DeltaTouch: a 3D Haptic Display for Delivering Multimodal Tactile Stimuli at the Palm

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Abstract— **DeltaTouch is a novel wearable haptic display with inverted Delta structure for providing multimodal tactile stimuli at any point of the palm of Virtual Reality (VR) user or operator of remote robot. It is capable of generating 3D force vector at the contact point and presenting multimodal tactile sensation of weight, slippage, encounter, and texture. The BallFeel, BalanceIt, and AnimalFeel applications have been developed to demonstrate the capabilities of the proposed technology. In the first user study, we evaluated the perception of tactile cues delivered by the haptic display on a participants' palm. The second experiment estimated the distinction in the perception of different forces generating by DeltaTouch on the human palm in a virtual weight sorting task. DeltaTouch can potentially bring a new level of immersion of the user in VR and improve the quality of teleoperation of the robot equipped with tactile and force sensors.**

I. Introduction

Palm has a large touch-sensitive area and plays an essential role in object detection and manipulation. Nowadays, many different entertainment applications, games, and simulators that implemented with VR/AR technologies are available on the market. However, the most VR/AR applications have a lack of providing feasible feedback to the user. Many of these applications require to deliver the sensation of the object moving on the hand. To achieve a highly immersive VR experience, it is needed to provide multimodal stimuli to the user's palm such as weight, slippage, encounter, softness, and texture.

In this paper, we propose DeltaTouch, a novel wearable haptic display with inverted Delta structure attached to the hand of the user (Fig. 1). It is capable of generating 3D force vector at the contact point and providing multimodal tactile stimuli at the palm. We evaluated the performance of the new tactile display through two user study experiments. In the first user study, we tested the ability of participants to recognize the location of the contact point and modality of a vibrotactile signal at the same time. In the second experiment, we investigate whether the participant could discriminate different normal forces generated by DeltaTouch on the palm through the weight sorting task in a virtual environment.

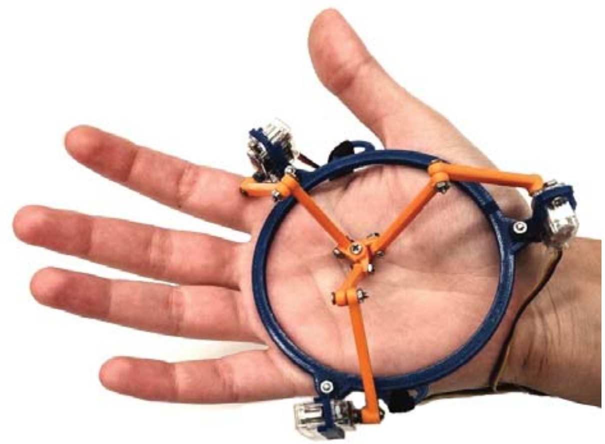

Fig. 1. A wearable haptic display DeltaTouch.

II. Related Work

A. Fingertip haptic devices

Currently, some wearable devices are designed for delivering tactile feedback at the fingertip since finger pads are used for physical interactions with objects and probing the virtual environments in most cases. Some devices comprise a small platform as end effector which shifts on the finger pad [1], [2]. Gabardi et al. [3] designed Haptic Thimble, a wearable haptic device for surface exploration. The device can display virtual surface orientation and curvature, as well as render edges, collisions, and texture. In [4], D. Prattichizzo et al. proposed a 3-degree-of-freedom (DoF) fingertip wearable device for presenting curvature of the virtual object. However, the tactile display can present a force vector only at one point of finger pad, and it is not possible to generate encounter sensation with it as it keeps constant contact with skin.

A series of works is devoted to providing the simulation of slippage through lateral skin stretch [5], [6], [7]. Leonardis et al. [8], [9] developed a 3-DoF wearable haptic device with revolute-spherical-revolute (RSR) kinematics for modulating contact forces at the fingertip. The device features a lightweight design and relatively high output forces and allows to render constant to low-frequency deformation of the finger pad. In [10], Tsetserukou et al. presented a 2-DoF wearable haptic device, LinkTouch, which provides high fidelity force vector sensation at the finger pad. In addition to the presentation of normal and tangential components of the force vector at any contact point of the fingertip, the device allows representing the transitional state from non-contact to contact condition. Schorr et al. [11], [12] presented a wear-

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able fingertip haptic device based on the delta parallel mechanism with three translational DoF for contact simulation, rendering shear and normal skin deformation to the finger pad. In [13], De Tinguy et al. developed a 2-DoF fingertip wearable haptic display for stiffness simulation of tangible objects in VR/AR environment. However, this display cannot represent a making/breaking contact sensations with virtual object since a fabric belt which provides stimuli to the skin has constant contact with the finger.

B. Haptic interfaces for grasping

Some wearable interfaces for simulating the grasping of rigid objects in a virtual environment have been proposed, such as Wolverine [14], and Grabity [15]. They can provide the sensation of contact, gripping, gravity, and inertia. However, the proposed displays deliver only tangential forces to the user's fingers and cannot render normal forces. Baker et al. [16] designed a haptic device for spatial design tasks which can provide proprioceptive and tactile feedback. It is fixed between the index finger and thumb. The tactile feedback is provided only to the index finger via a vibration motor, while proprioceptive feedback is generated by a solenoid locking mechanism which limits the movement of the users finger upon grabbing the vertices of VR object.

C. Haptic gloves

In [17], Achibet et al. proposed FlexiFingers, a haptic glow for multi-finger interaction in VR. It can represent grasping and stiffness of the VR object. Similar to FlexiFingers, Lee et al. [18] developed a haptic interface for multi-fingered virtual manipulation. It consists of a finger tracking module (FTM) and a cutaneous haptic module which is capable of providing 3-DoF fingertip force. In [19], Yem et al. proposed FinGAR, a finger glove for Augmented Reality, which combines electrical and mechanical stimulation to the skin. The haptic device is attached to the thumb, index finger, and middle finger. It can provide a set of different stimuli: skin deformation, high-frequency vibration, low-frequency vibration, and pressure stimulation. Minamizawa et al. [20] designed a GhostGlow, a haptic interface for the whole hand presenting realistic interactions with virtual reality environments on each finger and the palm. In [21], Zubrycki et al. proposed a haptic glove for delivering kinesthetic feedback to the hand. It can simulate grabbing and holding an object. Hinchet et al. [22] developed a wearable haptic glove which integrates kinesthetic and cutaneous feedback for grasping objects in VR. Gu et al. [23] designed Dexmo, a mechanical exoskeleton for motion capture and force feedback in VR and AR environments. It provides feeling the size, shape, and stiffness of virtual object for the user. Nevertheless, it is not able to deliver tactile feedback to the user's palm. In [24], Son et al. proposed a haptic interface that can generate kinesthetic feedback at the fingers and cutaneous feedback at a palm. Although cutaneous interface on the palm improves the haptic perception during interaction with VR objects the developed mechanism has only 1-DoF. Therefore, the provided tactile sensation has limited modality.

III. Design of Haptic Display DeltaTouch

A. Overall structure

The DeltaTouch has a parallel structure. It is comprised of a stationary circle bottom platform and a smaller upper moving platform (end effector). This inverted delta mechanism consists of three identical kinematic limbs which connect the end effector to the base plate (Fig. 2).

Fig. 2. A CAD model of wearable tactile display DeltaTouch.

The servo motors actuate three revolute joints of lower arms. The device is worn on the user's hand in such a way that the bottom platform is fixed on the palm via elastic tapes, while the end effector can freely move along the palm within the boundary of the base platform. The end effector comprises a vibration motor (tablet type, 10x3 mm, 3 V) to increase the number of modalities provided by the display. The prototype of DeltaTouch was produced with additive manufacturing technology using 3D printer Ultimaker 3. The components were printed from PLA material. The developed display has a wearable, lightweight, and compact structure. At the same time, it is capable of generating a strong force of 4.2 N in a normal direction. The specification of the device is shown in Table I.

TABLE I
Characteristics of DeltaTouch

Motors	Hitec HS-35HD
Weight	30 g
Material	PLA
Work area at the palm	40 cm^2
Normal force	4.2 N

B. Kinematic modeling of the inverted mechanism

The haptic display is represented as a parallel mechanism. The scheme of the wearable haptic display is shown in Fig. 3.

We indicated the centers of the rotational joints on the mobile platform as C_i and the center of the circle passing through them as P, hereby $\overline{C_iP} = a$, $i = 1, 2, 3$. The centers of the rotational joints on the base platform and

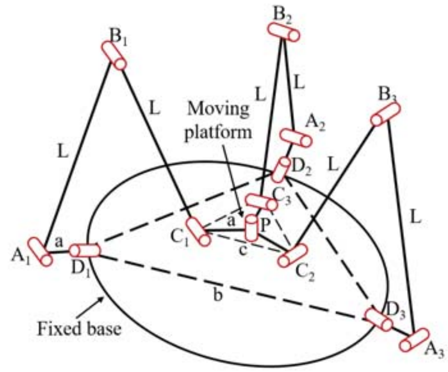

Fig. 3. Kinematic scheme of DeltaTouch.

the center of the base plate are denoted as $D_i, i = 1, 2, 3$, and O, respectively. The fixed base Cartesian coordinate system is located in the center of the base equilateral triangle ($\triangle D_1D_2D_3$) in such a way that x-axis is parallel to $\overline{OD_1}$, z is orthogonal to the plane defined by the D_i points. The angles $\Theta = \{\theta_1, \theta_2, \theta_3\}$ denote the actuated angles between links A_iB_i and $A_iD_i, i = 1, 2, 3$. The position and orientation of the moving platform can be defined by the position of one point P described by its coordinates $\{x, y, z\}^T$. The side length of the base triangle is b, and the side length of the equilateral triangle of the moving platform equals c (see Table II).

TABLE II
DESCRIPTION OF MECHANISM COMPONENTS

Name	Meaning
L	The length of the link A_iB_i
b	The side length of the base triangle
c	The side length of moving triangle platform
a	The length of the link A_iD_i

IV. USER STUDY

To evaluate the performance of the developed haptic display, we conducted two user studies. Firstly, we investigated the perception of different tactile cues (contact or contact with vibration) simulated on the user's hand. Secondly, we explored the ability of users to discriminate various normal forces generated by DeltaTouch on the user's palm via sorting objects by weight in a virtual environment.

A. User study 1: Discrimination of the different tactile stimuli

In this user study, we evaluated multi-modal feedback through the perception of tactile cues delivered by the device at a participant's palm. Eleven subjects, ten males and one female, aged between 21 and 32 participated in the study, all of them were right-handed.

We defined thirteen contact points across the surface of the palm, labeled A through M (Fig. 4). This array of points was selected in such a way to include points distributed around the center of the palm and on the boundary of the work area. In addition to the contact points, we defined three vibrotactile patterns generated by vibration motor at the end effector with a duration of three seconds each. The first pattern represents a vibration with constant amplitude, the second is a square wave where the amplitude changes abruptly, and the third is a sine wave with a smoothly varying amplitude (Fig. 5).

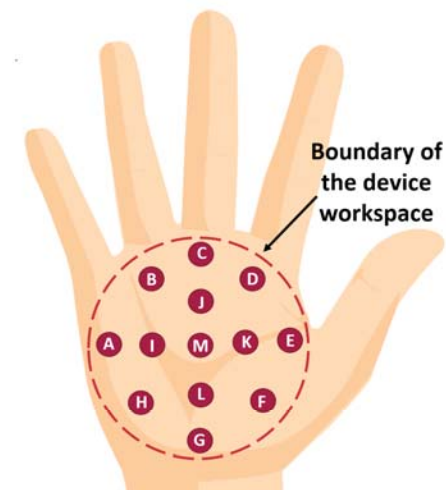

Fig. 4. The possible contact points (letters A-M) on the palm for discrimination of the location of a stimulus.

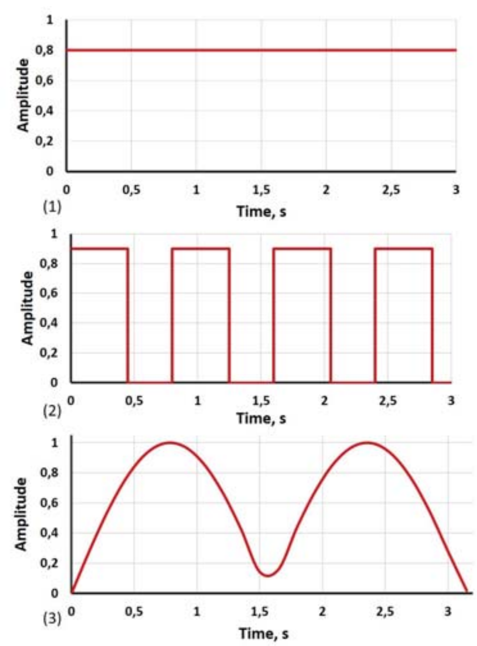

Fig. 5. Vibrotactile patterns for the user study: 1) Constant signal. 2) Square wave. 3) Sine wave.

Before the experiment, each subject had a preliminary trial to demonstrate the procedure and test if the end effector had a contact point with the palm in every defined location. During the experiment, the device was hidden from view, and the participant was given a visual guide with possible contact positions and waveforms of vibration signals. During the test, the subjects were asked to wear headphones to eliminate the noise from the vibration motor and servomotors and provide only the tactile perception.

For each trial, the end effector was positioned to a lettered location at a non-contact position (a distance of 15 mm from the palm). Hereafter it was moved down to contact with the palm for three seconds and translated back to the non-contact position. Initially, the subject was asked to indicate contact point and then to determine if there was delivered one of three possible vibrotactile patterns or not during the contact state. Besides, the participant should have provided the confidence state of his or her answer within a scale from one to five.

In total, 65 stimuli (35 contact and 30 contact with vibration) were generated during the experiment in such a way that subject was delivered only contact or contact with vibration. Each point was repeated five times in the random order whereas each vibration signal was presented ten times.

Experimental results and discussion

The results of the user study are represented in Table III. The diagonal elements of the confusion matrix specify the percentage of correct responses of subjects. Every row in the confusion matrix represents all 55 times a contact cue was provided.

TABLE III

CONFUSION MATRIX FOR ACTUAL AND PERCEIVED CONTACT LOCATIONS ACROSS ALL THE SUBJECTS

Subject response

Actual contact point	A	B	C	D	E	F	G	H	I	J	K	L	M
A	**0.78**	0.04	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.00
B	0.22	**0.76**	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
C	0.00	0.16	**0.58**	0.00	0.00	0.00	0.00	0.00	0.00	0.24	0.00	0.00	0.02
D	0.00	0.00	0.03	**0.84**	0.11	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00
E	0.00	0.00	0.00	0.18	**0.73**	0.04	0.00	0.02	0.00	0.00	0.03	0.00	0.00
F	0.00	0.00	0.00	0.00	0.16	**0.80**	0.02	0.02	0.00	0.00	0.00	0.00	0.00
G	0.02	0.00	0.00	0.00	0.02	0.49	**0.47**	0.00	0.00	0.00	0.00	0.00	0.00
H	0.03	0.00	0.00	0.02	0.00	0.00	0.04	**0.85**	0.02	0.02	0.00	0.02	0.00
I	0.31	0.02	0.00	0.00	0.00	0.00	0.00	0.29	**0.38**	0.00	0.00	0.00	0.00
J	0.02	0.04	0.16	0.00	0.00	0.00	0.00	0.00	0.07	**0.51**	0.00	0.00	0.20
K	0.00	0.00	0.00	0.05	0.29	0.13	0.00	0.00	0.00	0.00	**0.53**	0.00	0.00
L	0.00	0.00	0.00	0.00	0.00	0.18	0.09	0.04	0.00	0.04	0.05	**0.56**	0.04
M	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.04	0.05	0.05	0.00	**0.84**

Across all delivered contact points, subjects reported a mean confidence level of 4.3 out of 5. Upon the whole, we can conclude that the most distinguishable contact locations were in the center of the palm and along the radius of the bottom plate (Fig. 6). The most recognizable positions were D, H, and M with a recognition rate of 84%, 85%, and 84%. And the least distinct positions were G and I with rates of 47% and 38%, respectively. In addition, we can determine the areas where the points were most often confused among each other. These are $A - I - H$ and $F - G$ areas.

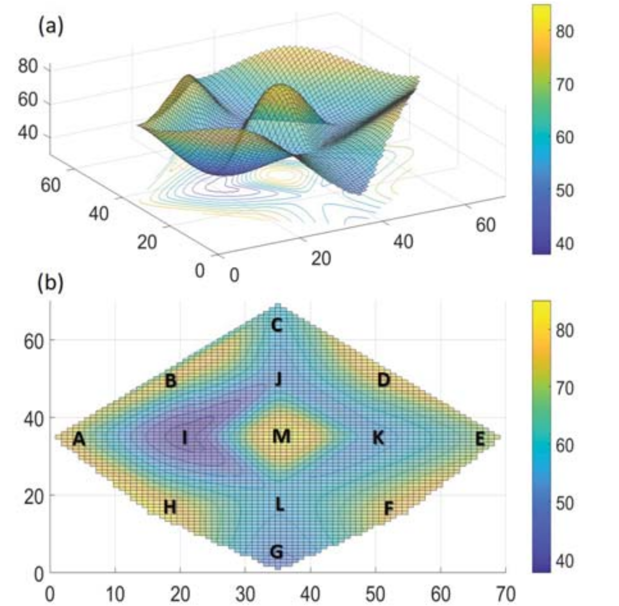

Fig. 6. Distribution of correctly defined contact locations at the palm among all the subjects. a) Isometric view. b) Top view.

We analyzed the results of the user study using two-factor ANOVA without replications, with a chosen significance level of $p < 0.05$. According to the test findings, there is a statistically significant difference in the recognition rates for the different contact locations $(F(12,120) = 4.42, p = 7.87 \cdot 10^{-6} < 0.05)$. According to ANOVA results, point H has a significantly higher recognition rate than the points $I(F(1,10) = 18.9, p = 1.45 \cdot 10^{-3} < 0.05)$, $J(F(1,10) = 7.1, p = 0.024 < 0.05)$, and $G(F(1,10) = 10.9, p = 8 \cdot 10^{-3} < 0.05)$. It was significantly easier for participants to recognize the points M and D, than $I(F(1,10) = 15.7, p = 2.7 \cdot 10^{-3} < 0.05)$, $G(F(1,10) = 6.3, p = 0.03 < 0.05)$, and $J(F(1,10) = 6.1, p = 0.033 < 0.05)$.

Table IV shows a confusion matrix for actual and perceived vibrotactile patterns. The mean percentage of the correct answers is 89%, and the mean confidence in responses among all the participants is 4.7 out of 5. All the patterns have a highly distinctive recognition rate and can be easily distinguishable from vibrations generated by servo motors in the absence of a signal from the vibration motor.

TABLE IV

CONFUSION MATRIX FOR ACTUAL AND PERCEIVED VIBROTACTILE PATTERNS ACROSS ALL THE SUBJECTS

Subject response

Actual vibration pattern	1	2	3	None
1	**0.89**	0.01	0.08	0.02
2	0.00	**0.89**	0.06	0.05
3	0.03	0.11	**0.84**	0.02
None	0.05	0.01	0.00	**0.94**

B. User study 2: Distinguishing the weight of virtual objects

In this user study, we investigated the perception of users of different simulated weights in the VR environment. The VR setup included HTC Vive Pro base stations, head-mounted display (HMD), and Leap Motion controller attached to the headset for tracking of the user's hands motion in VR (Fig. 7). The application for the experimental procedure was implemented with the Unity platform. We used a model of Rigged Hands from the basic set of Leap Motion module for Unity to visualize user hands in the VR scene. In total fourteen subjects took part in the experiment, one female and thirteen males, with no previous knowledge about the experiment. The participants were right-handed between the ages of 22 and 32.

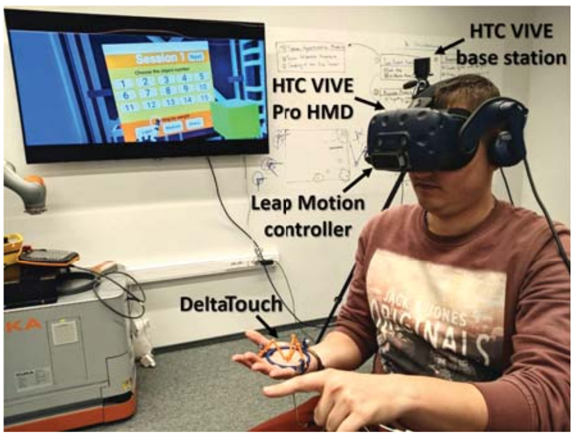

Fig. 7. Experimental setup for the evaluation of discrimination of the weight of virtual objects.

The task for the participant was to hold objects with different virtual masses and sort them by weight using the sensation provided by DeltaTouch (Fig. 8). The force generated on the palm was measured by the force sensing resistor (model FSR 400, Size: 7.62 mm diameter, Force Sensitivity Range: 0.1 - 10.0 N) which was calibrated before the experiment. We simulated three different force magnitudes: 0.7 N for the light, 1.5 N for the medium, and 2.5 N for the heavy objects, respectively.

Fig. 8. Unity scene for the experimental task.

The VR environment contained five objects: sphere, cube, cylinder, cone, and polyhedron. The experiment consisted of two rounds of sorting task. Each geometric object was repeated three times during the test with a random color and given weight. Before starting the sorting task subjects were informed that colors do not have a relationship with the weights of objects. During the experimental procedure, participants were wearing headphones which played a neutral tune to exclude a possible effect of the sound of the servo motors.

Experimental results

The confusion matrix is shown in Table V. Using the two-factor ANOVA without replications, with a chosen significance level of $p < 0.05$, we found a statistically signicant difference among the different virtual weights ($F(2, 26) = 10.44, p = 4.71 \cdot 10^{-4} < 0.05$). Light group showed a significantly higher recognition level than Medium ($F(1, 13) = 28.5, p = 1.34 \cdot 10^{-4} < 0.05$), and Heavy group was recognized significantly easier than Medium ($F(1, 13) = 5.42, p = 0.037 < 0.05$).

TABLE V
CONFUSION MATRIX FOR DIFFERENT VIRTUAL WEIGHTS

Actual virtual weight \ Subject response	Light	Medium	Heavy
Light	0.97	0.02	0.01
Medium	0.06	0.81	0.13
Heavy	0.02	0.08	0.9

V. DEVELOPMENT OF VR APPLICATIONS

We designed several applications with haptic feedback using the Unity platform. The application BallFeel (Fig. 9a) is designed to demonstrate how DeltaTouch accurately presents the sensation of bouncing and rotating the ball in the hands of the user to get the immersive experience of VR games. The sensation of 3D force generated by haptic display will let a person balance the rod (inverted pendulum) by moving the hand in BalanceIt (Fig. 9b). The interaction with living creatures was taking into account in the development of the AnimalFeel application (Fig. 9c), where the motion of spider in any direction and its weight is reproduced by the haptic stimuli on the palm of the user by the DeltaTouch.

VI. CONCLUSIONS

We have developed a novel wearable haptic display which can present 3D force vector and multimodal stimuli (contact, pressure, slippage, texture) at any point of the user's palm. The inverted Delta mechanism is proposed to achieve a compact and lightweight structure. The first user study revealed a high recognition rate of the vibrotactile patterns presented by the haptic display. The second experiment showed a high discrimination of different virtual weights.

(a) BallFeel: experience of bouncing ball on the hand.

(b) BalanceIt: experiencing the stick balancing with haptic feedback.

(c) The AnimalFeel application: feeling the VR spider crawling on the palm.

Fig. 9. VR applications with haptic feedback.

The device can be applied in medical settings, teleoperation, and VR simulators. The developed wearable cutaneous display can potentially significantly improve the immersion into VR experience and quality of teleoperation. The future work will be aimed at the thorough user study on discrimination of multimodal feedback. The additional modality will be provided by attaching a Peltier element at the tip of the robot. Thus, the user will be capable of experiencing continuous thermal feedback along the palm skin during motion of DeltaTouch.

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