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A Closed-Loop Tactor Frequency Control System for Vibrotactile Feedback

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ABSTRACT

In this paper, we address the problem of maintaining a precise frequency in vibrating motors for use as vibrotactile cueing devices. Our solution utilizes a piezoelectric film sensor that measures the motor frequency and uses a feedback-loop circuit to dynamically adjust the motor power to maintain the target frequency. We confirmed the accuracy of the film with a laser sensor and tested the ability of the feedback system to match a target frequency by changing the physical load placed on the motor. A user study showed that subjects perceived a difference in vibration intensity under loaded conditions with and without our compensation system, indicating the usefulness of such a feedback system on influencing perception. The results can help designers create better interfaces when vibrotactile cues are employed.

Author Keywords: Haptic, vibrotactile, calibration, closed-loop, feedback.

ACM Classification: H.5.2 [User Interfaces]: Haptic I/O; H.1.2 [User/Machine Systems]: Human factors; I.3.6 [Methodology and Techniques]: Interaction techniques.

INTRODUCTION

Current research focusing on displaying near-field haptic cues in immersive virtual environments often use DC motors to function as vibrotactile units (tactors). These motors create a vibration with a spinning eccentric mass where an increase in voltage produces an increase in vibration intensity.

One problem with using this type of tactor is that the actual frequency depends on various factors beyond the control of just the applied voltage. The changing characteristics of how the tactor is mounted, such as the orientation of the tactor or pressure applied to it, can significantly change the frequency with which the tactor vibrates.

In certain scenarios this is not a significant problem. For instance, in some cases, tactors run with only a binary state, ON or OFF. A change in the frequency does not matter, as long as the subject can feel the vibration. However, in situations where the intensity of the tactor is important, external effects, such as pressure, can alter the intended result of the tactor stimulus. The goal of our work is to maintain a precise frequency of the tactor, regardless of outside forces.

Perceived Vibration

We can define a transfer function *J* that maps from an input state *t* to and output state *s*, where *t* is the control signal to the vibrotactile device and *s* is the perceived vibration by the user (Figure 1a). When we first started using DC-motor-type vibrators as tactors, we found that the oscillating frequency and amplitude of this type of device were affected by such factors as the method used to mount them on the person, or the orientation of the device in relation to the gravity vector, even when the electric signal was kept constant [1]. Considering these effects, we can decompose *J* into two components, *G* and *H*, and model the process of how this type of tactor makes us perceive tactile sensations as shown in Figure 1b.

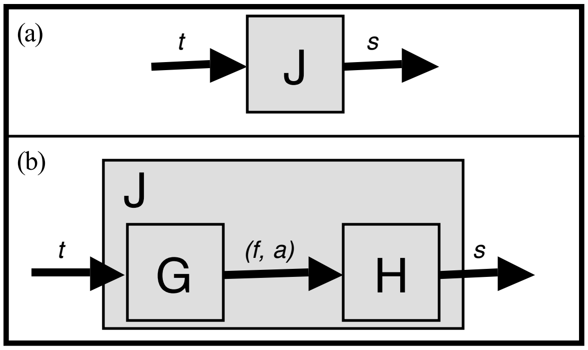

Figure 1. Transfer functions for vibrotactile stimuli (a) modeled as a single function, and (b) modeled as a series of functions affected by various factors.

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An input state variable for the transfer function *G* is the electric signal for the vibrator, and the output state variable is the vibration characteristics, such as frequency *f* and amplitude *a*. Variable factors for the transfer function *G* are mainly electrical and mechanical conditions of the vibrator: how the vibrators are mounted. The output state variable for the transfer function *H* is the tactile sensation *s*: how the user feels the vibration. The transfer function *H* is related to the method of mounting, as well as the mental and physical condition of the user.

As long as a constant electrical signal is applied, DC-motor-type vibrators work at a constant frequency and amplitude when rigidly fastened to a surface, such as a tabletop. In other words, the state of vibration corresponds one-to-one to the state of the applied electric signal, as illustrated in Figure 1a. Most of the tactile displays using vibrotactile tactors have been designed with this one-to-one mapping as a presupposition; they model the transfer functions *G* and *H* as a single transfer function, record the correspondence relation of output *s* to a certain input *t* beforehand, and expect that this relation will always hold. However, as described in our model, dynamic changes in the environment make the output of *H* vary constantly due to mechanical factors. Therefore, there is the possibility that a user receives a different tactile sensation when his or her posture changes, even when *t* is held constant.

We propose the Feedback Tactor, which is more exact, counteracting dynamic influences on *G*. This feedback mechanism is necessary in order to present information reliably using tactile stimulation. In this paper, in order to show the validity of our approach, we measured how subjects felt vibration in an environment where an oscillating state is guaranteed by closed-loop feedback. We consider the experiment as an example of how to evaluate the transfer function *H i.e.*, the characteristic of the feeling to the vibration itself.

BACKGROUND

In recent years, several researchers have begun to experiment with the use of low-cost pager motors as a way of delivering vibrotactile stimuli for human-computer interaction [5, 6, 1, 4, 3, 2, 7]. These systems use multiple tactors located at different points on the body to provide cues for use in real and virtual environments. With vibrotactile systems, vibration can be used to signify that contact has been made with an object in a virtual environment, but the user's hand, for example, will pass through a virtual table, because support for arresting user movements is absent from these approaches. Providing the ability to control the intensity of the vibration [4], as opposed to simply turning the motors on or off [1, 3], can provide added information about the nature of the contact (*e.g.*, velocity, depth of penetration). This paper represents a first step in solving the problem with the combination of electro-mechanical and psychological/physiological factors.

Design

The three main units in our design are a PIC microcontroller, a piezoelectric film sensor, and a tactor. The PIC 16F873 applies a particular voltage to the motor using Pulse-Width Modulation (PWM), which causes the motor to vibrate, thereby causing the film to generate a frequency signal for the PIC to read (Figure 2). The PIC then increases or decreases the duty cycle of the PWM, which can range from 0 to 1023, for the tactor to match a given frequency. The motor is mounted to the film, and the film is connected to the PIC. Currently there is an amplifier between the film and the PIC, so that the PIC can recognize the signal from the film. The host sends the target frequency and receives the current frequency read by the film and the PWM duty.

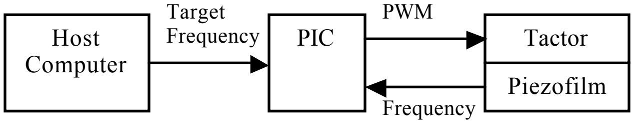

Figure 2. System operation

The film (Figure 3) is used to monitor the amplitude and frequency of the vibrating tactor by mounting the tactor on the film. A piezoelectric substance generates an electrical charge when mechanically deformed. Currently the system only measures the frequency of the tactor, but future versions of the system could incorporate amplitude measurement as well. This will be interesting for controlling voice-coil- and piezo-type tactors.

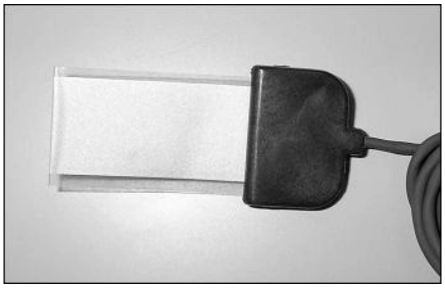

Figure 3. Film sensor

Design Goals

The initial design goal was to create a proof-of-concept to show that the film could be used to match a target frequency. Once the functionality of the film was tested and verified, complexity was added to the design, and the tactor and film were packaged into a single unit to improve the reliability of the system for use in a user study.

IMPLEMENTATION

The host computer communicates with the PIC using a standard RS-232 serial interface and a custom control protocol. The protocol allows for setting the initial tactor duty, the target frequency, and enabling and disabling the corrective feedback.

The frequency signal from the film is connected to the CCP pin on the PIC and the frequency signal is calculated using the timer. Every time a falling edge of the film signal is received by the PIC, the timer value is saved as the frequency and the timer is then reset. However, because of small fluctuations in the frequency, an average is taken of the past six frequencies and used as the correct frequency. The PIC sends a status update of the current duty and frequency every 100ms to the host computer.

The algorithm to match the frequency of the tactor is fairly simple. The pseudo code is shown in Figure 4. Every time the PIC calculates a new frequency average, the PIC also recalibrates the duty value. If the feedback functionality is enabled, the duty value will increase or decrease by half the difference between the target and current average frequency. There is a buffer of 1Hz to allow the feedback system to level out on one duty value.

```
diff = abs ( freq_avg - target ) / 2

if ( freq_avg < ( target - 1 ) ) {
  duty = duty + diff
  set_pwm ( duty )
}

if ( freq_avg > ( target + 1 ) ) {
  duty = duty - diff
  set_pwm ( duty )
}
```

Figure 4. Frequency matching pseudo code

LIMITATIONS

One problem with piezoelectric devices is noise created from electromagnetic interference. The need for averaging each falling edge time is partially due to the noise from outside the system. The simple solution of shielding as much of the system as possible does not remove all of the noise. Another possible solution, which could be implemented in future iterations of the device, is to use a Fast-Fourier Transform (FFT) chip before or after the amplifier to 'clean' the signal before it is sent to the PIC.

Another concern is the different ways of attaching the film to the tactor, as well as of attaching the combined package to the subject. How the motor is attached to the film can change the frequency reported by the PIC. Often the tactors are very small and can be placed in different positions on the film. Depending on where the tactor is placed on the film, different results can be produced. Also, once the two pieces are combined, it is sometimes awkward to find a reliable way of attaching the tactor/film unit to a subject. Currently, the film and tactor are taped together and then taped to an armband, which is attached to the subject.

VERIFYING FILM AND PIC ACCURACY

To verify the accuracy of the film's frequency signal, a laser device was used. The laser was attached to an oscilloscope and pointed at the side of the tactor. The readings on the oscilloscope were then compared to the output reported from the film. The results were very successful, with upwards of 99% accuracy.

With successful results from the PIC, it was relatively easy to test the ability of adjusting the PWM to meet the correct frequency. The simplest test was to put a weight on the motor, thereby increasing the frequency, and allowing the PIC to lower the duty cycle. Different types of calibration algorithms, such as the one shown in Figure 4, were attempted. The simplest one would be to increase or decrease the duty by 1 value each time the function is called, but this leads to a relatively slow calibration. The current algorithm reaches a steady target frequency in less than one second.

EMPIRICAL STUDY

We performed a user study on 16 subjects by attaching the tactor/film combination to an armband on the subject's arm, and then wrapping a blood-pressure cuff around the subject's arm (Figure 5).

Figure 5. Armband and cuff

The tactor was then started and pressure applied to the arm by inflating the cuff. When the cuff was inflated, the increased pressure on the tactor increased the vibration frequency from 100Hz to 130Hz. After the change in pressure, the subject was asked if he or she felt a difference in intensity of the tactor. The subject was given a choice of increased or decreased intensity in a forced-choice test. Each subject was given 32 trials, with half the trials starting with the cuff inflated and half starting with the cuff deflated. The feedback system was only activated in half of the trials.

The expected results of the study would be that when the pressure from the cuff increased, and therefore the frequency of the tactor increased, the perceived intensity of the tactor would also increase. If the feedback system was enabled, however, the tactor's frequency would stay the same, and the subject would choose a statistically similar number of 'increases' and 'decreases'.

What we saw, however, was that as the pressure/frequency increased (with the feedback-loop inactive), subjects sensed a rise in frequency, as indicated by the left two bars of Figure 6. Likewise, when the feedback system was active, most subjects sensed a drop in the frequency of the vibration, even though the frequency was being held constant relative to the case when the cuff was deflated. One explanation for this is that when the feedback system lowers the duty, the combined effect of increased pressure and constant frequency makes the stimulation feel weaker, indicating that H has changed somehow, supporting our model. The added pressure of the cuff changed the area around the vibration point, thereby altering the way the vibration is perceived.

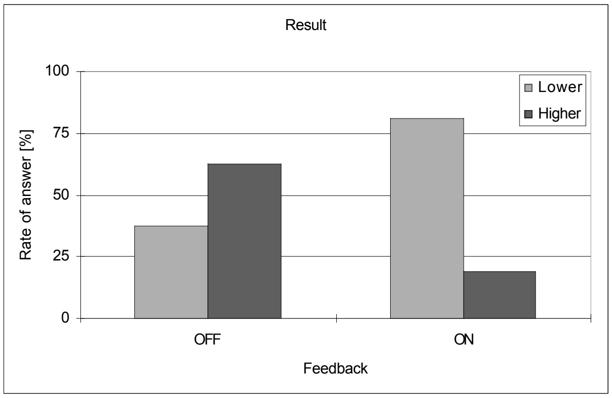

Figure 6. User-study results

APPLICATIONS

The use of vibrotactile cues in user interfaces can take on many forms. They can be used in virtual reality systems to provide a sense of virtual contact between the person and virtual objects. With the ability to vary the frequency, we can map collision properties, such as velocity, to vibration intensity. Alternatively, vibrotactile cues can be used as training aids to improve the situational awareness of participants, providing cues for such things as the location of teammates in a team-based scenario. Vibrotactile cues could also be used to compensate for shortcomings of current technology, such as directional vibration cues used to alert a user to visual information currently outside the field of view of a visual display.

We can also augment the physical environment with vibrotactile cues, providing training aids through the haptic modality that support the visual task being performed. Motion-following tasks, such as in hip-replacement rehabilitation, could be aided by providing a vibrotactile force field. When the motion violates a threshold, vibrotactile stimulation could be used to "nudge" the patient back to within a safe range of motion. We can also envision an approach where drivers are alerted to changing traffic patterns, such as a car approaching rapidly on the left when the wearer is trying to change lanes. This type of system will be even more interesting as the population ages, and people are less able to look over their shoulders.

The closed-loop approach we propose is important because a change in load on the tactor caused by a shift in posture, or by a pressure suit worn by a pilot, will alter the frequency of a vibrotactile cue in undetermined ways; it would be beneficial to have greater control of the parameters of the vibration. Allowing system designers to be able to use the low-cost solutions afforded by vibrotactile devices effectively could greatly increase the applications where these cues are employed.

FUTURE WORK

The results from our first attempt at providing closed-loop frequency control of DC-motor-type tactors are encouraging. Because varying the voltage changes the frequency and amplitude in a coupled fashion, and neither can be changed independently, in the future we will extend our system to allow for controlling both frequency and amplitude for tactors that allow such control. In addition, we will explore other algorithms for reaching the target values more efficiently. Finally, we will test new ways of mounting the tactor to the film, and for mounting the resulting package to a user. Encasing the package in silicon gel, or a rigid plastic housing, might prove interesting.

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