OFFLINE SIGNATURE VERIFICATION USING ORDINAL STRUCTURE FUZZY LOGIC AND INTEGRATED FEATURES BASED ON SINGLE SIGNATURE

GHASSAN MARWAN ABDULFATTAH

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School of Computing
Faculty of Engineering
Universiti Teknologi Malaysia

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DEDICATION

This study is wholeheartedly dedicated to our beloved parents, who have been our source of inspiration and gave us strength when we thought of giving up, who continually provide their moral, spiritual and emotional.

To My beloved wife and my sons and my daughters, who have been our source of inspiration and gave us strength when we thought of giving up, who continually provide their moral, spiritual and emotional.

To My supervisor and our relatives, mentor, friends, and classmates who shared their words of advice and encouragement to finish this study.

And lastly, we dedicated this book to the Almighty God, thank you for the guidance, strength, power of mind, protection and skills and for giving us a healthy life. All of these, we offer to you.

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ABSTRACT

An offline signature verification system (OSVS) is an industry-driven technology with the ability to verify and recognize a signer's signature, as required for different situations such as performing financial transactions, undertaking security and identifying processes, and detecting fraud. In the OSVS field, substantial investigations have been undertaken mainly using a sizeable number of sample signatures available, from which a profile of an individual signer is constructed. However, very few studies have been undertaken regarding how a limited number of signatures can be used to build a signer's profile. Furthermore, most of the previous works in the OSVS field have used isolated signatures to verify system performance, and there are very limited studies on signatures from documents, cheques and forms. This research developed a system, which supports the worst-case scenario where only one sample signature is available to build a profile. This system achieved accurate OSVS through which, one single signature is used to build the signer's profile with different genuine signatures extracted from forms and cheques. Besides, different types of proposed forged signatures were evaluated using different techniques in the different stages of the system. This work was divided into two different stages called the adaptive representation module (ARM) and reliable verifier (RV). ARM starts by proposing a new adaptive binarization module (ABM) to isolate clear binary objects from the signatures embedded in the forms and cheques. ABM consists of a background-based estimation (BBE) stage that generates different greyscale images, zero-crossing thresholding (ZCT) technique which produces binary images, and fuzzy structured ordinal module (FSOM) designed by rules to select the best binary signature image with clear objects out of three nominated binary images. The second ARM module of is descriptors representation, which proposes generating two sets of features that distinguish signatures, including lines-based features and blob-based features. All the collected features are used to build a statistical feature vector to be applied later in RV. Next, the RV fused the distance-based and statistical verifiers to increase the accuracy of both FAR and FRR. The signature dataset for this research consisted genuine signatures embedded in forms, random signatures generated by signing simple names, unseen forgeries through signing known characters, and seen forgery signatures that simulated real signatures collected from the signer. Genuine signatures embedded into low resolution and noisy background forms were also generated to improve the efficiency of the adaptive offline signature verification (AOSV) system. The calculation showed low error rates for both FAR as seen in the forgery samples at 0.139 and FRR at 0.156. The findings have shown that researcher has successfully developed the an accurate offline signature verification system which uses one single signature to build a signer's profile with different genuine signatures extracted from forms and cheques, as well as evaluate of different types of forged signatures.

ABSTRAK

Sistem pengesahan tandatangan luar talian (OSVS) merupakan teknologi yang didorong oleh industri dengan keupayaan untuk mengesah dan mengenali tandatangan penandatangan seperti yang diperlukan untuk situasi yang berbeza seperti melakukan transaksi kewangan, menjalankan keselamatan dan pengenalpastian proses dan mengesan penipuan. Dalam bidang OSVS, banyak kajian dilakukan terutamanya menggunakan sejumlah tandatangan sampel yang tersedia, yang daripadanya profil seorang penandatangan individu dibina. Walau bagaimanapun, kajian yang sangat sedikit telah dilakukan tentang bagaimana sebilangan tandatangan yang terhad boleh digunakan untuk membina profil penandatangan. Seterusnya, kebanyakan kajian dalam bidang OSVS telah menggunakan tandatangan terpencil untuk mengesahkan prestasi sistem, dan terdapat kajian yang sangat terhad pada tandatangan dari dokumen, cek dan borang. Kajian ini membangunkan satu sistem, yang menyokong senario kes terburuk di mana hanya satu tandatangan sampel yang tersedia untuk membina profil. Sistem ini mencapai OSVS yang tepat di mana satu tandatangan tunggal digunakan untuk membina profil penandatangan dengan tandatangan asli yang berbeza diekstrak daripada borang dan cek. Selain itu, pelbagai jenis tandatangan palsu yang dicadangkan telah dinilai menggunakan teknik yang berbeza dalam pelbagai peringkat sistem. Kerja ini dibahagikan kepada dua peringkat yang berbeza iaitu modul perwakilan penyesuaian (ARM) dan pengesah andal (RV). ARM bermula dengan mencadangkan modul pembinarian adaptif baharu (ABM) untuk mengasingkan objek binari yang jelas daripada tandatangan yang terdapat dalam borang dan cek. ABM terdiri daripada peringkat anggaran berasaskan latar belakang (BBE) yang menghasilkan imej *greyscale* yang berbeza, teknik penambilan *zero-crossing* (ZCT) yang menghasilkan imej binari, dan modul ordinal berstruktur kabur (FSOM) yang direka oleh peraturan untuk memilih imej tandatangan binari yang terbaik melalui objek jelas daripada tiga imej binari. Modul ARM kedua yang dicadangkan ialah perwakilan pemerihal, yang mencadangkan penghasilan dua set ciri yang membezakan tandatangan, termasuk ciri berdasarkan baris dan ciri berasaskan tompokan. Semua ciri yang dikumpul digunakan untuk membina vektor ciri statistik yang akan digunakan kemudian dalam RV. Seterusnya RV mencadangkan untuk menyatukan pengesah berasaskan jarak dan pengesah statistik untuk meningkatkan ketepatan kedua-dua FAR dan FRR. Set data tandatangan untuk kajian ini terdiri daripada tandatangan asli yang terbenam dalam borang, tandatangan rawak yang dihasilkan dengan menandatangani nama mudah, pemalsuan yang tidak kelihatan dengan menandatangani aksara yang diketahui, dan pemalsuan tandatangan yang mensimulasikan tandatangan sebenar yang dikumpulkan daripada penandatangan. Tandatangan asli yang tertanam dalam resolusi rendah dan bentuk latar belakang yang bising juga dihasilkan untuk meningkatkan kecekapan sistem pengesahan tandatangan luar talian yang dicadangkan (AOSV). Pengiraan menunjukkan kadar kesilapan yang rendah bagi kedua-dua FAR seperti yang dilihat dalam sampel pemalsuan pada 0.139 dan FRR pada 0.156. Dapatan menunjukkan bahawa pengkaji telah berjaya membangunkan sistem pengesahan tandatangan di luar talian yang tepat menggunakan satu tandatangan tunggal untuk membina profil penandatangan dengan tandatangan asli yang diekstrak daripada borang dan cek serta menilai pelbagai jenis tandatangan palsu.

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LIST OF ABBREVIATIONS

2D	-	2 Dimensional
ABM	-	Adaptive Binarization Module
AOSV		Adaptive Offline Signature Verification
AI	-	Artificial Intelligence
AMR	-	Arithmetic Mean Rule
ANN	-	Artificial NN
AOSVS	-	Adaptive Offline Signature Verification System
API	-	Application Programming Interface
ARM	-	Adaptive Representation Module
ASCII	-	American Standard Code for Information Interchange
ATM	-	Automatic Teller Machine
B	-	Bigger
BBE	-	Background-Based Estimation
BCV	-	Between Class Variance
BE	-	Below
BoVW	-	Bag of Visual Words
BoW	-	Bag of Words
BPNN	-	Back propagation NN
BQMP	-	Binary Quaternion-Moment Preserving
CHT	-	Circular Hough Transform
CRLA	-	Constrained Run Length Algorithm
CRLA	-	Constrained Run Length Algorithm
DCT	-	Discrete Cosine Transform
DPNN	-	Dynamic Process Neural Network
DSCC	-	Directional Single-Connected Chain
DSRM	-	Design Science Research Methodology
DTW	-	Dynamic Time Wrapping
EM	-	Expectation Maximization
ERM	-	Empirical Risk Minimization

ERR	-	Equal Error Rate
ES	-	Evaluation Stage
FAR	-	False acceptance rate
FL	-	Fuzzy Logic
FSOM	-	Fuzzy Structure Ordinal Module
FRR	-	False rejection rate
GA	-	Genetic Algorithm
H	-	Higher
HMM	-	Hidden Markov Model
HSV	-	Handwritten Signature Verification
HOG	-	Histogram of Gradient
IDE	-	Integrated development environment
IEEE	-	Institute of Electrical and Electronic Engineers
IM	-	Initialization Module
INNS	-	International Neural Network Society
IR	-	Inferred
IR	-	Information Retrieval
IS	-	Initialization Stage
ISO	-	International Standard Organization
L	-	Lower
LED	-	Light-Emitting Diode
LPD	-	Linear Programming Descriptor
LPR	-	License Plate Recognition
LPP	-	Local Projection Profile
LS	-	Less
LS-SVM	-	Least Square Support Vector Machine
LVQ	-	Learning Vector Quantization
M	-	More
MAE	-	Max absolute Error
MC	-	Much
ME	-	Maximum Entropy
ME	-	Math Expressions
ME	-	Misclassification Error

MEC	-	Maximum Extent Circle
MISO	-	Multi-inputs Single Output
MLP	-	Multi-Layer Perceptron
NN	-	Neural Network
OCR	-	Optical Character Recognition
OSVS	-	Offline Signature Verification System
FSOM	-	Fuzzy Structured Ordinal Module
PDF	-	Probability Density Function
RBF	-	Radial Basis Function
RC	-	Reliable Classifier
RDD	-	Robust Directional based Detector
RF	-	Radio Frequency
RGB	-	Red Green Blue
ROSVS	-	Robust Offline Signature Verification System
RGM	-	Robust Generic Module
RGT	-	Robust Generic Thresholding
RV	-	Reliable Verifier
S	-	Smaller
SC	-	Shape Context
SDK	-	Software Development Kit
SDM	-	Soft Decision Method
SC	-	Shape Context
SI	-	Signature Image(s)
SIS	-	Simple Image Statistics
SOM	-	Self-Organizing Map
SRM	-	Structural Risk Minimization
SSE	-	Static Signature Extraction
SSVM	-	Smooth Support Vector Machine
SV	-	Support Vector
SVM	-	Support vector machines
TBM	-	Text Binarization Method
TH	-	Threshold
USB	-	Universal Serial Bus

VB	-	Very Big
VBE	-	Very Below
VC	-	Vapnik-Chervonenkis
VH	-	Very High
VPR	-	Vascular Pattern Recognition
VS	-	Very Small
WT	-	Wavelet Transform
ZCT	-	Zero-Crossing Thresholding
2D	-	2 Dimensional

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CHAPTER 1

INTRODUCTION

1.1 Overview

Forming a platform for reliable authentication has been a challenging topic for research for over three decades. The field has received significant attention with respect to different demands, including performing financial transactions, security processes and person identification, and detecting fraud (Singh et al., 2014). Biometrics are one of the most useful methods applied to achieve the target. Biometrics refer to the automatic identification of a person based on their physiological or behavioral characteristics. In other terms, biometrics is a method used to calculate and analyze a person's biological data, as a means of helping make key decisions. Biometric measurements can be made based on a part of the human body, referred to as physiological measurement. Different parts of the body, including fingerprints, hand geometries, retinas, irises and facial forms, can all be used to lead physiological biometrics. On the other hand, behavioral characteristics are also relied on to calculate and evaluate actions taken by a given person. Signatures, voice recordings and keystroke rhythms are all examples of behavioral biometric technologies. Each of these are previously-mentioned biometrics which can identify one person out of hundreds, with different degrees of robustness. Differences in performance can be attributed to many factors including background noise, signal distortion, biometric feature changes and environment variations. As no one biometric technology has a set of criteria that's right for all situations, adopting a proper biometric trait is impacted by different metrics. These include accuracy, ease of use, ease of deployment, cost, or a place of implementation (Xiao and Yan, 2003). The following Zephyr chart as shown in Figure 1.1, prepared by the International Biometric Group, compares different biometrics in light of ease of use, cost, accuracy and perceived intrusiveness, respectively.

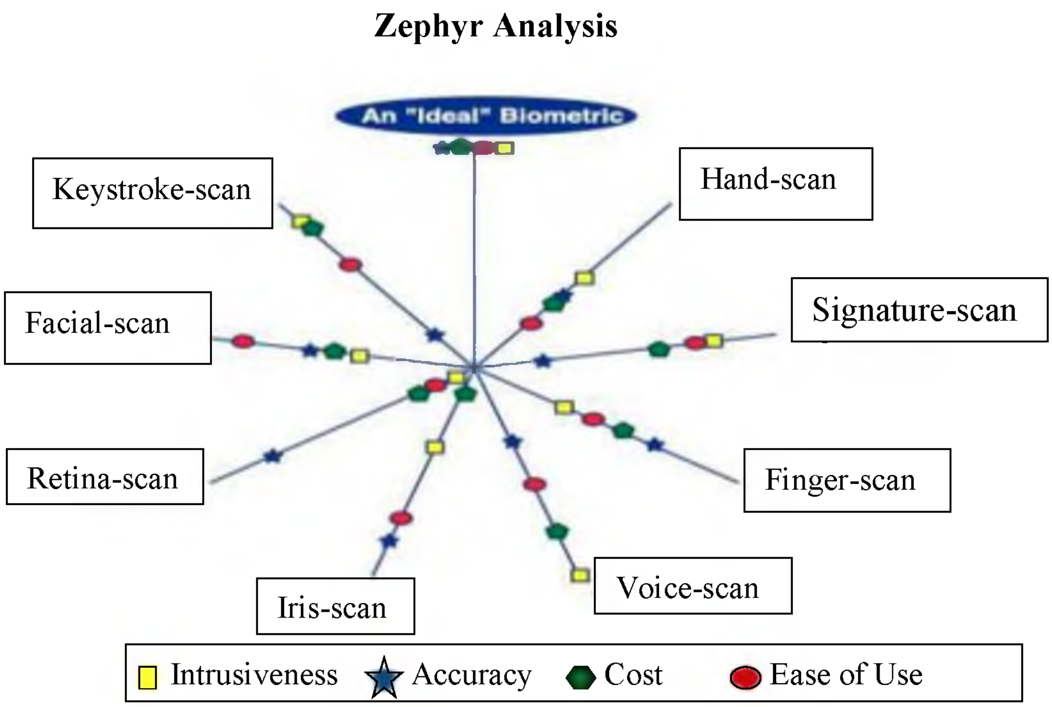

Figure 1.1 Comparison of different applicable biometric systems

A person's signature is one biometric system which can be implemented across different sectors, including banking, retail or security due to its relatively low cost. This there enhances its accuracy. This accuracy, in relation to other suggested systems, is currently one of the most in-demand research topics.

The next section details the background of the research problem, and sets out the research process. The problem statement is described in Section 1.3, while its objectives are discussed in Section 1.4. The research's scope and significance are presented in Sections 1.5 and 1.6, respectively. The uniqueness of the conducted research is detailed in Section 1.7. For ease of understanding and reference, Section 1.8 provides an organizational layout for the thesis.

1.2 Problem Background

In general there are two forms of signature verification systems, specifically online and offline ones (Pan et al., 2010; Okawa, 2016). In online signature verification an electronic device, usually a tablet or camera, is used to capture both the shape of the signature and its physical characteristics, including stroke speed and pen pressure (Gupta and McCabe, 1997; Deore and Handore, 2015). This dynamic information allows individual signers to be accurately classified through the verified low false acceptance rates (FAR) and false rejection rates (FRR) of such systems (Rigoll and Kosmala, 1998; Hua and Ran-dong, 2012; Khalid et al., 2011; Survoy, 2015; Mokayed and Mohamed, 2016). Through an offline signature verification system (OSVS) only scanned images of sample signatures are available. Therefore, the FAR and FRR values are higher (Justino et al., 2001; Justino et al., 2000; Fang et al., 2001; Dixon, 2015; Hum et al., 2015).

This research addresses some issues regarding the offline signature verification system, based on different signatures provided as inputs for the whole system. These related problems are listed below:

- Building Signer Profiles: Most literature regarding offline signature verification assumes that there will be a sizeable number of sample signatures available from which a profile of an individual signer can be constructed. If there are too few sample signatures, the variability between signatures from the same person cannot be captured (Allgrove et al., 2000; Mokayed et al., 2009). This proposed technique looks at the worst-case scenario, being offline signature verification where only one sample signature is available. Such situations occur in the banking industry where a bank only has one hard copy of each customer's signature, and wishes to implement some form of automatic signature verification without requiring all customers to attend an enrollment session at a bank branch. On the other hand many factors will have a negative impact on the performance of the OSVS, namely individuals who are not able to provide the same signature each time, people with issues related to muscle control, and those who are use very simple signatures, limited to just their initials (the first letter of each of name).

- OSVS accuracy: Different conducted researches have frequently highlighted the issue of low accuracy in offline signature. The reason for low accuracy relates to the inappropriate or low performance of any one of the needed stages, so to complete the development of the whole system (Angélica A et al., 2008). One major stage involves binarizing the image and adapting a proper thresholding technique. This step is crucial as it provides a clear binarized signature extracted from a cheque or a form, in order to obtain the clear objects needed for descriptor representation (Heide et al., 2002; Lopresti and Kavallieratou, 2010). Nevertheless, so far very few thresholding techniques proposed by other researchers have been evaluated over extracting a signature embedded in different forms and cheques. Therefore the step of evaluating a performance of the most common thresholding techniques in offline signatures is valuable, as it assists in creating an accurate binarization method for that kind of needed system. No standard features adopted can be extracted always from signatures, with features possibly being image features, structural features or geometric features (Rath et al., 2003; Shin and Doermann, 2006; Rusinol and Llados, 2009; Ziaoling and Xiaofeng, 2009; Kumar et al., 2011; Bertrand Co¨uasnon and Aur´elie Lemaitre, 2014; Hafemann et al., 2016; Chandra and Maheskar, 2016; Pare et al., 2017). For that reason, there is still a need for research to evaluate and find new features, as there is no 'silver-bullet' recommendation for needed features, but still it is vital to improve accuracy as this can lead to better performance in decision making. In the verification stage decisions can be made through using either similarity-based or verification-based methods. For the first type, the challenge relates to deciding which technique can be used to calculate similarity, in addition to the challenge of finding the best similarity threshold value and thereby deciding whether the signature is genuine enough or not to provide a single signature (Ahmad et al., 2014). On the other hand, the verification-based methods are categorized into two well-known approaches, including supervised and unsupervised learning, both of which have been previously researched to improve the quality of the classification results (Zhong, 2006; Han and Karypis, 2000; Trappey et al., 2006; Manevitz and Yousef, 2007; Kanawade and Katariya, 2013; Deore and Handore, 2015; Mokayed and Mohamed, 2016; Hum et al., 2016; Diaz et al., 2017). Evaluating different methods and proposing the most effective ones should be an outcome of this work.

- Data preparation and testing: A significant weakness in using signatures to verify a person is that the process is vulnerable to forger reproduction as means of counterfeiting an identity. In signature verification, forged signatures can be divided into three different categories. These categories are based on how similar a forgery is to the genuine signature, classified as random, simple and skilled forgery. In random forgery, the forger does not know the signer's name or signature shape. In simple forgery or unskilled forgery, the forger knows the name of the original signer, but not what his signature looks like. In skilled forgery, a close imitation of the genuine signature is produced by a forger who has seen and practiced writing the genuine signature. Many of the proposed studies in the field of offline signature verification systems have restricted their evaluation, by covering only one type of the previously-mentioned forged signature, which is usually produced by a random or skilled category forger (Zois et al., 2016; Karouni et al., 2010). In the proposed study, three types of these forged signatures were tested and evaluated, so to prove the effectiveness of the conducted work.

Due to all these previously-mentioned factors, this study's aim is to propose a system which is able to work by using one single signature to build the signer profile with a low error rate, by calculating both the false acceptance rate (FAR) and false rejection rate (FRR) for different types of forged signatures.

1.3 Problem Statement

This conducted study has concentrated on evaluating various stages applied to offline signature verification systems, to propose an accurate and efficient OSVS which implements better methods for different stages, including binarization, descriptors representation and verification. This OSVS is also able to use one single signature for building a profile, and while the overall performance of the system has been tested through using three different types of forged signatures to cover most issues related to offline systems. The main research question to be addressed when evaluating the system is:

How to propose a highly-accurate offline signature verification system that uses one single signature to build the signer profile with different genuine signatures extracted from forms and cheques, in addition to different types of forged signatures used for evaluation.

The following questions should be answered through the research to achieve the proposed target:

1. RQ1: What are common techniques applied to different stages needed in OSVS as binarization, descriptors representation, and verification?
2. RQ2: How is the suitable adaptive binarization algorithm employed in obtaining clear objects embedded with forms and cheques?
3. RQ3: What descriptors need to be extracted out of the binary signature image, and how can they be represented to obtain an optimal result?
4. RQ4: How can the best methods be found for verifying an enrolled signature among the different proposed verification-based and similarity-based methods, with a single signature used to build the profile?
5. RQ5: How to propose an offline verification system using one single master signature, and consequently build a signer profile with high performance?
6. RQ6: What is the performance of the proposed AOSVS, using different genuine signatures extracted from different forms and cheques, in addition to three types of forged signatures?

1.4 Study Aim and Objective

The main goal of the conducted work is to propose an offline verification system with different proposed techniques in different stages, beginning from the first stage of enhancing the image for decision-making, with a low error rate for only one signature to be used in building the signer's profile, and different enrolled genuine and forgery signatures used for testing and evaluation. The following objectives should be reached by the end of the work, in order to have achieved the stated goals:

1. To propose an adaptive binarization method based on background-based estimation (page 118), zero-crossing thresholding (page 120), and fuzzy structure ordinal module (page 122) that able to extract the important features out of the signatures in different scenarios
2. To propose an image enhancement based on masking (page 145), unique descriptors representation (page 137), and fused statistical-based with distance-based verification methods (page 147) to achieve reliable verifier for the conducted adaptive offline signature verification system.
3. To build different offline signature dataset which includes enrolled genuine signatures embedded into different challenging forms and multiple types of forged signatures (random, unseen and seen) for testing and evaluation.
4. To evaluate the performance of the proposed adaptive offline signature verification system using only one signature to build the signer profile.

1.5 Research Scope

Proposing a better offline signature verification system, compared to the currently-used one which faces challenges related to inconsistencies in human behavior and the huge varieties of provided signatures, is this research's main scope. The better proposed system can be achieved through means of a reliable image enhancement phase, which is able to eliminate noise and correct the positioning of the provided signature, before sending it to the engine, as well as defining and using an adaptive binarizing module based on background estimation and applying an intelligent system to the final decision. To enhance the performance, new descriptors are proposed for correctly describing signature characteristics, before sending it to the decision module.

As with all verification problems the major issue related to evaluating system performance is understanding the type of verification method applied, be it similarity-based or verification-based. In cases where a similarity measure has been chosen for application, the calculation of the threshold to determine whether a test signature is accepted or rejected, is one of the main challenges faced. On the other hand there are many verification-based methods used to verify and classify different systems, with choosing the best method to achieve the study's stated aims is one challenge being faced. At the end, this work tries to verify the efficiency of the proposed OSVS using a worst-case scenario where only one sample signature is available to create a signer's profile, with a highly accurate system being established. Such scenarios occur in the banking industry, where a bank only has one hard copy of each customer's signature, and wishes to implement some form of automatic signature verification without requiring all customers to attend an enrollment session at a bank branch. The literature review of the work conducted by different researchers in different studied stages has been outlined in detail in the next chapter. To have a good evaluation of the conducted work, signatures collected from real cheques are provided. This dataset contains two databases, the first consisting of ten master signatures captured from five test individuals in a single session, as well as fifty genuine signatures, fifty random forgeries, fifty unseen forgeries, and fifty seen forgeries for each individual captured over a number of sessions. The second database consists of ten master signatures captured from five different individuals in a single session, as well as ten seen forgeries. This second database is constructed to allow for the further testing of threshold determination algorithms, as it was felt that signatures of just five individuals would not yield significant results.

1.6 Research Significance

The research can be implemented across different fields with the ability to add values related to the following areas:

A. The proposed binarization, descriptors representation, and verifier techniques all perform well, when compared to the proposed techniques from previous related works.
B. The proposed system can effectively verify offline signatures by accurately distinguishing between genuine and forged signatures, while only needing one signature for profile building, making it a major contribution of the proposed study.
C. The proposed system can be used in different financial applications which need to verify signatures for a specific purpose.

Huge numbers of offline signatures are collected by banks, businesses and government organizations for financial transactions made every day. Collected signatures have considerable differences, and are affected by factors which enrich the importance of the proposed topic. This research offers an ability to use an offline signature verification system in the banking sector. The work on this topic seeks to provide reliable verifiers, which will have great value for the document authentication process. Different fields need to verify offline signatures, such as banks and auditing agents, all of which will attain great advantages through using such a kind of verifier, with one possible scenario as explained in Figure 1.2:

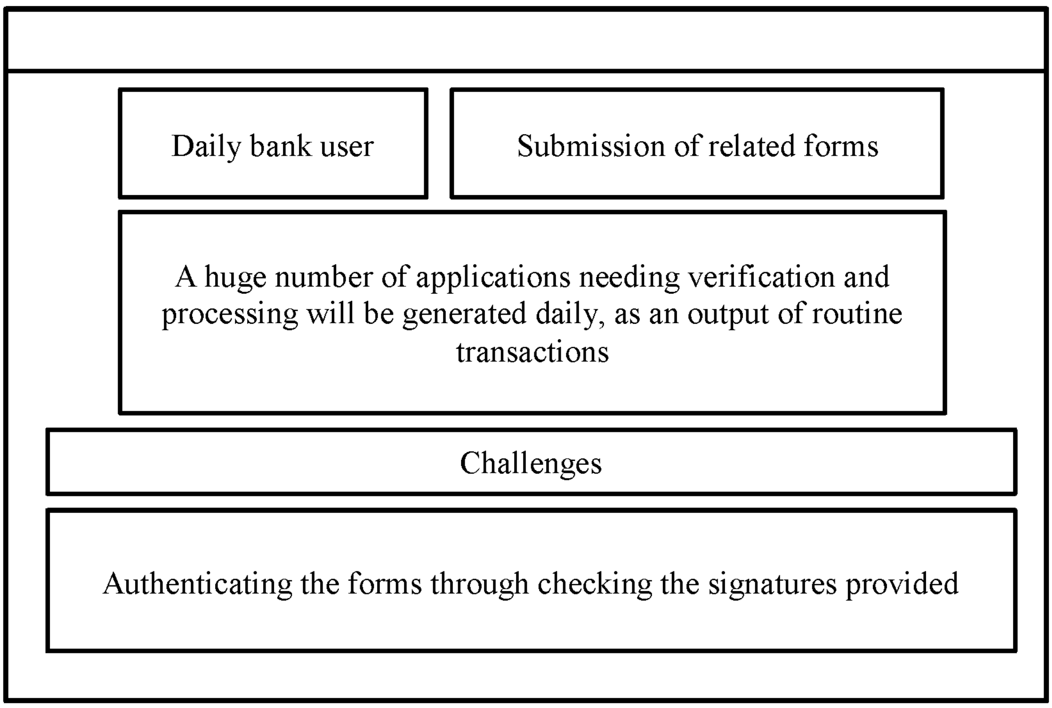

Figure 1.2 One of the proposed scenarios which demonstrates this research's significance

This research can contribute to creating a good start for other research topics related to the conducted work, such as enhancing multimodal biometric systems, finding unique descriptors and enhancing document classification, respectively.

1.7 Research Uniqueness

Wide-ranging research studies have been conducted over a long period of time, in an attempt to enhance the performance of the offline signature verification system. To achieve this, the research focuses on proposing an adaptive representation module which includes both binarization and descriptors representation, in addition to reliable verifiers which evaluate the performances of different verification techniques. Two approaches have been implemented in the verification stage. The first approach assumed the ideal threshold for a sample signature related to some of its features including size and pixel density. The second approach consisted of damaging a copy of the sample signature, by moving pixels about at random, and then comparing it against the original to determine a threshold. These two proposed stages, namely adaptive representation and reliability verifier which are explained fully in the implementation chapter, have contributed mainly to this study's uniqueness.

Most previous studies used a sizable number of signatures, ranging from three, five or more, to build the signer profile for the offline signature. On the other hand, only a few studies have supported verification based on one signature for building the profile, as mentioned before. The previous-proposed techniques developed in different stages are combined to build the OSVS system. The system has used one signature to build the signer profile, and has used different enrolled genuine and forged signatures to evaluate the system. The whole system shows high performance in achieving stated aims as explained in detail in the testing and evaluation chapter, which is considered to be another achievement of the conducted research.

In conclusion, this work has been undertaken to create a system, which can be effectively used in the industry due to its high performance. This system can be applied across different financial divisions, helping to verify the provided offline signature. The high performance of the proposed system adds value to the whole research.

1.8 Thesis Organization

This work attempts to add value to the topic of offline signature verification, due to the fact that not many works and relevant researches have been conducted in the field over a significant period of time. This research is considered to be a good start in building a system which can verify a signature, using only one signature to build the signer's profile. This study begins with an introduction, presenting the problem and specifying the objectives of the research being conducted. On the other hand, the study ends with an overview of the whole conducted work. A short explanation of all sections has been provided below, so to present a greater understanding of the whole study.

Chapter 2 provides an overall review of OSVS, concentrating on limitations currently facing the OSVS. This is followed by specifying major issues related to the proposed system. Details of the stages required to solve this issue are listed later on. These stages provide a review of thresholding techniques categorized as first level, second level, and combined over the last three decades. Techniques used for pre-processing stages in producing a better binary for the extracted signature, and solving the tilting matters, have been discussed. The different descriptors used by researchers in relation to signature issues for achieving reliable and high performance OSVS have also been discussed. Next, different proposed verification systems based on similarity or supervised and unsupervised techniques have been reviewed and discussed.

Chapter 3 constitutes the research methodology adopted after completing this research. The procedures and activities presented by the methodology have helped guide research in achieving its proposed objectives. Next the operational framework presents deliverables of each objective, followed by a brief presentation of the proposed solution. The data collection, evaluation model, evaluation criteria and assumptions are all explained later in the research.

Chapter 4 presents the detailed process of designing and developing the proposed reliable offline signature verification system (OSVS) solution. It begins by explaining the conceptual design of OSVS, followed by developing and building the related modules in detail.

Chapter 5 presents a detailed explanation of the preparation of the dataset used in the next chapter of the thesis, to test and evaluate the performance of the offline signature verification system (OSVS) solution.

Chapter 6 first describes the implementation procedures for the experiments to be conducted, and the evaluation methods to be applied. Following the evaluation model, experiments and analyses of different stages are performed to show the ability of the conducted research to achieve aforementioned objectives. The case study related to implementing the proposed OSVS in the banking sector, with only one signature collected to build the signer profile, is evaluated at the end of this chapter.

Lastly **Chapter 7** presents the thesis summary, the study's contributions, and provides suggestions for future research.

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