Enriched Thumb-to-fingertip Gesture Based Input for Virtual Environments

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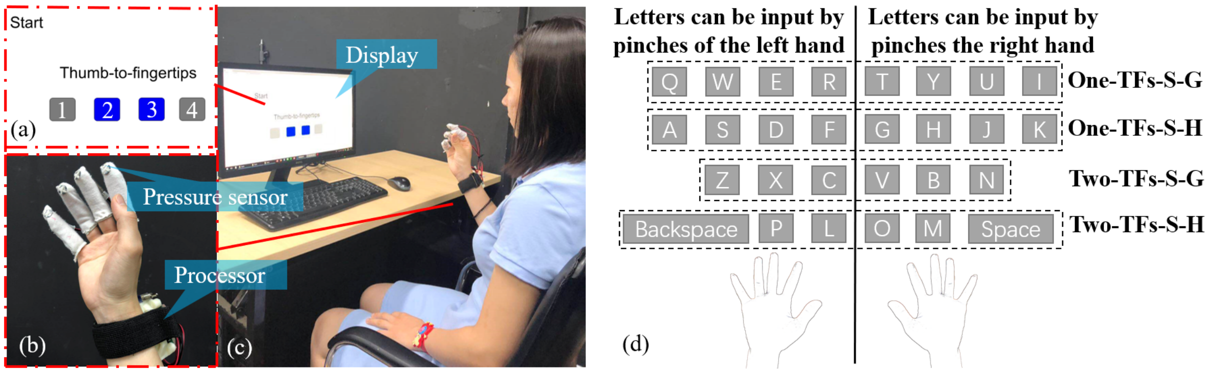

Figure 1: (a) The prompt interface in experiments; (b) Experimental system based on pressure sensors fixed on four fingertips; (c) The experimental scene; (d)Text input by thumb-to-fingertips (TFs). The left hand controls the character input on the left, and the right hand controls the character input on the right. One-TFs with a single-click and gentle pinch-pressure (One-TFs-S-G) controls the input of characters in the first line; One-TFs with a single-click and heavy pinch-pressure (One-TFs-S-H) mode controls the input of characters in the second line; Two-adjacent-TFs with a single-click and gentle pinch-pressure (Two-ATFs-S-G) mode controls the input of characters in the third line; Two-adjacent-TFs with a single-click and heavy pinch-pressure (Two-ATFs-S-H) mode controls the input of characters in the fourth line.

Abstract

Thumb-to-fingertip (TFs) gestures have high accuracy with eyes-free, showing great potential for fast and accurate input in head-mounted displays, especially for mobile scenarios. However, the number of input signals activated by conditional TFs of both hands is limited to 8. There are cases where more input signals are needed, *e.g.* text entry. This paper presents an enriched TFs based input technique combined with the multi-TFs gesture, multi-times gesture, and multi-level magnitude pinch pressure, enabling the activation of dozens of input signals. Three experiments are conducted to investigate the input performance affected by the three factors. The input speed of One-TFs with single-click (One-TFs-SC) and One-TFs with gentle pinch pressure (One-TFs-G) is about 0.7s. The input speed of One-TFs with double-click (One-TFs-DC) and One-TFs with heavy pinch pressure (One-TFs-H) is about 1.1s. Finally, the text entry method based on this TFs technique is presented.

Index Terms: Human-centered computing—Human computer interaction—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction—Interaction techniques—Text input; Human-centered computing—Human computer interaction— Interaction devices—Haptic devices

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1 Introduction

With mobile head-mounted-displays (HMDs) increasingly becoming ubiquitous, input techniques as an essential interaction still get much attention. Although controllers [1] are common used in commerce, there are cases where controllers are not available; Mid-air gesture used in Microsoft HoloLens [2] is a solution for input using the bare hand, which requires lifting up the hand to eye-level and easily causes arm fatigue called "gorilla arm" [13]. Speech [1, 8] is a potential input method for mobile scenarios. However, its accuracy may be affected by noise and it may have private problems.

There is growing interest in thumb-to-finger gestures, which enable users to expressively interact with a digital system. As fingers possess fine motor skills [14], by taking advantage of human proprioception, users could execute thumb-to-fingertip (TFt) gestures quickly, comfortably, and accurately [5] with eyes-free. TFt gestures have the highest comfort level in all thumb-to-finger gestures [5,6]. However, the number of thumb-to-fingertip gestures limits the interaction possibility.

The key goal of this paper is to design a thumb-to-fingertip input technique with the limited number of TFt gestures, enabling rich interaction for HMDs, *e.g.* text entry. To this end, three factors are considered: (1) The number of fingertips pinched synchronously. According to the characteristics of hand, users could use the thumb touch multifingertips simultaneously; (2) The times of pinches. The different number of consecutive touches can also be used as one input signal; (3) The magnitude of pinch pressure. Uses could distinguish between subtle amounts of force up to 6 levels [11]. By combining the aforementioned three factors, dozens of input

[1] HTC VIVE, https://www.vive.com/us/
[2] Microsoft HoloLens, https://www.microsoft.com/en-us/hololens

signals can be activated, enriching the TFs gesture interaction. The prototype system is constructed with 4 pressure sensors which can be used to detect touch pressure. Then, three experiments are conducted to evaluate the effect of the three factors. The results show that one-TFs with double-click was the best choice for adding the number of the input signals, and for multi-TFs, Two-TFs with the single-click and without regarding pinch pressure were the better choices. The input speed of One-TFs-SC and One-TFs-G is about 0.7s, and that of One-TFs-DC and One-TFs-H is about 1.1s. The results show that our technique enables a quicker input speed compared with the similar work [7, 15, 18]. Last, the text application based on this technique is presented, as shown in Figure 1(d).

This paper makes contributions as follows:

(1) Propose an enriched TFt gestures input technique, which considers the number of fingertips, pinch times, and pressure, supporting dozens of input for HMDs;

(2) Construct the prototype system and evaluate the effect of the three proposed factors;

(3) Demonstrate text entry application based on TFs.

2 Related work

Our technique is related to the hand-worn devices for input, thumb-to-finger input, and force-assisted input.

2.1 Hand-worn devices for input

Hand-worn devices can be used for hand gestures detection and have begun to emerge as they enable users to input with comfortable arm postures, avoiding the "gorilla arm" and social awkwardness problems [15]. EMGRIE [15] utilized a time-of-flight camera and a microphone situated on the inside of the wrist to extract finger-level features and detect pinch gestures, where the detected time was from 1.1s to 1.3s. FingerInput [14] enabled thumb-to-finger interaction detection by using a depth camera, where the accuracy of classifying the gestures reached 91.06%. Skinput [3] could input by leveraging the natural acoustic conduction properties of the human body, where the finger tap accuracy reached 89.5%. However, there are cases where system accuracy would affect performance and user satisfaction, *e.g.* text entry and menu selection. Ring devices were also commonly used for detecting hand microgestures. For example, uTrack [2] converted the thumb and fingers into input by using magnetic field sensing.

2.2 Thumb-to-finger input

With fine motor skills, thumb-to-finger gestures were used by many researchers for input, especially for text entry. The number of thumb-to-finger gestures is limited, while there are at least 26 characters that should be input for text entry. To solve this contradiction, new techniques were proposed. For example, techniques, such as KITTY [10], Chording Glove [12], and DigitTouch [16] detected thumb-to-finger gestures for text entry with QWERTY layout; HiFinger [6] input text with two-step method; and FingerT9 [18] mapped a T9 keyboard layout to the finger segments. However, they all needed the thumb to touch different areas of fingers or combined complicated methods. As shown in HiFinger [6] and DigitSpace [5], thumb-to-fingertip gestures had the highest level of efficiency and comfort in all thumb-to-finger gestures.

2.3 Force-assisted input

Users could distinguish different magnitudes of force up to 6 levels [11], even reached up to 10 levels [17]. Some work had focused on the input by detecting the different magnitude of force. Hsiu [4] proposed a 2-level ambiguous QWERTY keyboard, where two discrete levels of force could be used to discriminate between two characters located within the same key on smartwatches. SAK [9] was a force-assisted scanning ambiguous keyboard with a 1-line character layout. Lee [7] designed a glove for text entry, consisting of 9 force-sensitive nodes, each of which could detect three inputs with different magnitude forces.

3 Prototype

As shown in Figure 1, the hardware of our prototype included four pressure sensors and a processor. For detecting thumb-to-fingertips gestures with different magnitudes of force, four RFP-602 pressure sensors were fixed on the fingertips with elastic finger sleeves and wired with the processor. The measurement accuracy of pressure sensor accuracy was 0.01N, the range was $1 \sim 200$N, the thickness was 0.2mm, and the diameter was 10mm. The processor was used to process and obtain the value of each pressure sensor and transmit pressure data to the computer via Bluetooth.

4 Evaluation

Speed and accuracy were the two most important metrics to evaluate one input technique. As thumb-to-fingertip gestures can reach a high accuracy almost without errors when the system was working correctly, the speed of this technique was measured in the following sections by considering three different factors.

4.1 Apparatus

All experiments were conducted on a computer with an Intel Core i7 processor and an NVIDIA GTX 1080Ti graphics card. The software was implemented with Unity 2019.4.10f1. The experimental content was displayed on a DELA0FD DELL SP2318H LCD monitor (23 inch) with 1920 × 1080 resolution.

4.2 Participants and procedure

13 right-handed participants were recruited from our university to participate this study. They all participated three aftermentioned experiments with a random order. As shown in Figure 1, participants seated and completed experiments facing the screen. During the experiments, as shown in Figure 1(a), the four squares in the prompt interface corresponded to the four thumb-to-fingertips gestures. For the right hand, the leftmost "1" squares corresponded to the pinky fingertip, and the "2","3","4" to the ring (R), middle and index fingertips respectively. For the left hand, the leftmost "1" squares corresponds to the index fingertip, and the "2","3","4" to the middle, ring and little fingertips respectively. If the squares turn blue, the participant needed to execute thumb-to-fingertip gesture of corresponding fingertip, and if the input signal is detected, the square color returns to gray. For example, as shown in Figure 1(c), the "2" and "3" squares are blue, so the participant should execute thumb-to-middle fingertip and thumb-to-ring fingertip gestures simultaneously. In all experiments, each test repeated 5 times in random order. The experiments used within-subject designs.

4.3 Experiment 1 - the number of TFt gesture

Different input signals can be activated by executing different thumb-to-fingertip gestures synchronously. This experiment investigated the performance when participants pinched one, two, three, or four fingertips respectively, where the frequency of pinches was limited to once without regard to the magnitude of pinch pressure. Executing adjacent TFs (ATFs) gestures means users executed two or more adjacent TFs gestures synchronously, like thumb-to-index fingertips and thumb-to-middle fingertips.

(4(one TFs) + 6(two TFs) + 4 (three TFs) + 1 (four TFs)) × 2(hand) × 13(participants) × 5(repeated times) = 1950 trails data were collected in Experiment 1.

4.4 Experiment 2 - the times of pinches

Single-click (SC) and double-click (DC) are commonly used in current interactions, such as the mouse. Different input signals can be activated by single-pinch or double-pinch. So, this experiment

Table 1: The part data analysis results of experiment 1.

One-TFs			Two-TFs			Three-TFs			Four-TFs		
Groups	T(25)	*p*	Groups	T(25)	*p*	Groups	T(25)	*p*	Groups	T(25)	*p*
I - M	0.371	0.716	IM - IR	-5.039	0.000	IMR - MRP	-2.687	0.013	IMRP - IM	5.301	0.000
I - R	1.231	0.236	IM - IP	-3.254	0.003	IMR - IMP	-4.953	0.000	IMRP - MR	4.496	0.000
I - P	1.146	0.167	IM - MP	-5.757	0.000	IMR - IRP	-2.124	0.047	IMRP - RP	4.557	0.000
M - R	0.816	0.423	MR - IR	-3.059	0.005	MRP - IMP	-2.444	0.024	IMRP - IR	3.111	0.005
M - P	0.898	0.378	MR - IP	-2.5	0.020	MRP - IRP	-3.154	0.005	IMRP - IP	4.055	0.001
R - P	0.424	0.675	MR - MP	-5.106	0.000	IMP - IRP	0.308	0.762	IMRP - MP	1.55	0.136
			RP - IR	-2.051	0.051				IMRP - IMR	0.304	0.764
			RP - IP	-1.37	0.183				IMRP - MRP	-1.61	0.123
			RP - MP	-4.398	0.000				IMRP - IMP	-4.091	0.001
									IMRP - IRP	-2.684	0.015

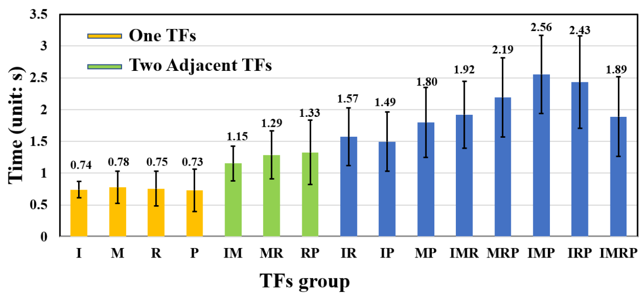

Figure 2: The input time of the different number of TFs gesture groups.

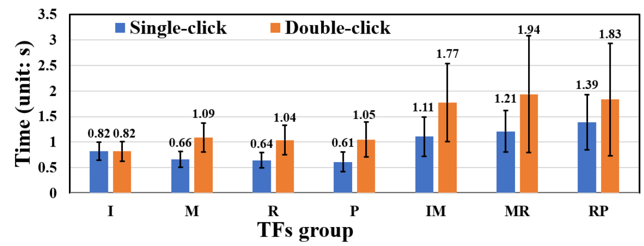

Figure 3: The input time of the different single-click and double-click TFs gesture groups.

investigated the performance when participants executed single-pinch or double-pinch without regard to the magnitude of pinch pressure and the number of TFt gestures were one or adjacent two.

(4(one TFs) + 3(two ATFs)) × 2 (pinch times) × 2(hand) × 13(participants) × 5(repeated times) = 1820 trails data were collected in Experiment 2.

4.5 Experiment 3 - the magnitude of pinch pressure

Different input signals can be activated by pinching with different magnitudes of pinch pressure. Although humans can distinguish 6 magnitude levels force, to ensure the input speed, this experiment only investigated gentle (G) and heavy (H) two levels magnitudes of touch pressure, where the number of TFt gestures was one or adjacent two and the frequency of pinches was limited to once.

(4(one TFs) + 3(two ATFs)) × 2 (pinch magnitude) × 2(hand) × 13(participants) × 5(repeated times) = 1820 trails data were collected in Experiment 3.

4.6 Results

The ANOVA and the paired T-test were used to analyze the data. The results show that for left and right hands, no significant difference was found in the input speed of the same gestures. So, the following results will not distinguish between left and right hands. Moreover, obvious experimental results would not be introduced, *e.g.* the speed of SC was higher than that of DC. In the following, I represents thumb-to-index fingertip gesture, M represents thumb-to-middle fingertip gesture, R represents thumb-to-ring fingertip gesture, P represents thumb-to-pinky fingertip gesture, and the letter combination represents two or more gestures performed at the same time, *e.g.* IM represents thumb-to-index fingertip gesture and thumb-to-middle fingertip gesture.

4.6.1 Experiment 1

The results of the input time of experiment 1 are shown in Figure 2. The part data analysis results are shown in Table 1. For the one TFs gesture group (I, M, R, and P), no significant difference was found between any two groups. The speeds of all one TFs group were higher than all two TFs group over 47.43%. The speeds of all two ATFs groups (IM, MR, and RP) were significantly higher than all two non-ATFs groups (IR, IP, and MP). For the three TFs groups, the speed of IMR was significantly higher than other groups and the speeds of the two non-adjacent groups (IMP and IRP) were no significant differences. In addition, IMRP had a similar performance as MP, IMR, and MRP, and the speed of IMRP was significantly higher than the other three TFs groups and lower than the other two TFs groups.

4.6.2 Experiment 2

The results of the input time of experiment 2 are shown in Figure 3. The part data analysis results are shown in the Table 2. The speed of the RP group with DC (RP-DC) was slightly higher than that of the RP group with SC (RP-SC) without significant difference, while for other groups, the speed of SC was significantly higher than the DC group. IM-SC and MR-SC had similar performance as all one TFs groups with DC (I-DC, M-DC, R-DC, and P-DC), while the speed of RP-SC was significantly lower than other two-ATFs-SC and one-TFs-DC groups.

4.6.3 Experiment 3

The results of the input time of experiment 3 are shown in Figure 4. The data analysis results are shown in the Table 3 For all groups, except I and RP groups, the speed of remaining groups with G pinch pressure was significantly quicker than with H pinch pressure. There was no significant difference between any two speeds of one-TFs-G groups, as well as between any two speeds of one-TFs-H groups. The speed of the I-H group was significantly quicker than the IM-G, MR-G, and RP-G groups. The speed of the P-H group was significantly quicker than the RP-G group.

4.7 Discussion and design suggestion

In addition to the obvious results, the experimental results show that: (1) For the performance of the number of TFt gesture: one-

Table 2: The part data analysis results of experiment 2.

Groups	T(25)	*p*	Groups	T(25)	*p*	Groups	T(25)	*p*	Groups	T(25)	*p*
I_DC - IM_SC	0.683	0.501	R_DC - IM_SC	-0.748	0.462	M_DC - IM_SC	0.8		P_DC - IM_SC	-0.659	0.516
I_DC - MR_SC	-0.943	0.355	R_DC - MR_SC	-1.862	0.074	M_DC - MR_SC	0.17		P_DC - MR_SC	-1.601	0.122
I_DC - RP_SC	-2.568	0.017	R_DC - RP_SC	-2.971	0.006	M_DC - RP_SC	0.003		P_DC - RP_SC	-3.121	0.005
I_SC - I_DC	-6.248	0	R_SC - R_DC	-5.75	0	IM_SC - IM_DC	0.001		RP_SC - RP_DC	-2.02	0.055
M_SC - M_DC	-8.156	0	P_SC - P_DC	-7.055	0	MR_SC - MR_DC	0.004				

Table 3: The part data analysis results of experiment 3.

Groups	T(25)	*p*	Groups	T(25)	*p*	Groups	T(25)	*p*	Groups	T(25)	*p*
I_H - IM_G	-3.039	0.006	M_H - IM_G	0.34	0.737	R_H - MR_G	0.109		P_H - MR_G	-1.675	0.108
I_H - MR_G	-3.239	0.003	M_H - MR_G	-0.035	0.972	P_H - IM_G	0.266		P_H - RP_G	-2.976	0.007
I_H - RP_G	-4.165	0.000	M_H - RP_G	-0.949	0.352	IM_G - IM_H	0.014				
I_G - I_H	-1.744	0.095	R_G - R_H	-4.48	0	MR_G - MR_H	0.000				
M_G - M_H	-4.644	0.000	P_G - P_H	-2.974	0.007	RP_G - RP_H	0.110				

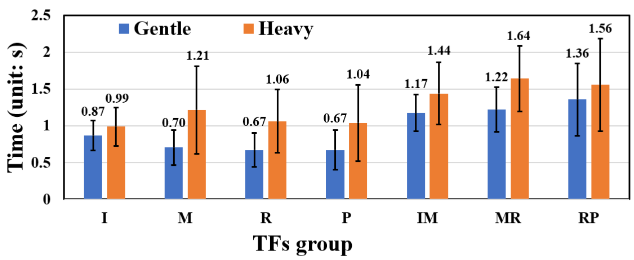

Figure 4: The input time of the different gentle touch and heavy touch TFs gesture groups.

TFs $>$ two-ATFs $>$ two-non-TFs $\approx$ IMP $\approx$ IMRP $\approx$ three-TFs. If considering the input using multi-TFs gesture except for one-TFs, two-ATFs should be adopted firstly; (2) For the performance of the times of pinch gesture: one-TFs-SC $>$ one-TFs-DC $\approx$ two-ATFs-SC $>$ two-ATFs-DC. Since participants pay more attention to controlling the input frequency, all the speeds of one-TFs-SC were quicker better than that in experiment 1. If considering the input using multi-times of pinch gesture, one-TFs with SC or DC should be adopted firstly; (3) For the performance of the magnitude of pinch pressure: one-TFs-G $>$ one-TFs-H $\approx$ two-ATFs-G $>$ two-ATFs-H. If considering the input using the magnitude of pinch pressure, one-TFs should be adopted firstly and avoid using multi-TFs with heavy pinch pressure.

For all one-TFs-G, all the speed were slower than that in experiment 1 and 2, since distinguishing the magnitude of pinch pressure may increase the workload of participants, as users said "I needed to pay more attention to control the pinch pressure in experiments than in experiments 1, which led to slow input speed. The results were consistent with the result of the work of Lee [7], the time of one letter input cost 4s in the first session, where participants need to distinguishing three levels magnitudes of touch pressure. In addition, performing two TFs gestures at the same time had increased the workload of participants, the two-TFs-G have a similar input speed as in experiments 1 and 2. However, the input speed of ATFs-H was quicker than that of ATFs-DC.

Considering three factors comprehensively, one-TFs with DC was the best choice for adding the number of the input signals. For multi-TFs, Two-TFs with SC and without regarding pinch pressure were the better choices. Considering the level of comfort, TFs combing with pinch pressure or double-click was better than combing with multi-fingers. The input of thumb-to-pinky fingertips was worse than other TFs.

In addition, the standard deviation results of all groups in experiments 1, 2, and 3 show that it is easy to cause input instability when input using two-TFs with double clicks gesture.

4.7.1 Text entry application

As the text entry technique should allow users to input 26 and more characters, the thumb-to-fingertips of both hands just allow 8 input, which cannot meet the input requirements. According to the experimental results, the text can be input by combining one-TFs, two-ATFs, SC, and DC, which leads to $(4 + 3) \times 2 \times 2 = 28$ input signal. It can input at least 28 letters with two could be as the functional keys - "Space" or "Backspace", as shown in Figure 1(d). Since the frequency of use of letters is different, we will combine it with the entry speed of different pinches to improve the entry efficiency of the technique. For example, it can be seen that the entry speed of the one finger pinch with once pinch is fastest, so we can use these microgestures to input the most commonly used letters, like "e", "t", "a", "o" and so on.

5 Conclusion

A thumb-to-fingertips(TFs)-based input technique is presented in this paper, which allows users to input text in mobile scenarios in HMDs with eyes-free. Microgestures have high accuracy and comfort, ensuring users can efficiently input for a long time. Specifically, the TFs input technique combining with multi-TFs gesture, multi-times gesture, and multi-level magnitude pinch pressure is presented, enabling dozens of input signals can be activated. Then, the experiments are conducted to investigate the input speed affected by the aforementioned three factors. The results show that the input speed of one-TFs combing double click or heavy can reach about 1s. Finally, this paper proposes a text entry method based on the TFs technique. Based on the experimental results we could guess that our technique has a better performance compared with the similar work [7, 15, 18], where the FingerT9 [18] can input at 3.43 word-per-minute (WPM) (3.49s per thumb-to-finger touch), the input speed in the work of Lee [7] is 3.34 WPM (4s per thumb-to-finger touch) in the first session, and the detected time of EMGRIE [15] is from 1.1s to 1.3s. However, more user studies should be conducted to investigate the input performance.

Acknowledgments

This work was supported by the Key-Area Research and Development Program of Guangdong Province (No.2019B010149001) and the National Natural Science Foundation of China (No.62072036) and the 111 Project (B18005).

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