ON-LINE WRITER DEPENDENT CHARACTER RECOGNITION FOR KHMER BASED ON FIR SYSTEM CHARACTERIZING HANDWRITING MOTION

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หัวข้อวิทยานิพนธ์ การรู้จำตัวอักษรภาษาเขมรโดยเฉพาะบุคคลแบบออนไลน์โดยใช้ระบบผลตอบสนองอิมพัลส์จำนวนจำกัดแสดงคุณสมบัติในการเคลื่อนที่ของปลายปากกาในกระบวนการเขียน
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บทคัดย่อ

วิทยานิพนธ์ฉบับนี้นำเสนอวิธีการรู้จำตัวอักษรภาษาเขมร โดยเฉพาะบุคคลแบบออนไลน์โดยใช้ระบบผลตอบสนองอิมพัลส์จำนวนจำกัดแสดงคุณสมบัติทางเวลาและความถี่ของการเคลื่อนที่ของปลายปากกาในกระบวนการเขียน ซึ่งการคลื่อนที่ของปลายปากกาในกระบวนการเขียนสามารถแสดงได้โดยวิถีโคจรและความเร็วของจุดศูนย์กลาง Bary ที่เกิดจากการเคลื่อนที่ของปลายปากกาในกระบวนการเขียนจากนั้นคุณสมบัติทางเวลาและความถี่ของการเคลื่อนที่ของปลายปากกาในกระบวนการเขียนอธิบายได้โดยกระจายวิถีโคจรและความเร็วของจุดศูนย์กลาง Bary ลงในอนุกรมเวฟเล็ตตัวกรองความถี่แบบ Wiener ด้วยระบบผลตอบสนองอิมพัลส์จำนวนจำกัดถูกนำมาใช้สำหรับลดการเบี่ยงเบนของค่าสัมประสิทธิ์เวฟเล็ตที่คำนวณได้ นอกจากนั้นในวิทยานิพนธ์นี้ได้นำระบบผลตอบสนองอิมพัลส์จำนวนจำกัดมาใช้แสดงคุณสมบัติทางเวลาและความถี่ของการเคลื่อนที่ของปลายปากกาในกระบวนการเขียน โดยนำเอาค่าสัมประสิทธิ์เวฟเล็ตของความเร็วและวิถีโคจรของจุดศูนย์กลาง Bary ที่ผ่านการลดความเบี่ยงเบนแล้วมาเป็นอินพุตและเอาท์พุตของระบบตามลำดับ ซึ่งค่าของผลตอบสนองอิมพัลส์ของระบบดังกล่าวจะใช้เป็นค่าที่แสดงคุณสมบัติเฉพาะแต่ละตัวอักษรเฉพาะบุคคล ในลำดับสุดท้ายสามารถรู้จำตัวอักษรได้โดยใช้การวัดระยะแบบEuclid ระหว่างค่าผลตอบสนองอิมพัลส์ที่คำนวณได้จากตัวอักษรอ้างอิงและตัวอักษรที่จะทำการรู้จำ จากผลการทดลองการรู้จำตัวอักษรภาษาเขมรซึ่งประกอบด้วยตัวอักษรทั้งหมด 6,750 ตัว เขียนโดยผู้เขียน 17 คน โดยใช้วิธีที่นำเสนอได้ผลคิดเป็นค่าเฉลี่ยของเปอร์เซ็นต์ความถูกต้อง 98.17%

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ABSTRACT

An on-line writer dependent Khmer character recognition method based on FIR system characterizing handwriting motion has been proposed in this study. Two features, the trajectory and velocity of Barycenter of pen-tip movement in handwriting process, were used to describe the handwriting motion in handwriting process. The Barycenter trajectory and its velocity of the pen-tip movement, afterward, are expanded into wavelet series to extract the time-frequency characteristics of the handwriting motion. Consequently, Finite Impulse Response (FIR) Wiener filter was then applied to reduce the fluctuation of the wavelet coefficients. Moreover, the FIR system characterizing the time-frequency characteristics of the handwriting motion is introduced by using wavelet coefficients of the velocity and trajectory of the Barycenter with fluctuation reduced as the input and output of the FIR system, respectively. As a result, the obtained impulse response of the FIR system is considered as the individual feature for a particular character. Finally, Khmer alphabets can be recognized by using the Euclidean distance between the impulse responses obtained from the reference alphabets and those of the alphabets to be recognized. Khmer character recognition experiments were performed on a database consisting of 6,750 of numerals and alphabets written by 17 people. The average of the recognition rate was 98.17 % as the obtained result from the experiments.

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CHAPTER 1

Introduction

Khmer is the official language used in Cambodia, a country in South-East Asia. The language belongs to the group Khmer-Mon in the family of Austro-Asiatic language spoken in South-East Asia and in India. Khmer language is based on the alpha-syllabic writing: The symbols can represent either a character, a syllable or a word.

Writing Khmer language is based on the 33 dependent consonants, 28 dependant vowels, 15 independent vowels, and some punctuations. Each consonant has its own foot. Figure1.1 shows the 33 dependent consonants, Fig.1.2 shows the 33 dependent consonants and each of their feet, and Fig1.3 shows the Khmer numeral.

Unlike other languages in the world, Khmer has its own unique style of writing. One consonant can change its own format depending on the place it stands. Moreover, its shape is different from other languages such as English, Japanese, Chinese etc. More information related to Khmer writing style is in [Appendix A].

The Figures 1.1, 1.2, 1.3, illustrate the sample of Khmer writing alphabet samples. However, in the handwriting styles, it has become a fact that the way people write the character is unique varying from person to person depending on many factors such as age, sex, habit, psychological or mental state, physical and practical condition as also stated in [3]. For instance, size and shape of the handwritten scripts, location of the handwritten scripts, and duration time in handwriting process of the scripts are never precisely the same although the scripts were written by the same writer. These are considered as the fluctuation in fluctuation of handwriting motion in handwriting process.

ក	ខ	គ	ឃ	ង
ច	ឆ	ជ	ឈ	ញ
ដ	ឋ	ឌ	ឍ	ណ
ត	ថ	ទ	ធ	ន
ប	ផ	ព	ភ	ម
យ	រ	ល	វ	
ស	ហ	ឡ	អ	

Figure 1.1: thirty-three dependent consonants of Khmer alphabet

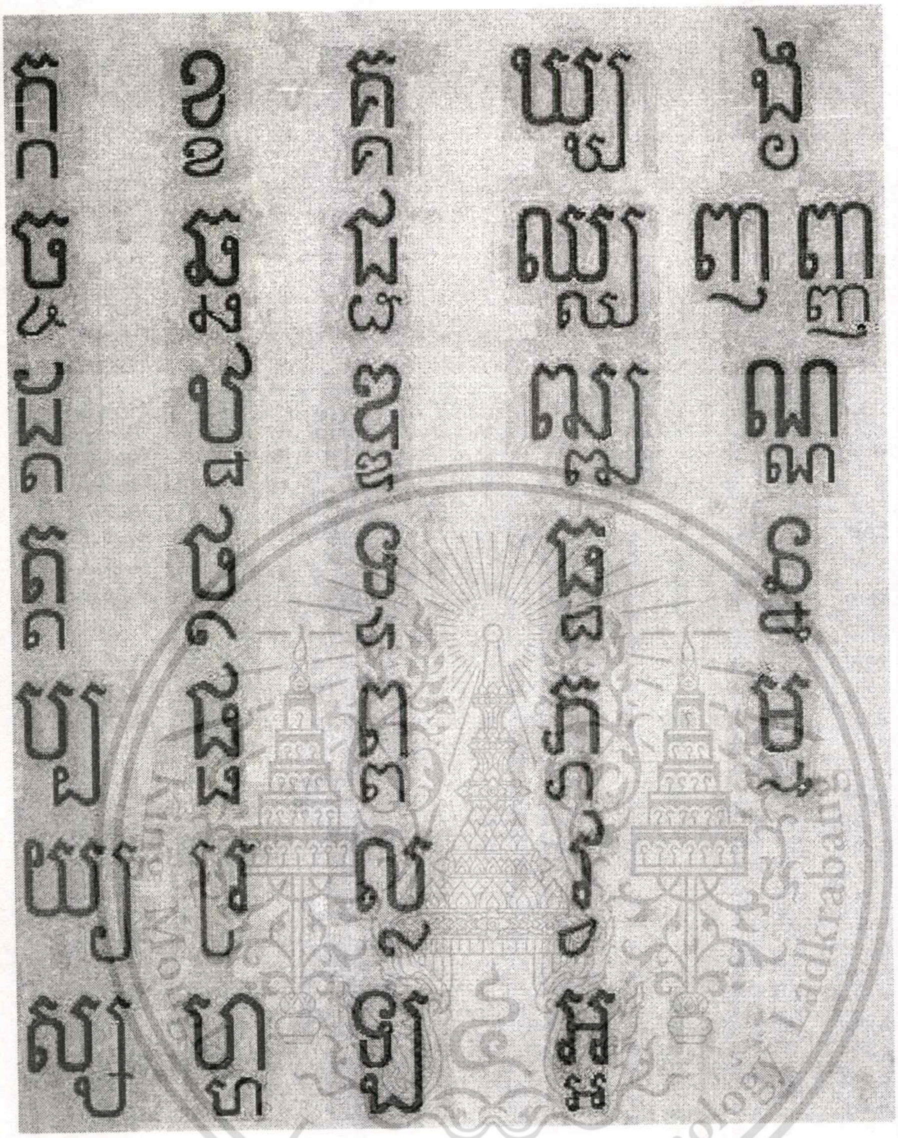


Figure 1.2: thirty-three dependent consonants of Khmer alphabet and their own feet

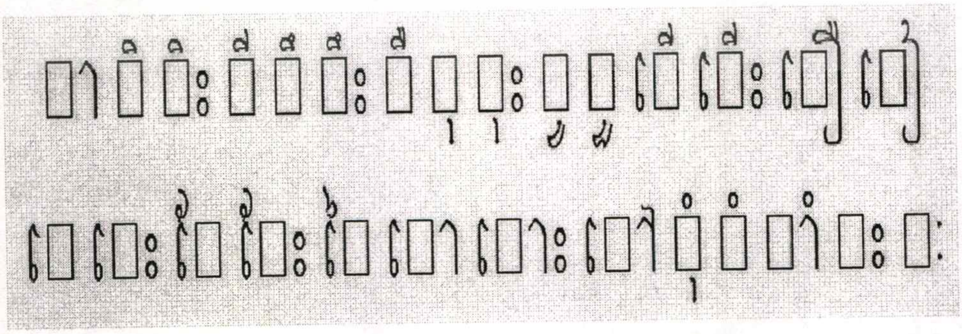


Figure 1.3: twenty-eight vowels of Khmer alphabet

Figure 1.4: Khmer numeral from “zero” to “nine”

Since there exist a high fluctuation in handwriting process as has just been mentioned, the question is “how can we determine a stable feature to represent a character written by a specific writer?”. To answer the question, it is absolutely necessary to extract a more consistent and not-likely-to-vary feature for a handwritten character of a specific writer. The so-called feature is known as the stable feature. To do so, the feature extraction is an unavoidable issue for on-Line Khmer character recognition.

Many researches have been done on on-line and off-line character recognition, among those there are some have been done on off-line Khmer character recognition like the work [2]; however there seem less of those have been done on on-line Khmer character recognition.

Many methods for on-line character recognition have been reported [1, 3, 5–7]. In those methods, the pen-tip position was used to recognize the characters. It is considered that pen-tip used directly in [3] is not effective enough to extract the feature of the handwriting character. In work [6, 7], the Barycenter determined from the center point of the script and two adjacent pen-tip positions with respect to time in handwriting process was used to extract the feature of the handwriting character. In this study, a writer dependent character recognition method is investigated using the Barycenter instead of the pen-tip position to extract the handwriting feature. The major advantage of the writer dependent method is that not only is it easier to customize special handwriting style for a particular writer, but also can be recognized special symbols for a particular writer as stated in the work [7]. In the work [7], the Fourier approximation was used to extract the handwriting feature for particular person. However the Fourier approximation was not enough to represent the handwriting feature for a specific person. It is considered that a person should have his/her own handwriting style in handwriting a script. In order to extract the individual handwriting feature in writing a script, it is desirable to use the time-frequency characteristics of handwriting motion. In this case, the trajectory and the velocity of the Barycenter are expanded into wavelet series to extract the time-frequency of the handwriting motion. After that, the FIR (Finite Impulse Response) Wiener filter is used to reduce the fluctuation of wavelet coefficients. Moreover, that FIR system is used to characterize the handwriting system by taking the obtained approximated wavelet coefficients of the velocity and the trajectory from the FIR-Wiener filter as the input and output, respectively, of another FIR system. Stated in [9], the impulse response can completely specify the characteristics of the FIR system; and the FIR system represents the relation between the handwriting motion and the trajectory of the handwriting characters so it means the impulse response of the system expresses the character handwriting system. This leads the obtained impulse response of the FIR system can be used as the individual features for a particular character of a specific writer. Finally, characters can be recognized by the Euclidean distance between the impulse response obtained from the reference characters and the characters to be recognized.

The objectives of this study are:

1. To propose a new method to extract a stable and individual feature of handwriting for on-line Khmer writer dependent recognition.
2. To represent the handwriting process for Khmer character as a system.

The thesis is composed of seven chapters as follows:

Come with the introduction, the background on the study of on-line writer dependent Khmer character recognition, the aim and structure of this thesis are described in Chapter 1.

In Chapter 2, the basic idea to represent the handwriting process as dynamic feature of handwriting process as a system is presented. First, the velocity and trajectory of the Barycenter of pen-tip movement in handwriting process have been considered as the dynamic feature of handwriting motion. The Barycenter is determined from the center point of the script and the two adjacent pen-tip positions with respect to time in handwriting process. In this study, the handwriting system is defined as a system characterizing the dynamic feature of handwriting motion. It is considered that the difference between the handwriting motions can be represented by that between the handwriting systems. The impulse response of the handwriting system is used to represent the different between handwriting systems. Furthermore, the handwriting system is realized by the Finite Impulse Response(FIR) system taking the wavelet coefficients of the velocity and the trajectory of the Barycenter as the input and the output of the system, respectively. Then the dynamic feature of handwriting motion can be described by the impulse response of the above FIR system.

As previously mentioned, size and location of the script, the duration time, and the sensitive in handwriting process of scripts written by the same or different writer are never the same. These are considered as the fluctuation of handwriting. In order to extract the stability of handwriting feature, the fluctuation of handwriting should be reduced. In this chapter, three kinds of normalization, size normalization of the script, location normalization, and duration time normalization of the handwriting script, are followed to reduce the above mentioned fluctuations of handwriting. In Chapter 3, the preprocessing to reduce the fluctuation in handwriting process is discussed. It is shown that the fluctuations of handwriting related to size of script, location of script, and the duration time in handwriting process of the script can be reduced by using the simple normalization of the size of the script, normalization of the location of the script, and the normalization of the duration time in handwriting process of the script.

A method to extract the stable feature of handwriting motion is described in Chapter 4. First, the velocity and the trajectory of the Barycenter determined from the center point of the script and the two adjacent pen-tip positions with respect to time in handwriting process are defined by a complex valued function to describe the handwriting motion. Then the above two features are expanded into wavelet series to extract the stable feature of handwriting motion. Next, the handwriting system characterizing the handwriting motion is realized by using the the above wavelet coefficients as the input and the output of the FIR system, respectively. Therefore, with the above FIR system , the on-line Khmer character recognition problem can be reduced to system identification problem. It is considered that the impulse response of the above FIR system represents the stable and individual feature of handwriting motion.

In Chapter 5, the on-line Khmer character recognition algorithm is introduced. The Euclidean distance between the obtained impulse response from the previous chapter of the reference characters and the character to be recognized is used for Khmer character recognition.

Details of the database for Khmer character recognition experiments will be presented in chapter6. The effectiveness of the proposed method will be concluded with the experimental results.

And finally, the Chapter 7 is the conclusion in which the results obtained in this study are summarized and future works are described.

CHAPTER 2

FIR System Characterizing a Handwriting Motion

In this chapter, the basic idea to represent the handwriting process as a system is described. We consider that the handwriting motion is described by the following two features:

1. The velocity $v(t)$ of the Barycenter trajectory determined from the center point of script and the two adjacent pen-point positions.
2. The Barycenter trajectory $z(t)$.

Figure 2.1 shows the trajectory of pen-tip position and the Barycenter for Khmer numeral "two." $(x(t_n), y(t_n))$ is a coordinate of pen-tip position and $(r_x(t_n), r_y(t_n))$ is a coordinate of the barycenter. Figure 2.2(a) shows examples of the $v(t)$ and $z(t)$ obtained from Khmer numeral "two." The effectiveness of the above features used to describe the handwriting motion will be presented in the Section 4.1.

In this study, the handwriting system is defined here as a system characterizing the dynamic feature of handwriting motion. In this case, the velocity $v(t)$ and trajectory $z(t)$ of the Barycenter are used as the input and output of the handwriting system, respectively. With this handwriting system, the difference between the handwriting motions can be represented by that between the handwriting systems. Then the impulse response of the handwriting system is used to represent the difference between the handwriting systems. In addition, the dynamic feature of handwriting motion can be characterized by the impulse responses of the handwriting systems. Figure2.2 shows the handwriting system characterizing the handwriting motion for writer A and B, where $v(t)$ and $z(t)$ are used as the input and output of the handwriting system, respectively. Thus, if $v(t)$ and $z(t)$ obtained from character A are different from those obtained from character B then the handwriting system of character A must

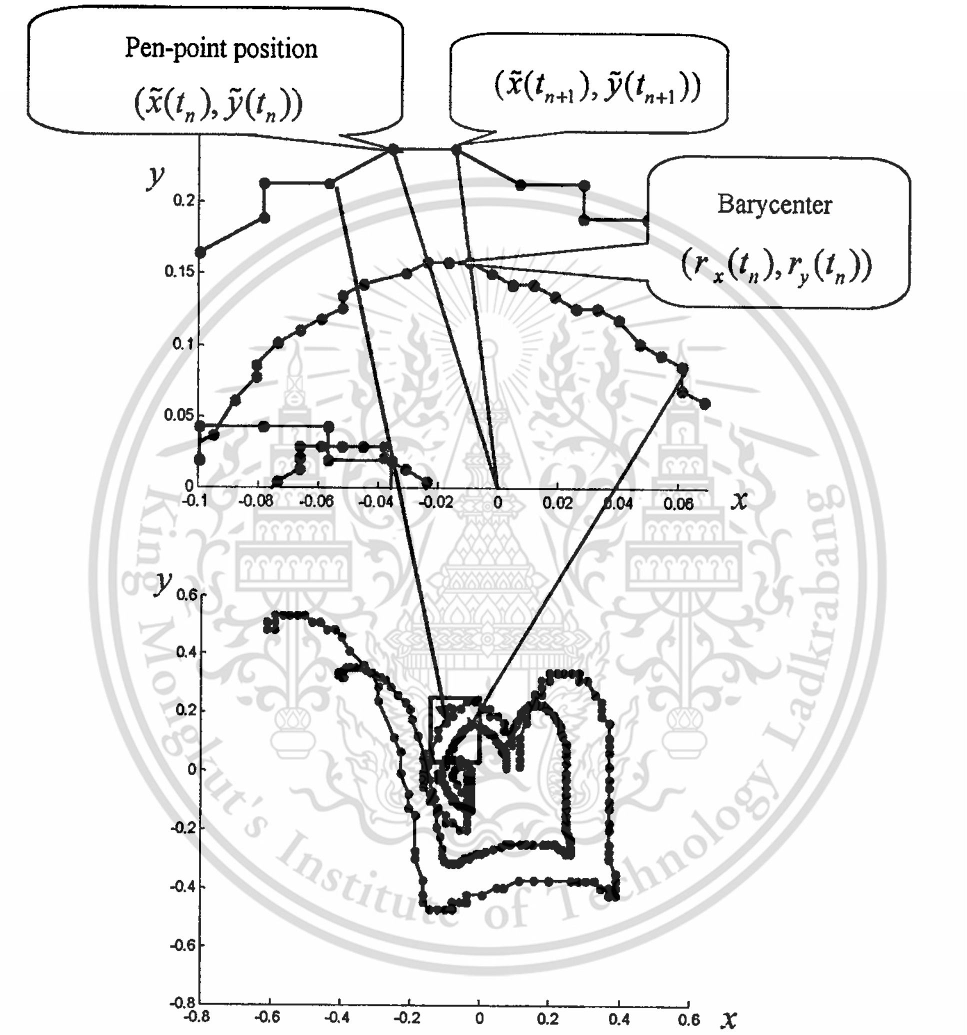


Figure 2.1: Barycenter trajectory of Khmer numeral "two" obtained from pen-tip position

be different from the handwriting of character B. Furthermore, the handwriting system is realized by the FIR system characterizing the handwriting motion. Moreover, in this study, the Wavelet series of $v(t)$ and $z(t)$ are used to extract the individual time-frequency characteristics of the handwriting motion in handwriting process. Then the FIR system approximating the handwriting system is realized by using the wavelet coefficients of $v(t)$ and $z(t)$ as the input and output of the FIR system, respectively. It is assumed that the FIR system can be described by the following equation:

$$\hat{g}(k) \; = \; \sum_{m=0}^{M-1} h(m)f(k-m), \tag{2.1}$$

$$(k = 0, 1, ..., K-1),$$

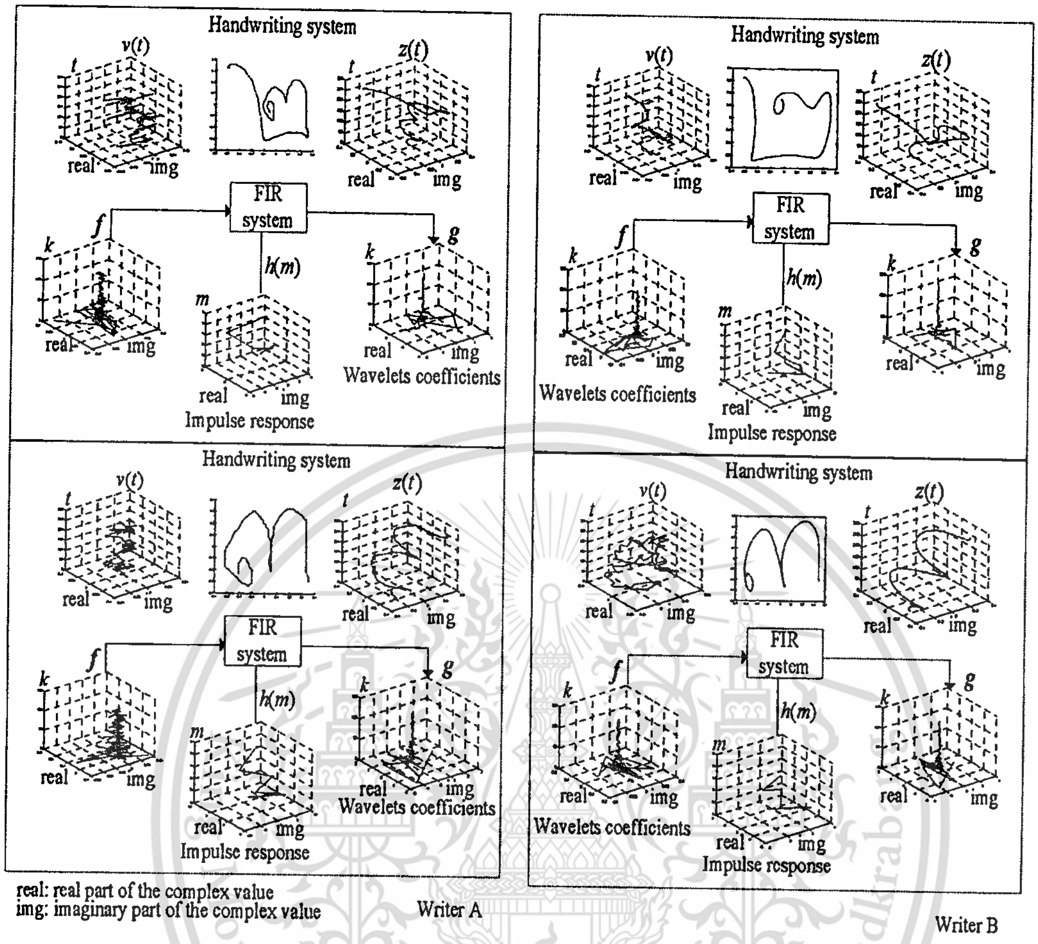
where $f(k)$ and $g(k)$ are the input and the output of the FIR system, respectively, corresponding to the wavelet coefficients of the velocity $v(t)$ and the barycenter trajectory $z(t)$ which were mentioned previously; and $\hat{g}(k)$ is the approximation of $g(k)$. M is the order of the FIR system with the optimum value of 6 selected by try and cut in many experiments, K is the total number of the input and output sequence of the FIR system, and $h(k)$ is the impulse response of the system.

Then the impulse response of the FIR system is determined in the least-square, described in [10, 11], and [Appendix B], sense as

$$E \; = \; \sum_{k=0}^{K-1} |e(k)|^2 \rightarrow min, \tag{2.2}$$

$$e(k) = g(k) - \hat{g}(k),$$

where the above $e(k)$ is the error of the approximation between $\hat{g}(k)$ and $g(k)$. Then the impulse response obtained from the above FIR system is used as the stable and individual feature of the handwriting motion in handwriting process. The details will be explained in Sections 4.2 and 4.3. Figure 2.3 shows the FIR system approximating the handwriting system. In this case, the wavelet coefficients of the velocity and the Barycenter trajectory as previously mentioned as the input $f(k)$ and the output $g(k)$, respectively. Figure 2.2



(a)

(b)

Figure 2.2: FIR system characterizing the handwriting motion for Khmer numeral “two,” and “three” from writer A (a) ; and writer B (b)

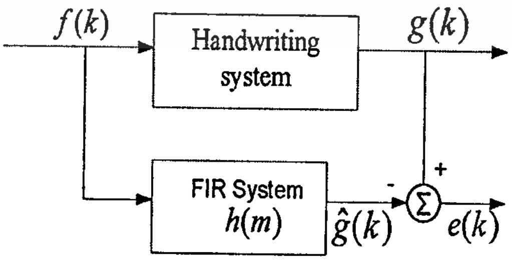


Figure 2.3: FIR system representing handwriting system

shows the FIR system of Khmer numeral "two." It can be seen from Fig.2.2 that the impulse response $h(k)$ of the FIR system obtained from character A is different from that obtained from character B; and therefore the difference between the handwriting motions of characters A and B can be represented by that between the impulse responses $h(k)$ of the FIR systems for characters A and B. In this study, the on-line Khmer character recognition problem is reduced to the system identification problem.

CHAPTER 3

Preprocessing

It is well known that there is a large fluctuation in handwriting process. For instance, the size, location of the written scripts, and the duration time in handwriting process of the same scripts, no matter if they are written by the same or different writers, are never precisely the same. As can be seen in Fig.3.1 which shows the example of the Khmer numeral "four"s written by the same writer, it can be seen from Fig.3.1(a) that all the sizes of the scripts and the locations of the Khmer numeral scripts are different. In addition, it also can be seen that all the duration time in handwriting process of the Khmer numeral scripts are different. It can be stated that time in handwriting process are the fluctuation in handwriting process. To be able to recognize the character more effectively such fluctuation should be reduced. In doing so, preprocessing process is the first step in character recognition.

In this chapter, the preprocessing process to reduce the fluctuation of handwriting motion in handwriting process is discussed. Three kinds of normalization to reduce the above mentioned fluctuations of the handwriting will be described here. First, a normalization to reduced the fluctuation of handwriting related to size of the scripts will be described in Section 3.1. Then the a normalization to reduce the fluctuation of handwriting motion in handwriting process related to the location of the scripts will be described in section 3.2. And finally, a normalization to reduce the fluctuation of the handwriting related to duration time in handwriting motion in handwriting process of the scripts will be described in Section 3.3.

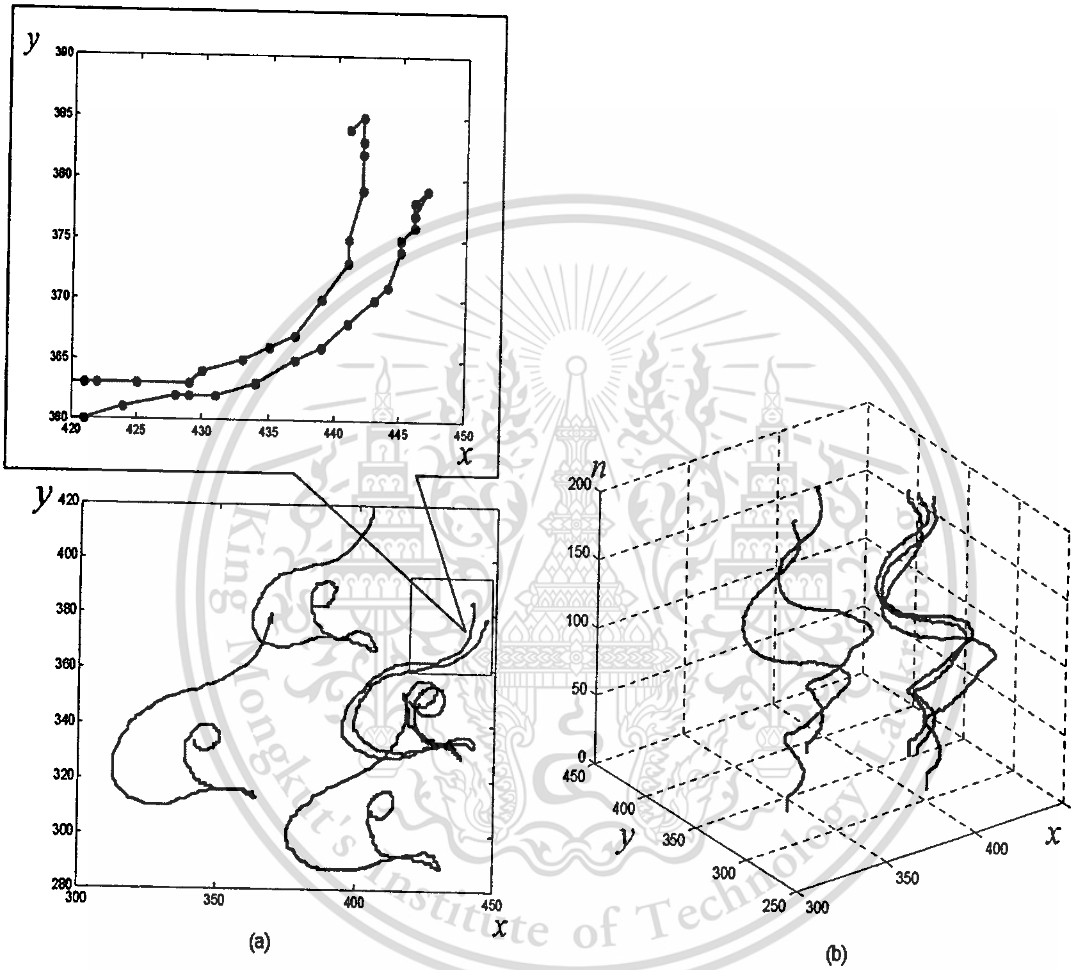


Figure 3.1: Example of Khmer numeral "four" written by the same writer; (a) The plots of x,y components of pen-tip positions, (b) The plot of x,y components of pen-tip positions respect to the time in handwriting process

3.1 Size normalization of the script

It is assumed here that Khmer characters are written on a graphical tablet. The horizontal and vertical components of pen-tip position at a time, $t = n\tau(\equiv t_n)$, in handwriting process are denoted here as $x(t_n)$ and $y(t_n)$, respectively, where τ is a constant sampling rate. As shown in Fig.3.1(a), all the sizes of the scripts even they were written by the same writer are different. In this section, the size of the script is standardized after removing the duplicated points of pen-tip position. In order to make a standard size of the scripts, the horizontal and the vertical components, $x(t_n)$ and $y(t_n)$ are normalized as

$$\hat{p}(t_n) = \frac{p(t_n) - min(p(t_n))}{max(p(t_n)) - min(p(t_n))}, p = (x, y) \tag{3.1}$$

where

$min(p(t_n)) = \min_{0 \leq n \leq N-1} p(t_n),$

$max(p(t_n)) = \max_{0 \leq n \leq N-1} p(t_n), p = (x, y),$

and N is the total number of sampled points of pen-tip position varying from one script to another.

The example of size normalization is shown in Fig.3.2. The first row shows the plot of x, y coordinates of pen-point positions for Khmer numeral “two” written by the same writer before and after normalization of size of the script, the second and the third row show the figures of the x, and y components of the pen-tip positions obtained from the first row with respect to time in handwriting process plotted separately. It can be seen that the fluctuation related to the size of the script can be reduced after passing size normalization. The effectiveness of size normalization was also described in the work [7].

3.2 Location normalization of the script

In the previous section, the fluctuation related to the size of the scripts has been reduced. Then arrived the fluctuation related to the location of the scripts to face with. As shown in Fig.3.1(a), all the location of the scripts even written by the same writer are different. This section will elaborate the location normalization of the script.

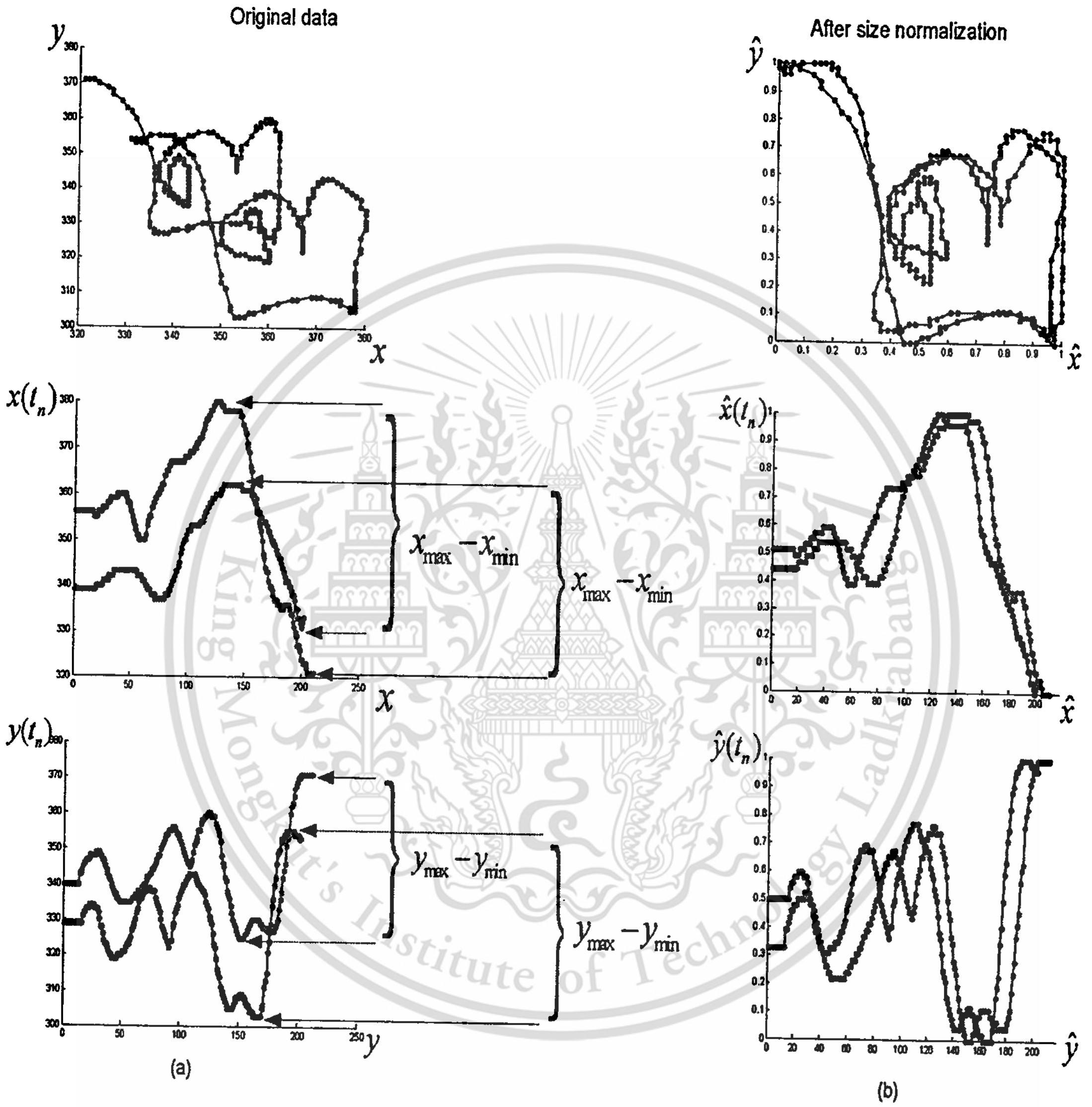


Figure 3.2: Khmer numeral "two" written by the same writer; (a) Original data, (b) after normalization of size of the script

The location of the script is normalized as follows:

$$c_p = \frac{1}{N}\sum_{n=0}^{N-1}\hat{p}(t_n), p = (x,y) \tag{3.2}$$

$$\tilde{p}(t_n) = \hat{p}(t_n) - c_p, n = 0,1,2...N-1 \tag{3.3}$$

where c_p is the center point of a script, and $\tilde{p}(t_n)$ represents the scripts after location normalization of size and location of the script.

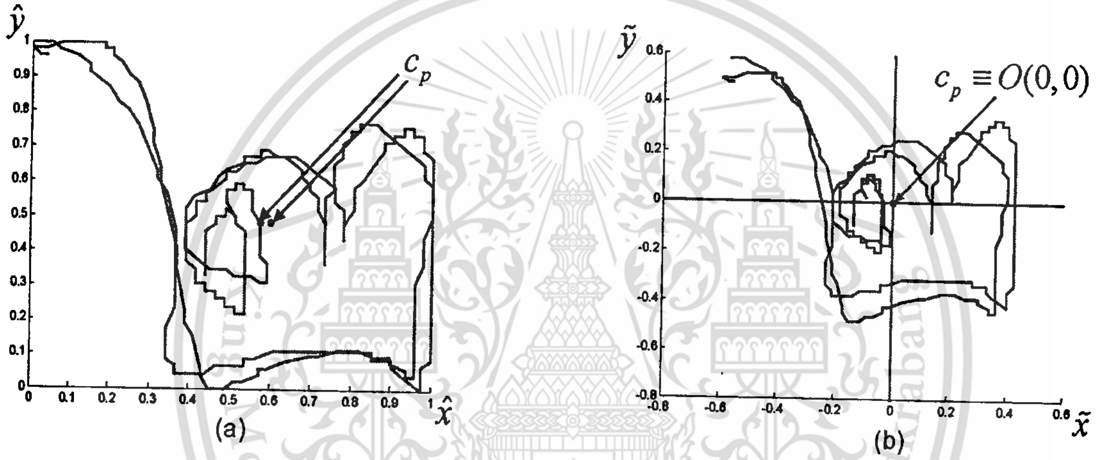


Figure 3.3: Khmer numeral "two" written by the same writer; (a) After size normalization of the size of the script, (b) After normalization of the size and location of the script, $c_p = (c_x, c_y)$ is the central point of the script

The example of location normalization is shown in Fig.3.3. Figure 3.3(a) shows the plots of Khmer numeral "two" written by the same writer after passing size normalization, and Fig.3.3(b) shows the plot of the scripts in Fig.3.3(a) after normalization of size and location of the script. From this figure, it can be seen that the fluctuation related to location of the scripts is reduced after passing the normalization of location of the script. Figure 3.4 shows the plots of the Khmer numerals "one," "two," and "three" obtained from writers A and B before and after normalization of the size of the scripts, respectively. The first column shows the original script, the second column shows the scripts after passing size normalization, and the last column shows the scripts after size and location normalization. The effectiveness of location normalization of the script was also described in the work [7].

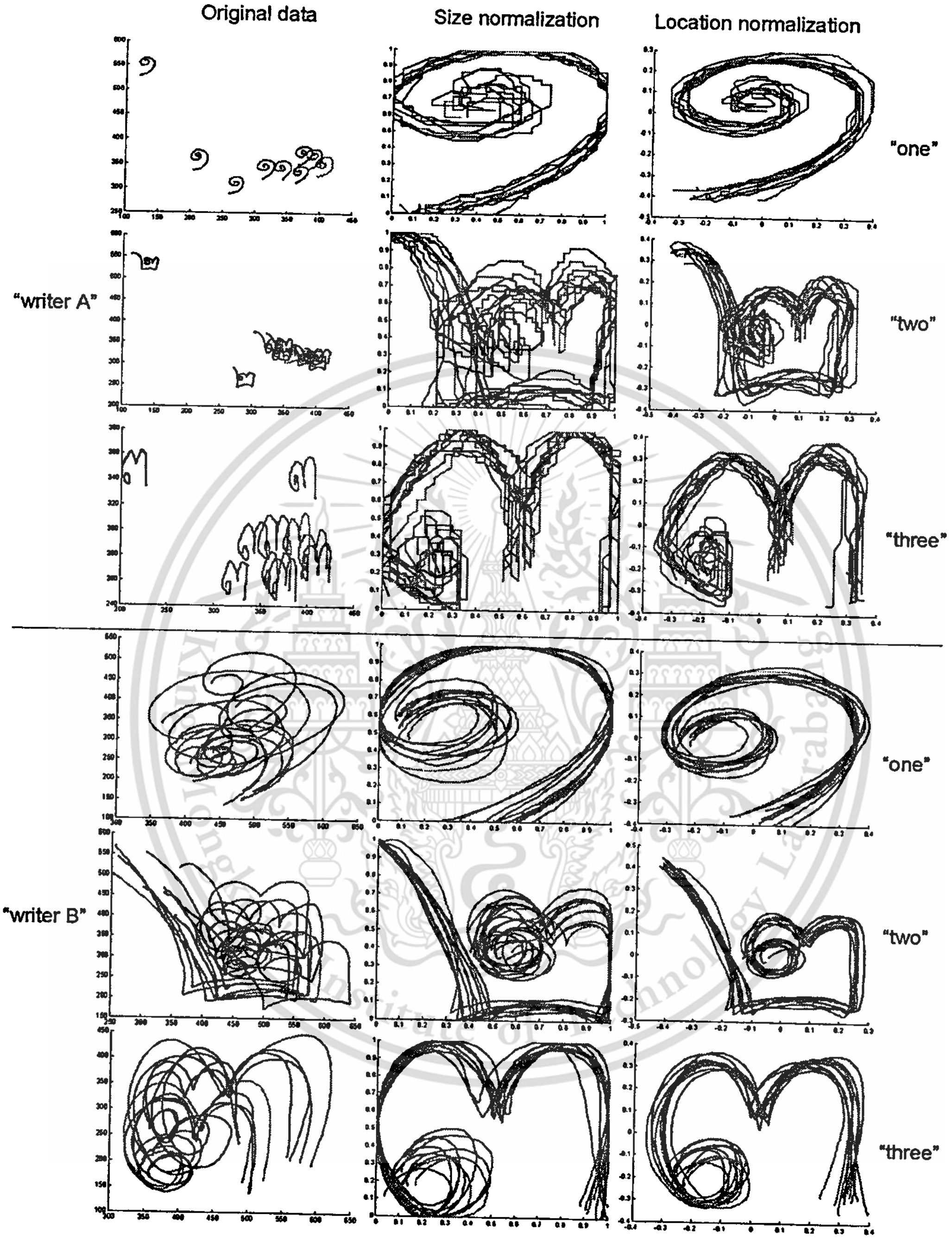


Figure 3.4: Khmer numeral "one," "two," and "three" written by two writers; before and after size normalization of the size of the script, and normalization of the size and location of the script

3.3 Time normalization of the script

As can be seen in Fig.3.1(b) that the duration time in handwriting process of the scripts written by the same writer are different. Subsequently, to reduce the fluctuation of the duration time in handwriting process the of scripts, a normalization of the duration time in handwriting process is performed in this section. In order to normalize the duration time in handwriting process, piecewise-linear functions (PLFs) of $v_i(t_n)$ and $z_i(t_n)$ are determined by connecting the two adjacent components with a straight line. The PLFs can be described as follows:

$$q(t) = \sum_{n=0}^{N_i-1} q(t_n)\phi_n(t), t \in T \tag{3.4}$$

where $q = (z_i^{real}, z_i^{img}, v_i^{real}, v_i^{img})$,

$$\phi_n(t) = \left\{ \begin{array}{ll} \frac{t-t_{n-1}}{t_n-t_{n-1}} & t \in [t_{n-1}, t_n] \\ \frac{t_{n+1}-t}{t_{n+1}-t_n} & t \in [t_n, t_{n+1}] \\ 0 & t < t_{n-1} \;\; or \;\; t > t_{n+1}, \end{array} \right\} \tag{3.5}$$

N_i is the sampled points of the script of a stroke i of a character varying from one stroke of a character written by a specific writer to another, and T is the duration time of the handwriting process. Then the duration time is T normalized as $T = T_{N_i}$ by using eq.(3.4), $T = T_{N_i}$ is the normalization of the duration time in handwriting process of the script determined by using the training data for a character of a particular writer. Figure 3.5 shows the plot of $\tilde{y}(t_n)$ before and after using piecewise-linear function. It can be seen from Fig.3.5 that the discrete data is interpolated into continuous data by using the piecewise-linear function.

Figure 3.6(a) shows the plots of the horizontal and the vertical components, $\tilde{x}(t)$ and $\tilde{y}(t)$, of the scripts obtained from the Barycenter after size and location normalization of the script; on the other hand fig.3.6(b) shows the plots of the horizontal and the vertical components $\tilde{x}(t)$ and $\tilde{y}(t)$ of the scripts obtained from the Barycenter trajectory after passing the normalization of the duration time in handwriting process of the scripts. It can be seen from Fig.3.6 that the fluctuation of handwriting related to the duration time in handwriting process of the scripts can be reduced after passing the normalization of duration time in handwrit-

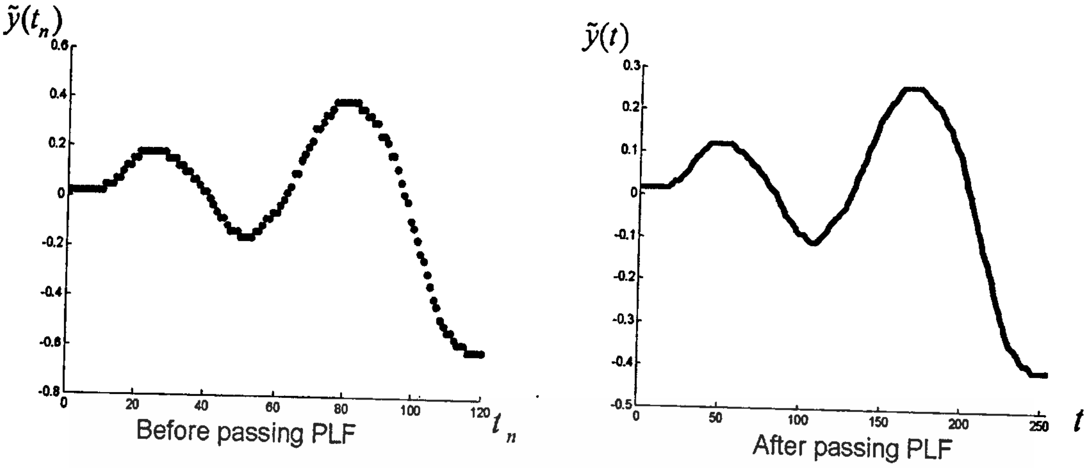


Figure 3.5: $\tilde{y}(t_n)$ before and after piecewise-linear function

ing process of the scripts. The effectiveness of size normalization was also described in the work [7, 8].

3.4 Summary

The fluctuations of the handwriting related to size of the script, location of the script and duration time in handwriting process of the script has been discussed. Then it was shown that the above fluctuation can be reduced by being passed the three kinds of normalization with respect to size of the script, location of the script, and the duration time in handwriting process of the script.

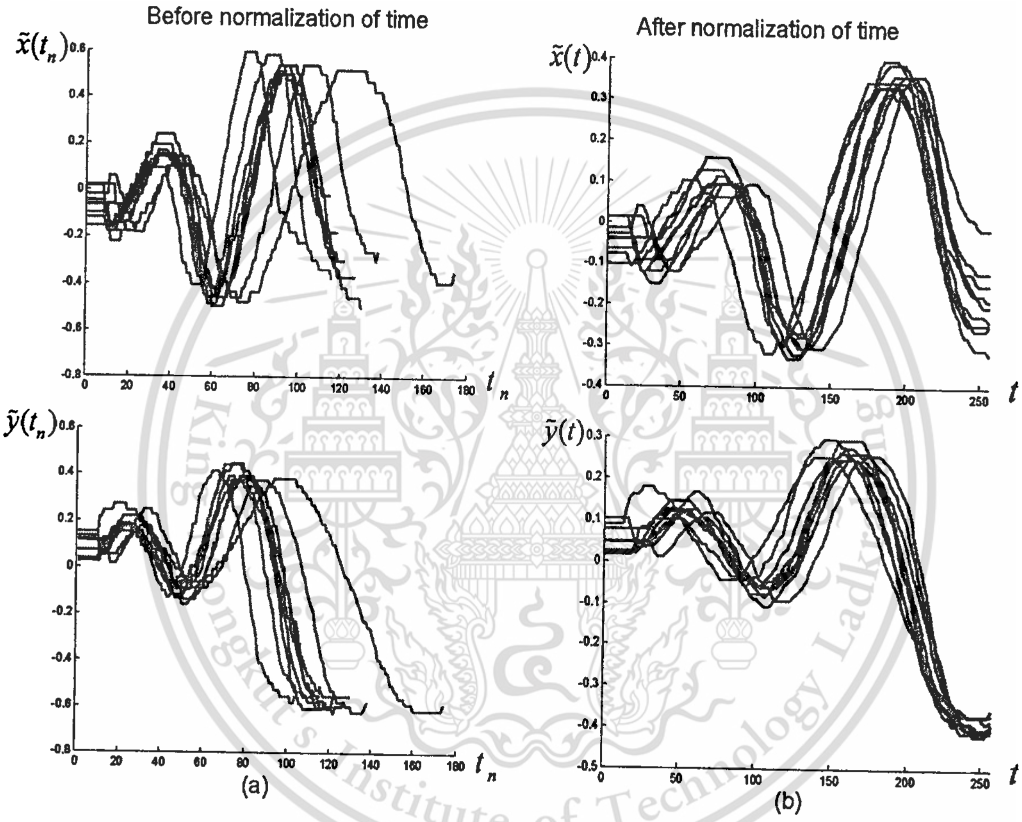


Figure 3.6: $\tilde{x}(t_n)$ and $\tilde{y}(t_n)$; (a) after normalization of size and location of the scripts, (b) after time normalization

CHAPTER 4

Feature Extraction

In this chapter, a method to extract a stable and individual feature of handwriting motion is discussed. First, the velocity and trajectory of the barycenter determined from the center point of the script and the two adjacent pen-tip positions with respect to time in handwriting process are defined by a complex valued function to describe the handwriting motion in section 4.1. Then the wavelet series of the velocity and the Barycenter trajectory are performed to extract the time-frequency characteristics as described in Section 4.2. Finally, the handwriting system characterizing the handwriting motion is realized by using the wavelet coefficients of the velocity and the Barycenter trajectory as the input and the output of the system, respectively. The impulse response of the above FIR system characterizing the handwriting motion is discussed in Section 4.3.

4.1 Velocity and Barycenter trajectory of pen-point movement in handwriting process

It is assumed that the handwriting motion can be described by two features– The velocity and the Barycenter trajectory of pen-tip movement in handwriting process [3]. Then in order to reduce a sensitivity of handwriting motion in handwriting process, a trajectory of the Barycenter determined from the center point of a script and the two adjacent pen-tip positions with respect to time in handwriting process is used. The Barycenter coordinates $(r_x(t_n), r_y(t_n))$ shown in fig.4.1 are calculated by the following equations:

$$r_x(t_n) = \frac{\tilde{x}(t_n) + \tilde{x}(t_{n+1})}{3}, r_y(t_n) = \frac{\tilde{y}(t_n) + \tilde{y}(t_{n+1})}{3} \qquad (4.1)$$

where $n = 0, 1, 2...N-1$. Furthermore, in order to reduce another fluctuation such as duration time in a part of handwriting process, a segmentation of handwriting process is performed. The pen-up signal is used as the segmentation point for separating a Barycenter trajectory into a set of components' strokes. Then the handwriting motion in the handwriting process for each stroke can be described by the following equations:

$$z_i(t_n) = r_x^{(i)}(t_n) + jr_y^{(i)}(t_n), \tag{4.2}$$

$$v_i(t_n) = z_i(t_n) - z_i(t_{n-1}), \tag{4.3}$$

$$j \equiv \sqrt{-1}, , i = 1, 2, \ldots N_s$$

where $z_i(t_n)$ represents the Barycenter trajectory, $v_i(t_n)$ represents the average of the velocity between the two adjacent Barycenter points, and N_s is the total number of strokes in the handwriting process of handwriting character after segmentation. After that, we define the

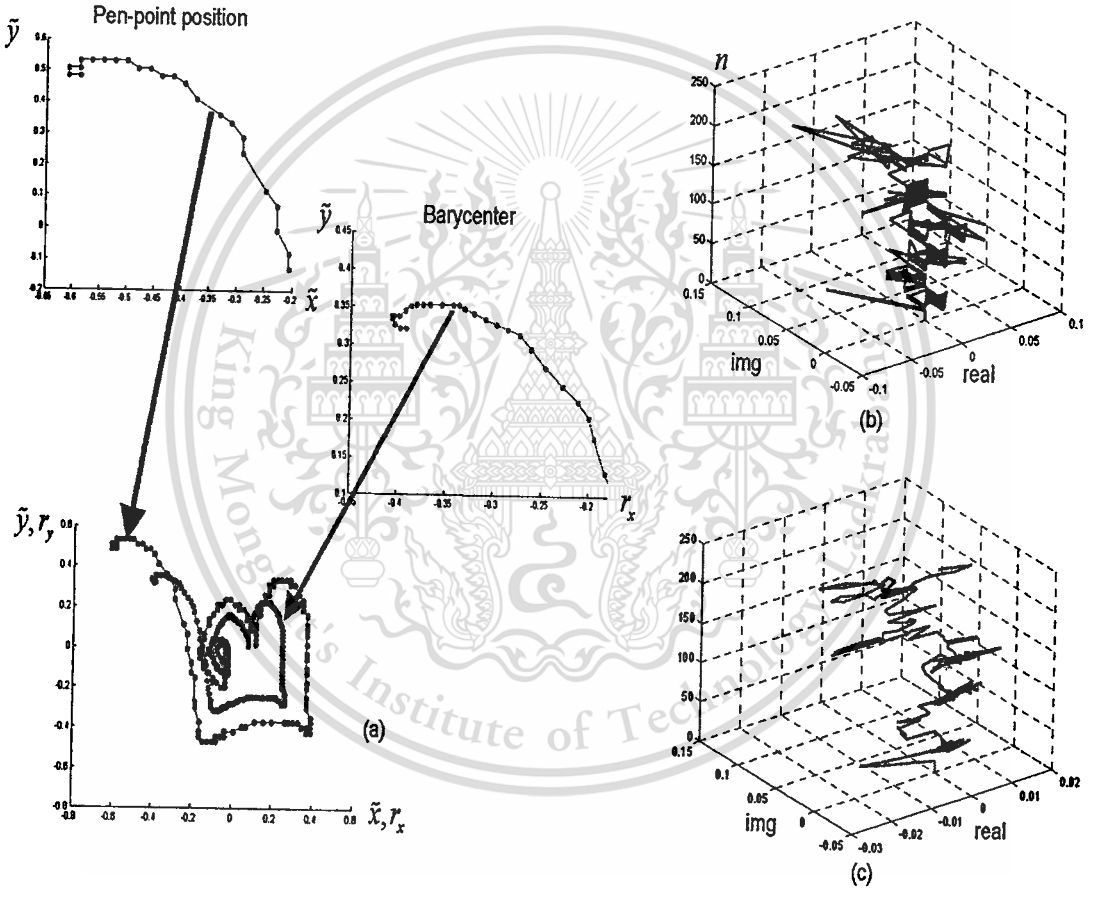


Figure 4.1: (a) Khmer numeral "two," (b) $v(t_n)$ obtained from pen-tip position, (c) $v(t_n)$ obtained from the Barycenter

following equations:

$$z_i(t_n) = z_i^{real}(t_n) + j z_i^{img}(t_n) \tag{4.4}$$

$$v_i(t_n) = v_i^{real}(t_n) + j v_i^{img}(t_n) \tag{4.5}$$

where $z_i(t_n)$ and $v_i(t_n)$ are complex valued functions which represent the trajectory and the velocity of the Barycenter, respectively. Figure 4.1(a) shows the plots of the pen-tip position and the Barycenter trajectory for Khmer numeral "two," Fig.4.1(b) shows the plot of the velocity obtained from the pen-tip position, and Fig.4.1(c) shows the plot of the velocity obtained from the barycenter. It can be seen from Figs.4.1(b) and (c) that the $v(t_n)$ obtained from the Barycenter is less sensitive than that obtained from the pen-tip position. The effectiveness of using the Barycenter for on-line writer recognition was reported [3].

4.2 Wavelet series of the velocity and the Barycenter trajectory

In this section, in order to extract the time-frequency characteristics of the handwriting process, the $z_i(t_n)$ and $v_i(t_n)$ obtained in the preceding section are expanded into wavelet series as

$$\breve{q}(t) = \sum_{k=0}^{2^{l_0}-1} c_{l_0}^{(q)}(k)\varphi_{k,l_0}(t) + \sum_{\underline{l}=l_0}^{M-1} \sum_{k=0}^{2^{\underline{l}}-1} d_{\underline{l}}^{(q)}(k)\psi_{k,\underline{l}}(t), \tag{4.6}$$

$q = (v_i, z_i), l_0 = 0, 1, 2 \ldots \underline{L} - 1$

where $\psi_{k,\underline{l}}(t)$ is orthonormal wavelet:

$$\psi_{k,\underline{l}}(t) = 2^{\underline{l}/2}\psi(2^{\underline{l}}t - k) \tag{4.7}$$

$$\begin{aligned} < \psi_{k,\underline{l}}, \psi_{m,n} > &\equiv \int_{-\infty}^{\infty} \psi_{k,\underline{l}}(t)\psi_{n,m}(t)dt \\ &= \delta_{\underline{l},m}\delta_{k,n} \end{aligned} \tag{4.8}$$

and $\varphi_{k,l_0}(t)$ is the scaling function:

$$\varphi_{k,l_0}(t) = 2^{l_0/2}\varphi(2^{l_0}t - k), (l_0, k \in Z)$$

where Haar function is used as mother wavelet $\psi_{k,l}$, $\delta_{l,m}$ is a Kronecker delta, and $c_{\underline{l}}^{(q)}(k)$ and $d_{\underline{l}}^{(q)}(k)$, respectively, are the approximated and the detail wavelet coefficients obtained through the inner product $d_{\underline{l}}^{(q)}(k) =< q, \psi_{k,\underline{l}} >$, and the scaling function coefficients obtained through the inner product $c_{\underline{l}}^{(q)}(k) =< q, \varphi_{k,\underline{l}} >$. Figure 4.2 shows how the approximation and the detail coefficient obtained from using the filter bank of Haar function.

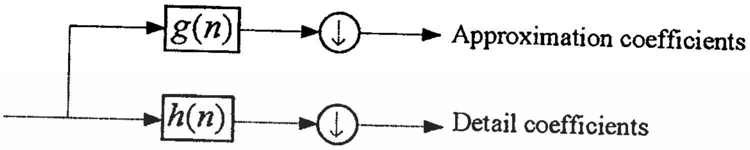


Figure 4.2: Block diagram of filter bank

Figure 4.3 shows the two level filter bank, from one level to another the input signal is down sampled by two.

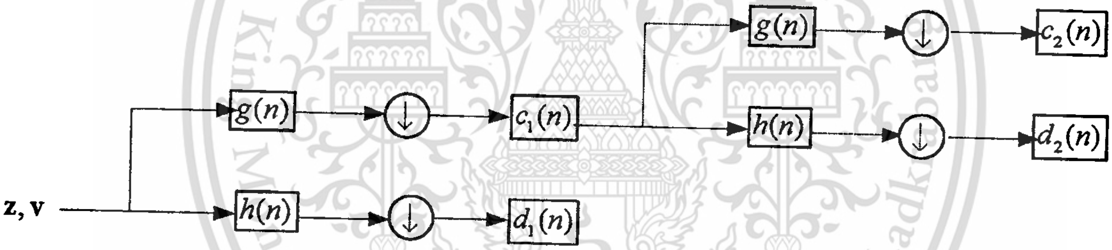
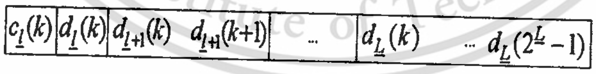


Figure 4.3: two-level filter bank



$c_{\underline{l}}(k)$	$d_{\underline{l}}(k)$	$d_{\underline{l}+1}(k)$ $d_{\underline{l}+1}(k+1)$	...	$d_{\underline{L}}(k)$ ... $d_{\underline{L}}(2^{\underline{L}}-1)$

Figure 4.4: Feature vector at level $\underline{l}$ taken as the input and output of the FIR system

To simplify the explanation, we define the following functions:

$$\mathbf{c}_{\underline{l}}^{(q)} = [c_{\underline{l}}^{(q)}(0), c_{\underline{l}}^{(q)}(1), ..., c_{\underline{l}}^{(q)}(2^{\underline{l}} - 1)]', \tag{4.9}$$

$$\mathbf{d}_{\underline{l}}^{(q)} = [d_{\underline{l}}^{(q)}(0), d_{\underline{l}}^{(q)}(1), ..., d_{\underline{l}}^{(q)}(2^{\underline{l}} - 1)]', \tag{4.10}$$

$$\mathbf{a}_{\underline{l}}^{(q)} = [c_{\underline{l},k}^{(q)}, d_{\underline{l},k}^{(q)}, d_{\underline{l}+1,k+1}^{(q)}, \cdots, d_{\underline{l}+\underline{L},k+2^{\underline{L}}-1}^{(q)}]' \tag{4.11}$$

$$\mathbf{a}_{(\underline{L},k)}^{(q)} = \mathbf{a}_{\underline{L},k}^{(q^{(real)})} + j\mathbf{a}_{\underline{L},k}^{(q^{(img)})}, q = (v_i, z_i) \tag{4.12}$$

$$\mathbf{a}_{\underline{l}}^{(v(i))} = [f_{\underline{l}}^{(i)}(1), f_{\underline{l}}^{(i)}(2), ..., f_{\underline{l}}^{(i)}(\underline{N})]' \tag{4.13}$$

$$\mathbf{a}_{\underline{l}}^{(z(i))} = [g_{\underline{l}}^{(i)}(1), g_{\underline{l}}^{(i)}(2), ..., g_{\underline{l}}^{(i)}(\underline{N})]' \tag{4.14}$$

where $\mathbf{a}_{\underline{l}}^{(q)}$ is the feature vector of wavelet coefficients at stage $\underline{l}$ shown in Fig.4.4, $\underline{N}$ is a total number of element in $\mathbf{a}_{\underline{l}}^{(q)}$, $\underline{L}$ is the number of the feature vector level, and $[.]'$ means the transposition. After that, the FIR Wiener filter shown in Fig.4.5 is applied to reduce the fluctuation of the wavelet coefficients of the barycenter and its velocity by using the following equations:

$$\hat{a}_{\underline{l}}^{(q)}(k) = \sum_{m=0}^{M-1} w_a(m)\bar{a}_{\underline{l}}^{(q)}(k-m), q = (v_i, z_i), \tag{4.15}$$

where $w_a(m)$ is the impulse responses of the FIR Wiener filter, M is the order of the FIR Wiener Filter. $\bar{a}_{\underline{l}}^{(q)}(k)$, $\hat{a}_{\underline{l}}^{(q)}(k)$ are the input and the output of the FIR Wiener filter, respectively.

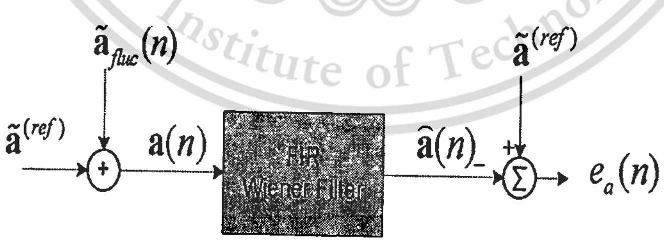
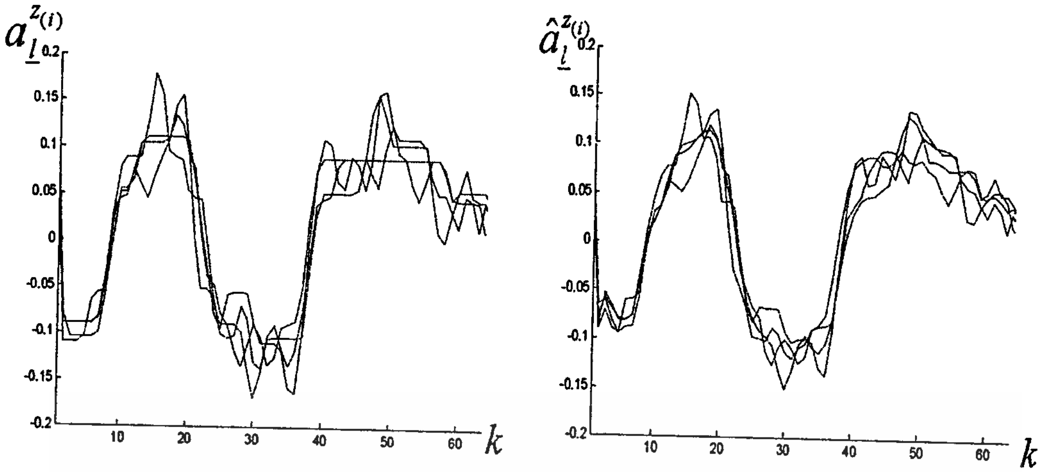


Figure 4.5: FIR-Wiener filter

Figure 4.6 shows that after passing the Wiener filter, some fluctuation within the wavelet coefficients is reduced.



(a) Wavelet coefficients before Wiener filter (b) Wavelet coefficients after Wiener filter

Figure 4.6: Wavelets coefficients before(a) and after wiener filter(b)

4.3 Impulse response of FIR system characterizing handwriting system

Let $f_{\underline{l}}^{(i)} = \hat{a}_{\underline{l}}^{v(i)}$ and $g_{\underline{l}}^{(i)} = \hat{a}_{\underline{l}}^{z(i)}$. We consider that a handwriting system characterizing the handwriting motion in the handwriting process is described by the dynamic features in the corresponding part of handwriting process. The system is realized by considering the wavelet coefficients $f_{\underline{l}}^{i}$ and $g_{\underline{l}}^{i}$ as the input and output of the system, respectively as can be seen in Fig.4.7.

It is assumed that the system can be described by

$$\hat{g}_{\underline{l}}^{(i)}(k;\mathbf{h}_{\underline{l}}^{(i)}) = \sum_{m=0}^{M-1} h_{\underline{l}}^{(i)}(m) f_{\underline{l}}^{(i)}(k-m), \tag{4.16}$$

$(k = 0, 1, 2, ..., K_i - 1)$

where $\mathbf{h}_{\underline{l}}^{(i)} = [h_{\underline{l}}^{(i)}(0), h_{\underline{l}}^{(i)}(1), ..., h_{\underline{l}}^{(i)}(M-1)]'$ is the impulse response of the system, M is the order the FIR system, and $\hat{g}_{\underline{l}}^{(i)}(k;h)$ is the approximation of $g_{\underline{l}}^{(i)}(k;h)$. The impulse response can be obtained by minimizing the least-square error at M as

$$E_{\underline{l}}^{(i)} = \sum_{k=0}^{K_i-1} |e_{\underline{l}}^{(i)}(k)|^2 \rightarrow min \tag{4.17}$$

where $e_{\underline{l}}^{(i)}(k) = \hat{g}_{\underline{l}}^{(i)}(k) - g_{\underline{l}}^{(i)}(k;\mathbf{h}_{\underline{l}}^{(i)})$.

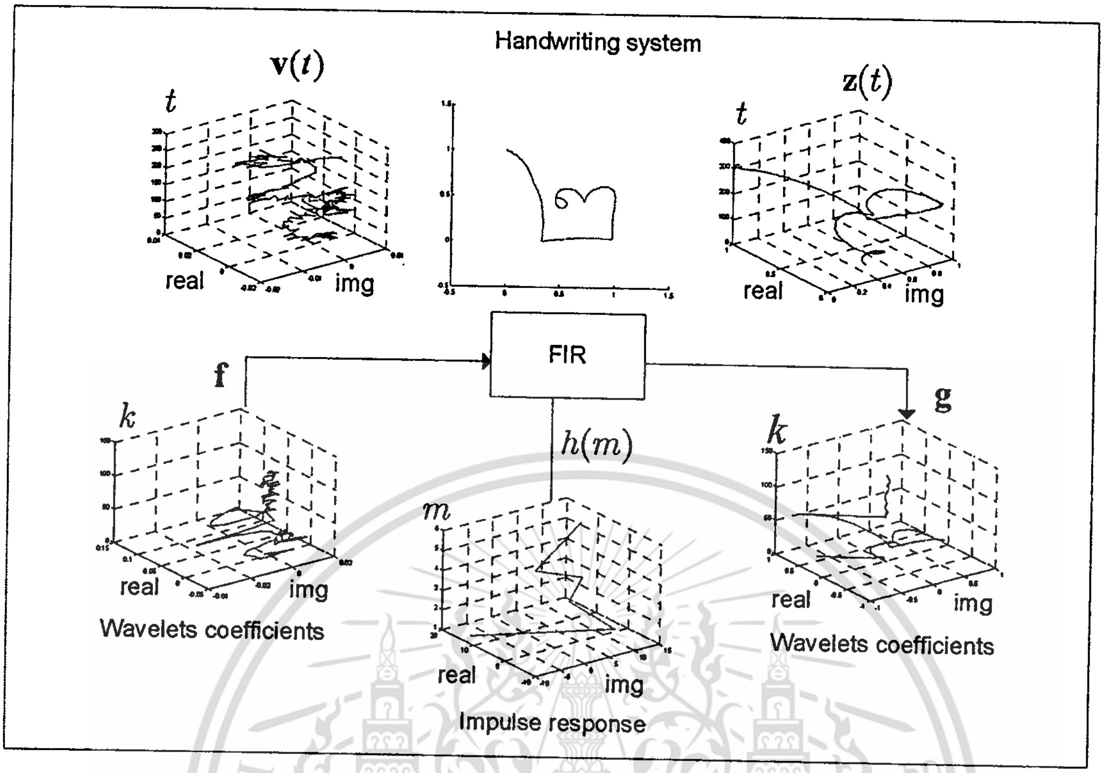


Figure 4.7: FIR system representing handwriting system

The details on how to minimize the least-mean square error is shown in [Appendix B]. Figure 4.8 shows the comparison of the impulse response obtained from same and different numerals written by same and different writers. It can be seen from Fig.4.8 that the impulse responses obtained from the same numeral and the same writer are quite similar and different from those obtained from different numerals and different writers.

Figure 4.9 shows the impulse responses of the FIR system obtained from two Khmer characters. It can be seen from Fig.4.9 that the impulse responses of the FIR system obtained from different numerals are different. Therefore, it is considered that the impulse response can be used as the individual feature for the particular Khmer characters.

4.4 Summary

The method to extract the stable and individual handwriting feature was discussed. Then the stable and individual handwriting feature was extracted. First, the velocity and

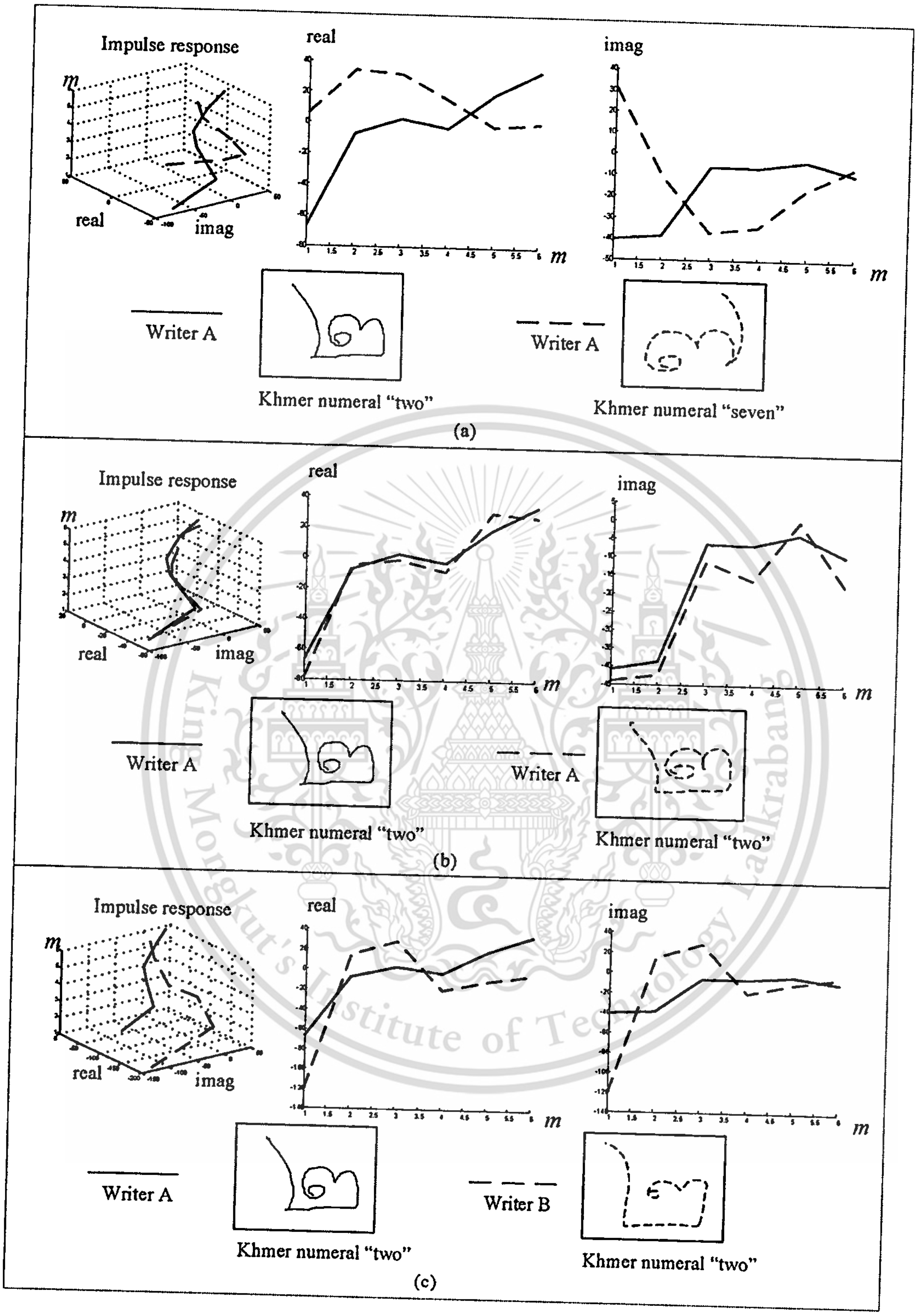


Figure 4.8: (a) Impulse responses obtained from numeral "two" and "seven" written by the same writer, (b) Impulse response obtained from numeral "two" written by the same writer, (c) Impulse response obtained from numeral "two" written by different writers

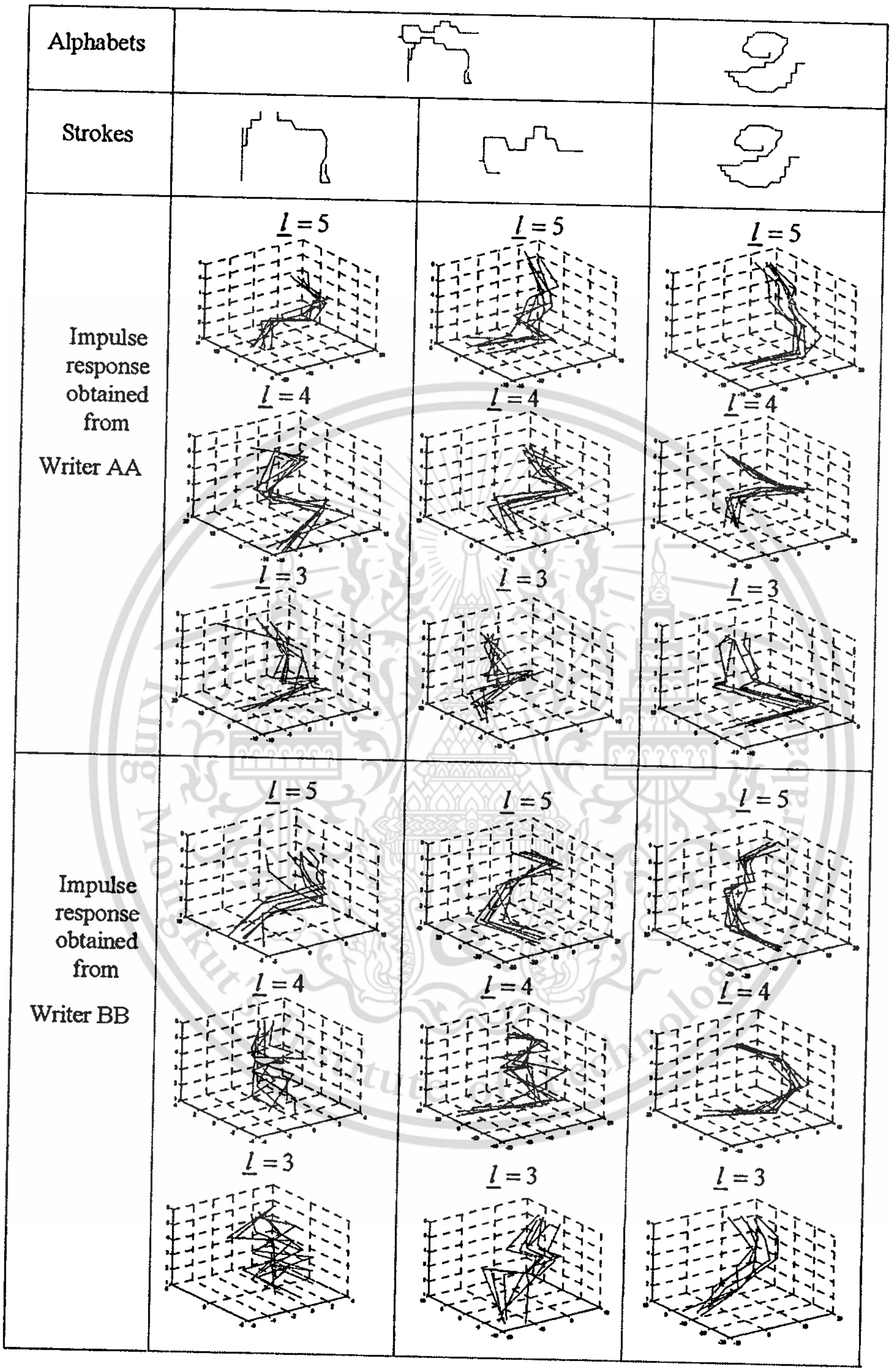


Figure 4.9: Impulse responses obtained from Khmer character "kor" and character "khor" written by two different writers from level 3-5 of coefficients of feature vector

trajectory of the Barycenter were defined by a complex valued function to describe the handwriting motion. After that, the above two features were expanded into wavelet series to extract the stable feature of handwriting motion. Next, the handwriting system characterizing the handwriting motion was realized by using the wavelet coefficients of the velocity and the trajectory of the Barycenter as the input and output of the FIR system, respectively. It was shown that the impulse response of the above FIR system is able to represent the stable and individual feature of handwriting motion.

CHAPTER 5

Writer Dependent Character Recognition

In this chapter, a method to recognize the character is described. In order to recognize the character in the limit of writer dependent, the Euclidean distance between the feature parameter vector obtained from the previous chapter is used. In addition, the writer recognition algorithm is given in Section 5.1.

5.1 Character recognition algorithm

In this section, the feature parameter vector obtained from in the preceding chapters is used for Khmer character recognition. The Euclidean distance between unknown character and the reference one which were chosen from any specific writer was used to recognize the character of that specific writer. It is assumed that the reference patterns of known classes for Khmer characters are defined by $C_0, C_1, ..., C_{N_c-1}$, respectively. Then an unknown character x is assigned to a class $C_i \in C_0, C_1, C_2, ..., C_{N_c-1}$ if

$$S_{min}(C_i, x) \;=\; \min S(C_l, x), (l = 0, 1, 2, ..N_c) \qquad (5.1)$$

where N_c is the total number of classes, and

$$S(C_l, x) = \frac{1}{\underline{N}\,\underline{L}} \sum_{\underline{l}=0}^{\underline{L}} \sum_{n=1}^{\underline{N}} \sum_{i=1}^{N_s} ||\mathbf{h}_{\underline{l},n,i}^{(ref_l)} - \mathbf{h}_{\underline{l},n,i}^{(x)}||$$

$$\mathbf{h}_{\underline{l},n,i}^{(ref_l)\prime} = [h_{\underline{l},n,i}^{(ref_l)}(0), h_{\underline{l},n,i}^{(ref_l)}(1), ..., h_{\underline{l},n,i}^{(ref_l)}(M-1)]$$

$$\mathbf{h}_{\underline{l},n,i}^{(x)\;\prime} = [h_{\underline{l},n,i}^{(x)}(0), h_{\underline{l},n,i}^{(x)}(1), ..., h_{\underline{l},n,i}^{(x)}(M-1)]$$

and $\underline{N}$ is total number of reference data for each class, N_s is the number of strokes in handwriting character, $h_{\underline{l},n,i}^{ref_l}$ is an impulse response obtained from the n^{th}reference data for class

C_l at the level $\underline{l}$ of the feature vector, $\|.\|$ is Euclidean norm, and $S_{min}(C_i, x)$ is the minimum Euclidean distance obtained from $S(C_l, x)$. An unknown class will be assigned to a known class if its Euclidean distance to one of known classes is the minimum one i.e. $S_{min}(C_i, x)$. Figures 5.1 and 5.2 show the plots of Euclidean distances obtained from some numerals. From these figures, it can be seen that the distances between the test numerals to the matched references are less than those obtained from the test numerals to the unmatched ones.

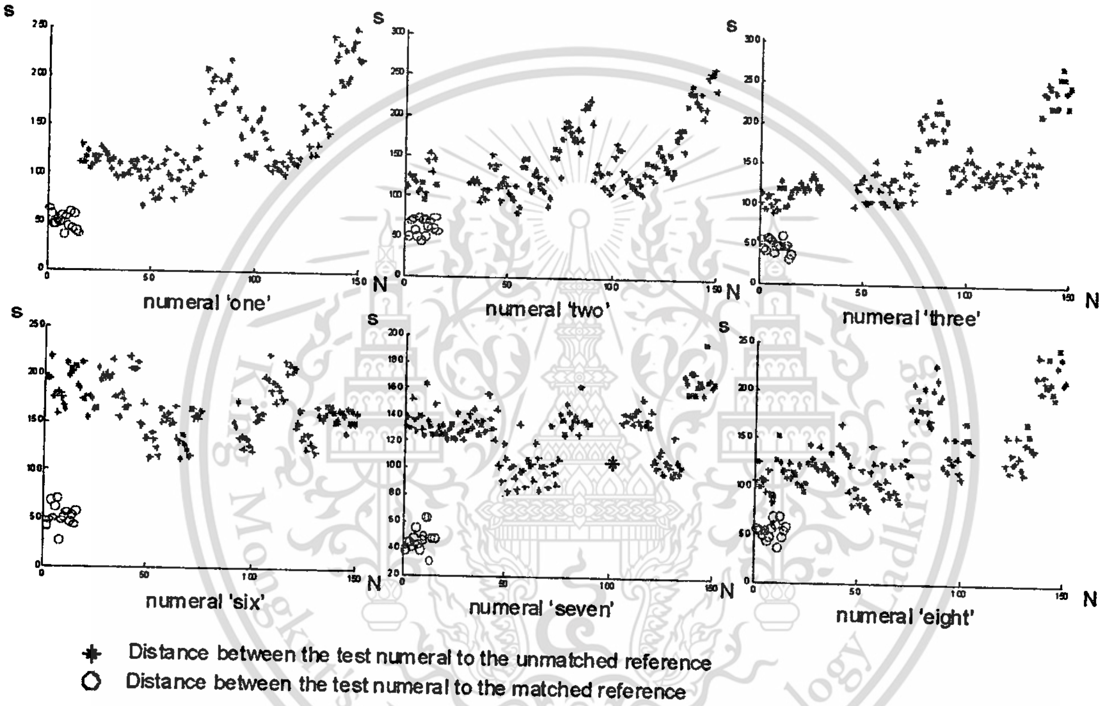


Figure 5.1: Euclidean distance obtained from some numerals

The on-line writer dependent Khmer character recognition experiments using the collected data in the database using a tablet PC and a program for collecting Khmer data will be described in the following chapter. Figure 5.3 show the tablet PC and an interface of the program for collecting Khmer data.

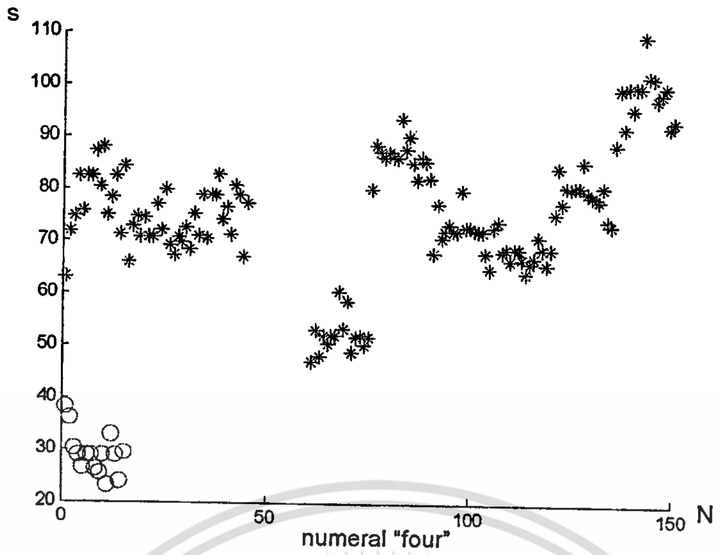
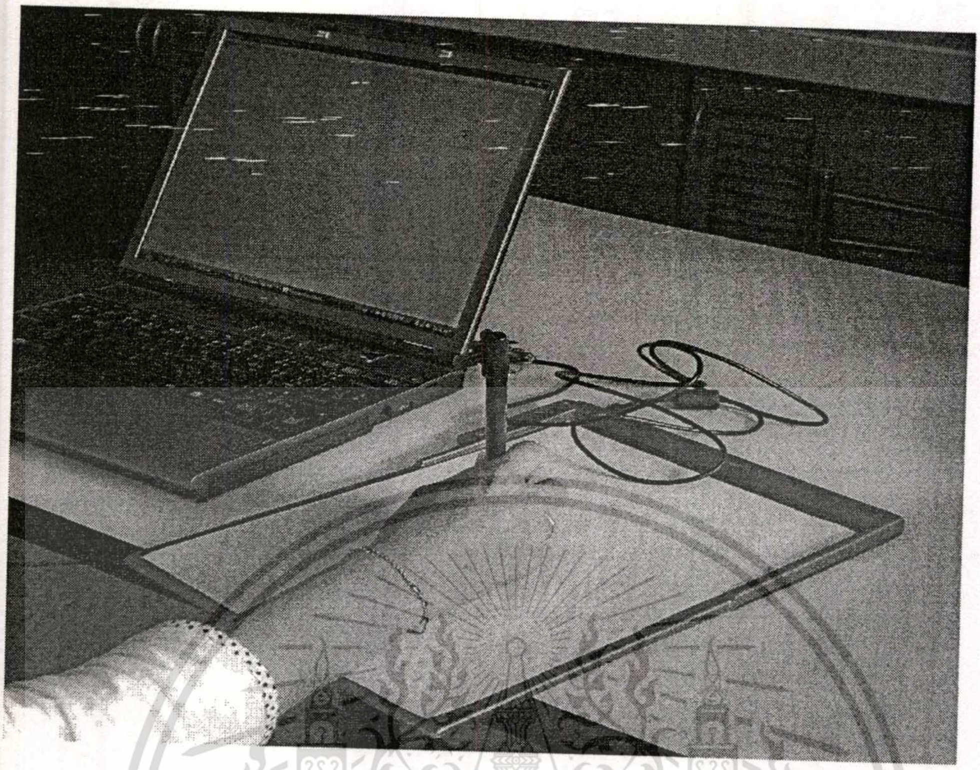


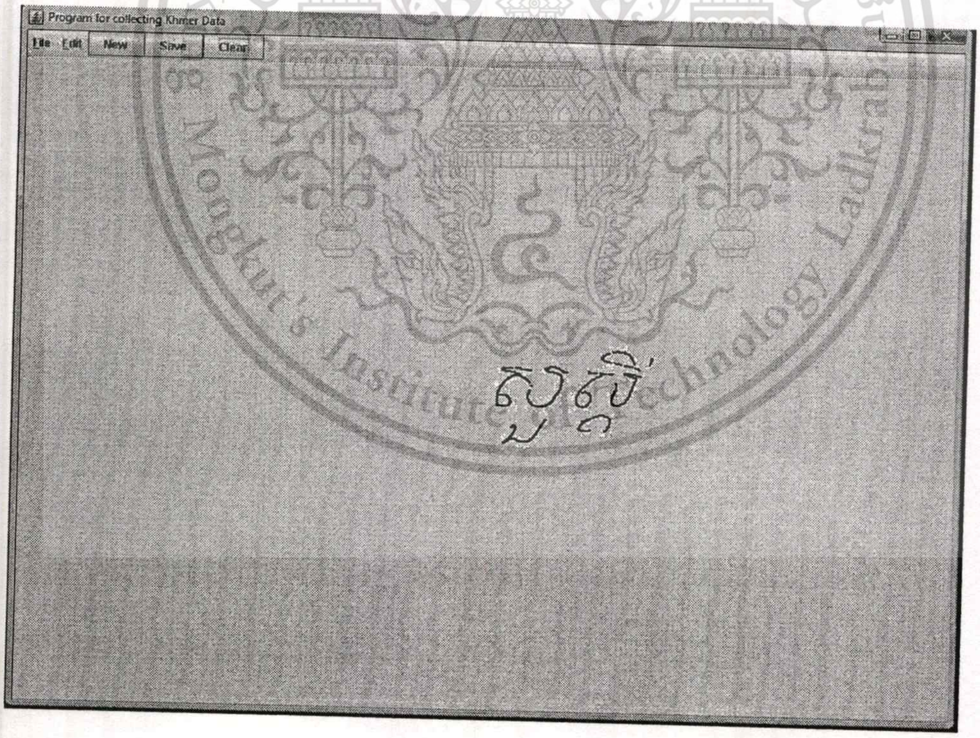
Figure 5.2: Euclidean distance between from numeral "four" and the others

5.2 Summary

The on-line writer dependent Khmer character recognition has been described in this chapter. The Euclidean distance was used to classify the Khmer numeral and characters. A program for collecting Khmer data has been presented.



(a) Facilities



(b) Interface

Figure 5.3: (a) the facilities for collecting Khmer data ;(b) example of an interface of program for collecting Khmer data

CHAPTER 6

Experimental Results

In this chapter, the performance of on-line writer dependent Khmer character recognition experiments of the proposed method is described. First, the details of the databases for the on-line writer dependent character recognition experiment are described in Section 6.1. Then the on-line writer dependent character recognition experiments are performed using the on-line writer dependent character recognition method described in the previous chapter and the experimental results are given to show the effectiveness of the proposed method in section 6.2. In order to show the effectiveness of the proposed method, the comparison to the other methods in the works [8]is made based on the database in this study. It is shown that the average recognition rates obtained from the proposed method in this study are better than those obtained from the works [8] in Section 6.2.

6.1 Database

The Khmer alphabets and numerals in the database used for the experiments were collected by using digital tablets connected to the computer. The database is consisting of two data sets. The first data set consists of 1500 Khmer numerals from "zero" to "nine" written by 12 people in one year; and the second data set consists of 30 times of 33 Khmer Alphabets, composing of 33 independent Khmer alphabets, written by 5 people in 8 months. Figure 6.1 shows the example of Khmer numeral from "zero" to "nine" written by different writer in the first dataset of the database; and the Fig.6.2 shows the example 33-Khmer consonants of the second dataset of the database.

6.2 Character recognition experiments

In this section, the on-line writer dependent Khmer character recognition are performed in order to evaluate the performance of the proposed method in this study. In the two experiments, 5 data were selected randomly and used as reference data for a particular character and a particular writer. Since there are many characters in Khmer language that have similar shape, some misclassification occurred in the simulation as shown in Fig.6.3. However, the overall recognition rates are acceptable as can be seen in Table6.1 and 6.2. The on-line writer dependent character recognition process of the first dataset is 0.68 seconds for one character with 112 sample points. The experiments were performed on the the 32-bits Windows Vista home basic, Intel(R) Core(TM) 2CPU T5600 @1.83GH_z 1.83GH_z and 1 GB of RAM. Table 6.1 shows the recognition rates obtained from the first experiment. Table 6.2 shows the recognition rates obtained from the second experiment. From Table 6.1 and Table 6.2, the results show that the average of the recognition rate obtained from the proposed method is better than those of the methods in [7, 8].

6.3 Summary

The on-line writer dependent Khmer character recognition experiments were performed using the on-line character recognition system developed in Chapter 5. It was found from the experimental results that the impulse response of the FIR systems characterizing the handwriting motions obtained from different characters are different and they can represent the stable and individual handwriting feature. Furthermore, in order to show the effectiveness of the proposed method, the comparison between the proposed method and those in [7, 8] was made based on the database in this study. From the experimental results, it can be seen that the overall recognition rates obtained by using the proposed method in this study are better than those obtained from the methods proposed in [7, 8] eventhough for some writers, i.e. "E, K, G," in the first dataset it gives a low performance comparing to the methods in [7, 8]. In other words, it can be clarified that the proposed method in this study gives a better performance comparing to those in the works [7, 8]. It means that the developed system in this

Table 6.1: Table of recognition rates of the first data set

Writer	Number of training numerals (5/numeral)	Number of testing numerals (15 /numeral)	Recognition rates (%)		
			Proposed method	Method in [7]	Method in [8]
A(0-9)	50	150	99.33	96.66	99.33
B(0-9)	50	150	100	99.33	99.33
C(0-9)	50	150	99.33	98.67	100
D(0-9)	50	150	98.00	90.67	96.67
E(0-9)	50	150	98.00	98.67	96.66
F(0-9)	50	150	92.66	90.66	95.99
G(0-9)	50	150	97.33	98.00	99.33
H(0-9)	50	150	99.33	95.33	92.67
I(0-9)	50	150	100	96.66	100
J(0-9)	50	150	100	97.33	100
K(0-9)	50	150	96.66	97.33	99.33
L(0-9)	50	150	100	95.33	97.33
Average			98.38	96.22	98.05

Table 6.2: Table of recognition rates of the second dataset

Writer (33 alphabets)	Number of Training data (5/alphabet)	Number of testing alphabets (30 /alphabet)	Recognition rates (%)		
			Proposed method	Method in [7]	Method in [8]
AA	155	990	96.36	94.14	88.68
BB	155	990	95.25	79.89	82.02
CC	155	990	98.88	91.51	93.83
DD	155	990	99.79	96.66	96.77
EE	155	990	99.79	96.16	97.57
Average			97.97	91.67	91.77

study is a practical on-line writer dependent Khmer character recognition system.

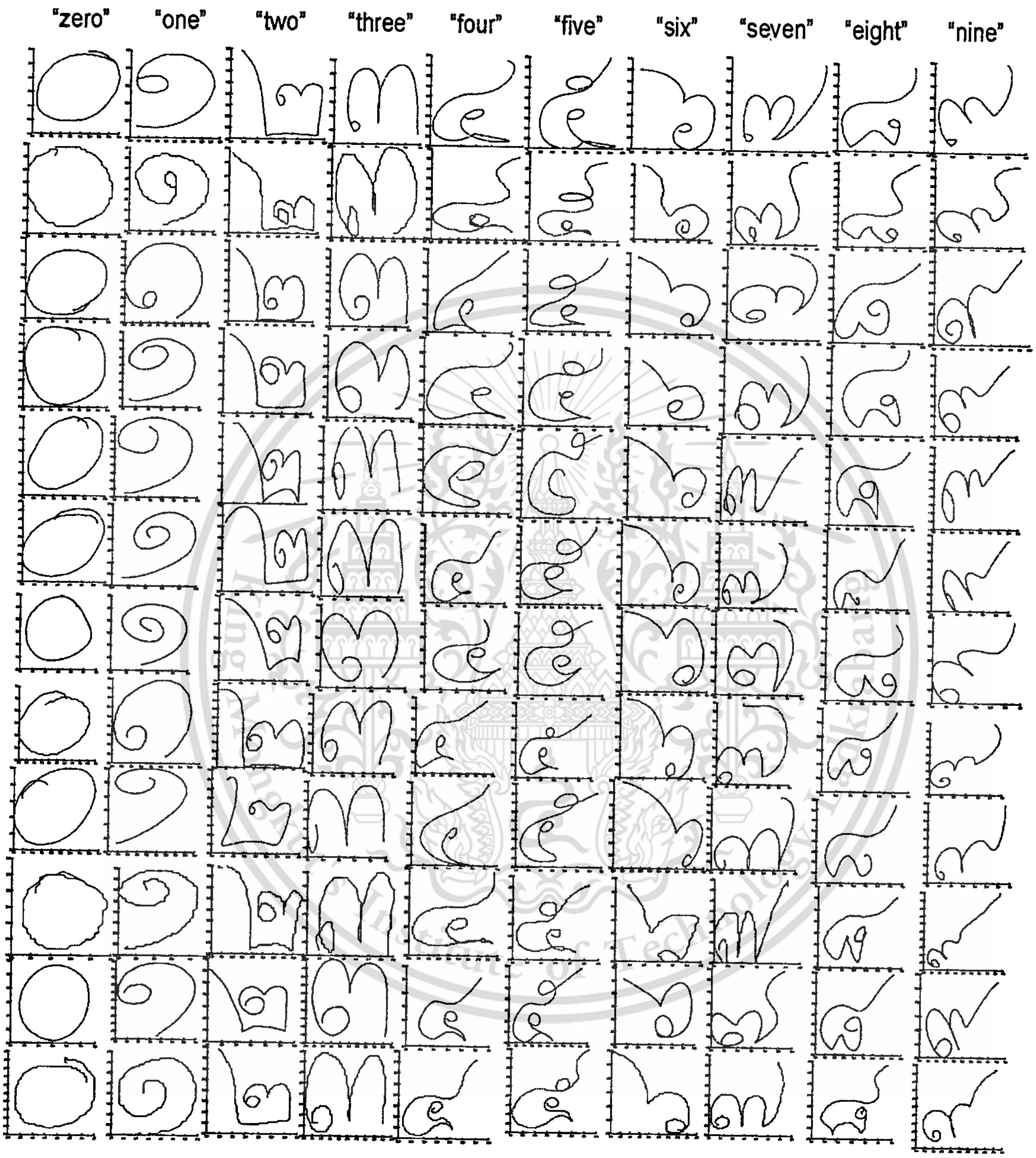


Figure 6.1: Example of Khmer numeral "zero" to"nine" written by twelve writers in the first dataset in the database

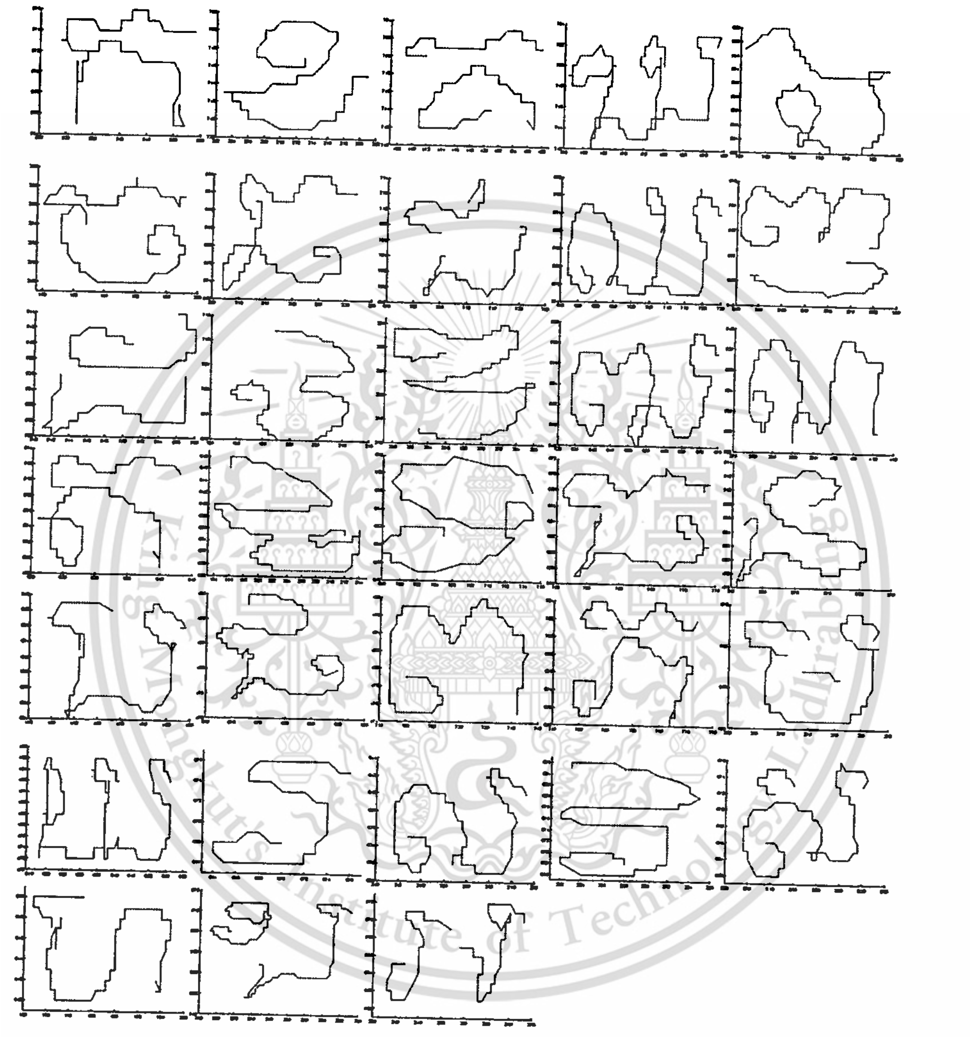


Figure 6.2: Example of 33-Khmer consonants written by a writer in the second dataset in the database

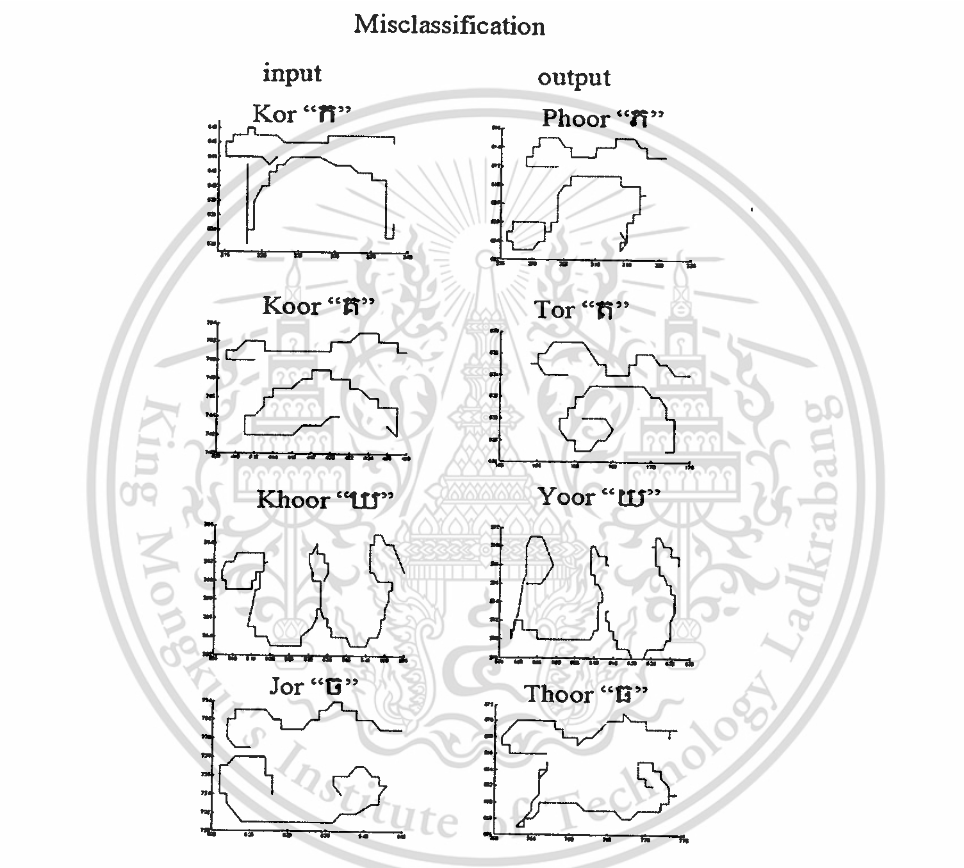


Figure 6.3: Example of some misclassification of some similar Khmer consonants

CHAPTER 7

Conclusion

In this thesis, an on-line writer dependent character recognition method based on FIR system characterizing handwriting motion for Khmer has been proposed. In Chapter 1, the background on the study of on-line writer dependent Khmer character recognition, the objectives, and the structure of the thesis were described. In the Chapter 2, the basic idea to represent the handwriting process as a system was described. That is, the Barycenter determined from the center point of the script and the two adjacent pen-tip positions with respect to time in handwriting process was used to reduce the fluctuation of pen-tip movement in handwriting process; and it was shown that the handwriting motion in handwriting process can be represented by two features, the velocity and the Barycenter trajectory. Then the handwriting system characterizing the handwriting motion was realized by the FIR system taking the wavelet coefficients of the velocity and the Barycenter trajectory as the input and the output, respectively. In addition, it was clarified that the impulse response of the FIR system can be used as the feature characterizing the handwriting motion. Therefore, in this study, the on-line writer dependent character recognition was reduced to system identification problem. In Chapter 3, the fluctuations of handwriting related to size of script, location of the script, and the duration time in handwriting process were reduced by applying the suitable three kinds of normalization; such as, normalization of size, location, and duration time in handwriting process. In Chapter 4 the stable and individual handwriting feature was extracted. First the velocity and the trajectory of the Barycenter were defined by a complex valued function to describe the handwriting motion. Then in order to extract the time-frequency characteristic of the handwriting motion for a particular person, the trajectory and the velocity of the Barycenter were expanded into wavelet series. Then the fluctuation of the obtained wavelet coefficients is reduced by passing into FIR Wiener filter. Moreover, the FIR system characterizing the handwriting motion was realized by considering the approximated wavelet coefficients of the velocity and the trajectory of the Barycenter from the FIR wiener filter as the input and the output of the FIR system, respectively. The obtained impulse response of the FIR system was used as the individual feature for a particular character. In Chapter 5, on-line writer dependent Khmer character recognition algorithm was introduced. The Euclidean distance between the impulse response of the reference character and the character to be recognized has been used to classify the unknown characters for a particular writer. In Chapter 6, the on-line writer dependent Khmer character recognition experiments were performed based on the algorithm in the Chapter 5. It has been shown from the experimental results that the impulse responses of the FIR system characterizing the handwriting motions obtained from different characters are different and they can represent the stable and individual handwriting feature. Furthermore, in order to show the effectiveness using the proposed method, the comparison between the proposed method and the methods in works [7, 8] was done by using the database in this study. It was shown that the average recognition rates obtained by using the proposed method are better than those obtained by using the methods in the works [7, 8]. In other words, it can be concluded that the method in this study gives a better performance comparing to those in the works [7, 8]. It means that the developed system in this study is a practical on-line writer dependant Khmer character recognition.

To sum up, the objectives of this study has been achieved as follows:

1. A stable and individual handwriting feature were described by the impulse response of the FIR system characterizing the handwriting motion.
2. A handwriting process was represented by the FIR system.

There are many possibilities to do the further research related to on-line Khmer character recognition such as on-line writer depenent Khmer character recognition by using all the available dependent and independent vowels, the feet of the consonants, and the symbols.

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APPENDICES

APPENDIX A

Khmer writing

Appendix A

Khmer Writing

Khmer is the official language used in Cambodia, a country in South-East Asia. The language belongs to the group Khmer-Mon in the family of Austro-Asiatic language spoken in South-East Asia and in India. Khmer langue is based on the alpha-syllabic writing: The symbols can represent either a character, a syllable or a word.

1. Khmer Alphabet

The 33 independent Khmer consonants, 28 dependent vowels, independent vowels, some symbols, and the punctuations are the basics for Khmer handwriting.

1.1. 33 consonants

The figure below shows the 33 Khmer consonants.

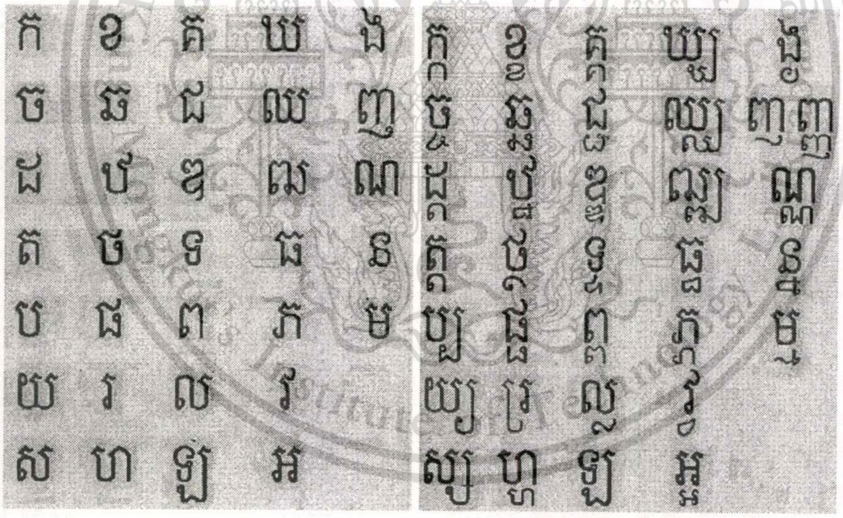


Figure 1: 33 Khmer consonants and their feet

Each consonant has it own foot which has different shape from the body (consonant). However there are some exceptional cases such as the letters "ញ, ហ ", each foot of these letters has the same shape. Plus, the consonant "ឡ" does not consist of a foot. The consonant "ត" and "ដ" have the same foot which is "្ត". To combine a word, a consonant can go with its own foot or others' feet. Where as, one consonant can be combined with either one or two feet. In case it is combined with two feet, one foot must be the foot of "រ" which is "◌្រ" .

Example: ស្ត្រ ង្គ្រ ន្ត្រ ន្ទ្រ

1.2. 28 dependant vowels

Khmer has 28 dependant vowels as shown in the figure below. They are called dependent vowels because they can not stand alone without one of the 33 consonants.

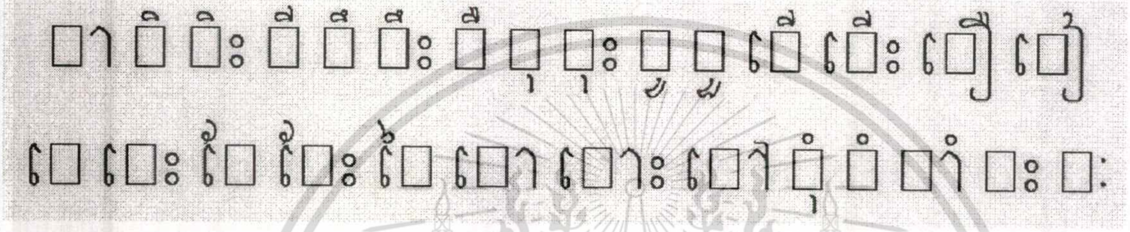


Figure 2: 28 Khmer dependent vowels

The rectangle is correspondent to a replacement of a consonant, a consonant with a foot, or a consonant with two feet in writing. For example, "កុំ", "តើ", "ខ្ញុំ", "ស្រី", "ស្ត្រី,".

However there is a special case appeared with the combination of a character "ហ" and "◌ា". The combination can be "ហ," but if it is so it must not be able to distinguish between the character "ហ" and the result of the combination of the "ហ" and "◌ា". To differentiate between the two, the combination between "ហ" and "◌ា" becomes "បា".

ប+◌ា read Baa, written as បា, not written as ហ because there is a consonant ហ (pronounce as Hor).

1.3. Independent vowels

Khmer consists of some independent as shown in the below figure. They are called independent for their own independency: They can stand alone without another consonant or vowel.

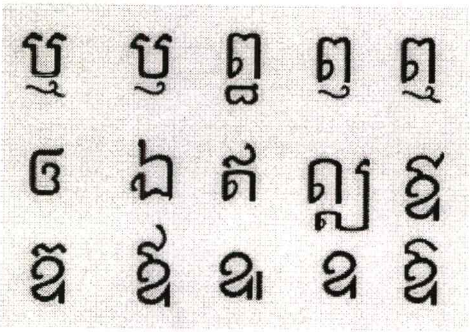


Figure 3: Independent vowels

They can form a word or a syllable without the help of other consonants or vowel.

For example: “ឪ” which means “father”, and “ឬ” which means “or”.

1.4. Symbols

Some Khmer symbols are shown in the below figure. They are used with the consonants and the consonant appeared with one or two feet.

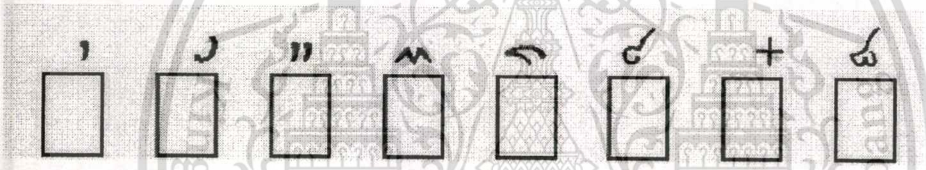


Figure 4: Some Khmer symbols

Examples:

សក់ និស្ស័យ ចំប៉ា

ពតិមាន ចំា ដ៏ ស៊ូ

1.5. Punctuation

Khmer has also its own punctuation symbols as shown in the below figure. They can be used to show the end of a paragraph, end of a sentence or at the end of the text etc. They can appear at the beginning, at the middle or at the end of a sentence, a paragraph or a text.

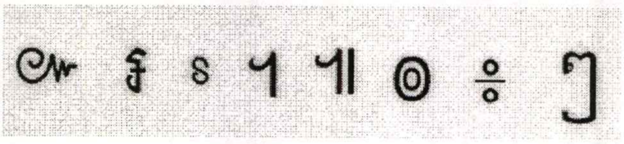


Figure 5: Symbols of punctuation

For example:

៛ : The symbol for the Khmer currency "riel"

។: The symbol to show the end of the sentence. It should be of course placed at the end of the sentence.

៕: The symbol to show the end of the text, placed at the end of the text or a document.

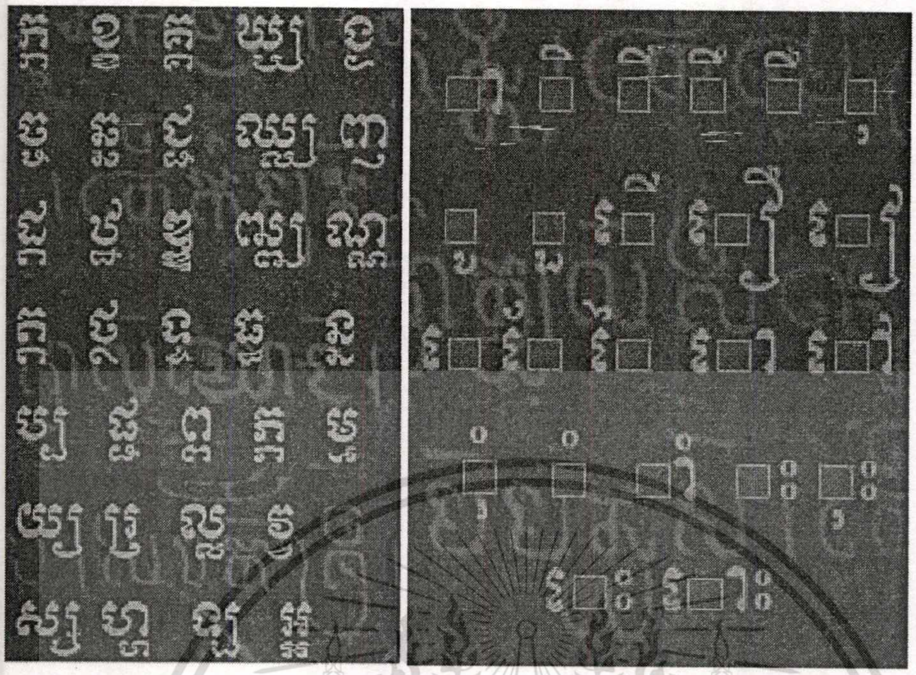
1.6. 10 Khmer numerals

Khmer has 10 numerals as many countries in the world which are shown in the below figure.

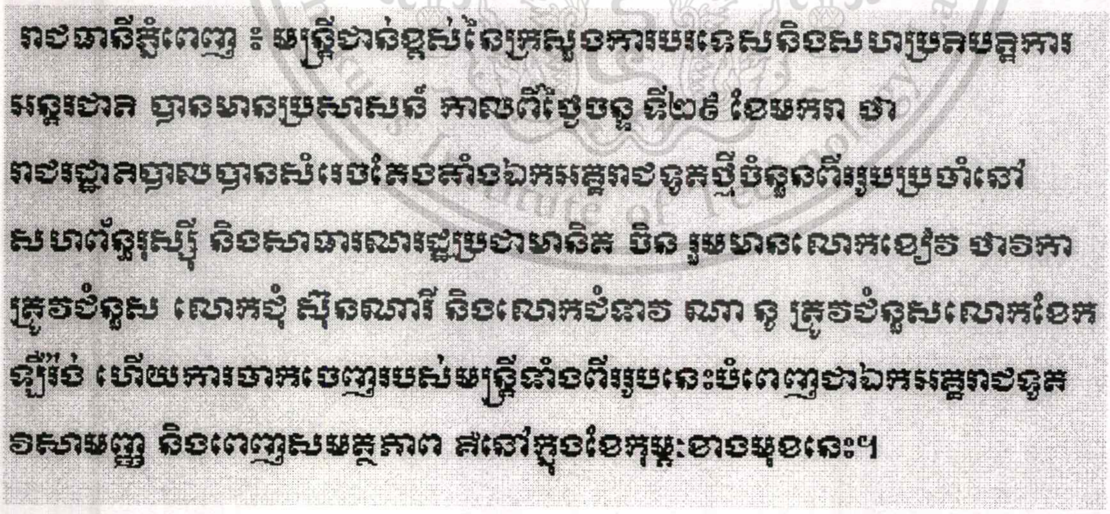
Figure 6: 10 Khmer numerals from "zero" to "nine"

2. Style of writing

In Khmer, there are different styles of writing as can be seen in the below figure the consonants and the vowels can be written in Moul(round) style. They are frequently used in the title or highlight of newspapers, magazines, or the books.



Example of some texts:



រាជធានីភ្នំពេញ ៖ មន្ត្រីជាន់ខ្ពស់នៃក្រសួងការបរទេសនិងសហប្រតិបត្តិការ
អន្តរជាតិ បានមានប្រសាសន៍ កាលពីថ្ងៃចន្ទ ទី២៩ ខែមករា ថា
រាជរដ្ឋាភិបាលបានសំរេចតែងតាំងឯកអគ្គរាជទូតថ្មីចំនួនពីររូបប្រចាំនៅ
សហព័ន្ធរុស្ស៊ី និងសាធារណរដ្ឋប្រជាមានិត ចិន រួមមានលោកខៀវ ថាវកា
ត្រូវជំនួស លោកជុំ ស៊ីនណារី និងលោកជំនាវ ណា ទូ ត្រូវជំនួសលោកខែក
ឡឺរ៉ង់ ហើយការចាកចេញរបស់មន្ត្រីទាំងពីររូបនេះបំពេញជាឯកអគ្គរាជទូត
វិសាមញ្ញ និងពេញសមត្ថភាព នឹងនៅក្នុងខែកុម្ភៈខាងមុខនេះ។

រាជធានីភ្នំពេញ ៖ មន្ត្រីជាន់ខ្ពស់នៃក្រសួងការបរទេស និងសហប្រតិបត្តិការអន្តរជាតិ បានមានប្រសាសន៍ កាលពីថ្ងៃចន្ទ ទី២៩ ខែមករា ថា រាជរដ្ឋាភិបាលបានសំរេចតែងតាំងឯកអគ្គរាជទូតថ្មីចំនួនពីររូបប្រចាំនៅ សហព័ន្ធរុស្ស៊ី និងសាធារណរដ្ឋប្រជាមានិត ចិន រួមមានលោកខៀវ ថារិកា ត្រូវជំនួស លោកជុំ ស៊ុនណារី និងលោកជំទាវ ណា នូ ត្រូវជំនួសលោកខែក ឡឹវ៉ង ហើយការចាកចេញរបស់មន្ត្រីទាំងពីររូបនេះ ទៅបំពេញជាឯកអគ្គរាជទូតវិសាមញ្ញ និងពេញសមត្ថភាព នៅក្នុងខែកុម្ភៈខាងមុខនេះ។

APPENDIX B

Least square error

Appendix B

Least-Mean Square Error Method Applied with FIR system

The least mean square problem can be elaborately posed as follows. Let A be an $m\text{x}n$ constant matrix, $\mathbf{b}$ be an $m\text{x}1$ constant vector, both are given.

Find an $n\text{x}1$ constant vector such that

$$A\mathbf{x} = \mathbf{b} \qquad \text{(i)}$$

There are three possibilities that can be occurred:

1. $m > n$
2. $m = n$—regular case. If A is a non-singular matrix then $\mathbf{x} = A^{-1}\mathbf{b}$
3. $n < m$

The cases number 1 and number 3 are considered as irregular cases. To solve the problems—irregular cases, "pseudo inverse or generalized inverse" is used. In such cases, we turn the problem to find an "optimal approximation" or "optimal solution."

In case of FIR system used in Khmer character recognition, it is usual case for solving the irregular cases. In this case, the vector $\mathbf{x}$ is replaced by the $\mathbf{h}$ which is the impulse response of the FIR system characterizing handwriting motion in handwriting process; and $\mathbf{b}$ is represented by $\mathbf{g}$.

The FIR system can be represented in the summation form by the following equation:

$$\hat{g}(k) = \sum_{m=0}^{M-1} h(m)f(k-m), \qquad k = 0,1,2...,K-1, \qquad \text{(ii)}$$

where $f(k)$ and $g(k)$ are the input and the output of the FIR system, respectively. The input and the output of the systems here are the approximated wavelet coefficients of the velocity and the Barycenter trajectory of a stroke of a character obtained after passing the FIR Wiener filter.

The equation (ii) can be rewritten in the matrix form as in eq.(i) by:

$$A\mathbf{h} = \mathbf{g} \qquad \text{(iii)}$$

where A is the matrix can be calculated from the input of the system by the equation (vi).

By minimizing the least mean square error of the system at order M, the optimal impulse response can be obtained. The least mean square error can be found by the following question:

$$E = \sum_{k=0}^{K-1} \left|\hat{g}(k) - g(k)\right|^2 \rightarrow \min \qquad \text{(iv)}$$

and the optimal impulse response can be calculated by the multiplication of the pseudo inverse of the matrix A and the output of the system $\mathbf{g}$:

$$\mathbf{h} = (A^T A)^{-1} A^T \mathbf{g}, \tag{v}$$

where

$$A = \begin{bmatrix} f(0) & 0 & 0 & \dots & 0 \\ f(1) & f(0) & 0 & \dots & 0 \\ f(2) & f(1) & f(0) & \dots & 0 \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ f(K-1) & f(K-2) & f(K-3) & \dots & f(K-M) \end{bmatrix} \tag{vi}$$

$$\mathbf{g} = [g(0) \quad g(1) \quad g(2) \quad \dots \quad g(N-1)]^T \tag{vii}$$

$$\mathbf{h} = [h(0) \quad h(1) \quad h(2) \quad \dots \quad h(M-1)]^T \tag{viii}$$

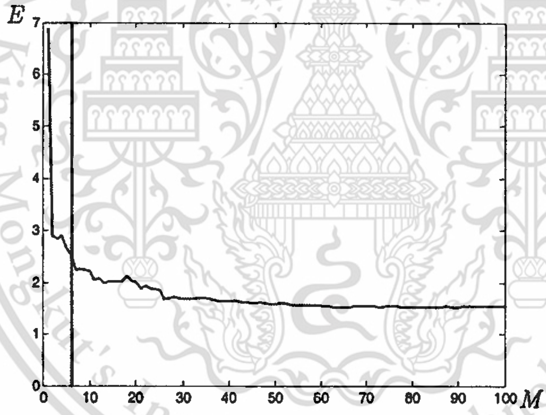


Figure i: The error obtained from the $\hat{g}(k)$ and $g(k)$ with the order of the impulse response system M

It is difficult to determine the exact order of FIR system to get the optimum least mean square error as it varies according to the training data. Figure i shows the error obtained by varying the order of the impulse response system M. The order of the FIR system which gives the minimum error is $M > 60$; however in our study we prefer an $M < 10$ to increase the speed of recognition process; in this case $M = 6$ is chosen as it gives in general a better performance because for $6 < M \leq 10$ the effectiveness of the recognition rates is not very significant comparing to the case $M = 6$.

Biography

Name-Surname	SOCHENDA KHEM
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Academic background	High school certificate from Preah Reach SomPhea High School in 2001. Bachelor's degree in Information Engineering from Institute of Technology of Cambodia.
Skill	Database, web programming, signal processing, on-line character recognition.

International Conference Proceeding Papers

1. P. Thumwarin, S. Khem, K. Janchitrapongvej, and T. Matsuura, "On-line character recognition for Khmer numeral based on DP Matching of Barycenter Trajectory," *ETCI-CON2007*, vol.2, pp.1015-1018, May 2007.

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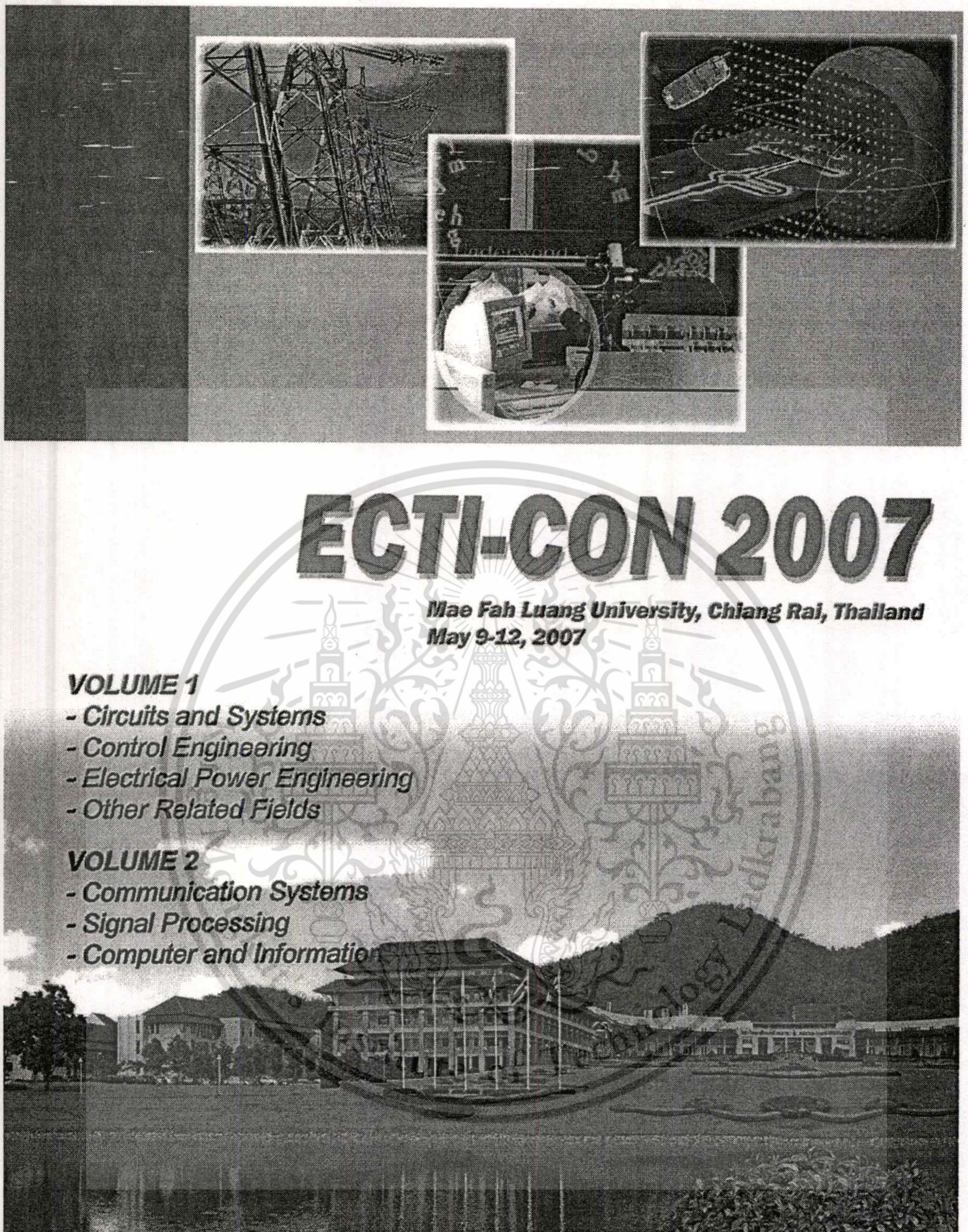

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On-Line Character Recognition for Khmer Numeral based on DP matching of Barycenter Trajectory

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***Abstract*-**We propose an on-line character recognition method for Khmer numeral based on DP matching of barycenter trajectory. First, the barycenter is determined from the center point of script and two adjacent pen-point positions with respect to time in handwriting process. Then the barycenter trajectory and its direction changes are used to describe the features of handwritten characters. Finally, the numeral is recognized by calculating the dissimilarity between the features of handwritten character using Dynamic Programming(DP) matching. Character recognition experiments are performed on database consisting of 5000 Khmer numerals. As the result, the average of recognition rate was 95.9%.

I. INTRODUCTION

Many methods for on-line character recognition have been reported[1][2][3]. In those methods, the pen-point position is used to recognize the character. It is considered that using pen-point position directly is not effective to extract the feature of the handwritten character. In this paper, the barycenter determined from the center point of script and two adjacent pen-point positions is used instead of pen-point position to extract the feature of the handwritten character. We considered that the feature of the handwritten character can be described by two features, the barycenter trajectory and its direction change. Finally, the incorporation of the barycenter trajectory and its direction changes into DP matching is used to recognize the character.

II. PREPROCESSING

It is considered that there are fluctuations depending on many factors such as age, habit, psychological and mental state, physical or practical conditions in handwriting process of writer. For instance, size, location, shape, and duration time in handwriting process of the same alphabet are never precisely the same even they were written by the same writer.

Fig.1 shows Khmer numeral 'one' written by different writers. From Fig.1, we can see that the characters are written in different sizes, locations and styles. In order to recognize the character effectively, such fluctuations of handwriting should be reduced.

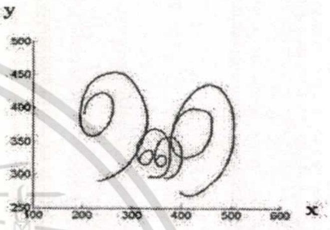

Figure 1: Khmer numeral 'one' written by different people.

It is assumed here that Khmer numerals are written on a graphical tablet to recognize the character. The horizontal and vertical components of pen-point position at a time, $t = n\tau (\equiv t_n)$, in handwriting process are denoted here as $x(t_n)$ and $y(t_n)$, respectively, where τ is a constant sampling rate.

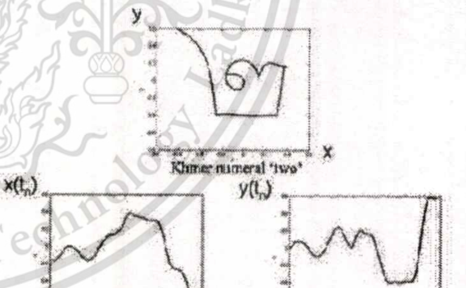

Figure 2: Khmer numeral 'two', its x components and y components (top to down, left to right).

Fig.2 shows Khmer numeral 'two' and its x, y components with respect to time in handwriting process. In order to reduce the fluctuation of handwriting, two kinds of normalization with respect to the size and location in handwriting process are performed as follows:

1) Normalization of size

The size of the script is standardized after removing the duplicated points of pen-point position. In order to make a standard size of script, the horizontal and vertical components, $x(t_n)$ and $y(t_n)$ are normalized as

$$\hat{p}(t_n)=\frac{p(t_n)-p_{\min}}{p_{\max}-p_{\min}},\ p=(x,y), \tag{1}$$

where $p_{\min}=\min\limits_{0\le n\le N-1} p(t_n)$, $p_{\max}=\max\limits_{0\le n\le N-1} p(t_n)$, (2)

and N is a total number of sampled points of pen-point position.

2) Normalization of location

The location of the script is normalized as follows:

$$c_p=\frac{1}{N}\sum_{n=0}^{N-1}\hat{p}(t_n),\ p=(x,y), \tag{3}$$

$$\tilde{p}(t_n)=\hat{p}(t_n)-c_p,\ n=0,1,2...N-1, \tag{4}$$

where c_p is the center point of script.

Fig.3 shows Khmer numeral 'two' before and after normalization. It can be seen from Fig.3 that the fluctuation of handwriting character can be reduced by using the normalization.

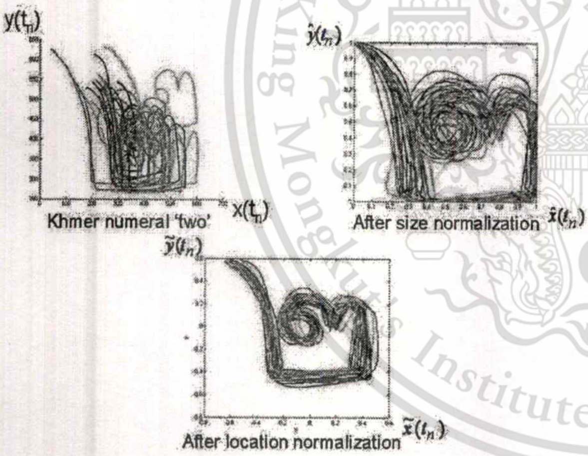

Figure 3: Khmer numeral 'two', after size normalizaton, and location normalization (left to rigth; top to down).

In order to reduce a fluctuation of pen-point movement in handwriting process, a trajectory of the barycenter determined from the center point of script and two adjacent pen-point positions with respect to time in handwriting process is used. The coordinates $(r_x(t_n), r_y(t_n))$ of the barycenter shown in the Fig.4 are calculated by the following equations:

$$r_x(t_n)=\frac{\tilde{x}(t_n)+\tilde{x}(t_{n+1})+0}{3},$$

$$r_y(t_n)=\frac{\tilde{y}(t_n)+\tilde{y}(t_{n+1})+0}{3}, \tag{5}$$

$$(n=1,2,3..N-1),$$

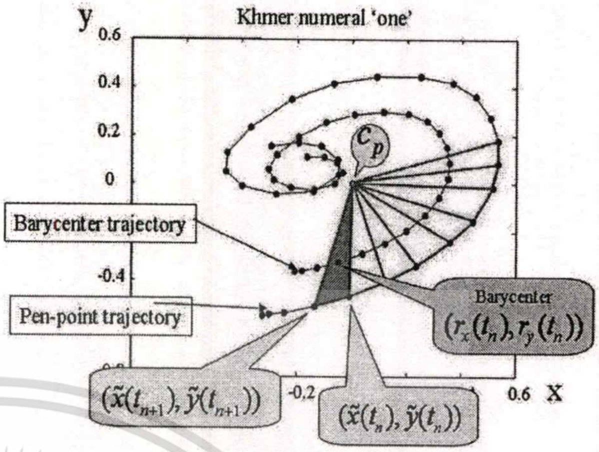

Figure 4: Khmer numeral 'one'.

III. FEATURE EXTRACTION

In this paper, we consider that the handwriting feature of Khmer numeral can be represented by two features, barycenter trajectory and its direction changes. The two features can be described as follows:

$$z(t_n)=r_x(t_n)+jr_y(t_n), \tag{6}$$

$$\theta(t_n)=\arctan\left(\frac{r_y(t_{n+1})-r_y(t_n)}{r_x(t_{n+1})-r_x(t_n)}\right), \tag{7}$$

where $z(t_n)$ is the complex function representing barycenter trajectory, and $\theta(t_n)$ represents the direction changes of the barycenter at the time t_n.

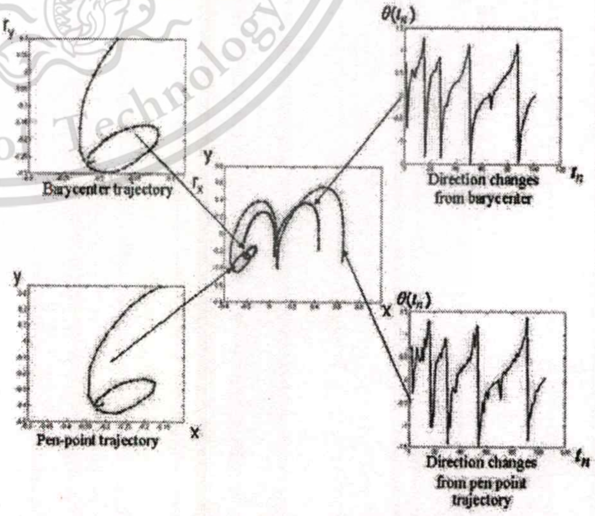

Figure 5: $z(t_n)$ and $\theta(t_n)$ obtained from the pen-point position and barycenter.

Fig.5 shows the comparison of $z(t_n)$ and $\theta(t_n)$ obtained from pen-point position and the barycenter. It can be seen from fig.5 that $z(t_n)$ and $\theta(t_n)$ obtained from the barycenter are less sensitive than those obtained from the pen-point position.

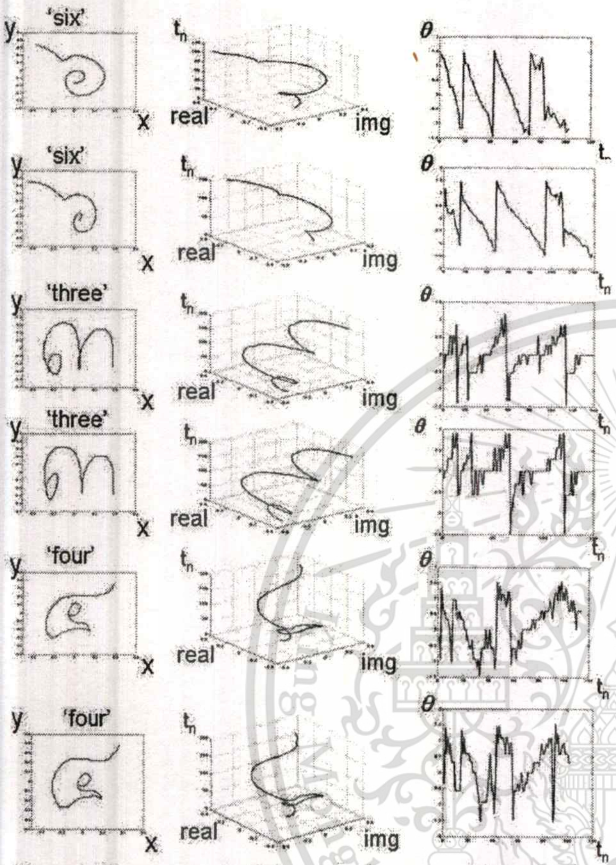

Figure 6: Khmer numerals, their complex features, and their direction changes from left to rigth.

Fig.6 shows $z(t_n)$ and $\theta(t_n)$ obtained from the same and different Khmer numerals. It can be seen from Fig.6 that $z(t_n)$ and $\theta(t_n)$ obtained from same numeral class are similar and different from those obtained from different numeral class. Therefore, we consider that the $z(t_n)$ and $\theta(t_n)$ can be used as the features of handwriting characters for Khmer numeral recognition.

IV. CHARACTER RECOGNITION

It is well known that the duration time in handwriting process obtained from the same character are never precisely the same. It is considered as the fluctuation in time-axis of handwriting character. To recognize the character effectively, Dynamic Programming(DP) matching method[4] is used to calculate the dissimilarity between the features of the reference handwriting character and a character to be recognized. With DP matching technique, the fluctuation of the duration time in handwriting process can be reduced. The DP matching can be performed as follows:

1) The feature parameter vectors of handwriting process are given by

$$\mathbf{z}^r = \left[z^r(1), z^r(2), z^r(3)\ldots, z^r(I)\right]' , \tag{8}$$

$$\mathbf{z}^t = \left[z^t(1), z^t(2), z^t(3)\ldots, z^t(L)\right]' , \tag{9}$$

$$\theta^r = \left[\theta^r(1), \theta^r(2), \theta^r(3)\ldots, \theta^r(I)\right]' , \tag{10}$$

$$\theta^t = \left[\theta^t(1), \theta^t(2), \theta^t(3)\ldots, \theta^t(L)\right]' , \tag{11}$$

where $\mathrm{z}^r(t_n)$, $\mathrm{z}^t(t_n)$, $\theta^r(t_n)$ and $\theta^t(t_n)$ are the barycenter trajectory and its direction changes obtained from preceding section, $\mathbf{z}^r$ and θ^r are the feature parameter vectors for reference character, $\mathbf{z}^t$ and θ^t are the feature parameter vectors for character to be recognized, and I and L are the number of elements in the feature parameter vectors for the reference character and the character to be recognized, respectively.

2) In order to obtain a good matching between the feature parameter vectors, a warping function $w(k)$ is defined as sequence

$$\mathbf{w} = w(1), w(2), w(3), \ldots, w(K) , \tag{12}$$

where $w(k) = (i_k, l_k)$, $(1 \le i_k \le I; 1 \le l_k \le L)$, with the initial condition as $w(1) = (1,1)$, and the terminal condition as $w(K) = (I, L)$. K is the number of warping points obtained from DP matching

3) The dissimilarity between the feature parameter vectors is calculated by

$$S = \frac{1}{I+L} \min_{w} \left(\sum_{k=1}^{K} d(w(k)) g_k \right), \tag{13}$$

where

$$\begin{aligned} d(w(k)) &= \left| \mathbf{z}^r(i_k) - \mathbf{z}^t(l_k) \right| + p \left| \theta^r(i_k) - \theta^t(l_k) \right|, \\ g_k &= (i_k - i_{k-1}) + (l_k - l_{k-1}), \end{aligned} \tag{14}$$

The minimum cost of matching two features are calculated by

$$h(w(k)) = \min \left\{ \begin{array}{l} h(i_k - 1, l_k - 1) + 2d(i_k, l_k) \\ h(i_k - 1, l_k) + d(i_k, l_k) \\ h(i_k, l_k - 1) + d(i_k, l_k) \end{array} \right\}, \tag{15}$$

Equation (13) can be rewritten as

$$S = \frac{1}{I+L} h(w(K)) , \tag{16}$$

where $h(w(1)) = 2d(w(1))$, p is the weight for θ .

Fig.7 shows the warping function of matching two vectors, $\mathbf{z}^r$ and $\mathbf{z}^t$. It can be seen that timing differences between two patterns are eliminated by the warping function.

It is assumed that the reference patterns of known classes for Khmer numerals 'zero', 'one', 'two', 'three', ..., 'nine' are defined by $\{C_0, C_1, C_2, \ldots, C_9\}$, respectively.

Then an unknown character x is assigned to a class $C_i \in \{C_0, C_1, C_2, ..., C_9\}$

$$\text{if } S_{\min}(C_i, x) = \min_{l}\{S(C_l, x)\},\ l = 0,1,2,...,9, \qquad (17)$$

where $S_{\min}(C_i, x)$ is the dissimilarity between the feature parameter vectors obtained from an unknown pattern x and that obtained from the reference pattern of known class C_i.

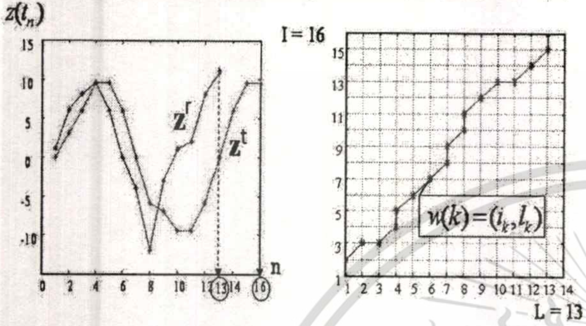

Figure 7: Reference vector z^r, test vector z^t (left), and the warping function (right).

V. EXPERIMENTS

Character recognition experiments were performed on a database consisting of 5000 Khmer numerals written by 20 people. In the experiments, 100 scripts for each Khmer numeral(0,1,...,9) are selected randomly from the database and used as the test data, and the training data for each Khmer numeral consisting of 5 scripts selected randomly from the database. The examples of some Khmer numerals in our database are shown in Fig.8.

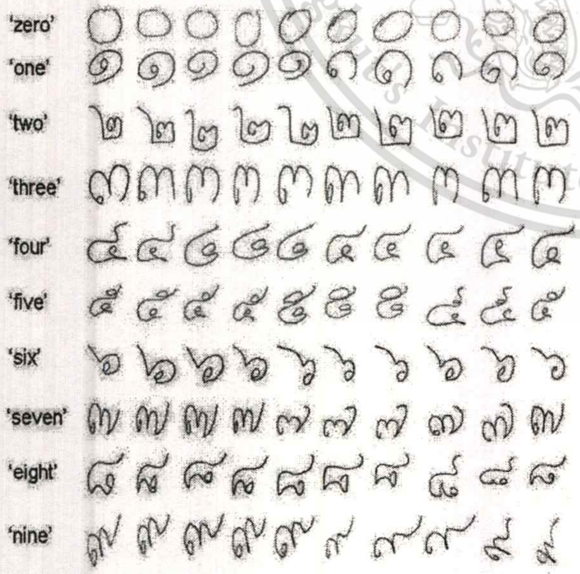

Figure 8: Some Khmer numerals in database.

The experimental results are shown in Table I. Table I shows the comparison of the experimental results of the proposed method using pen-point position and the barycenter. It can be seen from Table I that the recognition rate obtained from the barycenter is better than that obtained from pen-point position. The average of recognition rates was 95.9%, and it can be seen from Table I that the recognition rates obtained from numeral 'nine' and 'seven' are less than those obtained from other numerals because the handwriting style for numeral 'nine' and 'seven' obtained from some writers are similar. Fig.9 shows Khmer numeral 'nine' and 'seven' which were not correctly recognized.

Table I: Recognition rates of Khmer numerals.

Khmer numeral	Recognition rates (%)	
	Using pen-point	Using barycenter
'Zero'	96	96
'One'	63	94
'Two'	85	92
'Three'	98	99
'Four'	98	99
'Five'	74	92
'Six'	100	100
'Seven'	95	99
'Eight'	83	96
'Nine'	85	92
Average	87.7	95.9

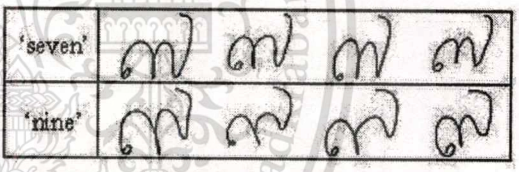

Figure 9: Numeral 'seven' (first row), and numeral 'nine' (second row).

VI. CONCLUSION

We proposed an on-line character recognition method based on DP-matching of barycenter trajectory. The barycenter, determined from the center point of the script and two adjacent of pen-point positions, was used to reduce the sensitivity of pen-point movement in handwriting process. The character was recognized by the incorporation of the barycenter trajectory and its direction changes in DP matching. The experimental results show that the proposed method is useful for on-line character recognition for Khmer numeral.

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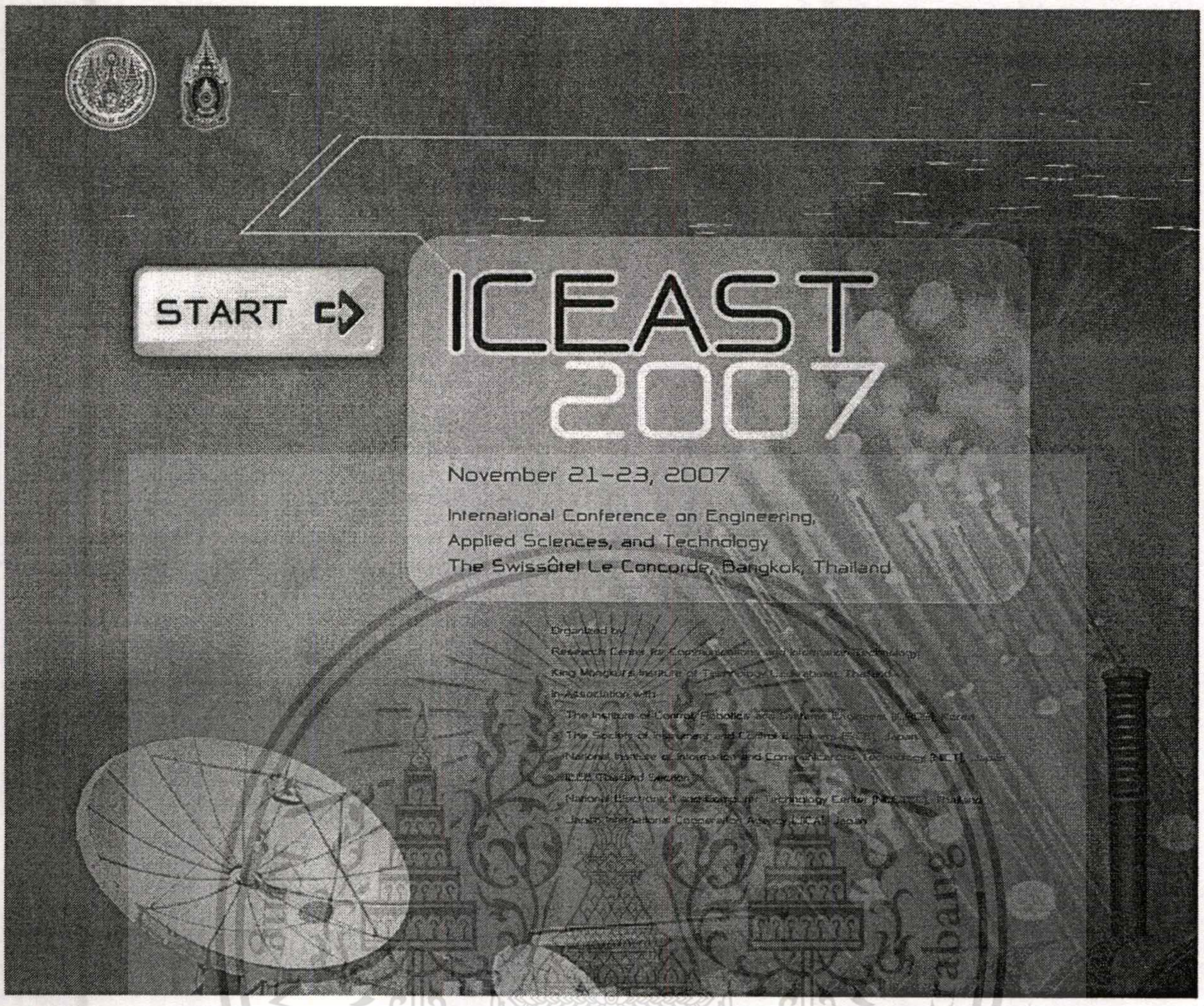

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On-Line Writer Dependent Character Recognition for Khmer Numeral based on FIR system characterizing Barycenter Trajectory

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Abstract—**An on-line writer dependent character recognition method for Khmer numeral based on FIR system characterizing barycenter trajectory is introduced. The barycenter is determined from the center point of script and two adjacent pen-point positions with respect to time in handwriting process. Then the velocity and trajectory of the barycenter are calculated and expanded into Fourier series. The obtained Fourier coefficients are used as the input and output of the FIR (Finite Impulse Response) system describing the handwriting feature. The obtained impulse of the FIR system is used as the feature of the handwritten character. Finally, Khmer numerals can be recognized by the distance between the approximations of the barycenter trajectory obtained from the reference character and the character to be recognized.**

Keywords—**Barycenter, FIR system, Fourier series, Khmer numeral, on-line character recognition**

I. INTRODUCTION

On-line character recognition translates a handwritten character into machine-editable text which is a usefull tool for pen-based computer system. Many methods for on-line character recognition have been reported [1]-[4]. In those methods, the pen-point position is used to recognize the character. It is considered that using pen-point position directly is not effective to extract the feature of the handwritten character. We use the barycenter determined from the center point of script and the two adjacent pen-point positions instead of pen-point position to extract the feature of the handwritten character. In this paper, a writer dependent recognition method is investigated. The major advantage of the writer dependent method is not only easier to customize a special handwriting style for a particular writer, but also the special symbol for a particular writer can be recognized. We considered that the feature of the handwritten character can be described by two features, the barycenter trajectory and its velocity. Then they are expanded into Fourier series to reduce the fluctuation of handwriting process. Moreover, the FIR system characterizing the handwriting feature is introduced by using the Fourier coefficients of the velocity and the trajectory of the barycenter as the input and output of the system, respectively. The obtained impulse response of the FIR system is used as the feature of the handwritten character. Finally, character can be recognized by the distance between the approximations of the barycenter trajectory obtained from the reference character and the character to be recognized.

II. PREPROCESSING

It is well known that in handwriting process, there is a mass fluctuation depending on many factors such as age, habit, psychological and mental state, physical or practical conditions in handwriting process of various writers. For instance, size, location, shape, and duration time in handwriting process of the same alphabet are never precisely the same even they were written by the same writer.

Fig.1 shows Khmer numeral 'one' written by different writers. From Fig.1, we can see that the characters are written in different sizes, locations and styles. In order to recognize the character effectively, such fluctuations of handwriting should be reduced.

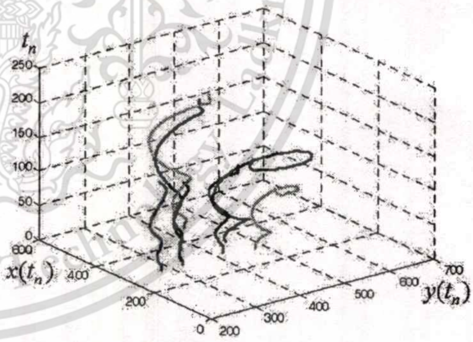


Fig. 1: Khmer numeral 'one' written by different people.

It is assumed here that Khmer numerals are written on a graphical tablet. The horizontal and vertical components of pen-point position at a time, $t = n\tau (\equiv t_n)$, in handwriting process are denoted here as $x(t_n)$ and $y(t_n)$, respectively, where τ is a constant sampling rate. In order to reduce the fluctuation of handwriting, two kinds of normalization with respect to the size and location in handwriting process are performed as follows:

1) *Normalization of size*

The size of the script is standardized after removing the duplicated points of pen-point position. In order to make a standard size of script, the horizontal and the vertical components, $x(t_n)$ and $y(t_n)$ are normalized as

$$\hat{p}(t_n)=\frac{p(t_n)-p_{\min}}{p_{\max}-p_{\min}},\ p=(x,y), \tag{1}$$

where

$$p_{\min}=\min_{0\le n\le N-1} p(t_n),\ p_{\max}=\max_{0\le n\le N-1} p(t_n), \tag{2}$$

and N is a total number of sampled points of pen-point position.

2) *Normalization of location*

The location of the script is normalized as follows:

$$c_p=\frac{1}{N}\sum_{n=0}^{N-1}\hat{p}(t_n),\ p=(x,y), \tag{3}$$

$$\tilde{p}(t_n)=\hat{p}(t_n)-c_p,\ n=0,1,2\ldots N-1, \tag{4}$$

where c_p is the center point of a script. The effectiveness of the preprocessing has been shown in[4]. Then in order to reduce a sensitivity of handwriting motion in handwriting process, a trajectory of the barycenter determined from the center point of a script and the two adjacent pen-point positions with respect to time in handwriting process is used. The coordinates $(r_x(t_n),r_y(t_n))$ of the barycenter shown in the Fig.2 are calculated by the following equations:

$$r_x(t_n)=\frac{\tilde{x}(t_n)+\tilde{x}(t_n)}{3},\ r_y(t_n)=\frac{\tilde{y}(t_n)+\tilde{y}(t_n)}{3}, \tag{5}$$

$(n=1,2,3..N-1),$

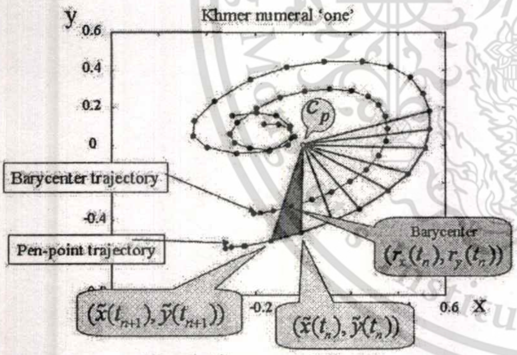


Fig. 2: Khmer numeral 'one'.

Then the handwriting motion in the handwriting process can be described by the following equations:

$$z(t_n)=r_x(t_n)+jr_y(t_n), \tag{6}$$

$$v(t_n)=z(t_{n+1})-z(t_n),\ j\equiv\sqrt{-1},\ v(t_N)=0, \tag{7}$$

where $z(t_n)$ represents the barycenter trajectory and $v(t_n)$ represents the average of the velocity between the two adjacent barycenter points. After that, we define the following equations:

$$z(t_n)=z^{(real)}(t_n)+jz^{(img)}(t_n), \tag{8}$$

$$v(t_n)=v^{(real)}(t_n)+jv^{(img)}(t_n), \tag{9}$$

where $z(t_n)$ and $v(t_n)$ are complex valued functions which represent the trajectory and the velocity of the barycenter, respectively.

Subsequently, in order to normalize the duration time in handwriting process, a piece-wise linear function (PLF) of $v(t_n)$, and $z(t_n)$ are determined by connecting the two adjacent components with a straight line. The PLF can be described as followings:

$$q(t)=\sum q(t_n)\phi_n(t),\ \ t\in T_T \tag{10}$$

where $(q=z^{(real)},z^{(img)},v^{(real)},v^{(img)})$,

$$\phi_n(t)=\begin{cases}\dfrac{t-t_{n-1}}{t_n-t_{n-1}}, & t\in[t_{n-1},t_n]\\ \dfrac{t_{n+1}-t}{t_{n+1}-t_n}, & t\in[t_n,t_{n+1}]\\ 0, & t\notin[t_{n-1},t_{n+1}]\end{cases} \tag{11}$$

and T is the duration time of the handwriting process. Then the duration time T is normalized as $T=T_N$.

III. FEATURE EXTRACTION

In this section, to extract the important feature of the characters, we assumed that $z^{(real)}(t_n)$, $z^{(img)}(t_n)$, $v^{(real)}(t_n)$, and $v^{(img)}(t_n)$ are even periodic functions of time. Then these functions are expanded into Fourier series by the following equations:

$$l(t)\cong\frac{1}{2}a_0^{(l)}+\sum_{k=1}^{K_l-1}a_k^{(l)}\cos(k\omega_0^{(l)}t), \tag{12}$$

where $\omega_0^{(l)}=\dfrac{\pi}{T_N}$, and $(l=z^{(real)},z^{(img)},v^{(real)},v^{(img)})$.

The Fourier coefficients can be calculated by the following equation:

$$a_k^{(l)}=\frac{2}{T_N}\int_0^{T_N}l(t)\cos(k\omega_0 t)\,dt, \tag{13}$$

where $(k=0,1,\ldots,K-1)$, K is the number of Fourier coefficients and $K\le N$. By selecting a suitable number of the Fourier Coefficient, the fluctuation of the individual handwriting motion can be reduced. The suitable number of Fourier coefficients is determined by minimizing the mean square error in the Fourier approximation of $\hat{z}^{(real)}(t_n)$, $\hat{z}^{(img)}(t_n)$, $\hat{v}^{(real)}(t_n)$, and $\hat{v}^{(img)}(t_n)$.

The details of how to determine the number of Fourier coefficients are reported in the work [5]. To simplify the explanation, we represent again the Fourier coefficients of $v(t_n)$, and $z(t_n)$ obtained from (13) by the following equations:

$$f(k)\equiv a_k^{\hat{v}^{(real)}}+ja_k^{\hat{v}^{(img)}},\ \ g(k)\equiv a_k^{\hat{z}^{(real)}}+ja_k^{\hat{z}^{(img)}} \tag{14}$$

We consider that the important feature of the handwritten character can be represented by the FIR system characterizing the barycenter trajectory. The FIR system is realized by considering the Fourier coefficients of the velocity and the trajectory of the barycenter as the input and the output of the system respectively. It is assumed that the FIR system can be described by

$$\hat{g}(k;h)=\sum_{m=0}^{M} h(m)\,f(k-m)\,,\ (k=0,1,\dots,K-1), \qquad (15)$$

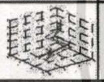
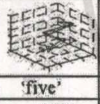
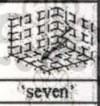
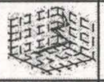
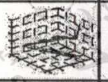
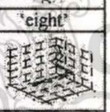
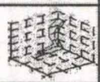
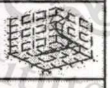
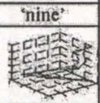
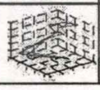
where $\mathbf{h}'=[h(0),\ h(1),\ h(2),\ \dots\ ,h(M)]$ is the impulse response of the FIR system, M is the order of the system and $\hat{g}(k;h)$ is the approximation of the $g(k)$. The impulse response *h(m)* can be obtained by minimizing the least-square error at M as follows:

$$E=\sum_{k=0}^{K-1}|e(k)|^2 \to \min\,, \qquad (16)$$

$$e(k)=g(k)-\hat{g}(k;h)\,. \qquad (17)$$

Table I shows the impulse responses of the FIR system obtained from writer A and writer B for Khmer numeral 0-9. It can be seen that the impulse responses obtained from same numerals and same writer are quite similar and different from those obtained from different numerals and different writer. Therefore, it can be considered that the obtained impulse response of the FIR system can be used as the important feature of the handwritten character for a particular writer.

TABLE I
IMPULSE RESPONSE.

	'one'	'two'	'three'	'four'
Writer A				
Writer B				
	'five'	'six'	'seven'	'eight'
Writer A				
Writer B				
	'nine'	'zero'	-	-
Writer A			-	-
Writer B			-	-

IV. CHARACTER RECOGNITION

It is assumed that the reference patterns of known classes for Khmer numerals 'zero', 'one', 'two', 'three',..., 'nine' are defined by $\{C_0, C_1, C_2, \dots, C_9\}$, respectively. Then an unknown character x is assigned to a class

$$C_l \in \{C_0, C_1, C_2, \dots, C_9\},$$

$$\text{if } S_{\min}(C_l,x)=\min\{S(C_l,x)\}, l=0,1,2,\dots 9, \qquad (18)$$

where $S(C_l,x)=\dfrac{1}{N}\sum_{n=1}^{N}\left\|\hat{\mathbf{g}}^{(ref)}_{l,n}-\hat{\mathbf{g}}^{(x)}_{l,n}\right\|$,

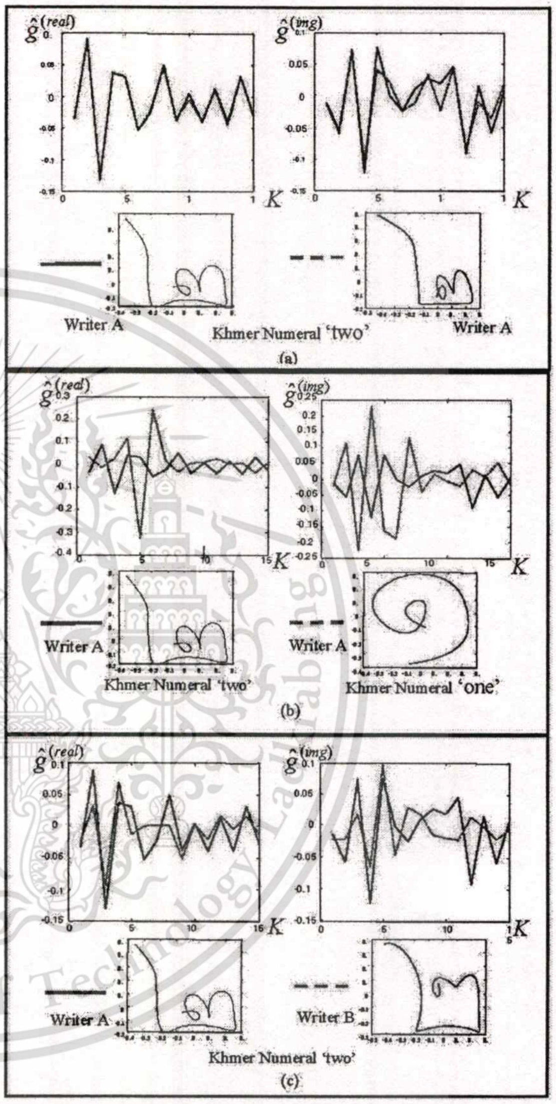


Fig. 3: The approximation of the Fourier coefficients of the Barycenter trajectory (a) obatined from same numeral and same writer (b) obtained from different numeral and same writer (c) obtained from same numeral and different writer.

$$\hat{\mathbf{g}}^{(ref)\prime}_{l,n}=[\hat{g}^{(ref)}_{l,n}(0;\mathbf{h}_{l,n}),\ \ \hat{g}^{(ref)}_{l,n}(1;\mathbf{h}_{l,n}),\ \ \dots,\ \ \hat{g}^{(ref)}_{l,n}(M;\mathbf{h}_{l,n})],$$

$$\hat{\mathbf{g}}^{(x)\prime}_{l,n}=[\hat{g}^{(x)}_{l,n}(0;\mathbf{h}_{l,n}),\ \ \hat{g}^{(x)}_{l,n}(1;\mathbf{h}_{l,n}),\ \ \dots,\ \ \hat{g}^{(x)}_{l,n}(M;\mathbf{h}_{l,n})],$$

$$\mathbf{h}'_{l,n}=[h_{l,n}(0),\ \ h_{l,n}(1),\ \ \dots,\ \ h_{l,n}(M)],$$

$$\hat{g}^{(ref)}_{l,n}(k;\mathbf{h}_{l,n})=\sum_{m=0}^{M} h_{l,n}(m)\,f^{(ref)}_{l,n}(k-m),$$

$$\hat{g}^{(x)}_{l,n}(k;\mathbf{h}_{l,n})=\sum_{m=0}^{M} h_{l,n}(m)\,f^{(x)}_{l}(k-m), (n=1,2,\dots,N)\,,$$

and $\underline{N}$ is total number of reference data for each class, $\mathbf{h}_{l,n}$ is an impulse response obtained from the n^{th} reference data for class C_l , $\|\cdot\|$ is Euclidean norm, $f_{l,n}^{(ref)}(k)$ is Fourier coefficients of Barycenter velocity obtained from the n^{th} reference data for class C_l, $f_l^{(x)}(k)$ is Fourier coefficients of barycenter velocity obtained from the unknown character x, and $S_{\min}(C_l, x)$ is the minimum Euclidean distance obtained from $S(C_l, x)$. Fig.3 shows the comparison of the approximations of the Fourier coefficients of the barycenter trajectory obtained from same and different numerals written by same and different writers. It can be seen from Fig.3 that the approximation obtained from same numeral and same writer are quite similar and different from those obtained from different numerals and different writers.

V. EXPERIMETNTS

Character recognition experiments were performed on a database consisting of 1500 Khmer numerals written by 10 people in one year used as the test data set and 30 Khmer numerals used as training data for one people. The examples of some Khmer numerals written by different people are shown in Fig.4. Table II shows the recognition rates using the Khmer numerals in our database.

TABLE II

RECOGNITION RATES OF KHMER NUMERALS(WRITER DEPENDENT).

Writer	Number of training data (3/numeral)	Number of numerals(15/numeral)	Recognition rates (%)
A (0-9)	30	150	98.67
B (0-9)	30	150	96.00
C (0-9)	30	150	97.33
D (0-9)	30	150	96.00
E (0-9)	30	150	96.67
F (0-9)	30	150	96.67
G (0-9)	30	150	92.67
H (0-9)	30	150	95.33
I (0-9)	30	150	97.33
J (0-9)	30	150	98.00
Average			96.47

VI. CONCLUSION

An on-line writer dependent character recognition method for Khmer numeral has been proposed. In the proposed method, the barycenter determined from the center point of the script and the two adjacent of pen-point positions, was used to reduce the sensitivity of pen-point movement in handwriting process. Then the Fourier approximations of the trajectory and velocity of the barycenter were used to reduce the fluctuation in handwriting process. Moreover, the FIR system approximating the barycenter trajectory was introduced by using the Fourier coefficients of the velocity and the trajectory of the barycenter as the input and output of the FIR system, respectively. Finally, character can be recognized by the distance between the approximations of the barycenter trajectory obtained from the reference character and the character to be recognized. The experimental results show that the proposed method is useful for on-line writer dependent character recognition for Khmer numeral.

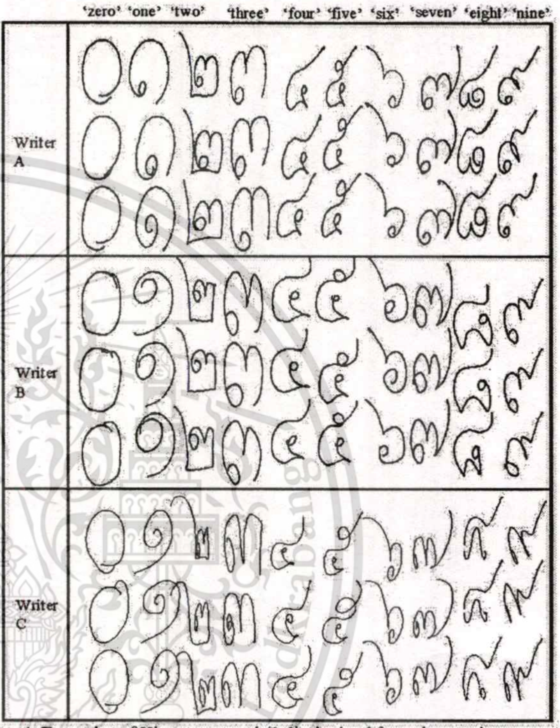


Fig. 4: Examples of Khmer numeral (0-9) obtained from three writers.

ACKNOWLEDGMENT

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On-Line Writer Dependent Character Recognition for Khmer based on FIR System Characterizing Handwriting Motion

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***Abstract*—We proposed an on-line writer dependent Khmer recognition method based on FIR system characterizing handwriting motion. The handwriting motion can be described by two features, barycenter trajectory and its velocity. The barycenter is determined from the center point of the script and the two adjacent pen-point positions with respect to time in handwriting process. Then the barycenter and its velocity are expanded into wavelet series to extract the time-frequency characteristics of handwriting motion. In this paper, the FIR(finite impulse response) system characterizing the handwriting motion is introduced. In this case, the wavelet coefficients of the velocity and trajectory of the barycenter are used as the input and output of the FIR system, respectively. The obtained impulse response of the FIR system is considered as the individual feature for a particular character. Finally, Khmer alphabets can be recognized by using the Euclidean distance between the impulse responses obtained from the reference alphabets and those of the alphabets to be recognized. Khmer character recognition experiments were performed on a database consisting of 4770 of numerals and alphabets written by 15 people. As the results, the average of the recognition rate was 97.05%.**

I. INTRODUCTION

Many methods for on-line character recognition have been reported [1], [2], [3]. In those methods, the pen-point position is used to recognize characters. It is considered that pen-point position used directly in [4] is not effective enough to extract the feature of the handwriting character. In work [5], the barycenter, determined from the center point of a script and two adjacent pen-point positions with respect to time in handwriting process, was used to extract the feature of the handwriting character. In this paper, a writer dependent character recognition method is investigated using the barycenter instead of the pen-point position to extract the handwriting feature. The major advantage of the writer dependent method is not only easier to customize a special handwriting style for a particular writer, but also the special symbol for a particular writer can be recognized[5]. In the work [5], the Fourier approximation was used to extract the handwriting feature for a particular person. However the Fourier approximation was not enough to represent the handwriting feature for the person. It is considered that a person should have his/her own handwriting feature in writing a script. In order to extract the individual handwriting feature in writing a script, it is desirable to use the time-frequency characteristics of handwriting motion. In this case, the trajectory and the velocity of the barycenter are expanded into wavelet series to extract the time-frequency of the handwriting motion. Moreover, the FIR(finite impulse response) system characterizing the handwriting motion is introduced by using the wavelet coefficients of the velocity and the trajectory of the barycenter as the input and output of the system, respectively. The obtained impulse responses of the FIR system are used as the individual features for a particular character. Finally, characters can be recognized by the Euclidean distance between the impulse response obtained from the reference characters and the characters to be recognized.

II. PREPROCESSING

It is assumed here that Khmer characters are written on a graphical tablet. The horizontal and vertical components of pen-point position at a time, $t = n\tau(\equiv t_n)$, in handwriting process are denoted here as $x(t_n)$ and $y(t_n)$, respectively, where τ is a constant sampling rate. In order to reduce the fluctuation of handwriting, two kinds of normalization with respect to the size and location in handwriting process are performed as follows:

1) Normalization of size

The size of the script is standardized after removing the duplicated points of pen-point position. In order to make a standard size of script, the horizontal and the vertical components, $x(t_n)$ and $y(t_n)$ are normalized as

$$\hat{p}(t_n) = \frac{p(t_n) - min(p(t_n))}{max(p(t_n)) - min(p(t_n))}, p = (x, y) \qquad (1)$$

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where

$min(p(t_n)) = \min_{0 \le n \le N-1} p(t_n)$,

$max(p(t_n)) = \max_{0 \le n \le N-1} p(t_n)$, and

N is the total number of sampled points of pen-point position.

2) Normalization of location

The location of the script is normalized as follows:

$$c_p = \frac{1}{N}\sum_{n=0}^{N-1} \hat{p}(t_n), p = (x, y) \quad (2)$$

$$\tilde{p}(t_n) = \hat{p}(t_n) - c_p, n = 0, 1, 2, ..., N-1 \quad (3)$$

where c_p is the center point of a script. The effectiveness of the preprocessing has been shown in[4]. Then in order to reduce a sensitivity of handwriting motion in handwriting process, a trajectory of the barycenter determined from the center point of a script and the two adjacent pen-point positions with respect to time in handwriting process is used. The barycenter coordinates $(r_x(t_n), r_y(t_n))$ are calculated by the following equations:

$$r_x(t_n) = \frac{\tilde{x}(t_n) + \tilde{x}(t_{n+1})}{3}, r_y(t_n) = \frac{\tilde{y}(t_n) + \tilde{y}(t_{n+1})}{3} \quad (4)$$

where $n = 0, 1, 2, ..., N-1$. Further more, in order to reduce another fluctuation such as duration time in a part of handwriting process, a segmentation of handwriting process is performed. The pen-up signal is used as the segmentation point for separating a barycenter trajectory into a set of components strokes. Then the handwriting motion in the handwriting process for each stroke can be described by the following equations:

$$z_i(t_n) = r_x^{(i)}(t_n) + j r_y^{(i)}(t_n), \quad (5)$$

$$v_i(t_n) = z_i(t_{n+1}) - z_i(t_n), j \equiv \sqrt{-1}, \quad (6)$$

$$(i = 1, 2, ..., N_s)$$

where $z_i(t_n)$ represents the barycenter trajectory, $v_i(t_n)$ represents the average of the velocity between the two adjacent barycenter points, and N_s is the total number of strokes in the handwriting process of handwriting character after segmentation. After that, we define the following equations:

$$z_i(t_n) = z_i^{real}(t_n) + j z_i^{img}(t_n) \quad (7)$$

$$v_i(t_n) = v_i^{real}(t_n) + j v_i^{img}(t_n) \quad (8)$$

where $z_i(t_n)$ and $v_i(t_n)$ are complex valued functions which represent the trajectory and the velocity of the barycenter, respectively; and $[.]^{real}$ is the real part of the complex value, while $[.]^{img}$ is the complex one.

Subsequently, in order to normalize the duration time in handwriting process, piecewise-linear functions (PLFs) of $v_i(t_n)$ and $z_i(t_n)$ are determined by connecting the two adjacent components with a straight line. The PLFs can be described as followings:

$$Q(t) = \sum_{n=0}^{N-1} q(t_n)\phi_n(t), t \in T \quad (9)$$

where $q = (z_i^{real}, z_i^{img}, v_i^{real}, v_i^{img})$,

$$\phi_n(t) = \left\{ \begin{array}{ll} \frac{t - t_{n-1}}{t_n - t_{n-1}} & t \in [t_{n-1}, t_n] \\ \frac{t_{n+1} - t}{t_{n+1} - t_n} & t \in [t_n, t_{n+1}] \\ 0 & t < t_{n-1} \quad or \quad t > t_{n+1} \end{array} \right\} \quad (10)$$

and T is the duration time of the handwriting process. Then the duration time is normalized T as $T = T_N$ using (9).

III. FEATURE EXTRACTION

In this section, in order to extract the time-frequency characteristics of the handwriting process, the $z_i(t_n)$ and $v_i(t_n)$ obtained in the preceding section are expanded into wavelet series as

$$q(t) = \sum_{k=0}^{2^{l_0}-1} c_{l_0}^{(q)}(k)\varphi_{k,l_0}(t) + \sum_{\underline{l}=l_0}^{M-1}\sum_{k=0}^{2^{\underline{l}-1}} d_{\underline{l}}^{(q)}(k)\psi_{k,\underline{l}}(t), \quad (11)$$

$$q = (v_i, z_i), l_0 = 0, 1, 2..., M-1$$

where $\psi_{k,\underline{l}}(t)$ is orthonormal wavelet:

$$\psi_{k,\underline{l}}(t) = 2^{\underline{l}/2}\psi(2^{\underline{l}}t - k) \quad (12)$$

$$< \psi_{k,\underline{l}}, \psi_{m,n} > \equiv \int_{-\infty}^{\infty} \psi_{k,\underline{l}}(t)\psi_{n,m}(t)dt$$

$$= \delta_{\underline{l},m}\delta_{k,n} \quad (13)$$

and $\varphi_{k,l_0}(t)$ is the scaling function:

$$\varphi_{k,l_0}(t) = 2^{l_0/2}\varphi(2^{l_0}t - k), (l_0, k \in Z)$$

where Haar function is used as mother wavelet $\psi_{k,l}$, $\delta_{\underline{l},m}$ is Kronecker delta, and $c_k^{(q)}(l)$ and $d_k^{(q)}(l)$, respectively, are the approximated and the detail wavelet coefficients obtained through the inner product $d_k^{(q)}(l) =< q, \psi_{k,l} >$, and the scaling function coefficients obtained through the inner product $c_k^{(q)}(l) =< q, \varphi_{k,l} >$.

$c_{\underline{l}}(k)$	$d_{\underline{l}}(k)$	$d_{\underline{l}+1}(k)$ $d_{\underline{l}+1}(k+1)$	..	$d_{\underline{L}}(k)$	.. $d_{\underline{L}}(2^{\underline{L}}-1)$

Fig. 1. Feature vector at level $\underline{l}$ taken as the input and output of the FIR System.

To ease the explanation, we define the following functions.

$$\mathbf{c}_{\underline{l}}^{(q)} = [c_{\underline{l}}^{(q)}(0), c_{\underline{l}}^{(q)}(1), ..., c_{\underline{l}}^{(q)}(2^{\underline{l}} - 1)]', \quad (14)$$

$$\mathbf{d}_{\underline{l}}^{(q)} = [d_{\underline{l}}^{(q)}(0), d_{\underline{l}}^{(q)}(1), ..., d_{\underline{l}}^{(q)}(2^{\underline{l}} - 1)]', \quad (15)$$

$$\mathbf{a}_{\underline{l}}^{(q)} = [c_{\underline{l},k}^{(q)}, d_{\underline{l},k}^{(q)}, d_{\underline{l}+1,k+1}^{(q)}, ..., d_{\underline{l}+M,k+2^M-1}^{(q)}]' \quad (16)$$

$$\mathbf{a}_{(M,k)}^{(q)} = \mathbf{a}_{M,k}^{(q^{(real)})} + j\mathbf{a}_{M,k}^{(q^{(img)})}, q = (v_i, z_i) \quad (17)$$

$$\mathbf{f}_{\underline{l}}^{(i)} = \mathbf{a}_{\underline{l}}^{(v_{(i)})} = [f_{\underline{l}}^{(i)}(1), f_{\underline{l}}^{(i)}(2), ..., f_{\underline{l}}^{(i)}(\underline{N})]' \quad (18)$$

$$\mathbf{g}_{\underline{l}}^{(i)} = \mathbf{a}_{\underline{l}}^{(z_{(i)})} = [g_{\underline{l}}^{(i)}(1), g_{\underline{l}}^{(i)}(2), ..., g_{\underline{l}}^{(i)}(\underline{N})]' \quad (19)$$

where $\mathbf{a}_{l,k}^{(q)}$ is the feature vector of wavelet coefficients at stage $\underline{l}$ shown in Fig.1, $\underline{N}$ is a total number of element in $\mathbf{f}_{\underline{l}}^{(i)}$,

$\mathbf{g}_{\underline{l}}^{(i)}$, and $[.]'$ means the transposition. We consider a handwriting system characterizing the handwriting motion in the handwriting process. The handwriting system is described by the dynamic features in the corresponding part of handwriting process. The system is realized by considering the wavelet coefficients $\mathbf{f}_{\underline{l}}^{(i)}(k)$ and $\mathbf{g}_{\underline{l}}^{(i)}(k)$ as the input and output of the system, respectively. It is assumed that the system can be described by

$$\hat{g}_{\underline{l}}^{(i)}(k;\mathbf{h}_{\underline{l}}^{(i)}) = \sum_{m=0}^{M-1} h_{\underline{l}}^{(i)}(m) f_{\underline{l}}^{(i)}(k-m), \qquad (20)$$

$$(k = 0, 1, 2, ..., \underline{N} - 1)$$

where $\mathbf{h}_{\underline{l}}^{(i)} = [h_{\underline{l}}^{(i)}(0), h_{\underline{l}}^{(i)}(1), h_{\underline{l}}^{(i)}(2), ..., h_{l}^{(i)}(M-1)]'$ is an impulse response of the system, M is the order the FIR System, and $\hat{g}_{\underline{l}}^{(i)}(k;h)$ is an approximation of $g_{l}^{(i)}(k;h)$. The impulse response can be obtained by minimizing the least-square error at M as

$$E_{\underline{l}}^{(i)} = \sum_{k=0}^{K_i-1} |e_{\underline{l}}^{(i)}(k)|^2 \rightarrow min \qquad (21)$$

where $e_{\underline{l}}^{(i)}(k) = g_{\underline{l}}^{(i)}(k) - \hat{g}_{\underline{l}}^{(i)}(k;\mathbf{h}_{\underline{l}}^{(i)})$. The details to determine the impulse response are reported in the work[6].

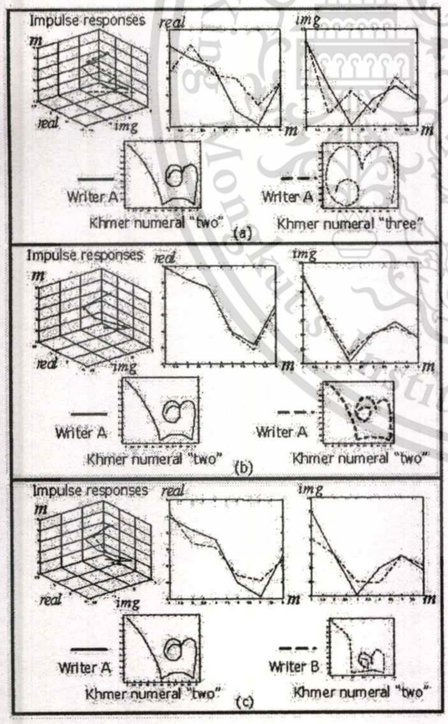

Fig. 2. (a) Impulse response obtained from numeral "two" and "three" written by the same writer, (b) Impulse response obtained from numeral "two" written by the same writer, (c) Impulse response obtained from numeral "two" and "three" written by different writers.

Fig.2 shows the comparison of the impulse response obtained from same and different numerals written by same and different writers. It can be seen from Fig.2 that the impulse responses obtained from the same numeral and the same writer are quite similar and different from those obtained from different numerals and different writers.

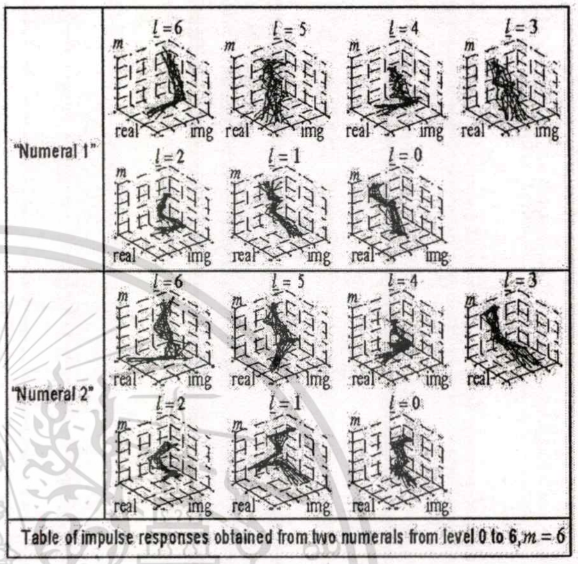

Fig. 3. Impulse responses obtained from numeral "one" and numeral "two" from each level of coefficients of feature vector.

Fig.3 shows the impulse responses of the FIR system obtained from two Khmer numerals. It can be seen from Fig.3 that the impulse responses of the FIR system obtained from different numerals are different. Therefore, it is considered that the impulse response can be used as the individual feature for the particular Khmer characters.

IV. CHARACTER RECOGNITION

It is assumed that the reference patterns of known classes for Khmer characters are defined by $C_0, C_1, C_2, ..., C_{N_c-1}$, respectively. Then an unknown character x is assigned to a class $C_i \in C_0, C_1, C_2, ..., C_{N_c-1}$ if

$$S_{min}(C_i, x) = \min S(C_l, x), (l = 0, 1, 2, .., N_c - 1) \qquad (22)$$

where N_c is the total number of classes, and
$S(C_l, x) = \frac{1}{\underline{N}\ \underline{L}} \sum_{\underline{l}=0}^{\underline{L}} \sum_{n=1}^{N} \sum_{i=1}^{N_s} \|\mathbf{h}_{\underline{l},n,i}^{(ref_l)} - \mathbf{h}_{\underline{l},n,i}^{(x)}\|$

$$\mathbf{h}_{\underline{l},n,i}^{(ref_l)'} = [h_{\underline{l},n,i}^{(ref_l)}(0), h_{\underline{l},n,i}^{(ref,l)}(1), h_{\underline{l},n,i}^{(ref_l)}(2), ..., h_{l,n,i}^{(ref_l)}(M-1)]$$

$$\mathbf{h}_{\underline{l},n,i}^{(x)\ \prime} = [h_{\underline{l},n,i}^{(x)}(0), h_{\underline{l},n,i}^{(x)}(1), h_{\underline{l},n,i}^{(x)}(2), ..., h_{\underline{l},n,i}^{(x)}(M-1)]$$

and $\underline{N}$ is total number of reference data for each class, $\underline{L}$ is the number of the feature vector level, N_s is the number of strokes in handwriting character, $h_{\underline{l},n,i}^{ref_l}$ is an impulse response obtained from the n^{th}reference data for class C_l at the level $\underline{l}$ of the feature vector, $\|.\|$ is Euclidean norm, and $S_{min}(C_i, x)$ is the minimum Euclidean distance obtained from $S(C_l, x)$.

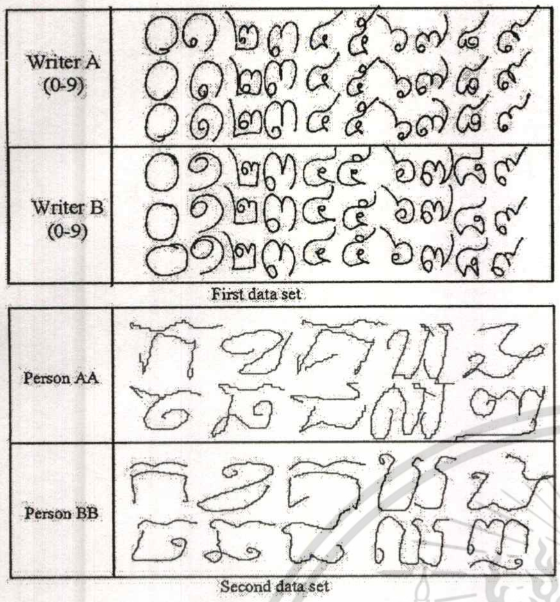

Fig. 4. Example of Khmer Characters in database.

V. EXPERIMENTS

Character recognition experiments were performed on a database consisting of two data sets. First data set consists of 1800 Khmer numerals written by 12 people in one year, and the second data set consists of 30 times of 33 Khmer Alphabets written by 3 people in 6 months. The Fig.4 shows the example of Khmer character in the first and the second data set in our database. In the two experiments, 5 data were selected randomly and used as reference data for a particular character and a particular writer. Table I shows the recognition rates obtained from the first experiment. Table II shows the recognition rates obtained from the second experiment. From Table I and Table II, the results show that the proposed method is able to recognize the character with better recognition rates in comparison with the work [5].

VI. CONCLUSION

An on-line writer dependent character recognition method based on FIR system characterizing handwriting motion for Khmer has been proposed. In the proposed method, the barycenter determined from the center point of the script and the two adjacent pen-point positions was used to reduce the fluctuation of pen-point movement in handwriting process. Then the handwriting motion can be described by two features, the trajectory and the velocity of the barycenter. In order to extract the time-frequency characteristic of the handwriting motion for a particular person, the trajectory and the velocity of the barycenter were expanded into wavelet series. Moreover, the FIR system characterizing the handwriting motion was realized by considering the wavelet coefficients of the velocity and the trajectory of the barycenter as the input and the output of the FIR system, respectively. The obtained impulse response of the FIR system was used as the individual feature for a particular character. Finally, character can be recognized by the Euclidean distance between the impulse responses obtained from test characters and those from the characters to be recognized. The experimental results showed that the proposed method is useful for on-line writer dependent character recognition for Khmer numerals and alphabets.

TABLE I : TABLE OF RECOGNTION RATES

Writer	Number Of training data (5/numeral)	Number Of numerals (15/numeral)	Recognition rates (%)	
			Proposed method	Method in [6]
A (0-9)	50	150	99.33	96.66
B (0-9)	50	150	99.33	99.33
C (0-9)	50	150	100	98.67
D (0-9)	50	150	96.67	90.67
E (0-9)	50	150	96.66	98.67
F (0-9)	50	150	95.99	90.66
G (0-9)	50	150	99.33	98.00
H (0-9)	50	150	92.67	95.33
I (0-9)	50	150	100	96.66
J (0-9)	50	150	100	97.33
K(0-9)	50	150	99.33	97.33
L(0-9)	50	150	97.33	95.33
Average			98.05	96.22

TABLE II : TABLE OF RECOGNTION RATES OF KHMER ALPHABETS

Writer (33 alphabets)	Number Of training data (5/alphabet)	Number Of alphabets (30/alphabet)	Recognition rates (%)	
			Proposed method	Method in [6]
AA	155	990	93.83	89.39
BB	155	990	96.77	96.36
CC	155	990	97.57	96.26
Average			96.06	94.01

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