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A Lightweight Wearable Multi-joint Force Feedback for High Definition Grasping in VR

Nicha Vanichvoranun*
KAIST
Daejeon, Republic of Korea

Sang Ho Yoon†
KAIST
Daejeon, Republic of Korea

ABSTRACT

Various research develops kinesthetic gloves that only render force on the distal interphalangeal joints (DIP) and often require a complex mechanism. Our research proposes a novel design of a wearable haptic device enabling kinesthetic feedback to all finger joints to promote precise grasping in VR. We employ electrostatic-based force feedback to form a clutch mechanism that we extend to all finger joints. Using the electrostatic-based clutch allows us to maintain a thin and light form factor for devising the prototype. Our proposed method supports a blocking force of up to 30 N per joint.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction devices—Haptic devices;

1 INTRODUCTION

As grasping is one of the crucial skills to interact with the object in VR, various studies have designed different mechanisms to render the haptic feedback. However, these complicated mechanisms are often heavy, and sometimes limit the user's hand movement. Due to the bulkiness of the design, most wearable haptic devices can only generate kinesthetic feedback force on the distal interphalangeal joints (DIP) of the fingers (fingertips), limiting the range of sensations that can be rendered. Fortunately, recent studies have introduced a principle of electrostatic brake, which allows for the design of thin and light wearable devices. For a more realistic and immersive haptic experience, we utilize this concept and propose a novel design to improve object shape sensation by rendering force on all joints of the finger which include the distal interphalangeal (DIP), proximal interphalangeal (PIP), and metacarpophalangeal (MCP) joints, while maintaining a low profile form factor. However, one issue of the electrostatic clutch is that the user cannot relax their hand when they want to release the object. We address this problem by fabricating and installing pressure sensors at each joint on the finger, and the change in detected pressure will indicate when to disengage the clutch.

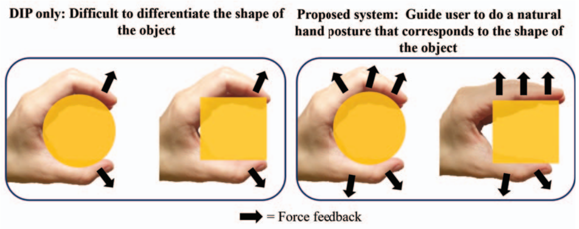

Figure 1: A comparison of haptic rendering between DIP-only haptic gloves and our multi-joint haptic gloves

Kinesthetic Feedback Gloves: There are various mechanisms and actuators to design kinesthetic haptic gloves. Traditionally, the popularly used actuators are DC motors. Despite being robust and having the capability to provide reliable force, they can be bulky, and the generated force scaled down significantly as the size decreased. As alternatives, some researchers use shape memory alloy (SMA) springs since the blocking force is created from the deformation of SMA while being heated. Although SMA is considered light and soft, it requires high power to operate and suffers from a long cooling time. While [3] proposes a tubular brake that utilizes the hydromechanical characteristic of polymers which are soft and able to obtain high braking force, this method also has a long response time.

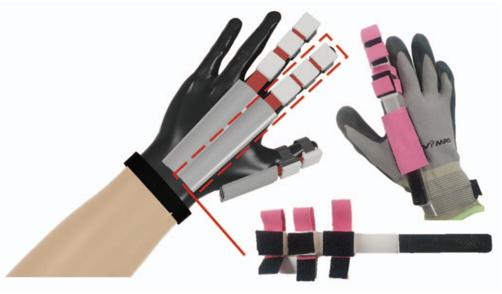

Figure 2: A CAD model and the assembly of a thin and flexible haptic feedback glove for virtual object's manipulation

Electrostatic Clutch: Recently, the use of electrostatic clutches in wearable devices is becoming popular in different applications [1] due to their thin, flexible structure and high braking force. Researchers have applied these clutches to various body parts, including the hand, elbow, and shoulder [2]. In haptic gloves, only a 1-degree-of-freedom mechanism controls finger movement, and most works have not investigated the conditions that make their device disengage.

Our contributions are as follows:

- A novel design of multi-joint haptic gloves to promote precise grasping in VR.
- Development of an on-demand braking system that engages/disengages based on the pressure sensing from the finger.

2 SYSTEM OVERVIEW

Kinesthetic Force Feedback from Electrostatic Clutch: Instead of controlling only a single joint of each finger, the configuration of our device allows the clutch to be stacked on top of each other and act as an actuator to precisely control and transfer the force to each phalange of a finger. The electrostatic haptic gloves can simulate feedback to render virtual force in VR by providing resistive force to the user's hands when the user virtually touches any objects or elements. This device consists of electrostatic clutches which are variable capacitors with slidable electrodes (including conductive

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*e-mail: nizetime@kaist.ac.kr
†e-mail: sangho@kaist.ac.kr

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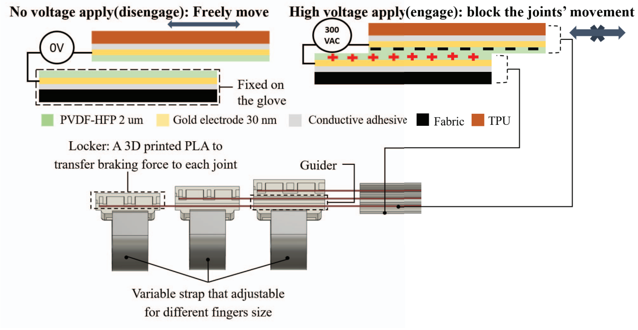
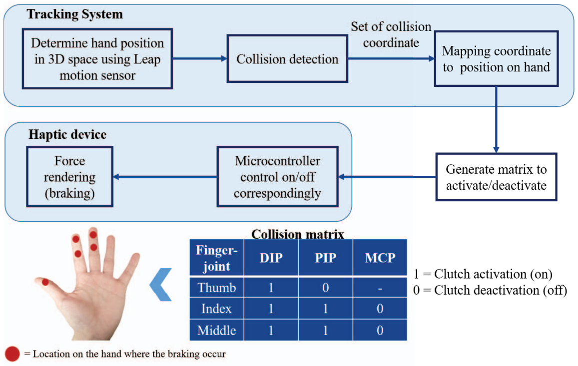


Figure 3: Working principle of electrostatic clutch

materials, and high dielectric material) to generate friction force during the engagement, and an exoskeleton to transfer friction force to the user's fingers and generate resistance to movement.

Pressure Sensors for Clutch Disengagement: Pressure sensors are fabricated and attached to each joint of the finger. As the pressure during grasping is relatively higher than during releasing, the difference in measured pressure determines whether the user is grasping or releasing the object.

Haptic Feedback Rendering: The haptic force is generated when the collision between the user's hand and an object is detected. The set of collision coordinates is then mapped to the position on the hand and the collision matrix is used to determine which clutch should be activated. This information is sent to the microcontroller, which controls the on or off state of the individual clutch, rendering haptic feedback that corresponds to the object's shape and grasping posture.



Collision matrix

Finger-joint	DIP	PIP	MCP
Thumb	1	0	-
Index	1	1	0
Middle	1	1	0

Figure 4: System workflow from hand tracking to haptic rendering

3 IMPLEMENTATION DETAIL

Force Testing: Theoretically, the maximum braking force can be computed from the below equation.

$$F(Maximum\,frictional\,force) = \frac{\mu \varepsilon_r \varepsilon_o A V^2}{2d^2}$$

where μ is the surface friction coefficient, ε_r is the dielectric constant, ε_o is the permittivity of free space, A is the braking area, V is the voltage, and d is the thickness of dielectric between electrodes. The frictional force of PVDF-HFP (Poly (vinylidene fluoride-co-hexafluoropropylene)) with 4 μm thickness with a braking area of 5 cm^2, and a dielectric constant of 10 is measured with a digital push-pull gauge under the condition of 300 VAC with the square waveform of 10 Hz, and the average maximum force is 30 N.

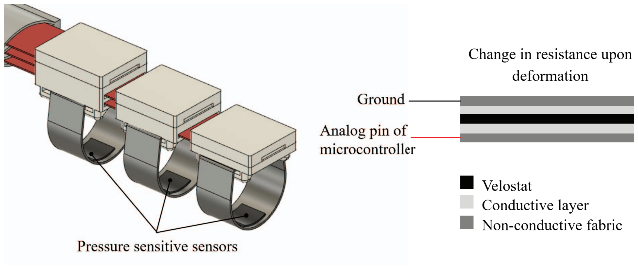


Figure 5: Implementation and fabrication of pressure sensor

Electrostatic Clutch and Pressure Sensor Fabrication: We use a flexible PVDF-HFP film as dielectric material since it has good mechanical strength so its surface properties sustain upon frequent braking. The PVDF-HFP film is coated with the gold electrode and we attach it with TPU (Thermoplastic polyurethane) to strengthen the clutch. Three clutches are stacked on top of each other: the top clutch controls the MCP, the middle clutch controls PIP, and the bottom clutch control DIP.

For pressure sensor fabrication, we use Velostat, a pressure-sensitive conductive sheet. Upon deforming the change in resistance is detected and translated into pressure.

Haptic Glove Integration: We apply a set of clutches on the thumb, index, and middle as they are the most crucial fingers and sufficient for grasping. The operating voltage is 300 VAC at 10 Hz (to avoid a space charge issue) and the Leap motion sensor is deployed for hand tracking.

4 CONCLUSION

In this paper, we present a lightweight wearable multi-joint force feedback for high-definition grasping using an electrostatics clutch. Our device provides a novel mechanical design haptic glove that allows kinesthetic feedback to be rendered on every joint of the finger according to the object's shape to improve object identification and sensation. In addition to multi-joint haptic rendering, we implement the pressure-sensitive sensor as a finger strap to deactivate the electrostatic clutch when the user wants to release the object based on the change in pressure. For future applications, our haptic gloves can be used to enhance the control of teleoperation through rich haptic sensations. They also improve gaming and simulation with accurate object sensation for a more immersive experience.

ACKNOWLEDGMENTS

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