation induced by TSTM (A.P. refers to action potential).

Solving Equation (2) for the electric field (E) using Equation (1) gives us

$$E = -\frac{\mu_0 NI}{4\pi} \int \frac{1}{R} dl \tag{3}$$

where *N* is the number of coil turns, and *R* is the distance from *dl*. When the mechanoreceptors are activated by electric field stimuli, the brain perceives them as tactile stimulation. The size of the electric field, which is closely related to the intensity of the tactile sensation, can be controlled by varying the current flowing through the coil, the number of turns of the coil, and the distance to the coil.

2.3. Subject

Preliminary experiments were conducted to examine whether TSTM could induce tactile sensations. Subjects were exposed to magnetic field stimuli with three different frequencies and their EEG signals were measured accordingly. A subjective evaluation was also conducted using adjectives.

The experiments were performed on 10 healthy right-handed males in their 20s $(23.2 \pm 3.05 \text{ years old})$ with normal perceptive and cognitive functions. External factors that could have affect the experiment such as smoking, alcohol, and coffee were regulated. The purpose and procedures of the experiment were fully explained, and the consent of each participant was obtained. All subjects were determined to be right-handed as per evaluation using the revised Edinburgh Reading Test [25]. The experimental protocol for this study was approved by the Institutional Review Committee of Konkuk University where the work was undertaken and conforms to the provisions of the Declaration of Helsinki.

2.4. Experimental Protocol

A hand rest was used to position the hand 4 cm from the coil (Figure 3a). The hand rest was composed of a sponge wrapped in soft leather and has a larger area than the coil.



Figure 3. Experimental protocol: (**a**) Flat spiral coil, hand rest, and hand position for tactile stimulation. (**b**) Block design for human experiments.

Prior tests confirmed that when the magnetic field at this location was approximately 2.1 T, the subjects felt an appropriate tactile sensation without pain. At this time, the magnitude of the magnetic field was measured using a TM-801EXP (KANETEC Co. Ltd., Ueda, Nagano, Japan) gauss meter. One experimental trial consisted of a stimulation phase (0.1 s) and a rest phase (20 s) (Figure 3b). A tactile stimulus is presented to the palm of the hand by the time-varying magnetic field during the stimulation phase, and the rest phase is the period in which no stimulus is presented. In the stimulation phase, a magnetic field stimulus with one of three frequencies of 10, 30, and 50 Hz was presented to the palm of the right hand. EEG signals were measured in sets of 30 trials for each of the selected frequencies. A subjective evaluation was performed after presenting the stimulus for the selected frequency. The other two frequency stimulation experiments were performed in the same way and the experiment order was counter-balanced. All subjects were instructed to close their eyes and wear headsets playing white noise to exclude auditory and visual factors, leaving only the magnetic field stimulation presented in the experiment.

2.5. EEG Measurements and ERP Analysis of the C3 Somatosensory Area

The EEG signals were measured at a sampling rate of 500 Hz using an Enobio 20 (Neuroelectrics, Barcelona, Spain). In accordance with the international 10–20 system, Ag/AgCl electrodes were attached to 16 locations, including C3, AF3, AF4, F3, Fz, F4, FC5, FC1, FC2, FC6, Cz, C4, CP1, CP2, Pz, and Oz. After attaching the electrodes to the subject, the researcher confirmed that the subject maintained a comfortable seated position and that

the EEG signal was stable before starting the experiment. The magnetic field for presenting the tactile stimulation was shielded with a Faraday cage so no noise was induced by the EEG signal.

Script code custom-made in MATLAB (Mathworks, Natick, MA, USA) was used to analyze the EEG signals. The obtained signals were filtered by a bandpass filter with a bandwidth of 0.5 to 20 Hz. Because the stimulus was presented to the right hand of all subjects, the signals for the C3 area were analyzed, which is in the contralateral direction and highly related to the somatosensory area. To determine whether the subjects perceived the tactile sensation induced by the magnetic field, this study analyzed the event-related potential (ERP) for a total of 0.8 s (0.2 s before presenting the stimulus and 0.6 s after).

2.6. Collection of Tactile Stimulation Sensory Adjectives and Subjective Evaluation

Vocabulary related to the tactile sensation was collected from a standard Korean dictionary [26] and previous studies related to sensory adjectives [27–29] to construct a subjective assessment consisting of 144 words. This was used to include all words corresponding to the sensations felt after each stimulus and subjectively evaluate each stimulus frequency. In addition to the presented words, the subjects directly wrote down the sensations they felt. The researchers counted all the selected words for the three frequencies and analyzed what tactile sensations were felt after the magnetic field stimulus.

3. Results

3.1. Output Waveform of TSTM

Figure 4 shows the voltage change of the capacitor at 50 Hz stimulus frequency, the maximum frequency output. The period where the voltage suddenly decreases indicates when the energy stored in the capacitor is transferred to the spiral coil actuator to generate the time-varying magnetic field. The section with a gentle rising slope is the period corresponding to which the capacitor is recharged to generate the same magnetic field at the next output. As shown, a stable continuous output is achievable while maintaining an average voltage of approximately 1200 V. At this time, the current flowing through the coil can be estimated as an average of about 1318 Ampere flowing through the coil's inductance (58 μ H), the high-voltage discharge capacitor's capacitance (70 μ F), and Ohm's law.



Figure 4. Changes in the capacitor voltage of the TSTM at 50 Hz stimulus frequency.

Figure 5 shows the induced electric field measured using a searching coil at a position 4 cm perpendicular to the center of spiral coil. This signal stimulates the nerves and muscles around the mechanoreceptors. The search coil was created by winding copper wire (The conductivity is 5.96×10^7 S/m) five times in a 5 cm-diameter circle, and the

TDS2104B (Tektronix Inc., Beaverton, OR, USA) oscilloscope was directly connected to measure the induced electric field.



Figure 5. Testing the tactile stimulator based on time-varying magnetic field: (**a**) Induced electric field waveform measured by searching coil. (**b**) Experimental environment for testing the TSTM and measuring electric field.

Simulation of the magnitude and shape of the induced electric current in the skin was calculated using Equation (4), and the results are shown in Figure 6 [30,31]

$$\frac{\partial \overrightarrow{E_e}}{\partial x} = \frac{I_e(2x^2 - z^2)}{4\pi\sigma(x^2 + z^2)^{\frac{5}{2}}}$$
 (4)

where, E_e is the electric field, x is the length in the lateral direction of the skin, z is the skin depth, I_e is the injected current, and σ is the extracellular medium conductivity ($\sigma = 0.5 \text{ s/cm}$) [32]. I_e was calculated using the amplitude of the signal measured using the searching coil and the impedance of the skin [31]. The waveform of the simulated electric field induced in the skin was similar to the shape of the signal measured from the searching coil. In addition, from the stimulation point of the skin, at a depth of about 0.18 mm about 392 mA, at a depth of 0.5 mm about 21 mA, at a depth of 1 mm about 2.6 mA, and at 1.5 mm, it rapidly decreased to about 0.8 mA.



Figure 6. Simulation of electrical signals induced in the skin: (**a**) Simulation results of the magnitude and shape of the induced current by depth and lateral direction from stimulation points in the skin. (**b**) Change of the maximum peak value of induced current according to depth.

3.2. Event-Related Potential (ERP)

Figure 7 shows the ERP signals measured from the C3 area for the three different frequencies of magnetic field stimuli. Each signal shows the average of 10 subjects. After the stimulus time for all three signals, at approximately 100 ms and 300 ms, N100 and P300 components were observed. From a one-way ANOVA using frequency as the variable, no significant differences in maximum peak, minimum peak, peak-to-peak, negative latency, and positive latency (p > 0.05) were found. The maximum and minimum peaks are the maximum and minimum voltages of the ERP signal after the stimulus is presented, respectively. Peak-to-peak is the difference between the voltage of the maximum peak and the voltage of the minimum peak. Negative latency and positive latency are the time intervals from the stimulus presentation to the minimum peak and the positive peak, respectively.



Figure 7. Average ERP signal measured in the C3 somatosensory area for magnetic field stimulation with three frequencies.

3.3. Subjective Evaluation

Table 1 shows the words selected from the 144 words at least once to describe the sensation felt due to the magnetic field stimulus for three different frequencies. The subjects reported feeling a total of 10 sensations, in the order of "tingling," "trembling," "tapping," "percussing," "stinging," "stabbing," "tickling," "stiffing," "blunt," and "pushing". "Tingling" dominated the adjectives in all frequencies; it is a commonly reported sensation when an electrical stimulus is provided. After "tingling," the most frequently chosen words by frequency were "tapping" at 10 Hz and "trembling" at 30 Hz and 50 Hz.

Table 1. Subjective evaluation results of magnetic field stimulation at three different frequencies. The number indicates the number of subjects who selected the word.

	Tingling	Trembling	Tapping	Percussing	Stinging	Stabbing	Tickling	Stiffing	Blunt	Pushing
10 Hz	7	2	6	3	3	1	1	1	0	0
30 Hz	8	9	3	3	2	2	1	0	1	1
50 Hz	10	7	2	3	3	2	2	2	0	0
Total	25	18	11	9	8	5	4	3	1	1

4. Discussion

This study developed a novel tactile stimulation system with non-contact and transobject characteristics using a time-varying magnetic field. The ERP response and subjective evaluation results confirmed that the developed system can induce tactile sensations and also the results demonstrated that varying the stimulus frequency can cause differences in the induced feeling. The tactile stimulation technique using a time-varying magnetic field has two advantages. First, tactile sensations can be evoked without contact. Energy generated by the spiral coil actuator forms the magnetic field, from which an electric field is induced inside the human body. This elicits a tactile sensation, thus enabling tactile sensations to be presented without direct contact between the actuator and the skin in the mid-air. As such, the disadvantages of existing contact tactile stimulation presentation techniques can be addressed, such as awkward positioning and movement restrictions.

Second, the tactile sensation can be delivered even if there is an obstacle between the actuator and skin. In the case of existing non-contact tactile sensation techniques including ultrasound, compressed air, and laser, obstacles between the actuator and skin block or distort the transmitted energy. The technique proposed in this study enables undistorted energy transfer even if the actuator or skin is completely or partially covered by a nonconductor, such as wood, acrylic, paper, fabric, or rubber.

Using this system, ERP was measured for each of the three frequencies of magnetic field stimulus, and a subjective evaluation was conducted after presenting the stimuli. N100 components, which reflect the perception of unpredictable stimulus from an ERP signal that can represent the perception information of the sensation [33], and P300 components, which reflect processes related to stimulus evaluation or classification [34], were clearly observed at the C3 somatosensory area. This is evidence that some sensation from the time-varying magnetic field, i.e., tactile stimulation, was perceived. However, there were no significant differences in ERP components (maximum peak, minimum peak, peak-to-peak, negative latency, and positive latency) according to changes in frequency. In the future, it will be necessary to study correlation with subjective evaluation, as the number of subject data increases.

According to the subjective evaluation, the word "tingling," which expresses a feeling related to electrical stimulation, was commonly selected regardless of frequency. This is likely due to the induced electric field that evokes the tactile sensation of the system. However, there were differences in the tactile sensations according to stimulus frequency. With a relatively low frequency stimulus (10 Hz), the slow vibrational sensation of "tapping" was mainly induced, and in the relatively high frequency stimuli (30 Hz, 50 Hz), the rapid vibrational sensation of "trembling" was mainly induced. In addition, the feelings of "percussing," "stinging," "stabbing," and "tickling" were also induced. These results demonstrate that although the system caused an electrical response and feelings similar to pain, it can also produce tactile sensations such as fluttering or vibrational sensations. The results also indicate that various types of tactile sensations can be induced by adjusting the stimulation parameters, such as frequency. From the simulation of the current induced inside the skin, it was presented. The deeper the depth, the sharper the decrease, but it is thought that an electrical feeling is triggered by the momentary current generation.

To conclude, this study confirmed that an electric field induced by a time-varying magnetic field can be used to stimulate the mechanoreceptors without contact, enabling tactile sensations to be perceived. However, this system has the following limitations and disadvantages. High voltages and currents must be applied to the coil to generate a magnetic field strong enough to induce tactile sensations. This makes the system large and heavy. Furthermore, although the sound generated when presenting the stimulus is a common disadvantage of existing non-contact tactile presentation techniques, this system also generates a single sound when high current flows through the coil. In the future, changing the coil material or shape and combining magnetic materials will make it possible to reduce the system size while simultaneously reducing the amplitude of voltage and current required and enabling sound attenuation.

This study conducted only simple experiments to determine whether the tactile sensations could be elicited on human subjects using ERP signals, coupled with a subjective evaluation. As such, quantitative and objective verification studies are still needed. A comparative study with physical tactile stimulation should also be conducted. In addition,

based on research on controlling the stimulus parameters by changing the intensity and frequency of the magnetic field or by applying a modulation technique, methods will also need to be developed for evoking various tactile sensations.

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