Haptic Feedback for Motion Guidance Based on Vibrotactile Illusions

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(運動誘導のための振動錯覚に基づく触覚フィードバック)

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論文内容要約

In this dissertation we present a novel way to use vibrotactile illusions in order to produce vibrotactile feedback on the skin and convey richer information to users. Specifically, we introduce three new paradigms to convey spatial information (direction) and temporal information (tempo) using vibrotactile feedback based on vibrotactile illusions. Throughout this thesis, we introduce the aforementioned paradigms and carry out experiments to verify that users are able to perceive the intended information.

Traditionally, humans learn a motion or motor skill by receiving instructions and feedback from a more experienced person. The instructor guides the person through the motion, and the trainee repeatedly practices the motion while receiving feedback, through speech or physical interaction. When we are being guided through physical interaction, the speed and the range of motion are limited, so users cannot perform the actual motion while being guided. If there is no instructor, then users cannot receive such guidance.

Vibrotactile technology has been widely explored as a real-time feedback mechanism to convey information and enhance the feedback and the motor learning process while training a motion. Instead of an instructor, vibrotactile cues are applied to the skin in order to correct certain parameters of the motion.

In the past, several approaches have been proposed in order to convey different information to users. The most common approach is to produce multiple vibrotactile cues near to the joints, in order to control each joint's angle. This approach has been used for multiple purposes, ranging from rehabilitation to training the violin bowing motion or rowing. Under these approaches, the number of controlled Degrees of Freedom (DOF) is proportional to the number of simultaneously produced cues. Following multiple cues at the same time to guide a high DOF motion is very difficult for humans. Instead of conveying one direction per place in multiple locations of the skin, in this study, we propose applying cues based on vibrotactile illusions that can convey multiple directions in a single place in order to guide high DOF motions following the direction indicated by the cue.

In Chapter 2 of this thesis, we proposed a vibrotactile feedback approach called “Direction Sensation”, or DS, which consists on producing a flow of vibration around the arm to indicate directions in a natural way using using vibrotactile illusions. We took inspiration from the way a fluid moves around a cylinder, and proposed cues that imitated that motion, by creating the illusion of a moving vibration around both sides of the forearm towards a certain direction, using the Apparent Tactile Motion (ATM) vibrotacile illusion. The vibration wave moves around the arm in the same way as the arm should be moved, indicating the users to move along this direction. We used a vibrotactile sleeve in which we embedded 4 rows of 8 motors evenly distributed around the forearm. To produce the illusion, we activated a single motor first, and then activated the adjacent motors after a certain time (called Stimulus Onset Asynchrony, or SOA), which produces a moving vibration from the starting motor towards the following motors. By changing the motor where the cue starts and ends, we can produce eight different directions around the forearm. To test whether users were able to recognize the direction, we performed a user study, and we found that users could recognize the right direction 83.33% of the times. Even in cases where they chose a wrong direction, they chose a direction adjacent to the produced. We applied these cues to guide the 1DOF elbow flexion/extension motion. We additionally controlled the duration of each cue and the time between one cue and the next in order to inform users about the distance between the current and the desired angles. Users were able to reach arbitrary elbow joint angles following these DS vibrotactile cues.

However, using other vibrotactile illusions we considered it possible to extend the number of possible directions that could be produced. In Chapter 3 we proposed three ways to enhance the proposed DS to produce cues in any direction around the limb and to make them easier to understand to users. We switched the place where the cues were applied from the forearm to the wrist, as conveying any direction on the wrist would allow users to know where to move it, guiding its position from an end-effector point of view. The number of vibration motors in the device was reduced to six, as the circumference of the wrist is smaller than that of the forearm.

The first improvement to the DS cues consisted on producing vibrations at entry/exit points where there is no physical actuator using the Phantom Sensation vibrotactile illusion. Thus, the DS cues can start and end at any point around the wrist, enabling us to produce a flow in any direction around the wrist. However, as the propagation after the start point was done using ATM illusion, this propagation would feel the same for any direction where the start/end points were placed between the same actuators.

Through experimentation with the vibrotactile illusions, we found out that the illusion of a moving vibration could not only be produced using ATM, but also by continuously changing the position of the produced PS illusion, which is achieved by varying the amplitude of the surrounding vibration motors accordingly. We then decided to produce the moving vibration flow only using the PS illusion, in order to produce consistent moving sensations throughout the whole cue. In this way, the vibration moves around both sides of the arm in an even way, which is different for each different direction, making it consistent with the imitated flow. This, however, introduced the additional limitation of the propagation when the start point was produced using PS, in which case the vibration can only move either way. To solve this limitation, the third improvement consisted in adding a second row of motors adjacent to the first, in order to guarantee the correct propagation of the virtual vibrations in the vicinity of the entry/exit points. Through experiments, we confirmed that the proposed improvements allowed users to reduce the direction recognition error of the DS cues by a 22.05%.

The proposed DS sensation intuitively conveys users the desired direction of motion, which makes it possible to use it for tasks that require correcting the user's pose. However, the time required for the moving vibration to propagate around both sides of the wrist can be long for tasks that require fast correction of the motion.

In Chapter 4 we borrowed the concept of producing a single point vibration at the wrist to convey the direction, but instead of using separate motors and producing limited static vibrations, we propose producing vibrations at any point around the wrist by using the Phantom Sensation vibrotactile illusion. We can dynamically and instantaneously change the position of the vibration produced by the PS illusion by changing which vibrotactile motors are actuated, and their relative amplitude.

By training users under a conceptual mapping to map the location where they felt the vibration with a determined response, we can guide the position of the user's wrist towards any direction in 2D space producing vibrotactile cues in a single location. Another thing that we considered in this chapter is the user's wrist rotation. If the position to produce the vibrotactile cue is calculated in the local coordinate frame, if the user rotates the wrist then the produced vibration indicates a direction different to the desired one. We adjust the position of the vibrotactile cue accordingly in order to maintain consistency between the cue location and the global frame.

We carried out a user study to determine whether users could recognize different directions produced using the PS illusion. We measured the recognition under two conditions; in the first one the user kept the wrist fixed, the cue was produced and the user registered the perceived the vibration, and in the second one we requested users to rotate their wrist while the cue was produced and then register their answers. Users performed with an average error of 7.87˚ for the first condition and 9.30˚ in the second condition. This seems to indicate that users are able to recognize the location where the cue was produced with relative accuracy, and the difference between tasks is not very large, which indicates that the wrist rotation is being correctly compensated.

On a second experiment, we applied the proposed cues to guide users' wrists in space under the two most common conceptual mappings, "pull" and "push" (i.e., move towards where the vibration is felt, or in the opposite direction, respectively). We set four desired positions in space, and based on the position of the wrist and the conceptual mapping, we produce a vibration in the corresponding direction to guide users towards that desired position. We considered that users reached the desired position once the hand entered an area or deadband around the desired position, as it's very difficult for humans to hold a position precisely without error. We used the magnitude of the vibration to indicate users whether they were far or close from the desired position. As they approached the desired position, the magnitude of the vibration decreased, and the vibration stopped once the user's hand entered the deadband area. Users were able to reach the arbitrary points in space by following the vibrotactile cues.

Up to Chapter 4, we proposed ways to convey direction to users. However, conveying direction can only correct the spatial aspects of the motion, but provides no information about the time-dependent characteristics. In Chapter 5, we propose a vibrotactile feedback paradigm to convey temporal information to users. Specifically, we produce cues to train the notion of tempo for a golf putting task. We convey tempo to the users by using the PS vibrotactile illusion to create a moving vibration inside the putter's grip that users can map to the desired motion. We change the position of the produced vibration based on the intended motion of the putter head, and request users to perform the putt following the vibration. We compared the effectiveness of the feedback conveying two different tempos. Users were able to follow the cues while putting, eliciting tempos close to those indicated by the cues, with an average tempo of 1.178 for cues conveying a tempo of 1, and 1.866 for cues conveying a tempo of 2. We also proposed using vibrotactile feedback to indicate users the timing to start the downswing phase of the putt in order to control the length of the stroke. We did a user study, where cues were produced for two different desired angles of -5˚ and -10˚, and users elicited stroke angles of -6.20˚ and -10.67˚ respectively. We observed that the cues allowed users to elicit stroke angles close to the desired ones.

In general, this dissertation proposes three major contributions to the field of haptics: the first one consists in proposing the concept of using the Phantom Sensation illusion to create a moving sensation by dynamically changing the relative amplitude of the actuators, which is something never done before in literature, to the extent of our knowledge. The second major contribution consists on the creation of direction display approaches that can convey any direction around the wrist, enabling us to control multiple DOF motion simultaneously using feedback in a single location of the skin, instead of requiring users to identify multiple cues in different locations. The third major contribution consists on designing vibrotactile cues that can convey temporal information involved in the motion, such as tempo, and applying this concept to the motion of putting in golf.

In the future, we want to extend the direction display concept to the 3D space, and apply it to motion learning tasks such as dance, calligraphy or sports. We would also like to extend the golf training framework to include other skills of golf which are also important, such as green reading or facing with a straight putt face. Furthermore, we want to evaluate the effect of the proposed training approaches in the motor learning in the long term, and whether the actual skills are improved even in the absence of feedback.