Augmented Reality for Stabilizing Hand Tremors

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Augmented Reality for Stabilizing Hand Tremors

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Abstract

Augmented Reality (AR) is a technology that displaying virtual information directly into real-world environment, has been wildly applied in many fields, such as entertainment, manufacturing, or education. In recent year, AR has been explored to help the impaired people, e.g. visually impaired, hearing impaired. I first develop AR to support hand impaired persons in human-computer interactions (HCI) and computer-mediated communication (CMC).

Hand tremors are featured with involuntary shaking of hands, reduce levels of hand capability to perform intentional activities. With widespread use of computers and touching panels, typing or touching becomes very common interactive way to access devices. However, it is difficult for individuals with hand tremors to type or touch devices, especially which having small densely placed targets, like keyboard. Traditional approaches that help trembling hands exist some limitations, including body burden, muscle fatigue, non-application of ordinary device, and rarely solve the problems of HCI and CMC of trembling hands. Therefore, in this thesis, I investigate approaches to facilitate individuals to use their trembling hand to directly interact with ordinary devices. I focus on two critical issues of hand tremors in HCI and CMC, develop AR to enhance individual with tremors in keyboard typing and reaching, and makes the following contributions.

First, I investigate an approach of virtually stabilizing hand tremors and develop a projection AR system to support trembling hands to type ordinary keyboard directly. The approach includes stabilizing the images of hand tremor and virtually replacing physical keys, which helps the AR system estimate steady finger positions and ensures

typing output, respectively. The AR system as well as the approach are investigated to be effective in helping trembling hands correctly type with ordinary physical keyboards under the condition of trembling movements. The approach shows the versatility and scalability used for different interactive platforms and system environments, e.g. it is applied to gain stabilized virtual hand gestures in an optical see-through AR system of chapter 3, and to steady the movement of projection extended hand in chapter 4.

Second, I propose optical see-through augmented reality system that visually stabilizing hand tremors to make individuals visually perceive their trembling hand to be stable. Under the system, individuals with hand tremors can feel they use a steady hand in interaction. The approach is synchronization and mixed reality between trembling hand and stabilized virtual hand with certain intensity ratio to produce a realistic typing experience of using steady hand. I calibrate different intensity ratios between virtual and real hand and investigate the best ratio that both promote tying performance and the proprioception of mixed hand. The approach shows a novel way, different from traditional physical suppression to make trembling hands stable in HCI, has advantage of no harm to user hands.

Finally, to facilitate individual suffering from hand tremors as well as body tremors to interact with objects exceeding hand reach range, I develop a projection AR technology — "Extended Hand (EH)" for hand tremors. In particular, I investigate some methods, including "distance stabilization", "touching area analysis", and "combination", which reduce the effect of inevitable magnified trembling touches and make the movement and gesture of projection extended hand to be steady. I investigate these methods that make trembling hands control EH steadily.

Preface

All publications that have resulted from the studies presented in this thesis are listed in the following.

A Typing Assist System Considering Involuntary Hand Tremor

(K. Wang, N. Takemura, D. Iwai, and K. Sato, Transactions of the Virtual Reality Society of Japan, 2016, Best Paper Award) [50]

This work is discussed in Chapter 2. I have conceived the idea and implemented the preliminary study under supervision of Dr. Ikeda, Dr. Iwai and Dr. Sato and implemented the further study, conducted experiments, and wrote the manuscript under supervision of Dr. Takemura, Dr. Iwai and Dr. Sato

Supporting Trembling Hand Typing Using Optical See-Through Mixed Reality

(K. Wang, D. Iwai, K. Sato, IEEE Access, 2017, IEEE Access Best Multimedia Contest Part 1, grand prize) [63]

This work is discussed in Chapter 3. I have conceived the idea, designed and conducted experiments, wrote the manuscript under the supervision of Dr. Iwai and Dr. Sato.

Stabilizing Graphically Extended Hand for Hand tremors

(K. Wang, H. Matsukura D. Iwai, K. Sato, IEEE Access) (Under review — March 2018) [66]

This work is currently under reviewing by IEEE Access and discussed in Chapter 4. I have conceived the idea, designed and conducted experiments, wrote the manuscript under the supervision of Dr. Matsukura, Dr. Iwai and Dr. Sato.

Contents

List of Figures

List of Tables

List of Abbreviations

AR	Augmented Reality
MR	Mixed Reality
HCI	Human-computer Interaction
MCM	Computer-mediated Communication
ET	Essential Tremor
IT	Intentional Tremor
EH	Extended Hand
ANOVA	Analysis of Variance
STFT	Short-Time Fourier Transform
SVM	Support Vector Machines

CHAPTER 1

Introduction

Augmented Reality (AR) is a technology that displaying virtual information directly into real-world environment, has been wildly applied in many fields, such as entertainment, manufacturing, and education. In recent year, AR has been explored to help the impaired people, for example, the research of University of Oxford developed AR for visually impaired to enhance vision [48], and the research of Microsoft developed AR for hearing impaired to support face to face communication [49]. However, AR has rarely developed to support other impaired persons.

Tremors, which refer involuntary trembling, shaking or twitching of body parts [1], are one of the most common movement disorders, afflicting up to 15% of people of age 50 to 89 years [2]. Tremors occur in 90% of tremor suffers' hand [3], and have different degrees of influence on the stability and motion precision of hand and finger, which results hand fail to precisely move and touch targets. However, with widespread use of computers and touch panels, typing or touching become very common interactive way to access devices. Due to hand tremors, much devices are inaccessible to sufferers. Moreover, tremors can also affect arms, torso, or legs [1], causing individual with mobility impairment [4] [5]. As moving swing body is difficult and dangerous, the hand reachable range of individuals with tremors are limited. Therefore, tremors seriously reduce individuals' hand capability to perform activities of daily living.

Individuals' hand tremors can be alleviated by medical treatment such as drug therapies or deep brain stimulation, however medical treatment cannot cure most of hand tremor [6] [7], and also associate with side effects and risk of stroke [8] [9]. Besides, the assistive technology have been developed to enhance the capability of trembling hands. Traditional approaches can be summarized as “mechanical suppression”, “functional electric stimulation (FES) suppression”, and “active suppression”. “Mechanical suppression” is by mounting machinery including damper and inertial onto hands to physically restrict trembling hand movements [10] [11]. However, the approach often exerts burden to user body because of having to wearing mass of sensors and elements [12], and may inhibit hands’ intentional movement. FES is cheap and effective to attenuate hand tremors by stimulating the movement of muscles out-of-phase opposite to tremor’s direction [13] [14]. However, the limitations of the approach include causing rapid muscle fatigue and having the risk of use [15]. Unlike “mechanical suppression” and “FES suppression” physically inhibit individual’s hand tremor, “active suppression” is by changing the conformation of interactive objects to adapt individuals’ hand tremors. The common methods are based on the measurement of hand tremors, and (1) adding vibration oppose to tremor in hand interactive objects to offset hand tremors [16], (2) adjusting the conformation or interface of objects to balance hand tremors [17] [18] [19], and (3) filtering the effect of hand tremors on interactive objects [20] [21]. “active suppression” approaches have advantages that supporting trembling hands without harming and fatiguing user. However, the approaches limit in specially customized devices or interface and lack of versatility to apply for ordinary devices. In addition, so far, most of traditional approaches solved issues on eating, writing, or body movements of individuals with tremors, rarely researches focused on the problems of individuals with hand tremors in Human-computer Interaction (HCI) or Computer-mediated communication (CMC).

Therefore, in this thesis, I focus on critical problems of hand tremors in HCI or CMC and investigate several approaches to make AR support individuals with hand tremors. In particular, I investigate approaches and AR systems that allow individuals with tremors directly and smoothly touch or type ordinary devices such as keyboards, touching panels, under the premise that hands are completely free. Since expecting that trembling hands are not limited while typing or touching, the uncontrolled trembling of hand and finger confuse or disrupt individuals' visual assessment in some HCI. For example, while typing keyboard, the shaking of hand adversely affect an individual to predict the finger contacted key, leading to a wrong typing result. Thus, I continually develop approaches as well as AR system that make individuals' trembling hand visually perceived to be stable in interaction, i.e. individuals with tremors feel they can use a steady hand to type the desired targets. In addition, as mentioned above, tremors can limit individuals' hand reachable range, thereby adversely affect hand activities. Fortunately, there exists "Extended Hand (EH)" (Projection AR) technology, which can virtually extend a user's arm to allow a user to manipulate distant objects [23]. However, as the design of the technology presumes a user with steady hand, EH has not yet benefited individuals with tremors. Therefore, I improve EH that touching controlled by trembling hands to extend sufferers' reach range.

To summarize, the main objectives of the thesis is investigating several approaches to make AR support individuals with hand tremors in HCI or CMC.

- AR supports individuals with hand tremors to type ordinary keyboard.
- AR supports individuals suffering hand tremors as well as mobility impairment to interact with distant objects.

To achieve these objectives, in chapter 2, I propose an approach and a projection AR system that enables trembling hands to correctly type with the ordinary physical keyboard. The approach includes approaches that virtually stabilizing hand tremors and virtually remapping the physical targets, which contribute to estimate intentional hand activities and to ensure the interactive results, respectively. In chapter 3, I explore to use AR to reduce the visual feeling of trembling in typing. Thereby I build an AR system in which an individual's trembling hand is optically overlapped with a stabilized virtual hand, and investigate the optimal virtual:real hand intensity ratio to provide a realistic typing experience of using steady hand. In chapter 4, I propose approaches that facilitate individuals with hand tremors to control projection extended hand steadily using touch panel. I improve the virtual stabilization method in chapter 2 and propose some stabilization methods, e.g. "distance stabilization", "touch area analysis", and "combination" that stabilize EH's gestures to make EH technology accessed by trembling hands.

Figure 1.1 illustrates the scope of the thesis. The proposed approaches and AR systems discussed in this thesis support individuals with hand tremors to type ordinary keyboard or to communicate real-world objects that exceeding hand reachable ranges. The approaches as well as the AR systems could also be developed to enhance the capability of trembling hands in other HCI and CMC.

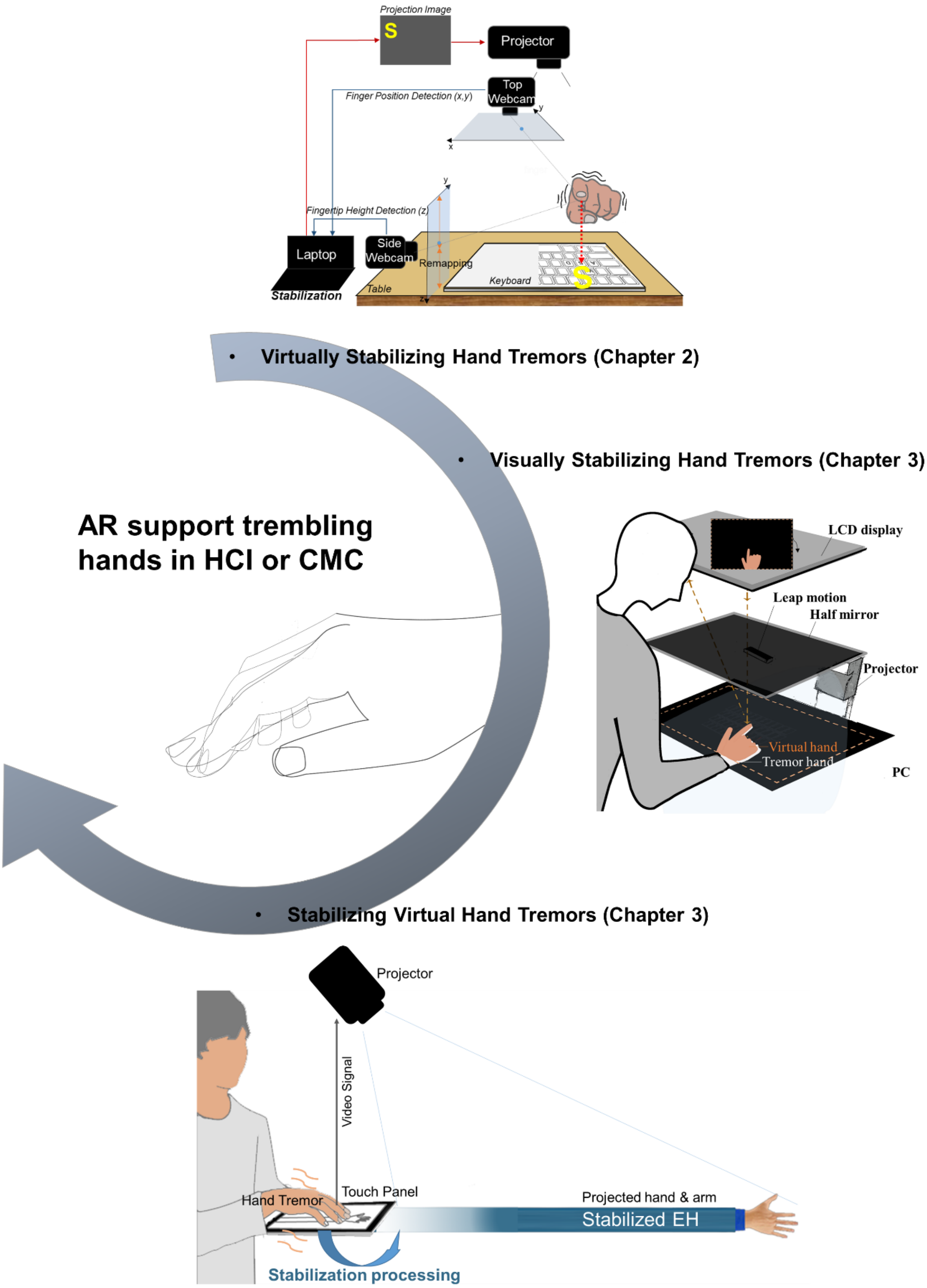


Figure 1.1 Scope of this thesis.

Hand Tremor

More than 20 types of tremors were clinically defined [1] and distinguished as rest tremors and action tremors based on phenomenological classifications [24]. Rest tremors occur in body parts that are not involved in purposeful activities. In contrast, action tremors occur during voluntary activities, such as in eating, writing, typing or touching [6] [25] [26] [27], and thereby undermine intentional hand activities. The hands affected by action tremors may show one of two typical features. One feature is rhythmic trembling with a fixed frequency (mainly within 4 Hz - 7Hz [28] [29]) and a regular amplitude (range from barely perceptible tremor to high [30]) during hand movements. It can typically be observed in hands afflicted by essential tremor (ET) (It affects nearly 1% of the world's population [31]), while sufferers using hands for e.g. typing [26]. Another feature is low frequency trembling (below 5 HZ [22]) as well as high increase in amplitude as the hand approaches a target. It can be found in hands afflicted by intentional tremor (IT) [6] [32] [33]. Depending on the tremor features, hand tremors have different degrees of influence on the stability and motion precision of hand and fingers, which results hand fail to precisely move and touch targets [18] [20] [34].

1.1 Contribution

The main contribution of this thesis is an exploration of augmented reality technology for supporting individuals with hand tremors in human-computer interaction (HCI) or computer-mediated communication (CMC). The broad contribution is organized in the remaining chapters of this thesis as virtually stabilizing hand tremors, visually stabilizing hand tremors, and stabilizing virtual hand tremors.

1.1.1 Virtually Stabilizing Hand Tremors

Considering widespread use of computers and touch panels, hand tremor sufferers fail to access them by typing or touching, and rare technology is available to solve the issues, I propose an approach of virtually stabilizing hand tremor as well as projection AR systems to enable trembling hands to easily type or touch the desire. In chapter 2, I propose virtual stabilization algorithm, which can stabilize the images of trembling hands to estimate intentional hand movement positions. I also propose a "virtual remapping" method, which can remap all physical keys of keyboard by the desired key when estimating a typing of action to guarantee a correct output result. Consequently, I investigate the effective of this approach by the experiment and demonstrate the approach can significantly reduce tying error ratio by comparing with typing directly.

Virtual stabilization shows its scalability for different interactive platforms and system environments in this thesis. For example, in chapter 3, I advance the approach to gain stabilized virtual hand gestures; and in chapter 4, I slightly improve the approach to make EH's movements controlled by trembling touches.

1.1.2 Visually Stabilizing Hand Tremors

In spite of the approach of virtually stabilizing hand tremors can help trembling hand to type or touch desire, however, the trembling of hand can confuse individuals to predict the finger touching position. In the experiment of chapter 2, I observed participants wasted much unnecessary time to predict typing position. Therefore, in chapter 3, I advance the approach to reduce the visual perception of hand trembling in typing. I propose an optical see-through AR system that can dynamically overlap a trembling hand with a stabilized virtual hand, and investigate the intensity ratios of virtual and real hand to provide a realistic typing experience of using steady hand.

I first propose to use AR technology to visually reduce individuals' hand tremors. Comparing traditional ways e.g. medical and physical approaches may harm body, the approach is safe and effective to support individuals with tremors to use a steady hand in interaction. The approach could have the versatility of application to support individuals with unsteady hands or body for other HCI or CMC.

1.1.3 Stabilizing Virtual Hand Tremors

The approaches in chapter 3 and chapter 4 are valid to enhance trembling hands to type or touch the objects defined in body reaching ranges. However, as tremors may cause mobility impairments, sufferers are not capable to independently communicate distant objects. Projection based EH technology has the potential to support mobility impaired to interact with real-world distant objects [35] [36], however, exclude trembling hands. In chapter 4, I improve EH technology for trembling hands and propose three gesture stabilization methods, including "distance stabilization", "touching area analysis", and "combination", which stabilize EH gestures to allow the stable control of EH by trembling touches. I conduct experiments to demonstrate the effectiveness of the proposal that can reduce unstable stationary state and gesture of EH affected by hand tremors.

In addition, I have to refer that the approach practically reduce the effect of tremor inevitably magnified in touching interaction, thus it can be promoted to be used in some system that are sensitive for unsteady hand touches,

1.2 Outline of Dissertation

This section outlines the remaining chapters of the thesis,

Chapter 2. Virtually Stabilizing Trembling Hands Using Projection Augmented Reality. This chapter introduce an approach and projection AR system that supports individuals with hand tremors to type with ordinary physical keyboards under the condition of hand tremor movements. The approach is stabilizing the orthogonal images of hand tremor to estimate intentional hand movement and virtually remapping physical key by the user wanted key to guarantee the correct typing input. To demonstrate the usefulness of approach, I compare with direct typing on tying error rates, the time wasted on correcting error input and so on.

Chapter 3. Visually Stabilizing Trembling Hands Using Optical See-Through Augmented Reality. In this chapter, I propose optical see-through AR system that dynamically maps a stabilized virtual hand to a trembling hand to provide individuals with tremors a visually steady hand. I investigate an optimal intensity ratio between virtual and real hand, which can promotes both the typing performance of two types of trembling hands and the proprioception of stabilized virtual hand.

Chapter 4. Expending Reachable Range of Trembling Hands Using Stabilized Projection Augmented Hand. This chapter improves EH technology for trembling hands by stabilizing its movements and gestures. I propose "distance stabilization", "touching area analysis" and "combination" stabilization methods that reduce the effect of tremor touches to improve the stability of EH gestures. I use a way to simulate ET and IT hands interacting with EH, and investigate the effectiveness of proposed methods through a series of pointing and grasping experiments.

Chapter 5. Discussion and Conclusion. This chapter summarizes the contributions of thesis, the remaining issues, and outlines the future works.

CHAPTER 2

Virtually Stabilizing Trembling Hands Using Projection Augmented Reality

In this chapter, I introduce an approach to supports individuals with hand tremors to type with the ordinary physical keyboard under the condition of hand trembling movements. The approach mainly includes "virtual stabilization" and "virtual remapping". I demonstrate the effective of this approach by keyboard typing experiments.

2.1 Introduction and Motivation

Typing keyboard is very common activities, as keyboard is one of most important tools accessing kinds of devices (such as Laptop, ATM, TVM) in daily life. However, it is difficult for individuals with hand tremors. Most of the keyboards have small keys and close arrangement, shaking hands usually fail to locate the desired key. Tremor sufferers using keyboards is often difficult or even impossible [37]. However, rare approaches are available to support trembling hands in typing keyboard currently. In the chapter, I targeted the issues, and proposed an approach, which can help individuals with hand tremor correctly type with the ordinary physical keyboard under the condition of hand tremor movements. I employ two web cameras and a projector to set up a typing-assist system. During the process of typing-assist, the system uses a series of image information captured from two views to analyze a stabilized finger position and its index key, then visualizes an estimated result before typing keyboard, or binds an estimated result to input when finger uncontrollably types a key.

2.2 Related Work

There are several related works focusing on the issue of tremor sufferers typing keyboard.

Hugo et.al examined text-entry performance of elderly users on touch-based devices. They indicated that input errors are strongly correlated with participants' tremor profile [38]. Zhong et.al studied the target acquisition of the smartphone for people with hand tremor. A single tapping task is split into two steps: disambiguation and selection. When the finger places the touch area intersected multiple targets, disambiguation will be activated and lists the target descriptions with larger region to makes sure people with hand tremor touch the target [18]. Alexander et.al proposed an interface where the important key is circle to edge, as they found that swabbing is easier than typing on the touchscreen for the people with intentional tremor [39]. Wachara-manotham.et.al found that oscillation is generally reduced during sliding. They suggested swabbing instead of typing on the touchscreen as input method for the elderly user with tremor [40]. Jacob et.al studied EdgeWrite helping trembling hand input characters to handhold device. The text entry is by stroking the edges and diagonals of a square hole and the input characters are recognized through the sequence of corners that are hit [41]. Soft keyboard can be customized, depending on the host system and specific software. So the users who are unable to type a regular keyboard have many choices. However, these customized keyboard is difficult to type for most people, it limit the applications in several private devices.

There are rare technologies on assisting trembling hand to type on the physical keyboard, as the assignment of keyboard is fixed. Most of works prefer to design aid tool or change keyboard size. "Slip-on Typing/Keyboard Aid" is a typing aid tool to help people who cannot access a keyboard with their fingers by its pointer striking the key [42]. But, it also requires hand to be steady. “Keyguards” is hard plastic covers that fit over the keyboard with holes for each key to prevent unwanted typing. But its layout need quite match the key locations of the keyboard [43]. “WinMini Keyboard” is 7.25 inch*4.2 inch small keyboard and is activated by mouth stick or head pointer [44]. “BigKeys LX keyboard” and “VisionBoard 2 Keyboard” have inch square key- almost 4 times bigger than the keys on a standard keyboard [45]. These designs may increase and improve capabilities of using keyboard. However, these keyboard cannot guarantee consequent input result accordant with intention. In another word, the accuracy of typing input cannot be controlled as user’s intention when typing these keyboard.

In assisting trembling hand to typing keyboard, the research focus on developing camera and projection based system to help trembling hand directly interact with standard physical keyboard. The system adopts the technologies of virtual fingertip stabilization and virtual key remapping to make tremor sufferers input the desired characters as intention.

2.3 System

My system was proposed to provide typing assistant by using camera and projector. I assume that a user uses his index finger to type keyboard. The configuration is shown in Figure 2.1. The system employs two web cameras (NET cowboy DC-NCR13U) to measure finger positions. One camera is set at top to track tremor finger horizontal movements on the keyboard. Another camera is set the side of keyboard to detect the fingertip height perpendicular to the keyboard. The captured frames are sent to PC (ThinkPad X1 Carbon i7-5500U) to do virtual fingertip stabilization. A projector

(Acer K10, 850*600 pixels, 100 lumen) at top projects an estimated key character on the keyboard for confirming the estimated result while tremor finger is hovering and moving on the keyboard (Figure 2.2 (a)). The system will start the key remapping to make sure correct key input when finger is willing to type keyboard. A uniform white projection illuminates the typing environment (Figure 2.2 (b)) for hinting all physical keys are remapped by the estimated key.

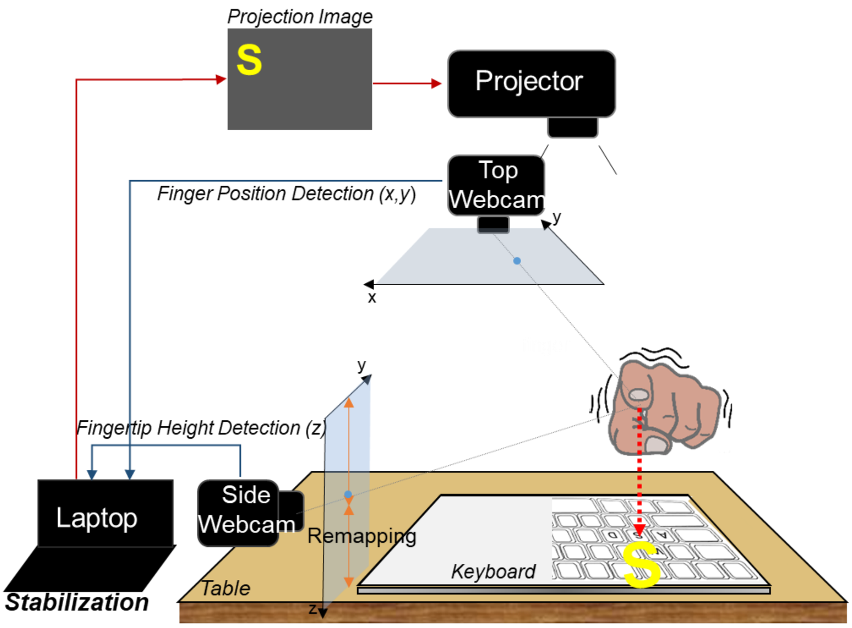
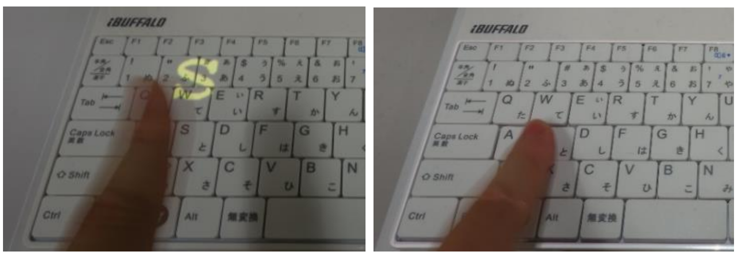


Figure 2.1 Configuration of system.



(a) (b)

Figure 2.2 (a) appearance of key projection: A projection key is displayed while finger hovering on the keyboard, and (b) appearance of key remapping: A uniform white projection illuminates the typing environment while finger is typing keyboard.

2.4 Method

2.4.1 Virtual Stabilization

People suffered with pathological tremor lost the ability to coordinate ten finger movements due to involuntary movement disorder. So that, the system is specially set to track one finger's typing activities. The typing activities are recognized by real-time measuring the fingertip's 3D positions from two camera perpendicular to each other. The system segments hand region from captured images based on skin color probability and calculates the maximum distance to the gravity of hand region along the contour of hand region to extract the fingertip. The fingertip's 3D position are finally determined by fingertip's x, y position measured from top camera and z position measured from side camera (Figure 2.1).

Hand tremor is inherently characterized by frequency components higher than intentional hand movement. My method is processing the captured frames with low-pass filters to get a stabilized fingertip position. I investigate low pass filter to virtual fingertip stabilization [46], and found that the changing of key projection on the key-board cannot catch up with finger movements, when finger suddenly moving with large distance. Therefore, I improve the system to user Kalman filter and Hysteresis for fingertip position stabilization. Hysteresis filter not only corrects the stabilized result of Kalman filter, but also can regulate to accept raw fingertip position as detecting a large change between the last and current stabilized fingertip position. So that, the combining filters can improve stabilization and eliminate the delay of projection changed. After fingertip stabilization, the system can estimate the key that user is intent to type basing on the stabilized fingertip position.

2.4.2 Virtual Remapping

While the hand tremor sufferer types the desired key on the keyboard, he/she may fall uncontrollable actions, such as typing the neighbor key of desired key, typing two keys at the same time, or typing a key many times. They result in many input errors. To reduce error input, my system adopts key remapping while finger is willing to touch the keyboard. When fingertip meet the threshold key remapping, the system will record the last estimated result and make all physical key virtually remapped by last estimated key. So that, although user may touch wrong keys, the correct key will be input (Figure 2.3).

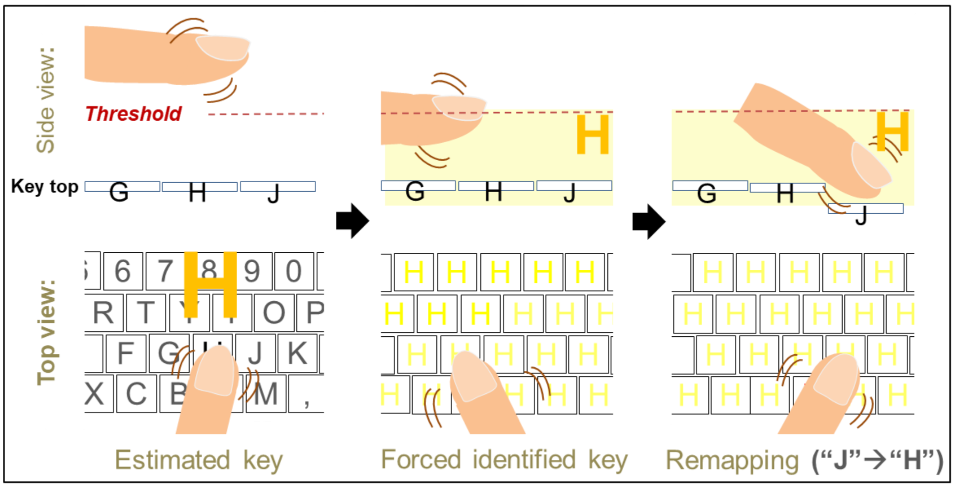


Figure 2.3 Virtual key remapping: Due to hand tremor, user actually type an undesired key ‘J’, but the user desired input ‘H’ is also input by virtual key remapping.

2.4.3 Procedure

As initialization, the system needs calibrate two cameras and keyboard position in the image plane of two cameras.

There is a data flow of the proposed method in Figure 2.4. In the k step, the system employs two cameras to capture images from two views, converts the captured RGB frames to YCrCb, and extracts hand region by Otsu's method that maximizes inter-class variance between skin color region and background, and detects the fingertip position by computing the fastest distance between the counter point and the gravity in hand region, recorded as $x^{(k)}$, $y^{(k)}$, and $z^{(k)}$, where $x^{(k)}$, $y^{(k)}$ are measured from the top camera and $z^{(k)}$ is measured from the side camera.

Then, the system virtually stabilizes the detected fingertip position, use Kalman filter to preliminarily stabilize the extracted fingertip position, denoted as, ($x'^{(k)}$, $y'^{(k)}$, $z'^{(k)}$). Next, the system computes the Euclidean distance between the preliminary stabilized position ($x'^{(k)}$, $y'^{(k)}$), and the estimated fingertip position in last step ($x^{est(k)}$, $y^{est(k)}$) by Equation 2.1. There are a lower threshold and a higher threshold that are experimented based on the shaking amplitude of adult's index finger (maximum 35mm at 10° angular amplitude) and key size of standard keyboard (18mm). If the distance is less than the lower threshold, the system will believe the preliminary stabilized result as the steady x, y position. If it is between two thresholds, the system will correct the stabilized result by using the $k-1$ step estimated fingertip position. If it is over than the higher threshold, the system will adopt the extracted fingertip position.

After stabilization, the system regards an estimated fingertip position as the wanted key and projects the key character responding to the estimated key for user confirmation. The system determines whether it projects an estimated character or key remapping result according to the fingertip position $z'^{(k)}$. When fingertip $z'^{(k)}$ is less than the set threshold which is based on the type of hand tremor, all the physical keys will be virtually remapped as the estimated key. The remapping allows the estimated key one time input and it is continue till fingertip triggers the threshold again (Figure 2.3).

- Hysteresis of fingertip's x coordinate (The system also applies the same processing in fingertip's y coordinate.)

$$x^{est(k)} = \begin{cases} x'^{(k)} & |x'^{(k)} - x^{est(k-1)}| \le T_l \\ x^{est(k-1)}, & T_l < |x'^{(k)} - x^{est(k-1)}| < T_h \\ x^{(k)} & |x'^{(k)} - x^{est(k-1)}| \ge T_h \end{cases} \quad 2.1$$

where: $x^{(k)}$ is x coordinate position of the detected fingertip in the k step. $x'^{(k)}$ is x coordinate of the preliminary stabilized fingertip in the k step. $x^{est(k-1)}$ is x coordinate position of the estimated in the k step. T_l, T_h represent low and high thresholds of filter, respectively.

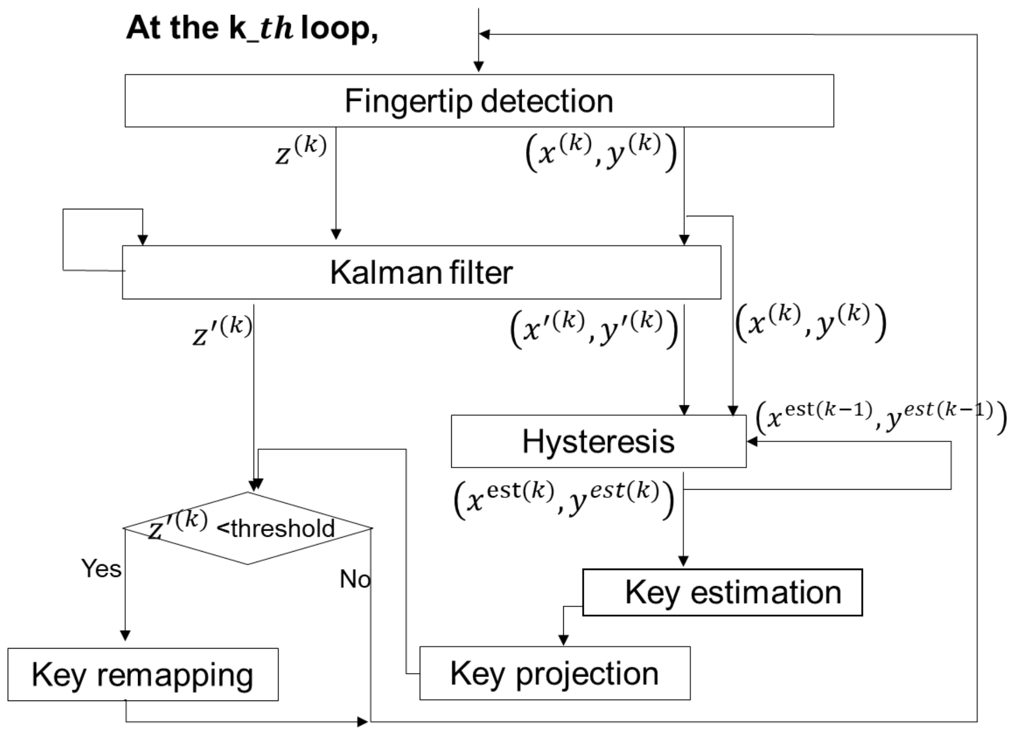
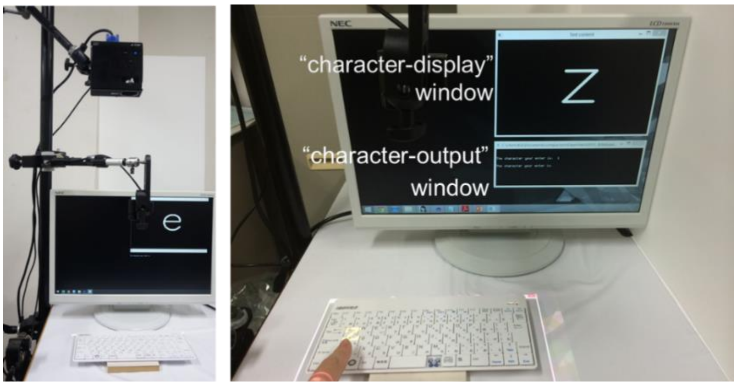
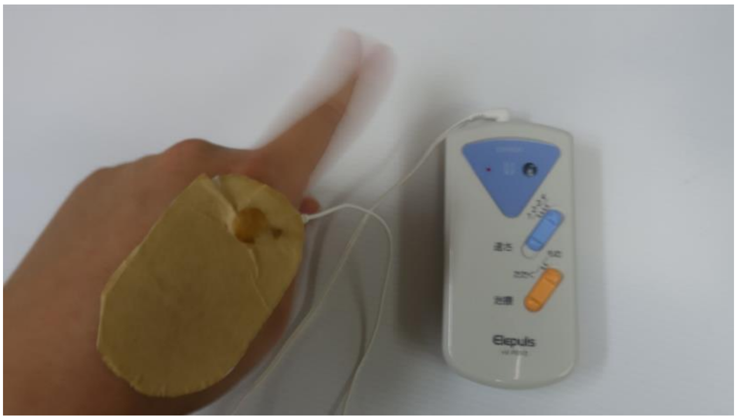


Figure 2.4 Flow of the proposed method.

2.5 Experiment



(a) (b)



(c)

Figure 2.5 (a) appearance of proposed system, (b) a participant type standard keyboard without physical constraints, and (c) the pad positions on hand.

2.5.1 Experimental Setup

I designed a typing experiments to test the usability of system. A typing program was prepared, which randomly displays the character of keys on “character-display” window and requires participant to correctly input the displayed character into “character-output window” (Figure 2.5 (b)). The program was designed based on the nature typing way. If the actual input is wrong, it will require participant to delete the wrong input and input again until correct input. The spending time in an experiment, error input time, and error times will be automatically obtained at the end of an experiment.

9 people (8 male, 1female) were invited to participate in the experiment in a simulated condition of hand tremor by using Low-frequency therapy instruments (Omron Elepus VRF050 and Panasonic EW6011). To control finger as much as possible, Omron Elepus VRF050 and Panasonic EW6011 were selected to be used according to participants' hand size and bio-impedance. Figure 2.5 (c) shows the paste position of pads on the hand. The machines can manufacture participants' finger uncontrollable shaking to be left and right, the frequency as low as 3Hz (about 3-5Hz) and the angular amplitude of finger shaking as low as 8° by visual assessment. Note that for normal adults, if angular amplitude of index finger shaking is over than 8°, the shaking range of finger is usually over than a key size. As the limitation of machine, frequency 5Hz cannot be simulated. But it does not affect experimental purposes. Intentional tremor is lower frequency tremor within3- 5 Hz. Kinetic tremor such as ET, is featured as the larger frequency of hand tremor, the lower amplitude. As the system using low-pass filter, the shaking finger of higher frequency and lower amplitude is easier to be stabilized. Three items on the time spent on finishing the experiment task (designate as "input time"), the percentage between the time wasted on correcting error input and the time spent on finishing the experiment task (designate as "error input time rate"), the input error rate in an experiment (designate as "error input rate") were compared among the four conditions which contents and labels are shown in Table 2.1. Each participants was arranged in 4 experiments and simulated the 4 conditions. 50 characters randomly generated in each experiment, participants were required to type with usual typing speed in each experiments and took a 10 minutes break to rest after an experiment.

Table 2.1 Four conditions and labels

Conditions	Label
Trembling hand typing keyboard with the proposed system	“tremor & system”
Trembling hand typing keyboard directly	“tremor & direct”
No trembling hand typing keyboard with the proposed system	“no_tremor & system”
No trembling hand typing keyboard directly	“no_tremor & direct”

2.5.2 Evaluation

Analysis of Quantitative Data

A two-way ANOVA between subjects was conducted to compare the effects of error input rate, error input time rate and input time in hand conditions(tremor and no tremor), typing ways (with and without system) and the intersected conditions between hand conditions and typing ways. The error input rate, error input time rate and input time were all found statistically significant difference with $p < 0.05$ in all conditions. Then, a one-way ANOVA between subjects was conducted to compare the effects of error input rate, error input time rate and input time on the 4 conditions of trembling hand typing with system, trembling hand typing directly, no trembling hand typing with system and no trembling hand typing directly. There were significant effects of error input rate ($F(3,32)=46.0$, $p < 0.01$), error input time rate, ($F(3,32)=31.6$, $p < 0.01$), input time ($F(3,32)=15.3$, $p < 0.01$) at the $p < 0.05$ level for the 4 conditions. Post hoc comparisons using Bonferroni indicated the differences between each two conditions.

In the condition of trembling hand and no trembling hand typing keyboard directly, the error input rate, the error input time rate and the input time were all found statistically significant difference with $p < 0.01$. Comparing the results of no trembling hand, trembling hand typing keyboard made higher mean input error rate (Figure 2.6), spent much more time on correcting errors input, the error input time rate (Figure 2.7), and used much more time in finishing the experiment task (Figure 2.8) These results verify that hand tremor seriously affects hand accurately and smoothly typing keyboard.

In the condition of trembling hand typing keyboard with system and trembling hand typing keyboard directly, the error input rate between the two conditions was found statistically significant difference with $p < 0.01$. Typing with system made very less mean input error rate than typing directly (Figure 2.6). The comparing results supported the assumption that the system was effective for reducing the error input of typing keyboard caused by hand tremor. The error input time rate between two conditions was also significant difference with $p < 0.01$. Typing with system wasted less time on correcting the error input than typing directly (Figure 2.7). The time spent on finishing the task of experiment was not statistically significant difference, $p > 0.05$ (Figure 2.8).

Comparing the error input rate and the error input time rate between the condition of trembling hand typing with system and no trembling hand typing directly, there were no statistically significant effect, $p > 0.05$. The results showed that trembling hand typing with system achieved lower typing error rate nearly as same as no trembling hand typing directly (Figure 2.6) and also spent less time on correcting error input (Figure 2.7). Taken together, these results suggest that the system contributed for trembling hand on correct typing.

Comparing trembling hand and no trembling hand on typing keyboard with system, there were no statistically significant difference of the input time, the error input time rate, and the error input rate at the $p > 0.05$ (Figure 2.6, Figure 2.7, and Figure 2.8). These results indicated that users no matter what hand conditions have same performance in typing keyboard with the proposed system.

In the condition of no trembling hand typing keyboard with system and no trembling hand typing keyboard directly, the error input rate and the error input time rate were not found to be significant differences, $p > 0.05$. With the system, people whose hand is in the good condition also achieved correct input rate as high as the direct typing keyboard, the error input rate (Figure 2.6). The error input time rate of the two conditions was also shown to be approximate (Figure 2.7). It verified that the system did not affect the health hand well typing on the keyboard. But, the input time between the two conditions were found significant difference with $p < 0.01$. No trembling hand typing with system may take more typing time than no trembling hand typing keyboard (Figure 2.8). Taken together, these results suggest that the system are universal for different hand conditions on correct typing.

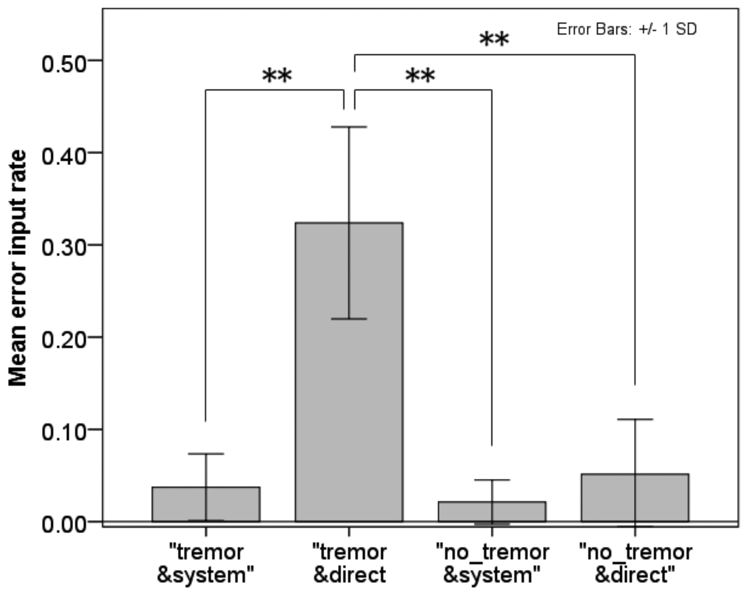


Figure 2.6 Comparison of mean error input time rate in 4 conditions: In the condition of "tremor & system" and "tremor & direct", p < 0.01. In the condition of "tremor & direct" and "no_tremor & direct", p <0.01.

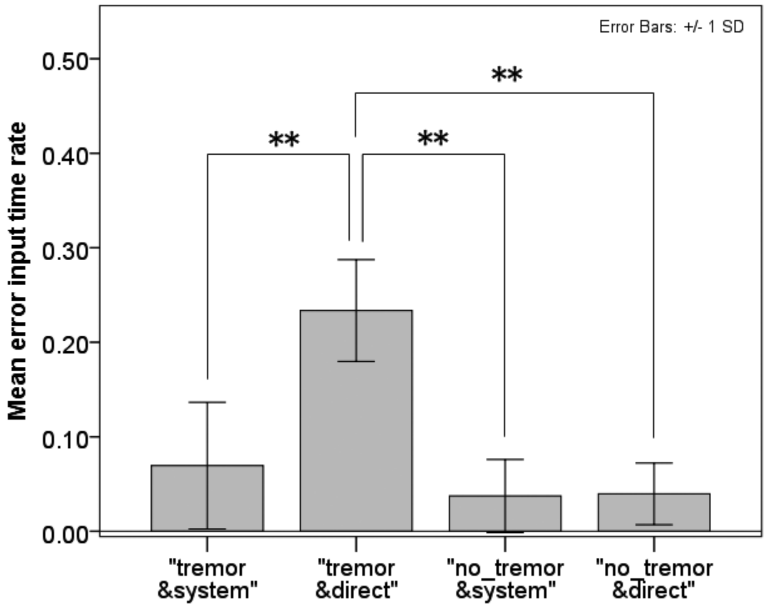


Figure 2.7 Comparison of mean error input time rate in 4 conditions: In the condition of "tremor & system" and "tremor & direct", p < 0.01. In the condition of "tremor & direct" and "no_tremor & direct", p < 0.01.

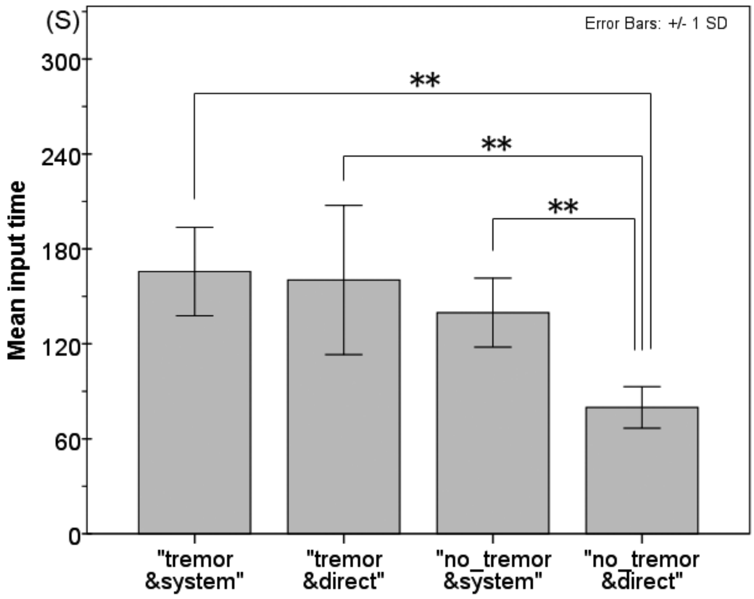


Figure 2.8 Comparison of mean input time in 4 conditions: In the condition of "no_tremor & system" and "no_tremor & direct", p < 0.01. In the condition of "tremor & direct" and "no_tremor & direct", p < 0.01.

Analysis of Questionnaire Data

According to the psychological questionnaires of 9 participants that were required to fill after experiment, we found that most of participants feel that trembling hand directly typing keyboard is uncomfortable, but using system increase comfortable feeling (Figure 2.9). And, almost all participants consider that many input errors bring frustration of using keyboard and little input errors will contribute to more satisfaction of using keyboard (Figure 2.10) and the system guarantees lower error input rate.

Q1. Do you feel typing is comfortable, while trembling hand typing keyboard directly.

Q2. Do you feel typing is comfortable, while trembling hand typing keyboard with system.

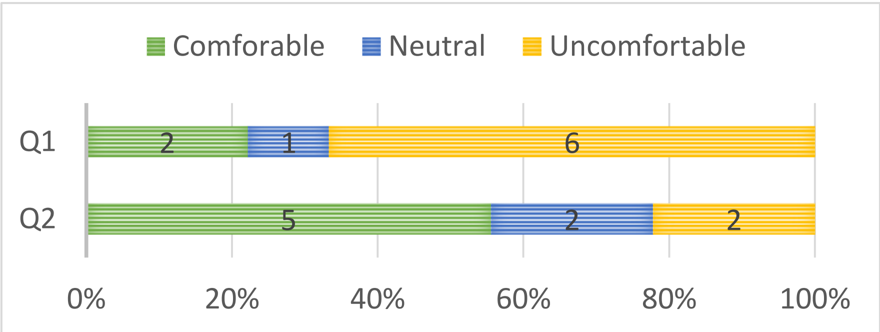


Figure 2.9 Survey of comfort under the condition of trembling hand typing directly (Q1) and trembling hand typing with system (Q2).

Q1. Do you think that much input error will bring more frustration of using keyboard?

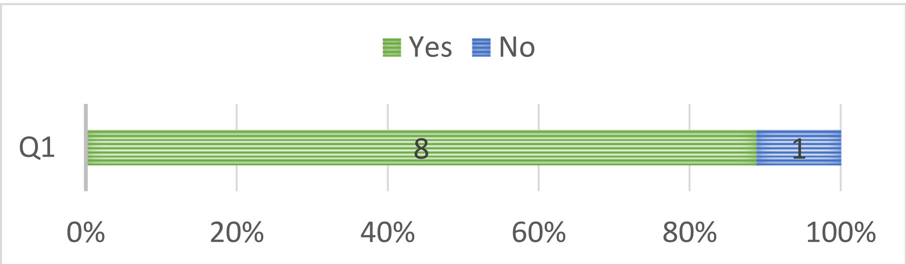


Figure 2.10 Survey of relation between error input times and frustration in typing keyboard.

2.5.3 Discussion

The experiment results showed the system have good performance on reducing the error input rate and the time of correcting error input for trembling hand typing ordinary keyboard. But the system did not show the contribution of reducing the input time of finishing an experiment task. There are several reasons. Typing behaviors of typing with system and typing directly are different. As with the system, user spends time in confirming whether the projection key is the wanted key before typing a key on the keyboard. But if typing directly, user types a key of keyboard quickly to see the input result. Comparing the wasted time of input one time, typing with system may spends more time than typing directly. However, a period of time of typing keyboard, trembling hand typing directly will waste much time on correcting error input as creating many input errors. By contrast, typing with system will use little time on correcting error input as it make little input errors. In addition, there is an uncertain factor-the hand control rate of shaking machine, which may affect the experiment result of input time. Shaking machine can make finger shaking, but cannot completely control finger. While finger is hovering on the keyboard, user’s attention focuses on the keyboard or key projection, the finger is almost controlled by machine. But while finger is willing to type a key, user’s attention will fall on finger and keyboard, participant’s intention is unavoidably added. So it may reduce input errors and then input time of trembling hand typing directly, but do not affect experimental results of trembling hand typing with system as system do not care about actual typing. So that, the input time of trembling hand typing with system and typing directly are not significant. In addition, as the participants are young and very familiar with keyboard, they can correct input errors quickly. But essential tremor sufferers cannot correct input errors so fast. In application, hand tremor sufferers typing with the system will perform better in time than they typing directly. Finally, synthesizing the analysis of experiment data and psychological aspects， the system is proven to contribute to support people with hand tremor typing the ordinary keyboard.

2.6 Conclusion

In this chapter, a projection-based assisted system consisted of cameras and projector was proposed to support trembling hand typing keyboard. The system makes sure the correct input while the involuntary shaking hand directly typing on the ordinary keyboard. It is achieved input assistance by the contributions of the methods of virtual stabilization and virtual key remapping. The experiment evaluated the effectiveness of system. In experiment results, hand tremor seriously affects typing the right keys of keyboard and correct inputs. But, trembling hand typing with system can reduce input error rate and spend less time in correcting wrong inputs, nearly achieves the level of no trembling hand directly typing keyboard. The system was proven to be useful for people with hand tremor correctly input the desired key with physical keyboard. Trembling hand typing with system, no trembling hand typing with the system, no trembling hand typing directly was not found the significant difference in error input rate and the error input time rate. The system expresses universal for different hand conditions. But, no trembling hand typing with system may take some time comparing typing directly. In the future work, I will improve to reduce the effect on input time at user using the system, to make system more universal.

CHAPTER 3

Visually Stabilizing Trembling Hands Using Optical See-Through Augmented Reality

In this chapter, I introduce approach that can visually reduce hand tremors. I propose an optical see-through AR system that can dynamically overlap a trembling hand with a stabilized virtual hand, and investigate the intensity ratios of virtual and real hand which promotes both the typing performance of trembling hands and a realistic typing experience of using steady hand.

3.1 Introduction and Motivation

This research explores the potential of AR in supporting people who experience ET and IT hand tremors when typing on keyboards, and it develops an optical see-through AR system to reduce the visual perception of hand tremor in typing. The system optically overlaps a stabilized virtual hand and a trembling hand by controlling the virtual: real intensity ratio to create a realistic typing sensation without hand tremors. I examined whether the proposed system supports the typing task for tremor sufferers by comparing the time and error ratios between the trembling hands with the system and without the system. By comparing the two types of hand tremors in the different virtual:real intensity ratios, I also determined the relationship among the proprioception of the virtual hand, the auxiliary effect, and the virtual:real intensity ratio.

3.2 Related Work

Hand Tremor Typing Support

"Keyguards" is a hard plastic cover that fits over the keyboard; it has holes for each key to prevent unwanted typing [43]. However, because of the slight differences in different keyboards, this cover does not easily fit all keyboards. Zhong et al. (2015) [18] developed a hand tremor service for smartphone called "Touch Guard". When the finger touches the area intersected with multiple targets, "disambiguation" will be activated, and it will provide a "target list" with a larger access region. Mertens et al. (2010) [39] designed an interface in which the important keys are aligned toward the outer circle because swabbing is considered easier than touch-typing for trembling hands. These studies attempted to develop special interfaces to assist trembling hands; however, changing a familiar interface often confuses the user, and the user fails to perform a faster and more accurate interaction [20]. Plaumann et al. (2016) [20] proposed a method to improve input speed and accuracy of trembling hand touch-typing by simultaneously stabilizing the motion data detected from smartphone sensors and finger-worn sensor. Although it enables the trembling hand to access the usual interface, both the interactive object and the user finger have to wear some motion sensors. My previous research proposed a system to support hand tremor sufferers to directly typing with ordinary physical keyboards [50]. The system estimates the desired key and provides users with a projection to help locate the desired key. However, this projection affects the typing efficiency. Therefore, this research develops an AR system to support the trembling hand to steadily type the desired key by using mixed reality of the stabilized virtual hand and the trembling hand

Proprioception

Proprioception, which explains how much the fake hand feels like one's own hand, has been discussed frequently in researches on virtual/rubber hand illusions. Botvinick and Cohen (1998) [51] first demonstrated the rubber hand illusion—people feel that the fake hands are their own hands when the artificial rubber hands and their own concealed hands are stroked synchronously. Sanchez-Vives et al. (2010) [52] indicated that this illusion of ownership occurred when the movements of the real hand and virtual hand were synchronous; and this illusion happened even in the absence of tactile stimulations. Additionally, the appearance was found to be associated with the illusion of ownership, and the illusion feeling was more pronounced in realistic hand representations than in any other appearances [53][54][55]. To sum up, three factors are responsible for promoting the proprioception of a fake hand, namely, visual-tactile synchrony, visual-motor synchrony, and realistic hand representations. Therefore, I designed the AR system by fully considering these three factors and by investigating the proprioception of the virtual hand under the visual-tactile-motor synchrony states.

IJsselsteijn (2005) [56] compared the body ownership illusion of the fake hand with the rubber hand condition, the virtual reality condition, and the mixed reality condition; no significant differences were found. However, the setting of the AR system limited the virtual hand movement and passively accepted the interaction; therefore, the system cannot be applied to support a trembling hand. By synchronizing the virtual hand with the real hand in spatial position and gestures and by controlling virtual:real intensity ratio, my system provides a convincing subjective illusion whereby the person does not perceive any tremor in the hand and is steadily able to type the desired keys on the keyboard.

In addition, many studies have examined the sense of ownership (i.e., experiencing the artificial hand as one's own body part) and the sense of agency (i.e., the phenomenal experience of initiating and controlling an action to confirm the proprioception of fake hand)[55] [58] [57]. My research also follows the two directions and improves the questionnaires used by previous researchers.

In the rubber/virtual hand illusion studies, the experimental setting did not avoid the deviations between the fake hand and the real hand; there were no discussion on the ideal synchronous states in which the fake hand and the real hand always maintained the same spatial position and gesture. My system setting provides no deviations between virtual hand and real hand in spatial position and gesture.

3.3 System

I propose an optical see-through AR system that merges the stabilized virtual hand and the real trembling hand to provide hand tremor individuals with assistance for typing stably using their own hands.

The hardware configuration of the system is shown in Figure 3.1. The main system apparatuses included the Leap motion, an LCD display (Sharp PN_T321), an half mirror (about 10% transmittance and about 50% reflectance), and an ultra-short throw projector (LG PH450U, 450 lumen). The Leap Motion tracked the hand and transmitted the hand positions to a computer for spatial geometrical transformation and stabilization. The LCD display showed the rendered virtual hand, and the display along with the half mirror overlapped the virtual hand image on the real keyboard. The projector controlled the luminance of the environment behind the half mirror to make the real scene visible through the half mirror. Adjusting the intensity of the virtual hand

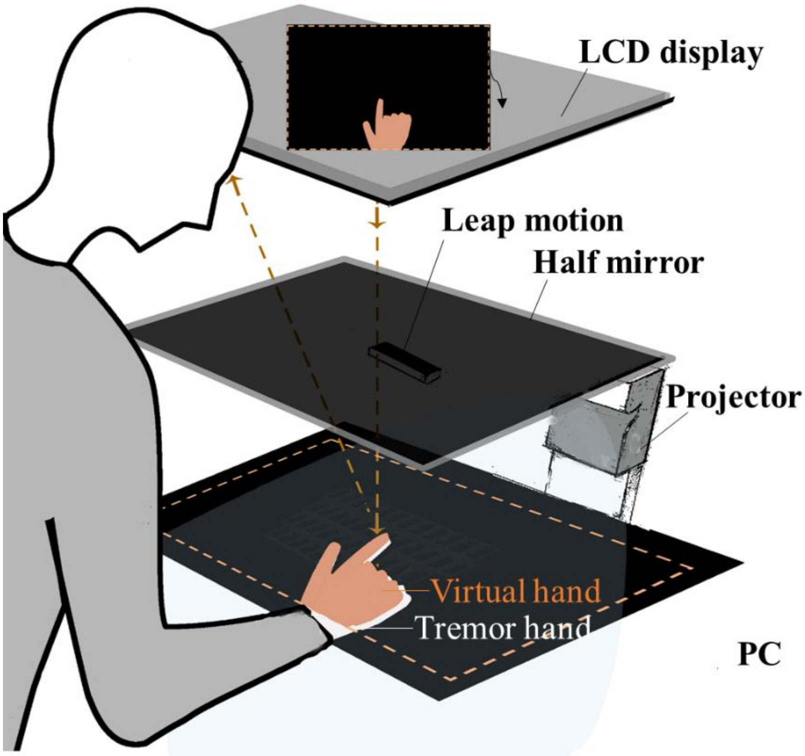


Figure 3.1 System configuration.

and the luminance of the environment, the different mixing ratios of the virtual:real presentations were observed from the half mirror (Figure 3.2).

The virtual hand is a generalized hand avatar of an adult male (Figure 3.2), but its size automatically changes based on the individual's hand size. It is mapped on the real hand, and it maintains the same movement pace as the real hand by spatial transformation. The virtual hand has the same joint number and degree of freedom as the real hand, and it changes synchronously with real hand gestures. The intensity of the virtual hand can be altered by Shader's parameters.

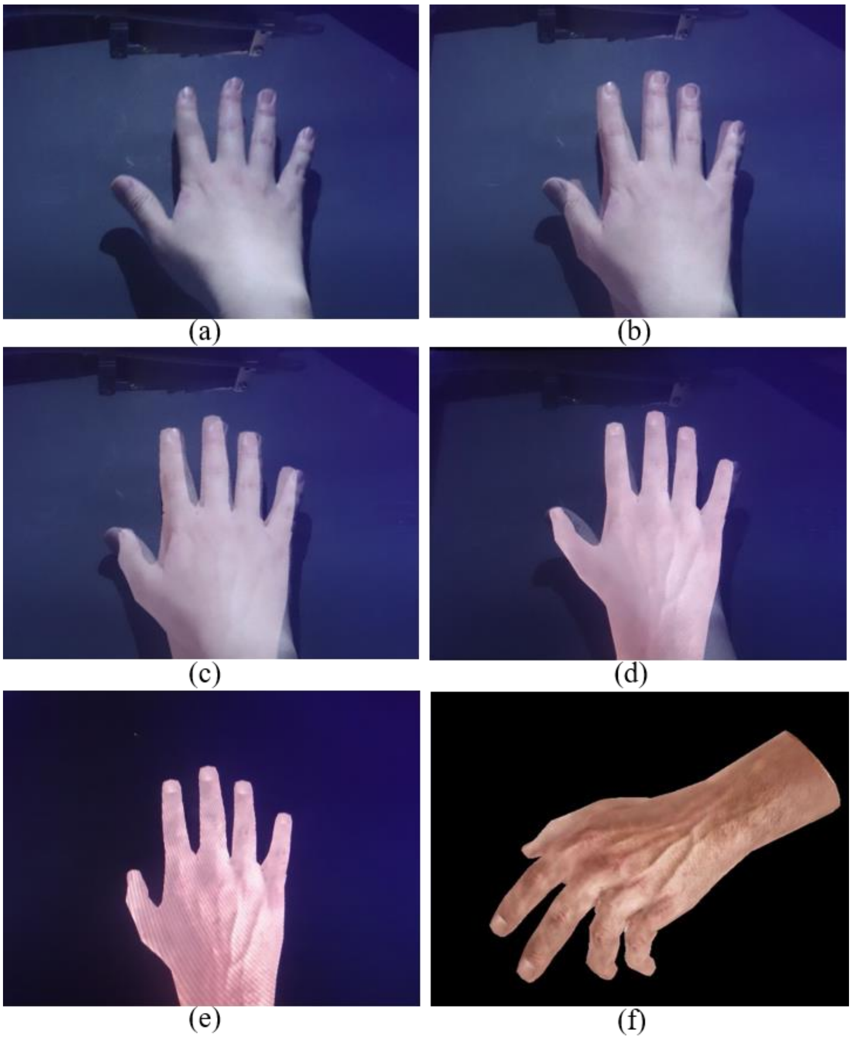


Figure 3.2 (a) to (e). The visual effect of the mixed hand, the intensity between the virtual hand and real hand are 0:1, 0.25:0.75, 0.5:0.5, 0.75:0.25, and 1:0, and (f) Virtual hand model.

3.4 Method

The system attempts to provide the user with the illusion that the virtual hand is his/her own body part; therefore, the virtual hand and the real hand are required to geometrically overlap each other with appropriate virtual/real mixing dimensions, and their movements to be synchronized. The methods are shown in sections A and B. Furthermore, to support the trembling hand typing and give it a stable appearance, tremor analysis and stabilization were implemented. The methods are described in section C.

3.4.1 Calibration

A series of calibrations was implemented offline, including spatial geometrics, virtual hand sizes, and intensity ratio of real/virtual hand.

To exactly align and overlap the virtual hand and the real hand, it is necessary to implement a geometric calibration to determine the spatial relationships between the virtual hand and the real hand. First, I generally set in parallel the display, the half-mirror, and the interactive plane where keyboard is placed; I manually adjusted their distances to make sure the virtual graphics lay on the keyboard. Then, I calculated the spatial geometry corresponding to the relationship between Leap motion and the display. As the image observed from the half mirror and the display is mirrored, I finally reversed the orientation of the virtual hand.

To avoid the incongruity between the virtual hand and individuals' real hand, the virtual hand size was designed to be adjusted automatically. First, the size of the standard virtual hand was taken as the average of adult men hand size. The distance between the center of the palm and the wrist joint and the distance between left and right edges of the hand are generally fixed and do not change with hand gestures. Therefore, when an individual's hand is detected, the system calculates and adjusts the length and width of the virtual hand as:

$$v_s' = \frac{v_s}{r_s} r_s' \tag{3.1}$$

where, s indicates length or width; r_s' is the individual's hand size; v_s' is the virtual hand size corresponding to the individual's hand; r_s is the average hand size of adult men; and v_s is the standard virtual hand size.

In this research, I selects the intensity ratios of 0:1, 0.25:0.75, 0.5:0.5, 0.75:0.25, and 1:0 between the virtual hand and the real hand to study the influence of different virtual/real mixing proportions. I calibrated the luminance of the environment lights, which determined the intensity of the real hand, and also calibrated the scale factors in the Shader program, which are related to the intensity of virtual hand. I set an RGB camera (Logicool Carl Zeiss) at the user viewpoint to capture the virtual hand and real hand images respectively, and measured the average intensity of hands by image processing. Specifically, I first projected a group of gray images with different values ranging from 255 to 0 onto the real hand and measured the intensity of the real hand under each light environment. The maximum intensity value of real hand is under light environment projected with 255 image, therefore, I normalized the maximum intensity value to 1. The searches of 3/4, 2/4, and 1/4 intensity values of maximum intensity and 0 intensity value were normalized to 0.75, 0.5, 0.25, and 0. The corresponding projections were recorded with gray values. Then, I set the virtual hand in the same place as the real hand and measured a group of intensity values by consecutively modifying the intensity scaling factors in Shader. I selected five scale factors that had the same intensity values as the recorded intensity values of the real hand, and I normalized the intensity values of the virtual hand. Finally, the virtual:real intensity ratios were 0:1, 0.25:0.75, 0.5:0.5, 0.75:0.25, and 1:0 when the intensity scaling factors of Shader were selected as 0, 0.07, 0.15, 0.26, and 0.33 respectively, and the projection values corresponding to the ratios were 255, 207, 170, 123, and 0 respectively.

3.4.2 Synchronization

This system synchronizes the virtual hand with the real hand in spatial position and gesture. The geometrically spatial relationships are calibrated; therefore, the spatial positions of the virtual hand are determined by transforming the tracked real hand position. The system synchronously controls the virtual hand gestures according to the real hand. Hand gestures include hand rotations, flexions/extensions and adductions/abductions of fingers. The hand rotation matrix is obtained by applying the built-in function of the Leap Motion. Finger gestures are decided by the spatial angles of the joints. The system first applies the cross product and the dot product to the position vectors of the connection of the bones to obtain the angle and the direction respectively. Then, the system multiplies the joint angles. Thus, if the joint from the palm toward the fingertip is numbered from 1 to 3, then each spatial angle of the joins is computed as

$$R_n = R_{hand} \prod_{i=1}^{n} R_i, \quad (3.2)$$

where, n denote the n th joint; R_{hand} is the hand rotation angle; R_n is the angle of n th joint, and is the angle of i th joint.

3.4.3 Tremor Analysis and Stabilization

The research considers two types of hand tremor features: type 1 (T1), which is a tremor with fixed tremor frequency and amplitude, and type 2 (T2), which is a type of tremor with highly variable amplitude.

Hand tremor analysis works at the beginning of the system process to help the system distinguish tremor features and determine stabilization schemes and parameters. Specifically, in the processing of hand tremor analysis, the system continually collects the 3D positions of the fingers (fingertips) and the hand (palm center), then it computes the average speed, average acceleration, main motion frequency and amplitude through fast Fourier Transform, and distinguishes the two types of hand tremors by support vector machines classification to determine the stabilization filter (The accuracy of classification reaches to 89% in the testing).

Then, the system virtually stabilizes the trembling hand position (i.e., palm center position) to compute the steady position of the virtual hand. When the T1 trembling hand is confirmed, the system uses the tremor frequency data and stabilizes the palm position by using a second-order IIR notch filter. When the tremor type is T2, the system uses a moving average median filter and sets the window size as 24 (according to the system sample rate and tremor frequencies) and average median 18 positions to eliminate singular tracked positions caused by sudden amplitude changes in the tremors. Moreover, the system further corrects the stabilized position by Hysteresis to avoid the delayed matching of the virtual hand and the real hand at larger hand movements. Suppose the position is stabilized in current step $p'(t)$ and the estimated position is in the previous frame $P(t-1)$, then the current estimated position $P(t)$ is computed by Hysteresis as follows:

$$P(t)=\begin{cases} p'(t) & |\, p'(t)-P(t-1)\,| \le D \\ p(t) & otherwise \end{cases} \qquad 3.3$$

where, D is the size of touching target, and $p(t)$ is the raw position. If the distance between $p'(t)$ and $P(t-1)$ is less than or equal to D, the final estimated position accepts the stabilized result. Whereas, the final position use raw position.

The tremor causes symmetrical flexion and extension of the fingers; therefore, the system eliminates these unsteady finger gestures by using average joint angles between the current frame and the previous frames.

The system also implements stabilization of the fingertips to estimate the interactive position of the finger. The method is the same as hand stabilization. When the trembling hand touches a target, the system implements fingertip stabilization; this integrates with key remapping and provides the results required by the user. The key remapping method was referred to in my previous research [50].

3.5 Experiment

I conducted simulation experiments to verify if the proposed system and methods successfully support trembling hand typing. In addition, the virtual:real intensity ratio of 1:0 or the video see-through setup would be the best for the proprioception of the virtual hand because there would be no double image. However, a completely virtual environment that hides the real world would eliminated hand typing on a physical keyboard. Therefore, the second purpose of the experiment is to determine the optimal virtual:real ratio using which the key typing performance is enhanced while the sense of ownership and other subjective issues are not significantly degraded.

3.5.1 Experimental Setup

I set up 12 experiments in different conditions, in which participants performed typing tasks on keyboards by using simulated trembling hands; the responded to the questionnaires given after each experiment.

Simulated Trembling hand

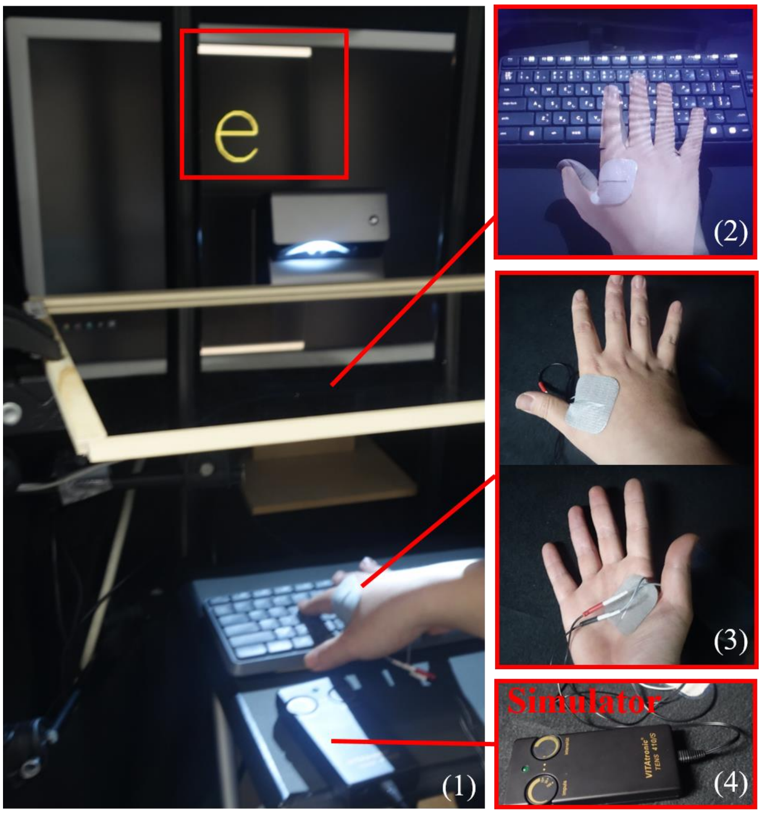


Figure 3.3 (1) Experiment setup: A participant performing a typing task with a simulated trembling hand, (2) the scene observed from the half mirror, (3) the position of the stimulator, and (4) stimulator.

As shown in Figure 3.3, the trembling hand was simulated using a simulator—a steplessly variable control unit (VITA tronic TENS 410/S) and electrodes. The electrodes were fixed on both the palm and the back of the participants' hand to control their hand by using electric muscle stimulation impulse. By manually adjusting the control unit to change the impulse intensities and frequencies, T1 and T2 hand tremors were simulated. The finger frequency was kept at 4 Hz to 7 Hz for simulating the T1 hand tremors and the finger amplitudes were dynamically changed to simulate the T2 hand tremors. The shaking amplitude was set above the half-key size.

Experimental Conditions

Two experiment parts were designed to study the two types of hand tremor with and without the system. Furthermore, "with the system" condition was subdivided into five conditions according to the different virtual:real intensity ratios. Therefore, 12 experimental conditions were designed and labeled in Table 3.1. Note that, the similar visual presentation—no stabilized virtual hand overlapping trembling hand was observed between C1 and C2 and between V1 and V2. However, C2 and V2 adopted the proposed system to support the typing task.

Table 3.1 The Labels of Experimental Condition

Tremor Feature	Without the system	With the system Virtual:real intensity ratio of the hand				
		0:1	0.25:0.75	0.5:0.5	0.75:0.25	1:0
T1	C1	C2	C3	C4	C5	C6
T2	V1	V2	V3	V4	V5	V6

Experiment Task Design

It is difficult for individuals having trembling hands to perform multiple finger interactions [24]. In the experiment, participants were required to perform keyboard-typing tasks with one trembling finger. A normal style keyboard with 18 mm × 18 mm standard key size was chosen. To quantify and compare the typing status in different conditions, I designed a program to guide the typing task (Figure 3.3 (1)). The program randomly displayed one character at a time on a vertical monitor, and the participant needed to type it. If the participant provided an incorrect inputs, an error notification will be sent to let him/her provide the input again. Simultaneously, the time wasted in error inputs and the times of the error inputs were recorded. When the participant completes a task, the experimental data including the entire spending time, error input time and error ratio in the task were automatically recorded in the program.

At the end of an experimental section, the participant answered a questionnaire on a 7-point Likert scale ranging from -3 (strongly disagree) to +3 (strongly agree). The questions refer to ownership (Q1, Q2), agency (Q2, Q3) to figure out the user's proprioception, and some pertinent evaluations (Q5, Q6, and Q7).

(Ownership)
Q1: I feel as if the virtual hand is part of my body.

Q2: I have illusions that the haptic perceptions come from the virtual hand.

(Agency)
Q3: Virtual hand moves just like I want it to.

Q4: I feel the virtual hand can be controlled to locate the required key.

(Pertinence)
Q5: I feel the hand is stable.

Q6: I feel the hand can be controlled to locate the required key.

Q7: I feel I can easily input the required key.

Experiment Procedure

Ten men in the age range of 20 years to 30 years having healthy hands completed the experiment in which 12 experimental conditions were randomly assigned to the experimental sections. The experimental procedure in an experimental section is illustrated in Figure 3.4. First, the participant reads and remembers questions. Second, the control unit of the tremor simulator that makes the participant's hand simulate the trembling is calibrated to meet the experimental requirement. Next, the hand tremor condition is further confirmed by the system measurement. Then, the participant performs the typing task where 30 letters are randomly generated. Finally, the participant answers the questionnaire and is given a rest to prepare for the next experimental condition until he/she finishes all the 12 conditions.

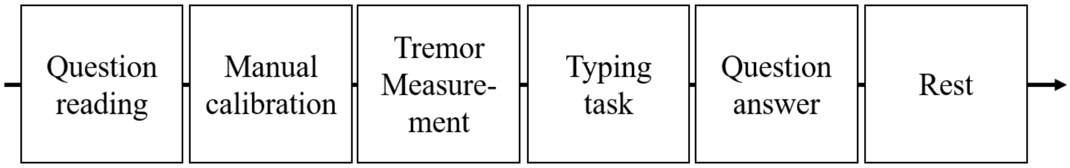


Figure 3.4 Experiment procedure.

3.5.2 Evaluation

Based on the generated data and questionnaires, I evaluate Group 1 (C1, C2, C3, C4, C5, and C6) and Group 2 (V1, V2, V3, V4, V5, and V6) based on time, error input ratio, ownership, agency, and pertinence.

Time reflects the performance of the trembling hand in an interactive task. The less time participants take on completing the task and on error inputs, the better performance they show. In Group 1, there was a statistically significant difference among groups as determined by the one-way analysis of variance (ANOVA) in the whole spending time ($p < 0.001$) and the error input time ($p < 0.001$). The Bonferroni pairwise comparisons of the C1 pairs (C1–C1 to C6) revealed that both the time taken to complete the task and the time wasted on error input were statistically significantly lower while typing with the system as compared with the condition without the system (all $p < 0.01$). There were no statistical differences between the C2 to C5 pairs. Group 2 also had similar results (

Figure 3.5). Thus, the system has been proven to be useful for improving the typing task performance for both types of trembling hands. The proportion of the error input time in the whole spending time is further computed in each condition (Group 1: C1 69%, C2 28%, C3 11%, C4 11%, C5 7%, and C6 11%; Group 2: V1 62%, V2 23%, V3 16%, V4 13%, V5 11%, and V6 12%). It can be concluded that the system assists the trembling hand to finish the typing tasks in less time by greatly reducing the error input time.

Error Ratio reflects whether the trembling hand can accurately type the desired key. A one-way ANOVA was conducted to compare the error ratio of Group 1 and Group 2 under six conditions. There was a significant effect of the system on prompting the error ratio at the $p < 0.001$ level for Group1 and Group2 (Figure 3.6). Post-hoc Bonferroni comparisons indicated that the results obtained with system conditions were significantly different from the results obtained without system conditions. However, both C2 to C5 and V2 to V5 conditions did not significantly differ from one another. These results show that the system does have an effect on reducing the error input for trembling hand.

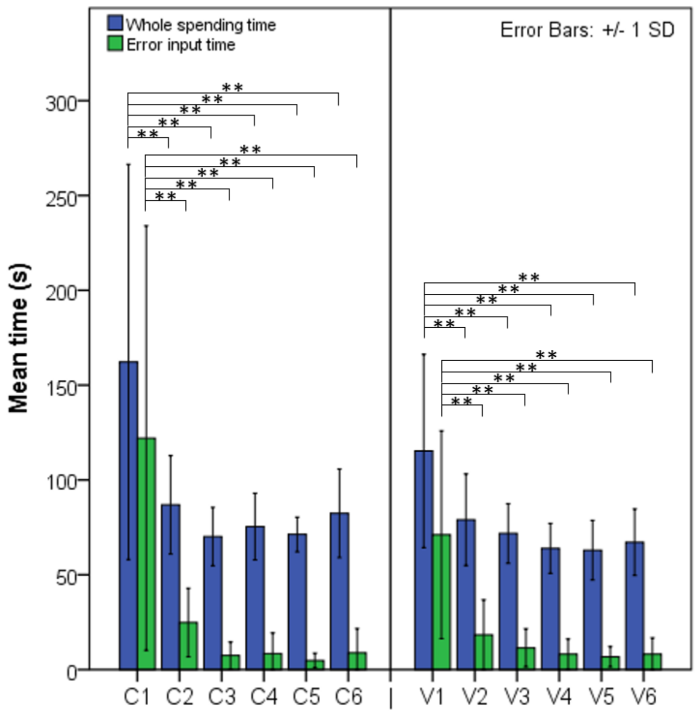


*Figure 3.5 Mean spending time and error input time (** p < 0.01, * p < 0.5).*

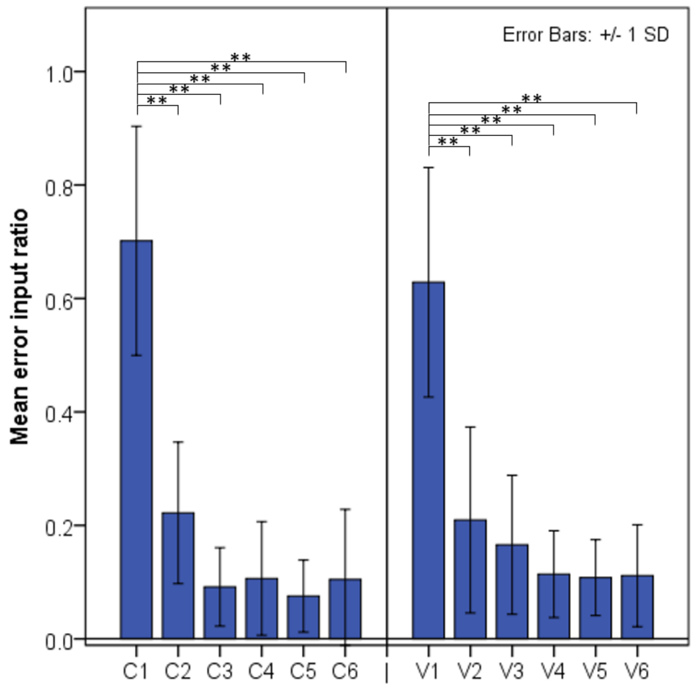


*Figure 3.6 Mean error input ratio (** p < 0.01, * p < 0.5).*

Questions referring to Ownership and Agency in the questionnaire investigate whether they perceive the virtual hand as part of their own body. The analysis was conducted in Group 1 (C3, C4, C5, and C6) and in Group 2 (V3, V4, V5, and V6) because the virtual hand is visible under these conditions.

Ownership. A one-way ANOVA was calculated on the participants' answers to Q1 in these above eight conditions and the analysis was found to be significant ($p < 0.001$) in both groups. The pairwise comparisons with the Bonferroni test showed a statistically significant difference in the pairs of C3–C5 ($p < 0.01$), C3–C6 ($p < 0.001$), C4–C6 ($p < 0.01$), V3–V5 ($p < 0.01$), V3–V6 ($p < 0.01$), and V4–V6 ($p < 0.05$) (Figure 3.7 (Q1)). The results showed that the high intensity of the virtual hand makes it easier to perceive the virtual hand as part of the body. There is no statistically significant difference in the intensity ratios of C5–C6, V5–V6. The same method was used to analyze Q2, and the pairs of C3–C5, C3–C6, C4–C6, V3–V5, and V3–V6 exhibited statistically significant differences ($p < 0.01$). Note that, comparing the result of the pair C4–C6 in Group 1, the pair V4-V6 did not show any statistical difference (Figure 3.7 (Q2)). Therefore, a higher intensity proportion of the virtual hand contributes to creating the illusion that the haptic perception is from the virtual hand. Taken together, regardless of the type of hand tremor, a higher intensity proportion of the virtual hand enhances the perception of ownership.

Agency. Figure 3.7 (Q3) illustrates the analysis results of the one-way ANOVA for Q3. There was a significant difference in the pairs C3–C5, C3–C6, and V3–V5, all having $p < 0.05$. Figure 3.7 (Q4) shows the analysis results on Q4. There was no significant difference in both groups. The virtual:real intensity ratio of 0.75:0.25 is the most effective condition for making the user feel that the virtual hand was controlled intentionally, regardless of the tremor conditions.

Pertinence (Stable Hand Illusion). Twelve conditions were classified in the two categories “with stabilized virtual hand” (C3, C4, C5, C6, V3, V4, V5, and V6) and “without virtual hand” (C1, C2, V1, and V2). A one-way ANOVA was computed on Q5 analysis, and it showed significant differences among these conditions in each group ($p < 0.001$) (Figure 3.7 (Q5)). Bonferroni pairwise comparisons indicated that the stable hand illusion was significantly stronger in the condition with the virtual hand than without the virtual hand. This means that the trembling hand mixed with the stabilized virtual hand makes the user feel as if his/her hand is stable. In addition, there was a significant difference in the pairs C3–C4, C3–C5, and C3–C6. Therefore, it should be noted that the intensity ratio of the virtual hand must be higher than that of the real hand to create a more stable hand illusion.

Pertinence (Typing Support). Based on the Q5 results above, the conditions C2 and C3 of Group 1 and V2 and V3 of Group 2 were not taken into account in the Q6 analysis. Therefore, the rest of the eight conditions were classified as the condition with the system (C4, C5, C6, V4, V5, and V6) and the condition without the system (C1 and V1). There were significant differences among the conditions in each group (Figure 3.7 (Q6)). Therefore, the system effectively supports the trembling hand to locate the target. The Q7 analysis of the one-way ANOVA also showed a significant difference ($p < 0.001$). Through the Bonferroni pairwise comparisons, significant differences were found in each pair of C1 and V1 (all having $p < 0.001$) and the pair of V2–V5 in Group2 ($p < 0.05$). This means that the proposed system is effective to make the typing input easier for trembling hand. In a word, the results above prove that the proposed system performance effectively supports the trembling hand and helps locate the desired key with less difficulty during typing.

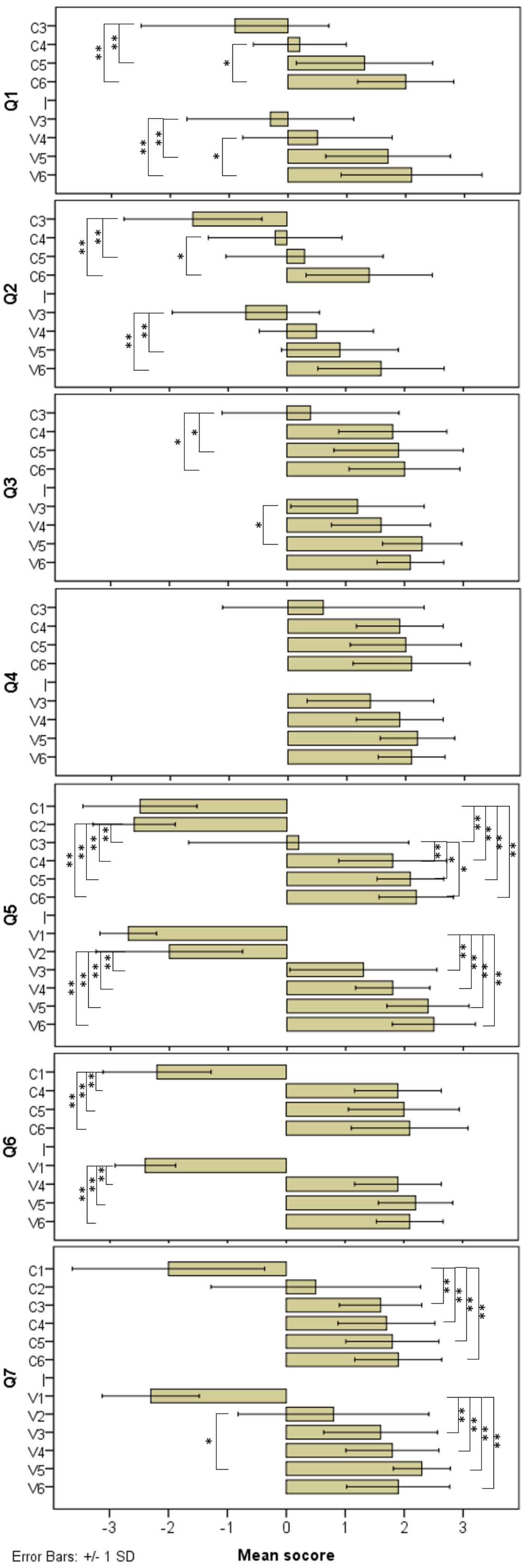


*Figure 3.7 The mean score of the questionnaire (** p < 0.01, * p < 0.5).*

3.5.3 Discussion

This study proposed an optical see-through AR system that enables hand tremor sufferers to type steadily on the keyboard using a self-consciously augmented hand. The two types of hand tremors are discussed and simulated in the typing tasks under 12 experimental conditions (including without the system and with the system in different intensity ratios of the virtual hand and real hand). The analysis of the time and the error input ratio demonstrates the system performance on typing support, and the psychological investigations further confirm a better virtual:real intensity ratio for promoting the proprioception of the mixed hand.

Comparing all conditions on the mean of the whole spending time on tasks, mean of error input time and error input ratio, the trembling hand with the virtual:real intensity ratio of 0.75:0.25 in the system provides best performance. The investigations of the ownership and the agency show that the intensity ratios of 0.75:0.25 and 1:0 are not significantly different, and they are appropriate for promoting the virtual hand as part of the body. An analysis of stable hand illusion shows that the virtual hand intensity is better to greater than the real hand intensity. The questionnaire about the users' subjective feelings of typing support also proves that trembling hand types the desired key more easily with the proposed system creating the mixed reality of the trembling hand, especially the virtual:real intensity ratio of 0.75:0.25 in the system.

In conclusion, for the purpose of the research, i.e. Supporting hand tremor individual type physical keyboard with steady hand, the virtual:real intensity ratio of 0.75:0.25 shows the best improvement in both the system performance and the proprioception of the virtual hand. Therefore, I suggest the use of this ratio in the AR system to support the trembling hands while typing.

Compared with the related researches on the proprioception of the fake hand, the research studies the proprioception in different virtual:real intensity ratios. In addition, compared with the related research for supporting trembling hand typing, our research is novel because it allows hand tremor sufferers to use a stabilized virtual hand to access targets accurately and efficiently.

However, I have to point out the simulated experiments did not consider the influence of the upper limb tremor because of the limitations of the simulation equipment.

3.6 Conclusion

In this study, I developed an optical see-through AR system to augment the visual stabilization of trembling hand while typing on the keyboard. The proposed system automatically analyzes and identifies the tremor type and implements specific stabilization to estimate stable hand position. Then, it aligns and overlaps the stabilized virtual hand to the real trembling hand during the typing process. The experimental results verified that the system successfully supports trembling hand typing. This research also shows that the system with virtual:real hand intensity ratio of 0.75:0.25 shows the best performance by comprehensively investigating the aspects of time, error ratio, ownership, agency, and pertinence. In the future, I will continue to improve the system performance to resolve accessibility problems related to other interfaces for people with trembling hands.

CHAPTER 4

Expending Reachable Range of Trembling Hands Using Stabilized Projection Augmented Hand

In this chapter, I proposed an approach of stabilizing virtual hand tremor that allows individual with hand tremors steadily control projection extended hand to commutate unreachable objects. The approach includes movement stabilization and gesture stabilization. And, I introduce a simulation method by which trembling hands interacting with the EH system were repeatedly simulated over participants. Finally, I investigate the effectiveness of proposed methods by a series of pointing and grasping experiments.

4.1 Introduction and Motivation

Tremors, which refers the trembling or shaking of body parts, are caused by the involuntary contractions of muscles and are one of the most common movement disorders that reduce the levels of the body's functions. Accordingly, individuals with tremors always experience difficulties, sometime dangers in which moving their swinging body [50], thereby their hand reaching area is limited in daily activities.

Ueda et al. introduced a touch panel based body cyberization technology, called "Extended Hand (EH)," which virtually extends the length of a user's arm by a projection-mapping technology to allow the user to manipulate unreachable objects [35]. The technology has been demonstrated for various applications, for instance, a user turning a room light on/off or controlling a cleaning robot to clean up a specified area on the floor. Since the technology virtually extends the reachable range of hands and reduces the need for body movements, it has the potential to enhance the physical activities of individuals who having movement disorders.

Although EH has advanced from its foundation [59] to applications [35], it has not yet benefited individuals with tremor. To use EH, a user must touch and move one hand across the screen on a touch panel to control the movements and gesture of EH. However, touching the panel with trembling hands causes EH to shake. Therefore, this chapter proposes methods to help individuals with tremors to use EH. In particular, I stabilized EH's movements using Kalman and Hysteresis filters; and stabilized EH's gestures by (a) stabilization of distances from the fingertips to their centroid, (b) analysis of the change in low frequency components of the touching area, and (c) combination of (a) and (b). I focus on using these methods to support hands with essential and intentional tremors whose features have been introduced in chapter 2, and built a system that simulates hands that exhibit these two types of tremors when interacting with EH. I compared EH with and without the proposed methods by a series of pointing and grasping experiments, and evaluated the effectiveness of proposed methods.

To summarize, this chapter makes the following contributions:

- I propose one method to stabilizes EH's movements and three methods to stabilize its gestures to make the EH technology available for individuals with tremors.
- I investigate the effectiveness of the proposed methods through experiments with a hand tremor simulator that I developed to imitate two types of trembling hands interacting with EH.

4.2 Related Work

In EH, a user virtually controls a projected hand as if it is an extension of user's hand. The technology helps people to communicate with others and to interact with distant physical objects [23]. Okahara et al. introduced camera-projector based EH system and proved that the EH graphically connected to the real hand provided a high degree of usability on body augment by investigating the self-ownership and agency of EH [60]. Considering the widespread use of smartphones and tablets, some operational methods have been proposed to allow EH to be controlled by a touch panel [59]. Ueda et al. built various EH applications for home appliances and human to human communication [35]. Asai et al. attached a tablet and projector to a wheelchair to help wheelchair-bound users communicate with other people by gesturing with EH when talking about a distant object [36]. Despite such advances, EH has not yet benefited individuals with tremors, as the design of the technology presumes a user with steady hands; therefore, I aim to improve EH such that it can be used by such individuals.

As it is difficult for individuals with hand tremors to directly touch the panels, some special interfaces have been proposed to reduce the difficulties. Wacharamanotham et al. found that swabbing generally reduced finger oscillations and improved the error rate [61], and then designed a web browser operated by swabbing [62]. Zhong et al. enhanced the touching area of a smartphone through a descriptive target list mode [18]. However, these special interfaces are only effective with browsers. There are also technologies that support trembling hand to touch the panels by filtering "noises" that are the arbitrary touches of trembling hand. Plaumann et al. implemented a mass-spring-damper model based algorithm for both smartphone and finger sensor to stabilize typing positions [20]. Mott et al. proposed a template-matching method that can map a user's arbitrary touching areas to an intended single point [21]. However, these methods were not applied in an AR field to stabilize a virtual object in the physical world. My previous researches virtually stabilized trembling hand to help directly typing the desired keys on ordinary physical keyboards [50], and proposed a further method by mixing a trembling hand with a stabilized virtual hand to create a realistic typing sensation without hand tremors [63]. However, these methods were not suited to EH system. Therefore, this study explored methods that allowed people with hand tremors to use EH comfortably.

4.3 Method

"Extended Hand"

As illustrated in Figure 4.1, EH is a projection-based augmented realty technology, which allows a user control a visually extended hand to communicate the distant objects using a touch panel. EH graphically includes a realistic hand and an extended arm presented by projection. The projected hand exists two or three rigid parts in fingers connected by joints. Thus, the hand can open and close the fingers. The projected arm is extended only toward the direction of a user's hand. The size of the projected hand and projected arm can be adjusted as the actual needs of interaction.

According to the 2D translation of a user's hand centroid on a touch panel, the projected hand moves with a magnified translation distance, while the projected arm extends its length in the same direction. I define that the processing step of EH system is 0 when user's fingers touch the panel. Suppose the detected fingertip positions $f^i(k)$ (i indexes fingers, 1: thumb, …, 5: little finger) and their centroid $p(k)$ in the

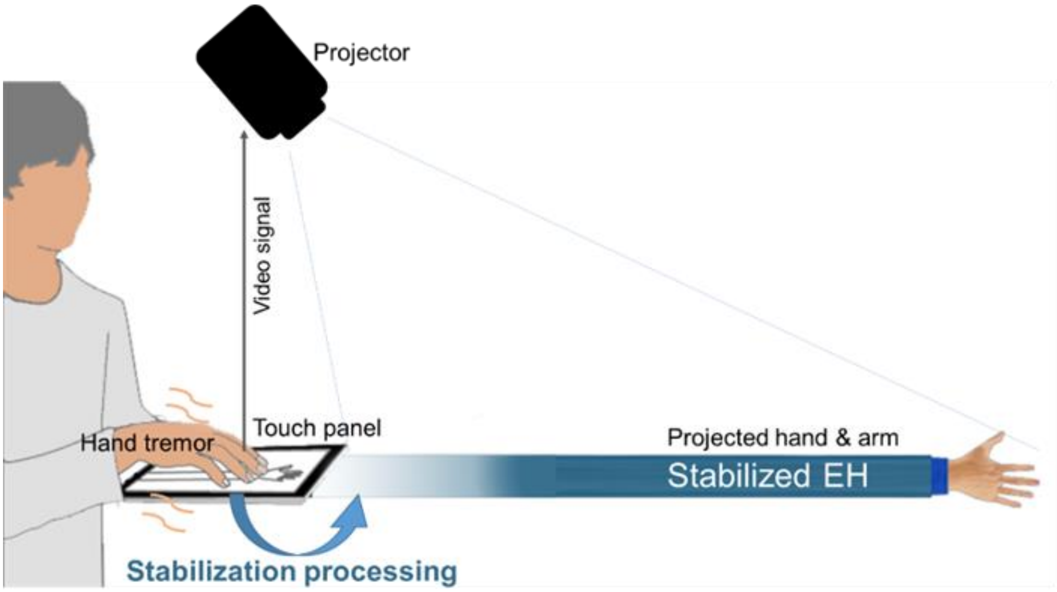


Figure 4.1 Stabilization of the EH for hand tremors.

current step k. The translation of EH is computed as Equation 4.1. The translation direction of EH directs the same direction of the user's middle finger from the centroid and is computed by $f^3(k) - p(k)$.

- The translation distance $T(k)$ in the current step k is computed as follows:

$$T(k) = (p(k) - p(0)) * \alpha + p(0) \quad 4.1$$

where, $p(k)$ and $p(0)$ are the centroid of the measured fingertip positions in the current step k and the initial step 0, respectively. α is an amplification factor, which can be adjusted according to the actual interactive distance of EH.

When multiple fingers touch the panel, each finger state of EH (i.e. open or closed) in the current step k is decided based on the ratio D^i of the current distance d^i between the fingertip and the centroid to the initial distance d^i_{init} () and a threshold. Thus, when the ratio D^i is lower (higher) than the threshold, the EH finger i is closed (open). When one finger state changes (from open to closed) and the other finger states are closed, EH presents a clicking gesture; and when multiple finger states synchronously close, EH presents a grasp gesture. Without loss of generality, in the following explanation of gesture stabilization algorithm, I assume that multiple fingers touch the panel.

- The ratio D^i in the current step is computed as follows:

$$D^i = \frac{d^i}{d^i_{init}} = \frac{f^i(k) - p(k)}{f^i(0) - p(0)} \qquad 4.2$$

Because a user's actual hand touches on touch panel are amplified to act on EH, any unsteadiness or trembling in the user's hand would cause the EH to shake, tremble, or twitch. Therefore, I improved the movements and gestures stabilizations in EH system to facilitate its use by individuals with hand tremors (Figure 4.1).

4.3.1 Movement Stabilization of EH

I proposed a movement stabilization method to suppress the unintentional shakes of EH as well as to amplify its intentioned movement. From the positions of the user's fingers on touch panel $f^i(k)$, a raw centroid is determined. Then, from the raw centroid position $p(k)$ and pervious decided centroid position $P(k-1)$, a stabilized centroid position $\bar{p}(k)$ is calculated by Kalman filter. Then, the stabilized centroid position is assessed by Hysteresis (Equation 4.3) to eliminate the delay while larger EH translation. Therefore, as shown in Figure 4.2, the stabilized centroid $\bar{p}(k)$ is finally accepted if the distance between the stabilized centroid $\bar{p}(k)$ and pervious decided centroid $P(k-1)$ is lower than a predefined threshed, otherwise, the raw centroid $p(k)$ is used.

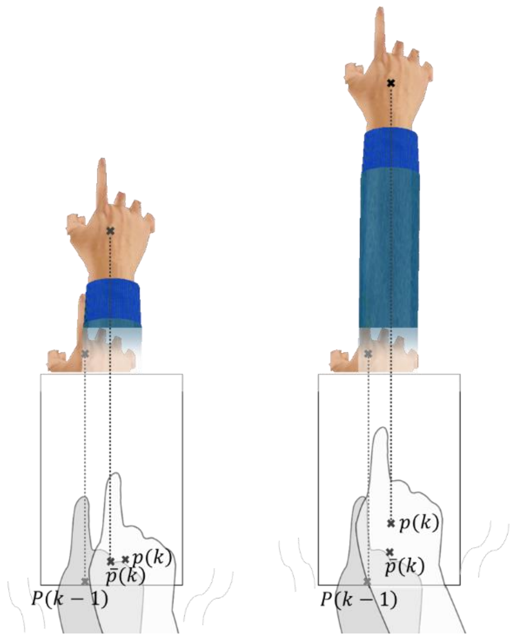


Figure 4.2 Hysteresis: (a) the final stabilized centroid position is decided by the stabilized centroid $\bar{p}(k)$*, and (b) the final stabilized centroid position uses the raw centroid* $p(k)$ *through Hysteresis.*

$$P(k) = \begin{cases} \bar{p}(k) & |\bar{p}(k) - P(k-1)| \le S \\ p(k) & otherwise \end{cases}, \qquad 4.3$$

where, $P(k)$, $p(k)$, and $\bar{p}(k)$ are the decided centroid, the raw centroid, and the stabilized centroid in the current step k, respectively, $P(k-1)$ is the finally decided centroid in the previous step $k-1$, and S is the predefined threshold.

Finally, the stabilized translation of EH is computed as Equation 4.1 by using the stabilized centroid $P(k)$.

4.3.2 Gesture Stabilization of EH

The distances between the fingers and the hand centroid change randomly due to finger tremor (Figure 4.3), thereby the ratios become arbitrary and result that the EH gestures are unsteady and uncontrolled. Therefore, I stabilize EH gestures: (a) stabilization of distances from the fingertips to the centroid, (b) analysis of the change in low frequency components of the touching area, and (c) combination of (a) and (b).

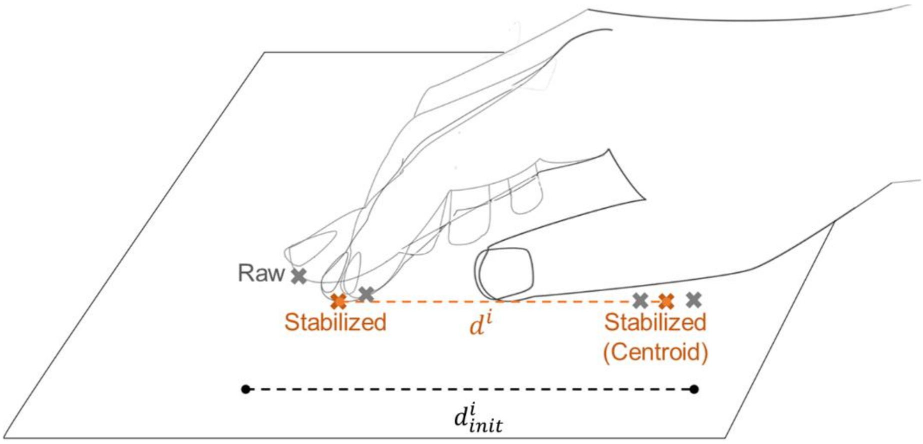


Figure 4.3 Distance between (stabilized) fingertip and (stabilized) centroid.

"Distance stabilization"

I stabilized both the detected fingertip positions and the centroid by using a Kalman filter and computed the stabilized distances from the stabilized fingertips to the stabilized centroid (Figure 4.3), and the ratios by Equation 4.2. Lower and higher thresholds are predefined for each user's fingers to determine whether the corresponding EH finger should close or open. As described in Equation 4.4, in the current step, an EH finger closes (opens) when the EH finger was open (closed) in the previous step and the ratio D^i was lower (higher) than the lower (higher) threshold. The state of a finger remained unchanged when the ratio D^i was within both thresholds. The method not only stabilized the EH's finger states but also reduced the noise produced by the distance stabilization.

$$State^i(k)=\begin{cases} close, & D^i < L^i \ \& \ State^i(k-1)=open \\ State^i(k-1), & L^i \le D^i \le H^i \\ open, & D^i > H^i \ \& \ State^i(k-1)=close \end{cases}, \quad 4.4$$

where, $State^i(k)$ and $State^i(k-1)$ are the current and previous states (open or closed) of finger i, D^i is the distance from stabilized fingertip to stabilized centroid, while L^i and H^i are the predefined lower and higher thresholds of finger i, respectively.

"Touching area analysis"

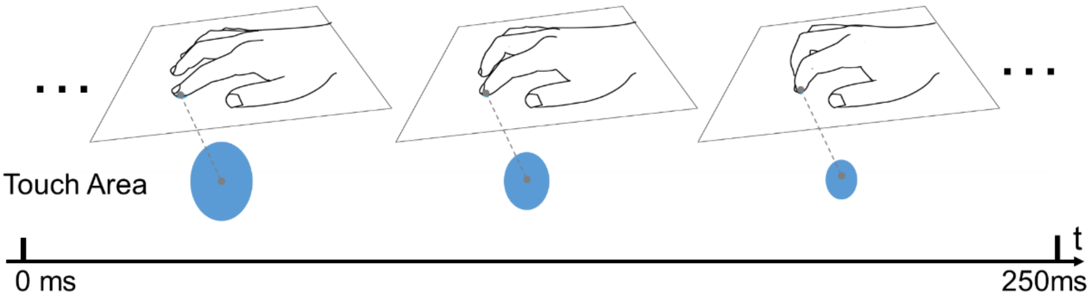


Figure 4.4 Touch area measurement.

Unlike the steady touches of a user's hand on the touch panel, a trembling hand causes the finger touching areas to change quickly. Thus, I can distinguish steady hand touches from trembling hand touches by analyzing the changes in the low frequency components of touching area. As Figure 4.4 shows, I measured and sampled finger touch areas and implemented a Short-Time Fourier Transform (STFT) at every 250ms (The time guaranteed the sampling and accuracy). I segmented out the components between 0 Hz and 1.5 Hz, because hand tremors generally have a frequency higher than 2 Hz, while intentional finger movements are usually lower. The segmented range can be observed greater power from intentional finger movements but less power from tremors. Then, I compared the difference between the previous and current low-frequency components. As described in 4.5, when the difference exceeds than the predefined threshold, the EH finger will bend if its pervious state was open, but straighten if it was closed.

$$State^i(k) = \begin{cases} close, & D^i > S \; \& \; State^i(k-1) = open \\ open, & D^i > S \; \& \; State^i(k-1) = close \\ State^i(k-1), & D^i \le S \end{cases} , \tag{4.5}$$

where, $State^i(k)$ and $State^i(k-1)$ are the current and previous states (open or closed) of finger i, D^i is the difference between the previous and current powers which are between 0 Hz and 1.5 Hz, and S is a predefined threshold that distinguishes the significant change in the frequency component.

"Combination"

I combined the methods of distance stabilization and analysis of changes in touching area to stabilize EH's gestures, described as follows:

$$State^i(k) = \begin{cases} close, & State_a^i(k) = close \,|\, State_b^i(k) = close \\ open, & State_a^i(k) = open \; \& \; State_b^i(k) = open \\ State^i(k-1), & otherwise \end{cases} , \tag{4.6}$$

where, $State^i(k)$ and $State^i(k-1)$ are the current and previous states (open or closed) of finger i, $State_a^i(k)$ is the finger state estimated by "distance stabilization", and $State_b^i(k)$ is the finger state estimated by "touching area analysis". The finger state is closed if $State_a^i(k)$ or $State_b^i(k)$ is closed, in which case EH bends the finger, but straightens it when both variables are open.

4.4 Experiment

I conducted experiments to verify if the proposed stabilization methods can help trembling hands to use the EH without shaking it. Specifically, I arranged experiments in which the participants touched a touch panel that was vibrated at a designated shaking frequency and amplitude. Both with and without the proposed methods' being applied, the participants controlled the EH to point or grasp balls projected in physical world. I evaluated the methods based on the objective and subjective data gathered from the pointing and grasping experiments.

4.4.1 Experimental Setup

Hand tremor simulation

Controlling the properties of participant's tremor is difficult, so I were inspired by [65] to build a system to easily simulate trembling hands interacting with an EH system by shaking a touch panel while being touched by the participant with a steady hand (Figure 4.5). This technique obtained the same results as a person with hand tremors touching a stationary panel.

Two vibration machines (ALINCO FAV3017 and THRIVE FD061) were employed to shaken a panel (Microsoft Surface Pro 4) (Figure 4.5). Before the experiments, we calibrated the shaking movements of the panel that is shaken by the vibration machines to ensure that the simulations of the desired tremor were accurate (Figure 4.6). Finally, the touch panel was shaken by a vibration machine, ALINCO, with a shaking frequency of 4 Hz and an amplitude of 10 mm to simulate a hand with essential tremor

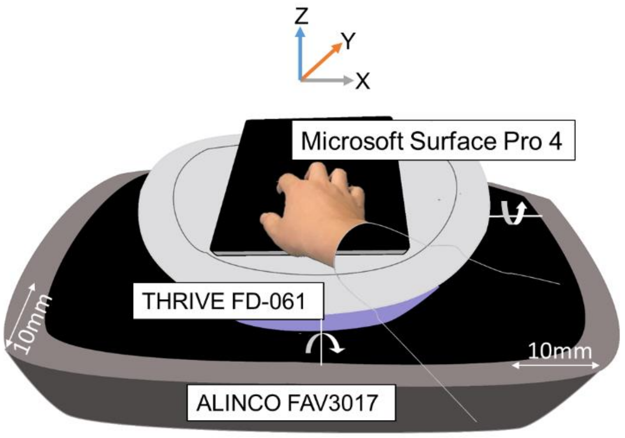
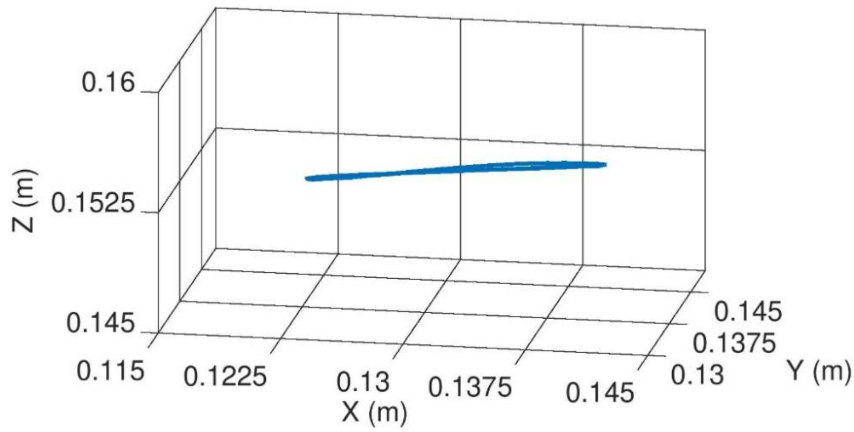


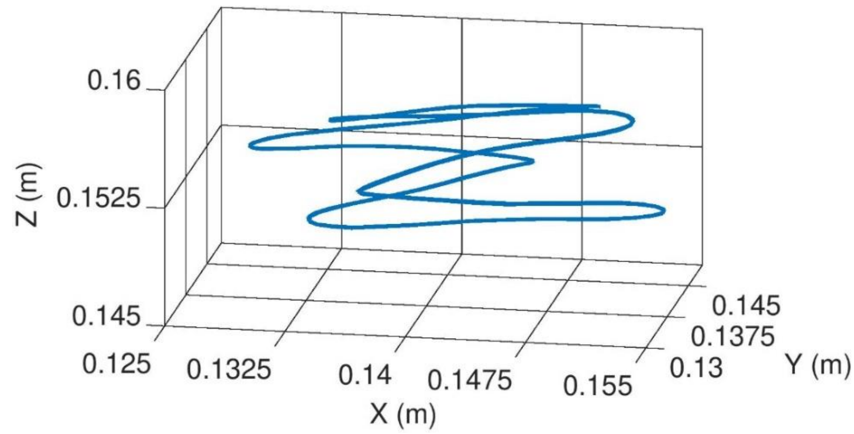
Figure 4.5 Simulator: It allows that the participant with a steady hand touching a specially shaken panel to simulate trembling hands interacting with the EH. The panel is mounted on THRIVE, which is in turn mounted on ALINCO. To simulate essential tremors, only ALINCO vibrates, while for intentional tremors, both machines vibrate.

Figure 4.6 Using the OptiTrack to track the five markers attached on the panel, we examined the shaking movements of the panel to ensure that the simulations of essential tremor and intentional tremor were accurate.

which is featured with fixed shaking frequency and amplitude; and the panel was shaken by ALINCO and THRIVE, in which the former one is set to 3 Hz and 2D movement, while the latter one is set to 1.5 Hz and 3D movement to simulate an intentional tremor which is featured with lower frequency and varying amplitude (Figure 4.7). In addition, friction between the fingers and the screen can easily change if the fingers are sweaty or oily, thereby affecting the simulation. Hence, the participants were required to wear the conductive gloves of the age simulation suit, GERT ([64]).



(a)

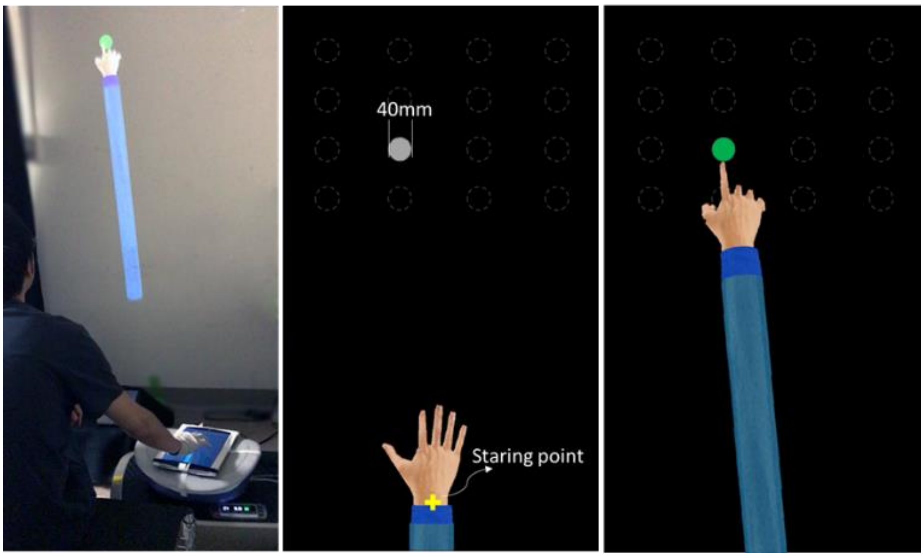


(b)

Figure 4.7 Shaking of touch panel tracked by OptiTrack: (a) and (b) show the xyz-coordinate directional shaking trajectories within a 2-s time frame, and respectively imitate essential and intentional tremors.

Design of the pointing experiment

In the pointing experiment, participants controlled EH with and without movement stabilization to point to the projected balls in physical world (Figure 4.8 (a)). Twelve participants interacted with a touch panel (Microsoft Surface Pro 4) that was shaken. In each experimental section, a total of 16 ball images were generated randomly at specified positions. Each ball first appeared gray and then turned green for 3s — this is called the "pointing time" — when the fingers of EH came close, and then disappeared. The radius of each ball's image was 20 mm. As the participants were manipulating EH to reach distant targets, the radius ensured that the balls could be seen clearly from five meters away. To point to a ball, a participant translated EH from the starting position prompted by a cursor, made EH keep touching the ball as long as possible while the ball was green, and then translated EH back to the starting position (Figure 4.8 (b, c)).



(a) *(b)* *(c)*

Figure 4.8 (a) Scenes of pointing experiment: a participant with the simulated trembling hand is controlling EH to point a projected image of a ball, (b) A ball is generated *in a specified position with gray color and EH is at the starting position prompted by a cursor, and (c) EH is extended and points to a ball, which turns green for 3 s.*

After each task, the following data were automatically recorded for further assessment of the movement states of EH.

- *Translation distance*: the length of trajectory of EH between the starting position of EH and the position of a ball.
- *Shaking distance*: the distance traveled by EH while it was shaking during the "pointing time."
- *The time of EH keeping pointing*: the whole time EH's fingers touched the balls during the "pointing time."

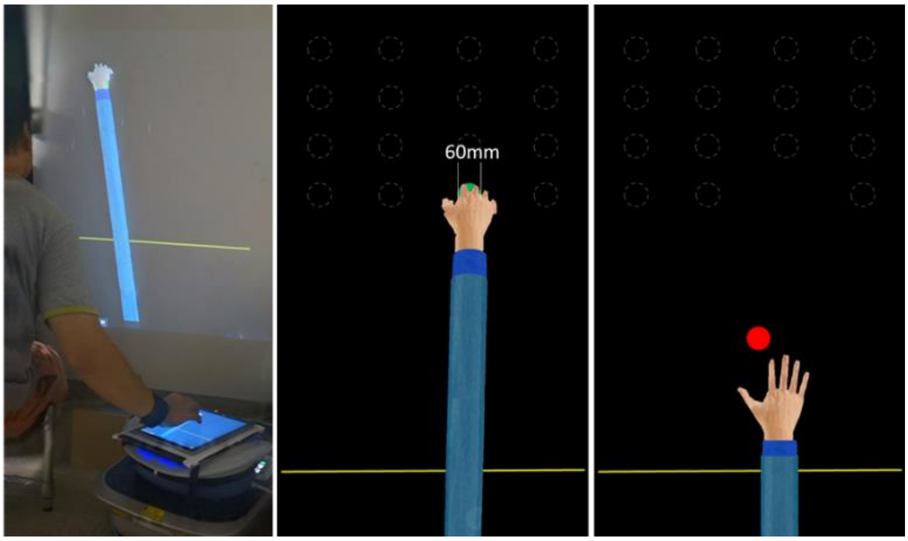
After each experiment, the participant psychologically evaluated EH by answering a questionnaire based on a seven-point Likert scale ranging from -3 (strongly disagree) to +3 (strongly agree).

Q1: I feel that the EH is stable when pointing to the balls.

Q2: I feel that I can keep EH pointing within the ball.

Design of the grasping experiment

In the grasping experiment, participants dragged the balls across a yellow line by controlling EH without gesture stabilization and with proposed stabilization by (a) “distance stabilization”, (b) “touching area analysis”, and (c) the combination of (a) and (b) (Figure 4.9 (a)). Ten participants tested EH with and without gesture stabilizations by interacting with the touch panel as it was being shaken. In each grasping experiment, 16 balls were generated in random order. Each ball appeared with a gray color, and then turned green when approached by EH with fingers bent or turned red when EH had its fingers open while dragging the ball, signifying that the ball had been dropped (Figure 4.9(b, c)). The radius of each ball was 30 mm, almost the same as the width of EH's palm.



(a) *(b)* *(c)*

Figure 4.9 (a) Scenes of grasping experiment: a participant with the simulated trembling hand is controlling EH to drag projected image of a ball, (b) EH grasps a ball, and (c) When EH's fingers are open, the ball turns red to indicate that it has been dropped.

To grasp a ball, each participant translated EH to cover the gray ball, and closed the fingers to grasp and drag it under the yellow line. If a ball was dropped, the participant was required to pick it back up. The number of times of ball falling and the average time expended completing a grasping task were automatically recorded to assess the gesture state of EH. After each experiment, the participant was required to evaluate the system.

Q3: I feel that EH does not drop the ball easily.

Q4: I feel that I can easily control EH to grasp the ball.

Experimental conditions

To verify the effectiveness of the proposal, I used vibration machine to simulate EH interacted by essential and intentional tremors and compared the preformation without and with stabilizations through a series of pointing and grasping experiments. I label the experimental conditions to clearly see the differences (Table 4.1).

Table 4.1 The labels of experimental condition

Hand / EH	Essential Tremor	Intentional Tremor
Without Movement Stabilization	**M+E**	**M+I**
With Movement Stabilization	**MS+E**	**MS+I**
Without Gesture Stabilization	**G+E**	**G+I**
With Gesture Stabilization: (a) " distance stabilization"	**GS(a)+E**	**GS(a)+I**
With Gesture Stabilization: (b) "touching area analysis"	**GS(b)+E**	**GS(b)+I**
With Gesture Stabilization: (c) the combination of (a) and (b)	**GS(c)+E**	**GS(c).+I**

4.4.2 Results

I verified that the proposed methods were effective in supporting the two types of hand tremors, based on the generated data and psychological evaluations from the series of pointing and grasping experiments. Specifically, for evaluating the proposed movement stabilization, I compared the average translation and shaking distances, the average time ratios of EH pointing within the balls, and the answers to the questions about M+E & MS+E and M+I & MS+I. To confirm the optimal gesture stabilization method, I compared average number of times of ball falling, the average spending time of grasping a ball, and answers to the subjective questions about G+E, GS(a)+E, GS(b)+E, & GS(c)+E and G+I, GS(a)+I, GS(b)+I, & GS(c)+I.

Results of pointing experiment

As the balls are generated in specified positions, the translation distance of a stable EH is fixed. Thus, I compared the differences in the actual translation distance of EH between the experimental conditions to estimate the degree of shaking. An Independent Samples T-test was conducted for both M+E & MS+E and M+I & MS+I. Both conditions showed statistically significant differences with $p < 0.01$. The translation distance of EH under stabilization was less than that under no stabilization (Figure 4.10). Therefore, the results proved that the proposed movement stabilization effectively reduced the unsteady translation of EH when affected by the two types of tremors.

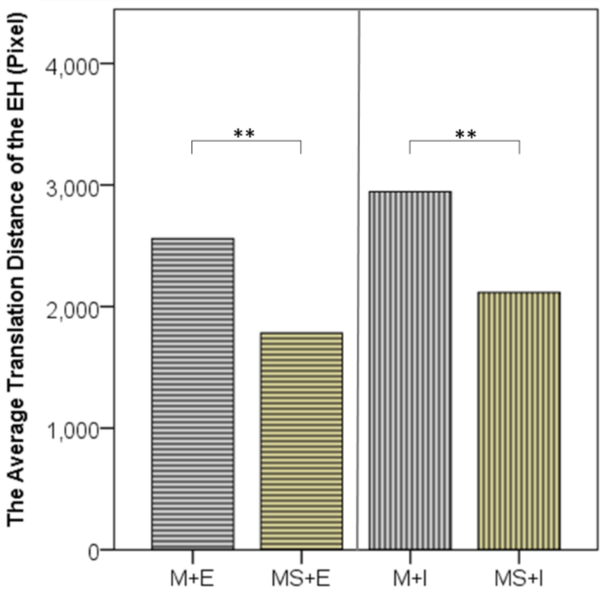


*Figure 4.10 Average translation distance of EH (** p <0.01).*

The shaking distance describes the unstable state of EH while the user wants to steady EH when it is approaching a target. There were significant differences at $p < 0.01$ between M+E and MS+E, as well as between M+I and MS+I, as determined by the T-test. As shown in Figure 4.11, the shaking distance of EH with the proposed stabilization was significantly less than that of EH without stabilization. Therefore, the proposed methods could reduce the effects of hand tremors and ensure that EH stayed in one place.

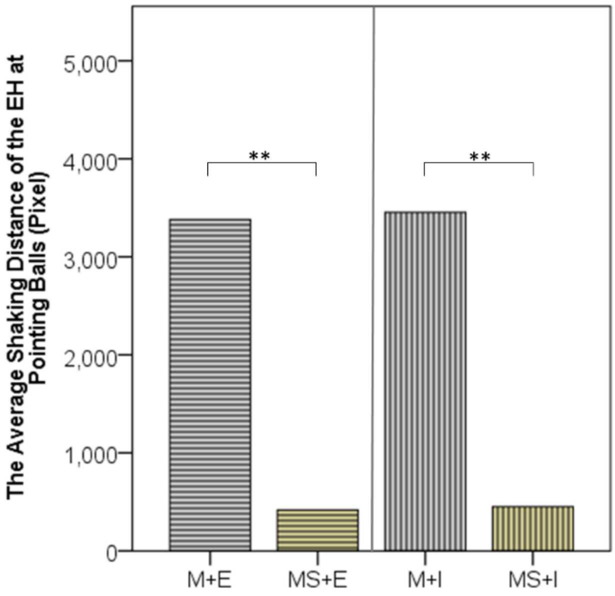


*Figure 4.11 Average shaking distance of EH at pointing the balls (** p <0.01).*

The time ratio of EH pointing within the balls reflects the degree of EH stability when it is being controlled. The time ratio is the length of the time of EH's pointing within the ball and the whole length of time of pointing. An Independent Samples T-test was found to have significant differences at $p < 0.01$ between M+E and MS+E, as well as between M+I and MS+I. As shown in Figure 4.12, EH with stabilization achieved higher ratios than that without it. Thus, the proposed methods could steady the EH control for the two types of hand tremors.

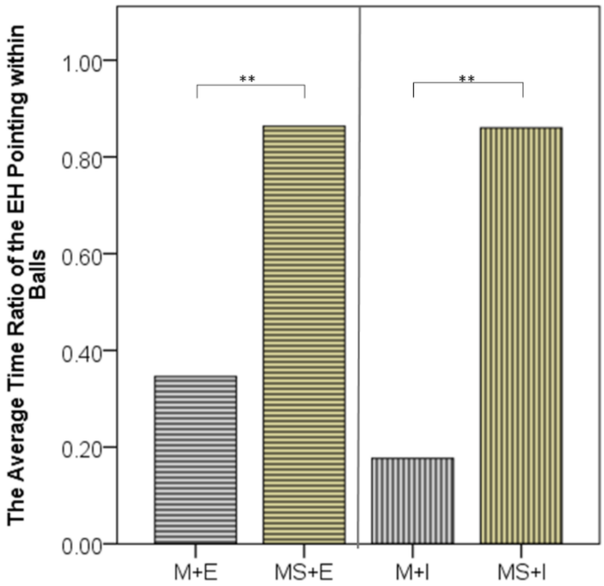


*Figure 4.12 Average time ratio of EH pointing within the ball (** p <0.01).*

The proposed methods were further examined by the psychological evaluations of participants. An Independent Samples T-test was conducted on the answers to Q1 and Q2 for M+E & MS+E and M+I & MS+I respectively. All pairs were found to have significant differences at $p < 0.01$ (Figure 4.13). These results showed that the participants felt that they could steadily control EH during translation or while stationary.

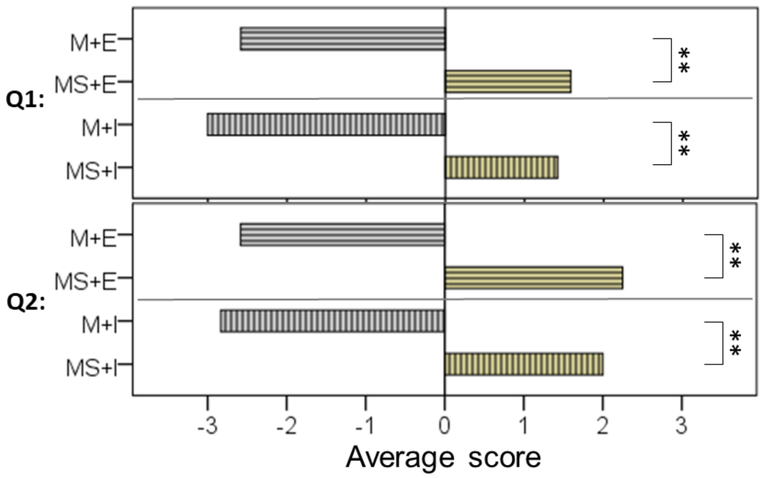


*Figure 4.13 Average score of the psychological evaluations. The seven-point Likert scale ranges from -3 (strongly disagree) to +3 (strongly agree) (** p <0.01).*

Grasping experimental results

The number of times of ball falling can reflects the stability of EH's gesture. If EH exhibits unsteady fingers while being close or open, the number of times of ball falling is high. I compared the differences for Group 1 under G+E, GS(a)+E, GS(b)+E, and GS(c)+E and for Group 2 under G+I, GS(a)+I, GS(b)+I, and GS(c)+I to examine whether the proposed methods diminished the effects of hand tremors on the stability of EH's gestures. A one-way analysis of variance (ANOVA) found significance for both groups at $p < 0.01$. The pairwise comparisons with the Bonferroni test showed a statistically significant difference in the pairs of G+E & GS(a)+E ($p < 0.01$), G+E & GS(c)+E ($p < 0.01$), GS(b)+E & GS(a)+E ($p < 0.05$), and GS(b)+E & GS(c)+E ($p < 0.05$) as well as the pairs of G+I & GS(a)+I ($p < 0.01$), G+I & GS(b)+I ($p < 0.01$), and G+I & GS(c)+I ($p < 0.01$) (Figure 4.14). In Group 1, the number of times of ball falling of GS(a)+E and GS(c)+E did not show a significant difference and had the least, confirming that the "distance stabilization" and "combination" methods effectively stabilize the essential tremor input and reduce the instability of EH's gesture. In Group 2, the number of times of ball falling of GS(a)+I, GS(b)+I, and GS(c)+I were not significantly different and were less than that for G+I. The results showed that all proposed methods had reduced the effects of intentional tremors and improved the stability of EH gestures.

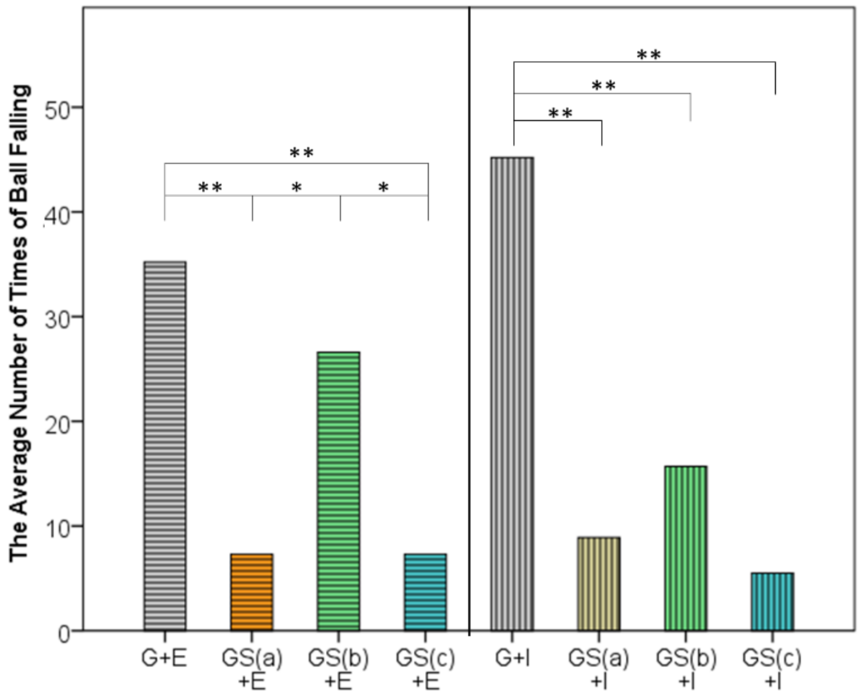


Figure 4.14 Average number of times of ball falling (p < 0.05, ** p < 0.01).*

The spending time of grasping a ball signifies whether trembling hands can easily manage the opening and closing of EH fingers when grasping targets. The longer the time, the more difficult EH was to manage. A one-way ANOVA was conducted to compare the differences in Group 1 for G+E, GS(a)+E, GS(b)+E, and GS(c)+E and in Group 2 for G+I, GS(a)+I, GS(b)+I, and GS(c)+I. The analysis was found to be significant in both groups at $p < 0.01$. For Group 1, the pairwise comparisons with the Bonferroni test showed a statistically significant difference between GS(c)+E and each of the other conditions. As shown in Figure 4.15, in GS(c)+E, the least time was expended grasping the ball. The results indicated that the "combination" method effectively aided hands with essential tremors to steadily control EH's gestures. For Group 2, post-hoc Bonferroni comparisons showed differences in the pairs of G+I & GS(a)+I, G+I & GS(c)+I, GS(a)+I & GS(c)+I, and GS(b)+I & GS(c)+I at $p < 0.01$. As shown in Fig. 14, the least time expended was under GS(c)+I. The results established the "combination" method as optimal for improving the controllability of EH's gestures for hands with intentional tremors. In summary, these results showed that the "combination" method is the most effective for aiding both essential and intentional trembling hands.

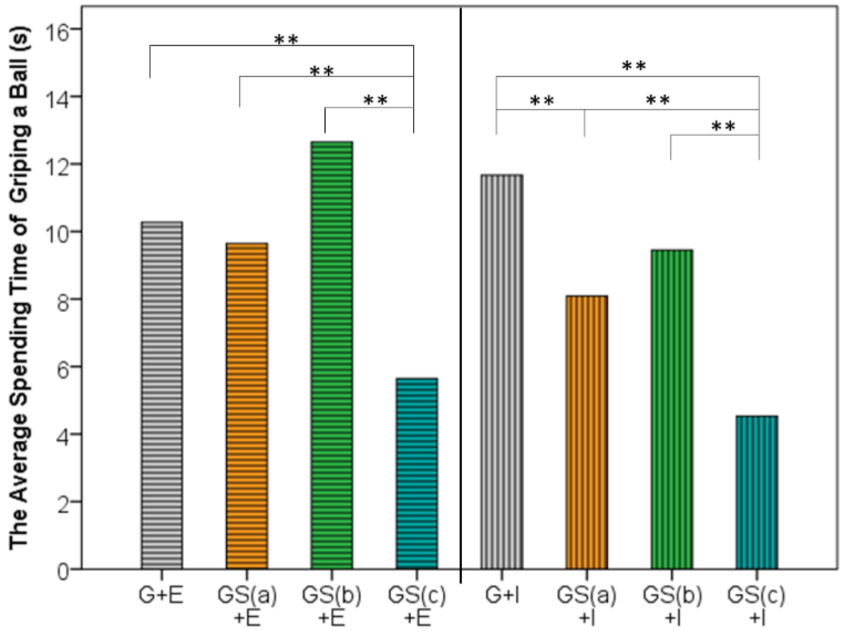


*Figure 4.15 Average e spending time of grasping a ball (** p <0.01).*

The proposed methods were further evaluated from the perspective of user psychology. Figure 4.16(Q3) illustrates the analytical results of Q3 by using the one-way ANOVA with post-hoc Bonferroni comparisons. There were significant differences at $p < 0.01$ in the pairs of G+E & GS(a)+E, G+E & GS(c)+E, GS(b)+E & GS(a)+E, and GS(b)+E & GS(c)+E, as well as G+I & GS(a)+I, G+I & GS(c)+I, GS(b)+I & G+I, GS(b)+I & GS(a)+I, and GS(b)+I & GS(c)+I. There were no differences between GS(a)+E and GS(c)+E or between GS(a)+I and GS(c)+I. The results showed that the participants felt that the ball had not been easily dropped, i.e., EH steadily opened and closed its fingers while being stabilized by "distance stabilization" and "combination" methods. The same analysis was conducted on the answers to Q4 and the results are given in Figure 4.16(Q4). There were significant differences in the pairs of G+E & GS(a)+E, G+E & GS(c)+E, and GS(b)+E & GS(c)+E, all at $p < 0.01$, as well as G+I &GS(a)+I ($p < 0.01$), G+I & GS(b)+I ($p < 0.05$), G+I & GS(c)+I ($p < 0.01$), and GS(b)+I & GS(c)+I ($p < 0.01$). These results show that the participants could grasp the balls most easily under GS(c)+E and GS(c)+I, meaning that the "combination" method was the best. In conclusion, the evaluations of Q3 and Q4 confirmed that the "combination" method was optimal for providing the feeling of steady and controllable EH gestures.

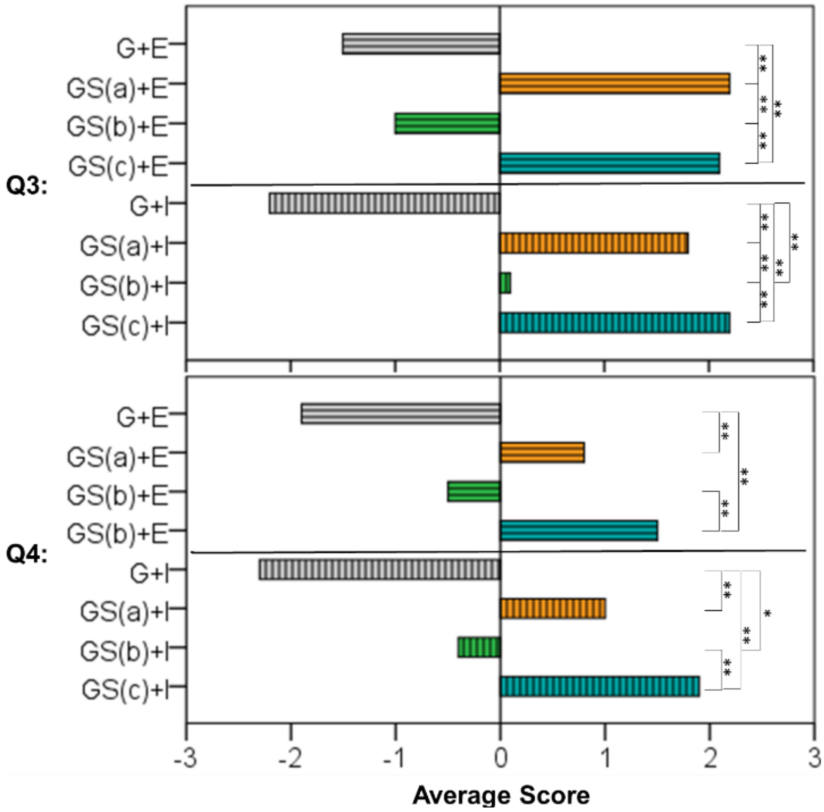


*Figure 4.16 Average score of the psychological evaluations. The seven-point Likert scale ranges from -3 (strongly disagree) to +3 (strongly agree) (** p <0.01).*

4.4.3 Discussion

By analyzing the objective and subjective data from the pointing and grasping experiments, I validated the effectiveness of the proposed methods for facilitating the two types of hand tremors in the use of EH, and then compared all conditions of the average distances of translation and of shaking of EH, the time ratio of EH pointing within the balls, and the psychological evaluations. The proposed movement stabilization methods were proven to be effective in reducing the unstable translation and the stationary state of EH affected by the two types of tremors. According to the analysis of the number of times of ball falling, the "distance stabilization" and "combination" methods proved to be the best in reducing the effects of essential tremors on the stability of EH's gestures, while all methods were good for intentional tremors. By comparing the spending time of grasping a ball, the "combination" method was found to be optimal for both types of tremors. In addition, these objective results were consistent with those of the psychological evaluations. Thus, I confirmed that the "combination" method was optimal for aiding an individual with any kinds of hand tremors to steadily control EH's gestures.

4.5 Conclusion

In this chapter, I advance EH to facilitate individuals with tremors to communicate unreachable objects. Some stabilization methods were proposed to support individuals with hand tremors to use EH steadily. A movement stabilization method composed of a Kalman filter and a Hysteresis stabilized tremor touches and provided a stable translation and stationary state for EH. To reduce the instability of the opening and closing of EH's fingers when affected by tremors, the three proposed gesture stabilization methods were (a) stabilization of distances from the fingertips to the centroid, (b) analysis of the change in frequency components of the touching area, and (c) combination of (a) and (b). A series of pointing and grasping experiments were conducted in which hands with essential and intentional tremors interacting with the EH system were simulated. Through comparing the differences on the differences in the average distances of translation, and shaking of EH, the average time ratios of EH when pointing within the balls, and psychological answers, the proposed movement stabilization method was confirmed to be effective in reducing the unstable translation and the stationary state of EH when affected by tremors; in addition, by evaluating number of times of ball falling, the spending time of grasping a ball and psychological answers, the method (c) was confirmed to be optimal for helping individuals with hand tremors to steadily control EH's gestures.

CHAPTER 5

Discussion and Conclusion

In this chapter, I briefly reiterate over the contribution of research work presented in this thesis and describe future works. The specifically discussion on details of research work can be found in the respective section of previous chapters.

5.1 General Discussion

Considering that computers and touch panels are widespread used and individual with tremors fail to type or touch to access them. In this thesis, I have explored AR to support trembling hands in HCI and CMC. The approaches are organized in pervious chapters, and briefly summarized as virtually stabilizing hand tremors, visually stabilizing hand tremors, and stabilizing virtual hand tremors.

The virtually stabilizing hand tremors is foundation approach, proposed in chapter 2, and advanced in the following chapters, which aims to enable a completely trembling hands to type or touch with ordinary devices. Chapter 2 introduces the application of the approach for support trembling hand to type keyboards correctly. I use Kalman filter and Hysteresis to estimate intentional finger movement positions on the keyboard and implement key remapping to guarantee a correct typing result. Chapter 3 introduces the application to gain stabilized virtual hand positions. According to the two type of hand tremors, I adopt Notch filter & Hysteresis and Medium-Average filter & Hysteresis. Chapter 4 presents the application for stabilizing virtual hand's movement influenced by trembling touches. I use Kalman filter & Hysteresis, but improve Hysteresis according to the characteristic of EH system. Speaking form the essence of the approach, it is utilized a low pass filter and Hysteresis to virtually steady (virtual or real) hand or finger. Both low pass filter and Hysteresis can be adjusted to fit the interactive platforms (i.e. camera sensor and touch sensor) and system environments (i.e. projection AR and optical see-through AR). Thus, the approach has the advantage of versatility and scalability.

The approach of visually stabilizing hand tremors introduced in chapter 3 enables individual with hand tremor to use a steady hand in interaction. I build an optical see-through AR system that can dynamically overlapping a trembling hand with a stabilized virtual hand to provide a realistic experience of steady hand. I investigate the intensity ratios of virtual and real hand, and confirm a virtual:real intensity ratio of 0.75:0.25 is optimal, which can promotes both typing performance and proprioception of stabilized virtual hand. In addition, comparing traditional way e.g. medical treatment and mechanical approaches may harm body, the approach are safe and effective to reduce individuals' hand tremors. Thus, the approach provide a novel ideal on hand tremor suppression, and can be widely developed to support much interaction of trembling hand in HCI and CMC.

In chapter 2 and chapter 3, I demonstrate the effectiveness of two approaches by testing the keyboard typing performance of trembling hands. The reason of choose of keyboard is that it is typical with small and dense placed targets and difficultly typed by trembling hands. The approaches also could be effective to support trembling hand to interact with other objects in the field of HCI. However, as the limitation of thesis, I will expand to researches in further work. In addition, chapter 2 and chapter 2 briefly solve the problems of trembling hand touching/typing within a body reach range. However, touching distant object also bothers individual whose body are disabled by tremors. Thus, I utilize the property of EH that is supporting distant interaction and improve the technologies for trembling hands.

The approach of stabilizing virtual hand tremor introduced in chapter 4 enable trembling hand to control projection extended hand's movement and gesture steadily. I slightly alter the approach of virtually stabilizing hand tremors according to the interactive platform of touching panel, and proposed three gesture stabilization methods that stabilize EH gestures to allow the stable control of EH by trembling hand touches. I conduct a series of ball touching and ball grasping experiment to respectively investigate the effectiveness of the proposal that can reduce unstable stationary state and gesture of EH and demonstrate the approach can support trembling hand to use EH. In practically, some interactive objects and systems are sensitive for unsteady hand touches, the approach provide a solution to cancel their effects.

5.2 Limitations and Future Work

While pursuing to perfect the approaches of this thesis, I need consider the limitations and the future works:

The proposed approaches and the AR systems cannot support of individual with hand tremors out of the field of HCI or CMC, because they don't physically control hands. In addition, the chapter 2 and chapter 3 systems limit extremely quick typing or "wing-beating" typing, and they aren't set to recognized the multiple finger typing as considering one finger typing is a nature way for most of hand tremor sufferers,.

The application of the approaches was only demonstrated through participants simulating trembling hands' interaction in experiments. There is no denying that the actual interaction of trembling hands is more complicated than simulation. Therefore, the usefulness of the AR system as well as approaches should be further investigated for tremor patients. In addition, I explored two hand tremor simulation methods in this thesis. In fact, both two methods cannot perfectly simulate the completed EI and IT tremors as the limitations of simulators. The simulators in chapter 2 and chapter 3 make finger trembling, but can't make upper limb shaking to simulate the completed hand tremors. Moreover, their electrical stimulation makes user uncomfortable. Comparatively, the simulators proposed in chapter 4 can imitate trembling hand involving upper limb tremors on touch panel, but barely create 2-3 Hz trembling. Therefore, hand tremor simulation methods should further be improved in the future.

I conceive the approaches of this thesis have the application of scalability. They could be developed to support the more HCI and CMC for individuals with unsteady hands as well as body in the future. For instance, these approaches could be applied to help unsteady hand correctly touch the interface of devices such as smartphone or tablets; they could be applied to support unsteady hands to perform precise gesture interactions and air interactions; and they also can be developed to support individual with unsteady body for stable somatosensory interaction in the fields of HCI or CMC.

5.3 Conclusion

Considering individuals cannot access the widespread used computers and touch panels with trembling hands and rare technologies were developed to solve the issues, in this thesis, I investigating several approaches to make AR support individuals with hand tremors in HCI or CMC. I has proposed an approach of virtually stabilizing hand tremors and demonstrated it's the scalability of application, e.g. supporting trembling hands to type the desire, gaining the steady spatial locations of virtual hand in the mixed reality of trembling hands, and stabilizing EH's movement influenced by trembling touches. To reduce the visual impact of trembling hand and to enable sufferers to use a steady hand in interaction, I investigate an optical see-through AR system that can dynamically overlap a trembling hand with a stabilized virtual hand with an appropriate intensity ratio to provide a realistic typing experience of steady hand. It presents a novel way to reduce individuals' hand tremors, which is different from traditional physical suppression. Moreover, to enhance trembling hand capability to interact with everywhere, I have improved the EH technology for trembling hands by the approach of stabilizing virtual hand and have demonstrated the approach facilitates trembling hands to touching control projection extended hand to interact with distance steadily.

The approaches presented in this thesis can potentially enhance the interaction of trembling hands in some interactive platforms and system environments, and I will advance more applications in the field of HCI and CMC in the future.

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List of Publications

Best Paper Award

Kai Wang, Noriko Takemura, Daisuke Iwai, and Kosuke Sato, “A Typing Assist System Considering Involuntary Hand Tremor,” Transactions of the Virtual Reality Society of Japan, vol.21, no.2, pp.227-233, June 2016.

Journal Publication

Kai Wang, Noriko Takemura, Daisuke Iwai, and Kosuke Sato, “A Typing Assist System Considering Involuntary Hand Tremor,” Transactions of the Virtual Reality Society of Japan, vol.21, no.2, pp.227-233, June 2016.

Kai Wang, Daisuke Iwai, and Kosuke Sato, “Supporting Trembling Hand Typing Using Optical See-Through Mixed Reality,” IEEE Access, vol. 5, pp. 10.700-10.708, June 2017. **(IEEE Access Best Multimedia Contest Part 1, grand prize)**

Kai Wang, Haruka Matsukura, Daisuke Iwai, and Kosuke Sato, “Stabilizing Graphically Extended Hand for Hand tremors,” IEEE Access, under review — March 2018.

Conference Publication

Kai Wang, Sei Ikeda, Noriko Takemura, Daisuke Iwai, and Kosuke Sato, “An Input-Assist System Considering Non-periodic Involuntary Hand Movements,” SCI’15, pp.313-3(2 pages), May 2015.

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