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RESEARCH ARTICLE

An Analytical System Design for Forensic Fingerprint Examination

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ABSTRACT Contactless visualization of latent fingerprints has gained considerable attention for crime scene investigations as it can offer an option to collect traces using non-invasive and non-destructive treatment. Considering the complex structure of fingerprint development methods and the tedious process steps performed in these methods, new approaches to acquire, store, transfer, and analyze latent fingerprints practically without requiring any deep knowledge and expertise are needed. This paper introduces a novel contactless latent fingerprint development method that uses a camera embedded in a mobile device and the apparatus used to increase the latent fingerprint's visibility. The enhancement approach is presented to make the fingerprint collected with the designed apparatus usable and valid. As a result, an alternative system design for latent fingerprint development and enhancement is described in detail. Two state-of-the-art fingerprint matchers are used to measure the verification performance of the acquired latent fingerprint. It has been seen that latent fingerprints can be developed with contactless methods using optical treatments alone from reflective and non-porous surfaces. Furthermore, the stages of detecting, developing, and acquiring latent fingerprints from reflective and non-porous surfaces are carried out using the suggested development method without the requirement for forensic professionals. The proposed enhancement approach allows for the direct use of the enhanced fingerprint in the biometric identification/ verification system by extracting distinctive properties from the latent fingerprint.

INDEX TERMS Fingerprint, latent, crime scene, mobile device, forensic, enhancement, acquisition, contactless, STFT, CLAHE.

I. INTRODUCTION

A. BACKGROUND

Biometrics is the science of identifying, verifying, and analyzing individuals reliably, quickly, and securely through the individual's unique biological characteristics. The biological features mentioned include face, fingerprint, hand geometry, handwriting, iris, retina, vein, and voice [1]. Although the use of biometrics has been limited to specific applications for a period, in today's technology world, biometrics have obtained profound importance and acceptance worldwide to identify and verify individuals accurately. Considering the features used by all biometric modalities, fingerprints have been differentiated from other biological properties, especially in most identification-based applications, and it has become the most popular biometric modality.

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The remarkable advancements in biometric technologies and recent progress in image processing capabilities have increased the demands of individuals for personal authentication applications. In this context, the fingerprint has started to be widely used in civil, law enforcement and forensic applications such as public security, surveillance, military, cross-border security, healthcare, access control, crime scene investigation, and mobile biometrics [2], [3]. For more than a century, forensics and biometrics have been closely intertwined, particularly in the field of fingerprint identification. Today, fingerprints remain a cornerstone of crime scene investigations, serving as a reliable tool for identifying individuals. The backward-looking association of forensics and fingerprint has enabled it to gain superiority over other biometric methods.

Depending on the data acquisition methodology, fingerprints are divided into three groups: rolled, plain, and latent. Rolled and plain impressions are called exemplar prints, which are deliberately taken from an individual for record-keeping purposes. Rolled impressions are obtained by rolling an inked finger from one side to the other to capture all the details of the ridge. Plain impressions are created when a finger is pressed down on a flat surface without being rolled. Either by scanning the inked impression on paper or using live scan devices, rolled and plain impressions are obtained [4]. Latent impressions are quite different from the aforementioned methods, and these are essential in forensics. Sweat, which comes out of the small holes called pores on the finger's surface, and intermittent contact of the finger with other parts of the body or with various objects cause a layer of moisture or fat on the surface of the fingers. This layer causes the finger to leave a mark on the surface when it touches, and a latent fingerprint is formed by this way. A series of physical and chemical interventions are carried out to detect, collect, and digitize latent impressions. Thus, searching and reliably recording latent fingerprints is a major task in fingerprint forensics. Rolled and plain impressions are usually acquired in an attended mode; if it is deemed that the collected data quality is not sufficient, the acquisition process can be repeated. In contrast, latent impressions occur when the individual accidentally grabs an object or touches the surface inadvertently. The latent impression formed can be partial, or the ridgelines can be indistinct, the surface where the trace is collected may have a complex background, or high noise and distortion can be observed in the trace due to challenging conditions of the crime scene. For this reason, the latent fingerprint has the worst image quality compared to the other two types of prints.

Latent fingerprints obtained from crime scenes serve as crucial evidence for forensic identification. However, a process that requires arduous steps is carried out to make these prints usable in detecting suspects/ criminals. First of all, possible surfaces or objects that contain latent fingerprints should be detected. Afterward, latent fingerprints are made visible and developed by using the procedures determined by considering the surface where the traces are located. In the last step, the developed latent fingerprints are recorded with imaging devices (video or photograph) or collected using data transfer methods and equipment for detailed analysis. As a result, collecting latent fingerprints requires many procedures, equipment, and auxiliary staff who performs these procedures by using this equipment compared to rolled and plain impressions.

Detecting and developing the latent fingerprint is the most challenging part of forensic identification. During detection and/ or development processes, one, some, or all of the physical, chemical and optical development methods are used in a certain order, taking into account the specifications of the surface where the impression is located, in order to increase the visibility of the latent fingerprint. The following situations arise as a result of treatments on latent fingerprints using these methods:

- When the components, equipment and/ or procedures that cause damage to the fingerprint residue are used, the opportunity to examine the residue for a different purpose such as DNA, drug testing is lost. Components such as solutions and powders used in chemical and physical development methods, and techniques in which ultraviolet/infrared reflection or luminescence are used in some optical development methods also disrupt the structure of the fingerprint residue, and negatively affect the results obtained from the methods used in the biological analyzes.
- Equipment such as brushes, especially used in the application of physical development methods, cause biological data to be carried between the evidence. As a result of this contamination, another situation arises that affects the DNA data that can be obtained from the fingerprint residue.
- To detect and develop latent fingerprints, well-equipped experts, advanced equipment, techniques, complex procedures, and high performance are required. Therefore, methods used for latent fingerprint detection and development are costly and time-consuming processes.
- Suppose the fingerprint detection, visualization, and collection steps are considered a chain connected to each other. In that case, a small carelessness or mistake in any of them can cause the case to be misinterpreted, the evidence to be lost, and the legal authorities to be misled. Therefore, every action performed in the development methods applied to the latent fingerprint affects directly the validity of the collected data.
- Every action taken during the detection and development process has a certain amount of risk. The treatments depending on the latent fingerprint's structure, texture, pattern, elements, etc. may have irreversible consequences. For this reason, detection and development methods that are used without directly affecting the trace's physical or chemical content and are applied without directly interfering with the trace are more widely accepted. The drawback of these methods is that the fingerprint cannot be appropriately and sufficiently developed.
- Analyzing latent fingerprints at a crime scene moves around two paradoxical facts: traces can be detected on nearly any surface and these traces might not always be developed properly. Thus, picking the proper method is a crucial step. When detecting and developing latent fingerprints, it should be moved from the least invasive and destructive method to the most intrusive and destructive method, in hopes of minimizing the potential damage to the evidence and maximizing the evidence's potential.

Making the latent fingerprints visible is a challenging process that requires the simultaneous evaluation of many parameters, includes different procedures, requires different disciplines to work together, and has long processing steps. In addition, many different procedures must be performed by field experts, and these procedures consist of many process steps taking excessive time. As a result, collecting latent impressions requires many processing steps, equipment, and auxiliary staff compared to rolled and plain impressions. These steps are also costly and time-consuming.

B. RESEARCH MOTIVATION

In our previous study, we classified fingerprint forensics under three main headings: information acquisition, field expert activity, and technical evaluation [5]. The main purpose of information acquisition is to detect and make visible the fingerprint with the most appropriate methodology. For this reason, many physical, chemical, and optical development treatments, which consist of many steps, must be managed by a latent analyst. In field expert's activity, both the personnel authorized by law enforcement agencies and forensic experts from different disciplines work to manage the most appropriate investigation process. During the technical evaluation, latent fingerprints are developed and enhanced with the best possible data quality, both by the equipment used while collecting at the scene and image processing methods in computer-aided systems. Considering these three headings, it is clear that high-quality and useful evidence to demonstrate accurate and comparable results can only be obtained if latent fingerprints are collected and analyzed professionally, and if the appropriate equipment is effectively used. From this perspective, the shortcomings of current approaches used for latent fingerprint detection, collection, and enhancement are summarized as follows [1], [6], [7], [8], [9], [10]:

- Performing latent fingerprint detection, collection, and enhancement processes requires professionalism, a high cost to develop, and a long time to take.
- The determination of the latent fingerprint's location and the procedures applied to ensure visibility are carried out by cooperating with different disciplines. The same process steps are performed for each fingerprint collected from the scene. In scenarios where too many fingerprints are examined, processing all data to understand which one is associated with the crime is challenging and time-consuming for the latent analyst.
- When the amount of latent fingerprints that need to be collected on different surfaces and with different methods is too high, the number of experts to collect data is expected to increase. However, due to the lack of personnel with suitable criteria to work in the field, crime scene investigation is mostly carried out with a small number of experts. Therefore, it is inevitable for the personnel to make mistakes in examinations carried out under overtime work conditions where a sufficient number of experts cannot be provided.

Fingerprints forensics is a multidisciplinary and systematic subject that applies knowledge from physics, chemistry, mathematics, and biology [11]. The disciplines mentioned in the investigation process, the technologies used in the realization of these disciplinary functions, and most importantly, the human factor components bring many problems in the fingerprint examination in terms of forensics. Considering these problems, it should be said that;

- To establish a new system from a computer science perspective for the detection, collection, enhancement, and recovery of forensic evidence at the crime scene
- To maximize the quality of procedures for detecting, collecting, and enhancing fingerprints,
- To collect latent fingerprints from specific surfaces without requiring field expertise,
- To develop the detection and collection method with a low-cost and easy-to-use and without time-consuming processes,
- To suggest an enhancement approach to guarantee that the latent fingerprint collected by non-contact methods is used for identification/ verification,
- To ensure that the fingerprint obtained from the crime scene is examined accurately and in-depth,
- To simplify the transfer of valid evidence between crime scene investigators and law enforcement,

are solutions to the mentioned problems as well as the main motivation of this paper.

C. RESEARCH CONTRIBUTION

This paper introduces a new system that can minimize cost, time, expertise, and equipment requirements for crime scene investigation. The primary purpose of this system is helping the experts conduct on-scene investigations, eliminating or minimizing the problems that may occur in the steps of detecting, collecting, and recording fingerprints. The proposed system ensures mobile environments to be used effectively in criminal assessments. The system presented within the scope of the study, consisting of the development method and the enhancement approach, provides:

- The opportunity to detect, acquire, store, and analyze latent fingerprints practically without requiring any deep knowledge and expertise
- Advantages to reduce cost and time-consuming process steps
- A tool to collect data without damaging the structure of the DNA residues found in the latent fingerprints
- An alternative data collection solution to reduce mistakes caused by experts, staff, or development techniques used
- Easing the workload of the field specialist responsible for fingerprint detection, development, and enhancement.

Considering the advantages of the study given above, the key contributions of this paper are summarized as follows:

- A development method that is effortless to use and has a low cost, and it is capable of collecting fingerprints from reflective surfaces at the crime scene has been proposed.
- A development method that works with low complexity, high functionality, collects and processes fingerprints in a fast and practical way has been proposed.

- A development method that aims to reduce the latent examiner's workload, its use does not require in-depth field knowledge, and which tries to reduce the effect of the human factor in crime scene investigation, has been proposed.
- An enhancement approach that makes the latent fingerprint obtained from the crime scene using the suggested development method useable in the biometric identification/ verification system has been proposed.

In this paper, latent fingerprints have been detected and developed only using non-destructive, non-invasive optical treatments. In contrast to the approaches that claim the usage of optical treatments does not provide sufficient improvement alone, latent fingerprints collected using the proposed development method have shown that:

- If the data acquisition process is well designed, fingerprints can be collected and developed using only optical methods, and
- Since these collected fingerprints have sufficient distinguishing characteristics, they can be used directly in a biometric identification/ verification system using the suggested enhancement approach.

The rest of the paper is organized as follows. In Section II, which fingerprint types are examined under the forensic concept, the analysis of latent fingerprints and the impact of the human factor on forensic fingerprint analysis are explained. Our system, including several implementation details, is introduced in Section III, and the apparatus designed to acquire latent fingerprints from the crime scene, and the enhancement steps of these marks collected are explained in detail. Experimental results and comparisons are provided in Section IV. Finally, the paper is concluded, and future works are determined in Section V.

II. FINGERPRINT FORENSIC IN CRIME SCENE

A. OVERVIEW OF LATENT FINGERPRINT DEVELOPMENT

A criminal act can take place in any environment and condition. Since the crime scene is defined as where the crime has taken place, the surface or object on which fingerprints to be collected varies according to the place where the incident has occurred. For this reason, the techniques and methods that should be used to develop and collect latent fingerprints are determined by considering the conditions of the environment and environmental factors to be examined (wet/dry surfaces, extreme hot/cold environments), the conditions and structure of the surfaces where the fingerprint will be collected (porous, non-porous), the impression type to be examined (latent, patent, plastic), the possible age of the fingerprint (surface residence time), and many other parameters. Latent fingerprint development can be achieved through various optical, physical, and chemical treatments [7]. The following subtitles express all factors in determining the priority of the processes mentioned above and order during the detection, development, and collection stages of the latent fingerprints.

B. TYPES OF FINGERPRINTS

Fingerprints are evaluated in three main groups as patent, latent, and plastic. A patent fingerprint is formed when a material containing colors such as blood and paint smears on the finger, and this finger comes into contact with the surface. A plastic fingerprint is a three-dimensional pattern that stays on a soft surface. This fingerprint type is formed by finger contact with surfaces such as soap, mud, and paste. Patent and plastic fingerprints can be seen with the naked eye without requiring external assistance. A latent fingerprint is a complex mixture of natural secretions and contaminants from the parts of the body or environment. This pattern is invisible to the naked eye [7].

Since patent and plastic fingerprints can be seen with the naked eye, simple treatments are sufficient to digitize and develop these traces. However, latent fingerprints are invisible. Thus, to visualize a latent fingerprint, many optical, physical, and chemical treatments are essential. Latent fingerprints are formed by the mixture of natural secretions produced by human skin. In some cases, other materials that environmentally contaminate the skin layer may get involved in fingerprint residue. The main components of the sweat gland secretions that make up the fingerprint have been identified and classified by many researchers. By detecting the chemical and physical properties of secretion compounds, physical and chemical substances that can increase fingerprint residue visibility by reacting with them are determined. These substances are used to make the latent fingerprint visible [8].

C. SURFACE CHARACTERISTICS AND COLLECTION METHODS

Accurately determining the type of surface on which the fingerprint is expected to be developed is crucial for successful development. Many latent mark detection and acquisition techniques exist, and understanding the features of the surface helps to decide suitable techniques to be used. Surfaces are generally divided into two classes as porous and non-porous (Fig. 1). This separation is necessary in order to apply the appropriate technique and component in the proper sequence. Porous surfaces are generally absorbent, and the substrate of this surface absorbs fingerprint residue. Fingerprint residues on these surfaces are preserved for a more extended period. On non-porous surfaces, fingerprint residues are on the outermost layer, and such marks are more susceptible to damage. To react with the fingerprint in the lower layer of the surface on porous surfaces, treatments using chemical components give more effective results. On non-porous surfaces, besides the dusting method and chemical development methods, which are among the most known methods, optical methods are also used to develop latent fingerprints with today's technology opportunities [1], [10].

Methods mostly used on porous and non-porous surfaces to make finger marks visible is powdering (dusting). Although the efficiency of fingerprint powders developed in different types and structures is low, they have been widely used in fingerprint residue development processes due to their ease of use and low-cost [12]. Fingerprint powders adhere to water and oil residues in the fingerprint trace revealing the details of the prints. Dusting is carried out to make the trace more visible. However, visibility does not mean detectability with the naked eye. After dusting, trace visualization can occur via optical methods such as reflected light (light powders), absorbed light (dark powders), and luminescence (fluorescent powders) [10]. Chemical methods are used to develop latent prints in porous and non-porous surfaces. The chemicals target specific components present in the latent print residue, react as a color change, and make the latent print visible. The surface is treated with these chemicals and examined under different light sources to observe the reaction. If latent prints are present, they can fluoresce upon exposure to the light source [13]. Optical methods can be used with chemical and dusting methods in the fingerprint development process together, as well as can be used to collect fingerprints alone without using an external method. When only optical methods are used without any chemical or physical developer applied to the fingerprint residue, this type of trace enhancement is called the contactless method.

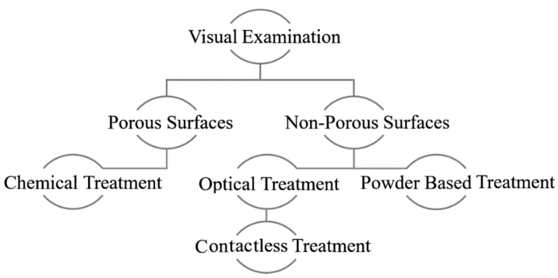

FIGURE 1. General approach to developing latent fingerprints.

It is imperative to apply the correct technique for a particular surface or set of conditions. Many factors such as applying more than one technique or reagent sequentially or together in order to detect latent patterns, applying the reagents in a systematic and correct order, application skill of the field expert, choosing the equipment used correctly, determining the procedures to be applied, directly affect the success of fingerprint recovery. An incorrect, inappropriate action or behavior performed on any of these elements can destroy latent traces and eliminate the opportunity for visualization with an alternative approach. For this reason, alternative treatments instead of physical and chemical development methods have been sought. Latent trace examination and visualization using purely optical examination have the advantage of being non-destructive concerning both the fingerprint deposits and any other forensic evidence. The purpose of contactless development methods is to detect a trace and make it usable for a forensic analysis without affecting any of the chemical compounds that constitute the fingerprint and using irreversible interventions.

DNA can be recovered using some components such as blood or sweat that enable the creation of patent and latent fingerprints. In addition, by analyzing the body fluids that make up the fingerprint residue, whether the person is under the influence of any drug can also be determined. This determination can be vital for the reconstruction and interpretation of the scene. The chemical, powdering, and some of the optical methods creating a reaction effect are destroyed or significantly altered the original fingerprint residue. Thus, non-invasive and non-destructive contactless acquisition systems can be essential for these specific cases, and these are emerging field of research [14].

The operability of contactless methods is based on collecting the print with the maximum contrast value, considering the surface's characteristics where the fingerprint is located. Some initial examinations to include surface interactions/ reflections, composition/ position/ age of the fingerprint, and the lighting techniques used should be realized correctly before the optical development process to acquire latent fingerprint with the highest efficiency possible [13]. Several known contactless acquisition approaches are selected and summarized in Table 1. The following findings have been drawn after carefully reviewing the studies in the literature:

- Optical treatments have been used only during the latent fingerprint detection process or as a co-developer for a more detailed observation of the physically and/ or chemically developed fingerprint.
- Optical development imaging mechanisms/ devices have high-cost designs, are difficult to operate without special training, and many of them are not portable.

D. OVERVIEW OF LATENT FINGERPRINT ENHANCEMENT

The main idea behind fingerprint enhancement is to modify the attributes of the image and make it more suitable for a visual examination and/ or automatic feature extraction. The enhancement process makes to detect specific information contained in the image easier by increasing the dynamic range of chosen features. After, a minutiae extraction algorithm uses these features for comparison [25]. Enhancement methods gain the characteristic data in well-defined fingerprint regions, make the quality in recoverable fingerprint regions better, and label the other fingerprint parts as unrecoverable. The purpose of enhancement techniques is to develop the clarity of ridge/ valley structures of input fingerprints to facilitate the subsequent processing steps. The most crucial factor to focus on is that enhancement interventions should not cause erroneous characteristic feature inference [26].

Fingerprint enhancement methods are divided into two groups: pixel-wise and contextual-filtering. In the pixel-wise approach, image pixels are handled directly. The pixel values are manipulated to achieve the desired enhancement. Common pixel-wise enhancement methods are normalization, intensity transformations, histogram processing, image subtraction, and image averaging [26], [27]. In contextual-filtering enhancement, the context is expressed using local orientation, local frequency, and local quality and is utilized to adapt the filter characteristics to each specific foreground

TABLE 1. Contactless approaches used for the latent fingerprint development.

Ref.	Surface	Treatment	Used Methods/ Materials	Proposed Approach
[15]	Non-porous	Contactless method	Chromatic white light sensors	Making latent fingerprints available for additional verification or further analysis
[16]	Porous and non-porous	Contactless method	Optical coherence tomography	Detecting and recovering latent fingerprint hidden beneath adhesive tape without any changes to the original state
[17]	Non-porous	Contactless method	The optical phenomena of polarization and specular reflection	Introducing a method to detect and extract latent fingerprint images without applying any powder or chemicals
[18]	Non-porous	Contactless method	Chromatic white light sensors and camera	Studying the application of a camera-based approach comparing CWL techniques for the latent fingerprint localization
[19]	Non-porous	Contactless method	Chromatic white light sensors	Age determination of latent fingerprints
[20]	Non-porous	Contactless method	Portable HSI and the CW green laser	Detection of untreated latent fingerprints/ palm prints and separation of overlapped fingerprints/ palm prints
[21]	Non-porous	Contactless method	optical coherence tomography (OCT)	Non-invasive fingerprint acquisition from low-reflecting surfaces
[22]	Non-porous	Contactless method	Diffractive element-based sensor	Detection of latent fingerprints on curved objects
[23]	Non-porous	Contactless method	Shortwave UV radiation	Detecting untreated prints on smooth, non-porous surfaces and capture in Ultra High Definition
[24]	Non-porous	Contactless method	Long-wavelength infrared radiation and a high-resolution thermal vision camera	Acquiring latent fingerprints with neither physical contact nor use of chemical agents

region [26]. Frequently used contextual-filtering based methods are in [27], [28], and [29]. These enhancement actions are implemented for modifying the image brightness, contrast or distribution of gray levels, and pixel value of the output image will be modified according to the transformation function applied on the input values [30].

Rolled and plain impressions contain sufficient information in comparison with latent fingerprints because of the formation. Thus, the matching performance of AFIS for rolled and plain impressions searches has reached satisfying achievements. Latent fingerprints are formed in unintentional mode and do not have sufficient information content to identify the individual due to poor quality, unclear ridge structure, and the difficulty of extracting data from complex backgrounds. Thus, the latent fingerprint matching process has certain challenges due to smudged or blurred ridges, nonlinear skin distortion, and containing partial region of the finger. Since the enhancement of latent fingerprints is more complicated than the rolled and plain fingerprints, different methods are used, and new techniques have continued to be developed for this purpose (Table 2). The main goal of these methods is to make the fingerprint more understandable so that it can be suitable for feature extraction. This enables latent examiners to mark the distinctive elements on the fingerprint more easily [31].

The major limitation of latent fingerprints, according to exemplar ones, is insufficient knowledge of the ridge structure. For this reason, it is essential to improve the ridge-valley structure in the latent trace. If the surface where the latent fingerprint is located has a complex background, the separation of the trace from the surface is another factor that makes its analysis difficult. If the segmentation and orientation estimation, which are the most critical steps for latent fingerprint analysis, are carried out properly, other enhancement steps can be performed with a few simple methods. Several known enhancement approaches are selected and summarized in Table 2.

In the reviewed studies in Table 2, it is seen that learning-based, pixel-wise, and contextual filtering techniques are used to enhance latent fingerprints developed by physical and/ or chemical treatment. Latent traces that have already developed physical, chemical, or both are easier to enhance than those that have only had optical treatment. This situation makes an external enhancing step necessity for the fingerprints obtained using the development method presented in the study. In this context, specific studies including methods used to enhance and recover images that are insufficient in terms of contrast, resolution, quality, etc. have been examined [32], [33], [34]. Latent examples collected by the proposed development method have been sufficiently enhanced at a level that could extract characteristic features by using the techniques suggested in examined studies and the traditional techniques used in latent trace enhancement together.

E. IMPACT OF HUMAN FACTOR

The process of making the latent fingerprint visible may consist of a single method to be applied, as well as applying appropriate methods and techniques one after the other or sequentially. The method /methods can be applied to make the latent trace visible to the naked eye or increase the visibility of the partially visible trace. Detection and acquisition processes may turn into complete chaos, especially in cases where latent fingerprints are detected at the scene and require experts from different disciplines to work together to detect, develop and collect, or where there are too many latent fingerprints that need to be examined. The topics affected by the human factor during the process of transforming from fingermark to fingerprint and accepting it as forensic data to identify the individual are summarized below [9], [46]:

- Method selection: It is the action taken by field experts who decide what kinds of analyzes have to be done. When the components, equipment and/ or procedures that cause damage to the fingerprint residue are used, the opportunity to examine the residue for a different purpose such as DNA, or drug testing is lost. Components such as solutions and powders used

TABLE 2. Latent Fingerprint Enhancement Techniques.

Ref	Objective	Proposed Approach	Used Databased	Performance
[31]	Orientation Estimation	Proposes a latent fingerprint enhancement algorithm, which expects manually marked ROI and singular points	NIST SD27	Results are shown using CMC figures
[35]	Orientation Estimation	Proposes an orientation estimation algorithm based on dictionary learning and sparse coding for latent fingerprints	NIST SD27	RMSD: 18.44
[36]	Enhancement	Proposes a novel latent fingerprint enhancement method based on FingerNet inspired by the recent development of CNN	NIST SD27	Results are shown using CMC figures.
[37]	Segmentation	Using gradient, ridge, and quality based features trained Random Decision Forest-based algorithm classifies the local patches as background or foreground	NIST SD-4 NIST SD27 IIIT-D	The SIVV-TPR improvement on the three databases before and after segmentation are shown in table
[38]	Segmentation	Proposes a latent fingerprint segmentation method based on a combination of ridge density and orientation	NIST SD27	MDR%: 13.03/ FDR %:23.17
[39]	Enhancement	Proposes a novel fingerprint orientation field estimation algorithm based on dictionary of reference orientation patches	NIST SD27	RMSD: 16.38
[40]	Segmentation	Correlation with ideal ridge templates	NIST SD27	EER: 33.8%
[41]	Segmentation	Proposes ridge orientation and frequency computation	NIST SD27 WVU DB	Rank-1 identification accuracy of 16.28%, 35.19% in NIST SD27 and WVU DB
[42]	Segmentation and Enhancement	Proposes a new image decomposition scheme, called the adaptive directional total variation (ADTV) model	NIST SD27	MDR%: 14.10 FDR %:26.13
[43]	Orientation Estimation	Proposes a ConvNet based approach for latent orientation field estimation	NIST SD27	RMSD: 13.51
[44]	Enhancement	Proposes a latent fingerprint enhancement method based on the progressive generative adversarial network (GAN)	NIST SD27	Results are shown using CMC figures
[45]	Orientation Estimation	Proposes an orientation field-based registration algorithm for partial fingerprints	NIST-SD27	Results are shown using CMC figures

in chemical and physical development methods, and techniques in which ultraviolet/infrared reflection or luminescence are used in some optical development methods also disrupt the structure of the fingerprint residue and negatively affect the results obtained from the methods used in the biological analyzes.

- Trace visualization: It is the action taken by field experts who decide which treatments should be used together and in what order to make the latent fingerprint visible.
- Trace collection: It is the action of how the latent fingerprint is collected with which equipment after the visualization or which protocols should be performed if the object containing the latent fingerprint is to be transferred to the laboratory environment.
- Enhancement: It is the action performed to make the latent fingerprint ready for the extraction of characteristic features.
- Preparing trace for comparison with AFIS database: It is the action of marking the characteristic features extracted from the enhanced latent fingerprint and removing the false features.
- ACE-V protocol: It is the action that includes the steps in ACE-V protocol being performed one by one by field experts.

The growing central role of human factors and cognition in fingerprint forensics has paved the way for developing wrong conclusions. One of the main objectives of this study is to propose a new system consisting of a development method and enhancement approach to reduce the human factor as much as possible in the crime scene investigation process.

III. PROPOSED SYSTEM

The proposed system consists of two components. In the development method, which is the first component, an apparatus integrated with the mobile device has been designed to collect latent fingerprints from non-porous and reflective surfaces. The second component, the enhancement approach, is designed to enhance latent fingerprints collected by the proposed contactless method. Detailed explanations of these two components are included in this section. The main purpose of this apparatus is to create appropriate environmental conditions for the visualization of the latent trace. For this reason, the interaction between the surface on which the latent trace is located and the environmental conditions has to be cut off. The latent trace is displayed using the special lighting and imaging mechanism provided by the apparatus. The goal here is to obtain the image of the latent trace with maximum contrast, quality, and resolution.

A. LATENT FINGERPRINT DETECTION AND DEVELOPMENT APPARATUS

Our purpose is based on non-invasive and non-destructive latent fingerprint acquisition from non-porous and reflective surfaces. Since the mobile device is used as the input device, standardizing the fingerprint detection and development process has been considered as the primary goal. In this context, fingerprint detection and development apparatus has been developed by considering the following criteria (Fig. 2). The proposed apparatus attached to the mobile device aims to detect and acquire latent fingerprints with maximum performance.

The developed apparatus is shown in Fig. 3. The apparatus consists of five components: a mobile phone (I), a connection piece that links the mobile phone to the lighting box (II), a lighting box used to make latent fingerprints visible (III), a lens for detecting details of the visible fingerprints (IV), and a power supply box that houses the batteries for powering the LEDs in the lighting box, along with a button to turn the

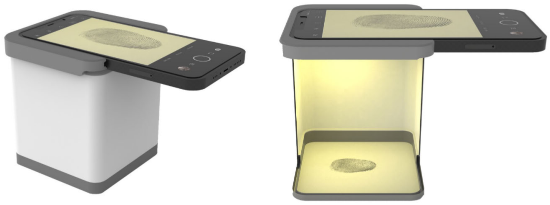

FIGURE 2. Latent fingerprint acquisition apparatus.

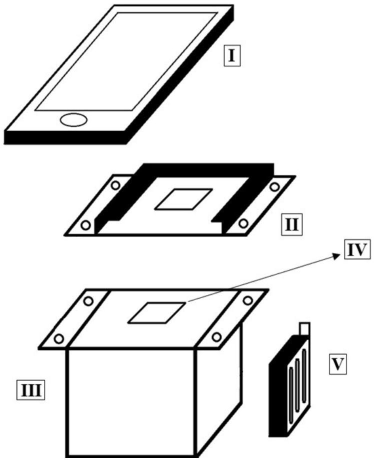

FIGURE 3. Components of the developed apparatus.

power source on and off (V). All parts are made of durable bakelite, a non-reflective material, with a thickness of 3 mm.

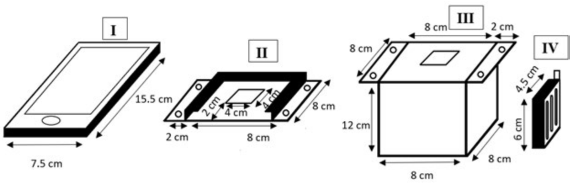

FIGURE 4. Design details of the parts consisting of the developed apparatus.

The apparatus is designed to enable the collection of high-quality latent fingerprints at a consistent standard, regardless of external lighting conditions. The technical details of the components of the latent fingerprint detection and development apparatus are shown in Fig. 4. The characteristics of the yellow LEDs used in the device are 0.2 watts and 2 volts. Macro lenses with +1, +4, +8, and +10 close-up features are used to observe the details of latent fingerprints made visible by these LEDs. These lenses reduce the minimum focusing distance of the mobile phone lens, allowing closer inspection of the fingerprints. This enables a detailed examination of the fingerprint features. The LEDs within the device are powered by batteries, which can be rechargeable or of various sizes and dimensions. The LEDs can be turned on and off using the button integrated into the device.

B. SURFACE DETERMINATION AND OPTICAL TREATMENT SELECTION

When the techniques and methods used for acquiring and developing latent fingerprints are examined, it is seen that optical development methods are the ideal treatment if non-invasive and non-destructive methods are desired to be used. The idea of optical development is to use lighting to provide as much contrast as possible between the trace ridges and the surface, to remove any interference from background patterns or textures where possible. In order to detect marks, optical development is carried out by investigating various lighting angles and different types of light sources. As a result of the experiments conducted within the scope of our study, it is seen that among the light sources of different wavelengths in the visible spectrum, the best result was obtained in yellow light for non-porous surfaces. Thus, yellow light was used as the light source for reflective surfaces such as metal and glass.

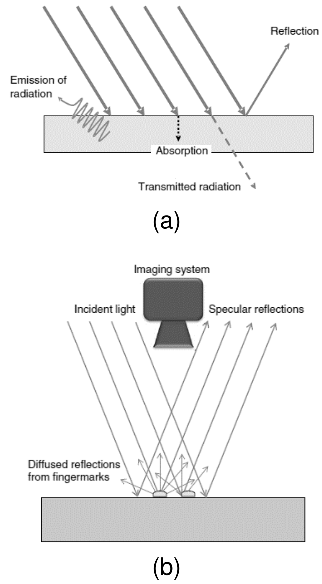

FIGURE 5. (a) Surface and light source interactions, and (b) the interaction of non-porous surfaces with light [47].

The three principal interactions between the surface (and the mark) and the incident light are reflection, absorption, and transmission Fig. 5a. The proposed apparatus collects latent fingerprints from reflective surfaces. In this study, the latent fingerprints were detected by using reflection interaction on non-porous surfaces. Thus, the reflection interaction is emphasized in this paper. Non-porous surfaces and parts of the fingerprint residue respond to the lights sent from the source with different reflection patterns Fig. 5b. When the light falls on a reflective surface, it is reflected specularly at a certain angle. This reflected light cannot reach the eye. However, the same situation does not apply to lights falling on fingerprint residue. Where the light falls upon the fingerprint ridges, it is scattered or diffusely reflected. This diffuse reflection allows some light to reach the eye directly, so the regions with residue appear brighter. Thus, in the fingerprint that is tried to be detected with a light source on a reflective surface, the brighter regions represent the ridgelines, and the darker regions represent the valleys [47].

C. PREPARATION OF LIGHT CONDITIONS

Visual examination is not just performed by using only a light source alone. Suitable environmental conditions must be provided for latent fingerprint detection and development. Natural lighting conditions affect the surface where the fingerprint is collected, and the contrast between ridges and valleys of the trace is reduced. Since the wavelength, intensity, and incidence angle of the light used directly affect the latent fingerprint's visibility, an apparatus that serves as an isolator box has been developed to standardize these criteria (Fig. 6).

It has been seen that when the latent mark is illuminated from a single point with a single source or is illuminated very intensely, a part of the trace disappears in part corresponding to the position where the illumination occurs. Therefore, a light source having more than one is placed circularly in the developed interior of the apparatus. This positioning of the light is called the ring light technique in digital imaging [47]. In close-up work, this reduces sensitivity to surface roughness and provides very even lighting on the object. The light source creates a continuous circle around the lens, thereby providing even illumination from all angles around the optical axis of the camera. There are two types of ring lights: the flash and LED lights [47]. During the development of the proposed apparatus, light sources with different illumination intensities were used. Ultimately, the best performance was obtained using six yellow LEDs which had 0.2 watts and 2 volts positioned circularly and at a right angle. In this way, data loss in traces was prevented. The appropriate illumination intensity was determined to capture the contrast between ridgelines and the surface most clearly. This proposed apparatus aims to achieve better performance in the image enhancement process by increasing the contrast difference.

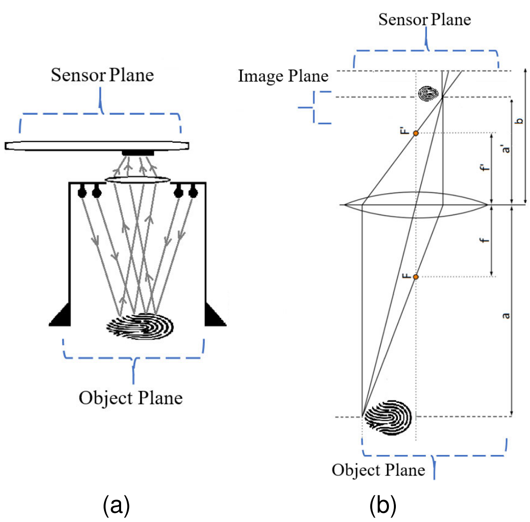

FIGURE 6. **(a) Latent fingerprint acquisition apparatus, (b) positioning macro lens.**

D. KEY ELEMENTS OF FINGERPRINT ACQUISITION

Once a mobile device camera is used as the input device, a convenient visualization of the latent image is the fundamental step for fingerprint identification. The fingerprint image must be in sharp focus, taken perpendicular to the surface, incorporate an accurate scale, and be captured at sufficiently high resolution and lighting for all identification purposes. Since mobile devices are not designed for direct biometric image capture, situations may arise where focus, blur, resolution, and illumination cannot be met sufficiently during the acquisition. The operations performed for the illumination parameter are explained in those mentioned above. In this section, the other parameters are discussed.

In general, the most accurately focused images have the highest quality, and in this aspect, autofocusing has proved to be useful. There are two steps in most autofocusing techniques: first, a focus measurement (FM) is calculated at various lens positions and the lens is moved to the maximum focus-measurement position. The lens-moving method is known as this method. Fig. 6 shows how a simple lens works in imaging an object. The following Gaussian lens law describes the relationship among the object distance a, the focal distance of the lens F, and the image distance a^{I}:

$$\frac{1}{F} = \frac{1}{a} + \frac{1}{a^{\mathrm{I}}} \tag{1}$$

The image distance should be equal to the sensor distance b, and the image plane corresponds to the sensor plane to obtain the maximum focus. When the sensor plane is displaced from the image plane, the image becomes blurry. The distance between the macro lens in the developed apparatus and latent fingerprint on the surface, and the distance between the lens and mobile device were calculated by considering the Gaussian lens law. In addition to this, the maximum focused latent fingerprints were collected by taking advantage of the autofocus feature of the mobile device. Since the focus measurement is appropriately completed, the blur problem was eliminated. In this way, sufficient criteria were provided for the focus and blur parameters of the developed apparatus.

The last parameter is the resolution. The number of pixels that compose the entire image is expressed as resolution. The more pixels in the image, the higher and better the image resolution. Although a mid-segment mobile device has sufficient resolution, it is aimed to increase the image resolution by using a macro lens with the mobile device in the study. Macro lenses are specially designed to offer optimum optical performance at very short focal lengths and often deliver the sharpest images at close distances. Since latent fingerprints are also collected with close-up shots, using a macro lens during the fingerprint acquisition has been very effective in capturing the details. Fingerprint image samples acquired using a macro lens with the recommended apparatus are shown in Fig. 7.

E. LATENT FINGERPRINT ENHANCEMENT

Enhancement processes are carried out to digitize the fingerprint image collected using the designed apparatus, eliminate the factors affecting the image quality, and extract meaningful information from the image. Fingerprint image enhancement is applied to increase the interpretability of data in decision mechanisms based on information extraction

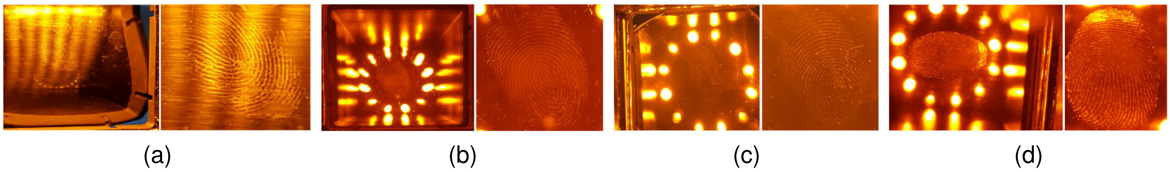

FIGURE 7. Collected latent fingerprint samples from different reflective surfaces, (a) iron cup, (b) sunglasses, (c) window, (d) television.

from the image. The purpose of image enhancement is to reduce noise, clarify ridgelines and join broken ones, fill gaps, increase image contrast, reduce data size, and make the image ready for feature extraction. The fingerprint enhancement process includes certain stages. Within the scope of this study, the techniques and methods applied in the enhancement process and the order of their implementation are explained below.

1) SEGMENTATION

The latent fingerprint image is expressed with two different regions, the background and the foreground. The foreground is defined as regions containing fingerprint ridgelines and important characteristics, and the background is defined as regions outside the boundaries of the image. Segmentation is a step applied to distinguish the foreground region from the background region. This step is applied to reduce the data size, shorten the image processing operations, and perform the correct feature extraction.

If the surface where the latent fingerprint is collected is flat and smooth, and the surface does not have a patterned texture that can interfere with the trace, it can be easily detected with the developed apparatus. Fingerprint segmentation is performed according to the pixel density variable determined based on the background to separate the dark region outside the fingerprint. This method is called thresholding. For thresholding, the image histogram showing the gray level distributions in the image is used. According to this histogram, the image is evaluated in two main groups: pixels belonging to objects and pixels belonging to the background. In this case, the easiest way to distinguish objects from the background would be to compare the pixel values in the image with a T threshold value determined relative to the histogram.

$$g(x,y) = \begin{cases} 1, & f(x,y) > T \\ 0, & f(x,y) \leq T \end{cases} \tag{2}$$

Accordingly, by using the Eq. 2 for any (i,j) pixel in the image, it is determined whether the (i,j) pixel is a point belonging to the object or the background. Thus, the image is segmented by setting all pixels with intensity values above a threshold to a foreground value and all remaining pixels to a background value.

2) NORMALIZATION

The main purpose of many development treatments applied to fingerprints is to remove the light effect and blur on the trace and improve the contrast between the ridges and valleys of the trace. Since many enhancement treatments increase the contrast between ridgelines and surface texture, several problems that may arise during the fingerprint acquisition phase can be easily eliminated without complex normalization methods. However, since a non-destructive and non-invasive data development approach is proposed within the scope of this study, physical or chemical interventions to increase the contrast of the trace cannot be performed. Therefore, specific arrangements should be made in the contrast enhancement to separate the latent trace from the background.

The normalization methods to be used should be selected according to the image on which the method is applied. In our previous studies, many acknowledged approaches used for fingerprint normalization were evaluated [48], [49]. Especially, increasing the sharpness of low contrast latent fingerprint images collected using mobile devices is stated, histogram equalization-based enhancement methods are the most preferred approaches. In our study, Contrast Limited Adaptive Histogram Equalization (CLAHE) method, which produces successful results in the contrast enhancement of images with poor visibility conditions and insufficient details, was used in the normalization stage.

CLAHE clips the histogram according to a predetermined clipping limit and distributes it to all histogram blocks. A small overflow from the clipping limit occurs during this distribution. A non-uniform distribution function should be used to prevent the cropped region from being distributed evenly over all regions when performing the histogram distribution. The Rayleigh distribution function is a general non-uniform function that can be used for this purpose. CLAHE algorithm implemented using the Rayleigh distribution function is summarized in [33]. In the first step, the input image is divided into blocks that do not overlap (MxN). In the second step, histogram calculation is made for each separated block. In step 3, the contrast limited histogram of the contextual region is calculated using CL value as:

$$N_{aver} = \frac{N_{CR-Xp}, x\, N_{CR-Yp}}{N_{gray}} \tag{3}$$

where N_{aver} is the average number of pixel, N_{gray} is the number of gray levels in the contextual region, N_{CR-Xp} and N_{CR-Yp} are the numbers of pixels in the X dimension and Y dimension of the contextual region. Based on the Eq. 4, the N_{CL} can be calculated by the equation:

$$N_{CL} = N_{clip}\, x\, N_{aver} \tag{4}$$

where N_{CL} is the actual CL, N_{clip} s the normalized CL in the range of [0, 1]. If the number of pixels is greater than N_{CL}, the pixels will be clipped. The total number of clipped pixels is defined as $N_{\sum clip}$, then the number of pixels distributed averagely into each gray level is given by:

$$N_{acp} = \frac{N_{\sum clip}}{N_{gray}} \tag{5}$$

$H_{CR}(i)$ is the number of pixels in each gray level of the contextual region, i is the number of gray level. Then, the contrast limited histogram of the contextual region is calculated using the rule given by the following statements:

$$\begin{aligned}
&If\ H_{CR}(i) > N_{CL},\ H_{NCR}(i) = N_{CL}\\
&Else\ If\ H_{CR}(i) + N_{acp} \geq N_{CL},\ H_{NCR}(i) = N_{CL}\\
&Else\ H_{NCR}(i) = H_{CR}(i) + N_{acp}
\end{aligned} \tag{6}$$

In step 4, the remaining pixels are redistributed until the remaining pixels have been all distributed. The step of redistribution pixels is given by:

$$S = \frac{N_{gray}}{N_{LP}} \tag{7}$$

In step 5, Intensity values in each region are enhanced by Rayleigh transform. This transform can be defined in the form of:

$$y = y_{min} + \left[2\alpha^2 ln\left(\frac{1}{1 - P(x)}\right)\right]^{0.5} \tag{8}$$

where y is the computed pixel value, α is the Rayleigh distribution parameter, y_{min} is lower bound of the pixel value, and $P(x)$ shows the CDF (Cumulative distribution function). In the last step, matching is made using a bi-linear interpolation to prevent discontinuity between each block and its neighboring blocks.

FIGURE 8. Acquired trace samples with the developed apparatus and normalization results with CLAHE.

The CLAHE algorithm has two advantages, especially for noisy and low-contrast images such as fingerprints analyzed within the scope of the study:

- Working separately on different parts of the image, not on the whole
- Preventing the problem of making the noise arising in adaptive histogram equalization stronger by limiting the values of the high and low functions of the function used in histogram equalization.

The lighting mechanism and data collection standards of the developed apparatus provided the opportunity to complete the normalization step with a non-complex approach. After the collected latent fingerprint is converted from RGB format to gray-level format, CLAHE is applied. We determined the clipping limit as 0.2 and the distribution parameter as Rayleigh type, which creates a bell-shaped histogram.

3) FILTERING

The quality of fingerprints is affected by many different conditions. Especially with the development of touchless fingerprint recognition technology, new challenges are encountered affecting fingerprint quality. Bulk and high-cost systems are needed to collect better quality fingerprints with contactless methods. However, when low-cost handheld devices are used instead, this leads to new constraints to be addressed [53]. External interventions are required to extract sufficient qualitative and quantitative features from the collected latent fingerprints.

During the segmentation and normalization stages, pixel-oriented enhancement methods were used. However, these are not enough to maintain the continuity of the ridgelines. Although it is not a problem for well-defined fingerprint regions, the separation of ridge and valley from one another may be a problem for the corrupted regions of the fingerprint. Thus, filtering is used to recover these regions, protect the regular structure and ridgeline continuity of the fingerprint, and remove noise and distortion. Since the enhanced fingerprints are both latent and collected by touchless methods, it is necessary to use approaches that are resistant to noise and that make improvements by considering regional differences of the trace. Considering these situations, it was seen that the most successful fingerprint enhancement algorithms perform in the spatial-frequency domain. Thus, we used Short Time Fourier transform (STFT) proposed by [50] in the last stage of the development process.

STFT is a well-recognized method of analyzing non-stationary signals in signal processing and has a field of application in the improvement of 2D fingerprint images. It is the process of applying a Fourier transform to each segment by dividing a given signal by windows of certain sizes.

$$\begin{aligned}
X(\tau_1, \tau_2, \omega_1, \omega_2) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} I(x, y)W^*(x - \tau_1,\\
y - \tau_2)e^{-j(\omega_1 x + \omega_2 y)}dxdy
\end{aligned} \tag{9}$$

The time-frequency analysis of the fingerprint images is performed as in Equation 8. In this equation, the image to be analyzed $I(x, y)$, the window function W, the spatial frequency parameters ω_1 and ω_2, the time parameter τ_1 and τ_2, time-frequency atoms $(\tau_1, \tau_2, \omega_1, \omega_2)$ are represented. After the image is converted to the frequency domain, filtering is applied by extracting information such as orientation and frequency from the image.

Latent fingerprints have well-defined, recoverable corrupted, and unrecoverable corrupted regions [27]. The

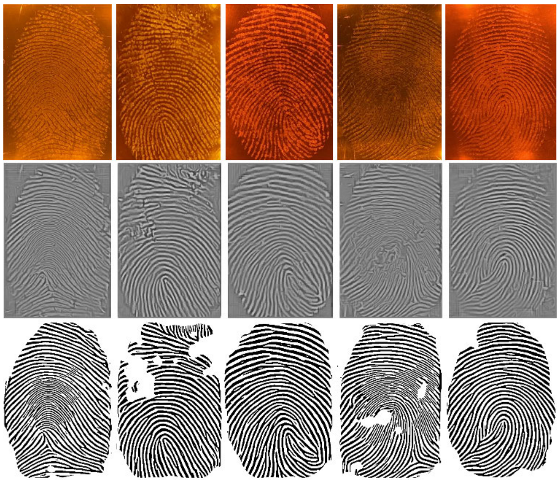

FIGURE 9. Fingerprint samples collected with the developed apparatus, filtering results with STFT, and regions of the fingerprint to be used for feature extraction.

regional quality difference in latent fingerprints causes that not every region can be improved with certain filter parameters. For this reason, a filter that is tuned to the radial frequency and aligned with the dominant ridge direction is applied in each window of 2D signals like a fingerprint image [50]. Thus, we obtain good enhanced results (shown in Fig. 9), especially the low-image quality and curved regions of latent fingerprints by using STFT.

IV. EXPERIMENT AND RESULTS

The experiments were conducted on a desktop computer with an Intel Core i7 processor and 16 Gb RAM, a mobile device with 16 MP camera and 4 Gb RAM. Latent fingerprint samples were collected using Samsung Note 5 mobile device, and touch-based fingerprints were collected using Papillon DS-21s optical sensor. We employed two state-of-the-art fingerprint matchers (VeriFinger and SourceAFIS) for performance evaluation. The apparatus setup and parameters, the dataset employed for the experimentation, analysis and validation of the proposed approach, and the experimental results are explained below in detail.

A. EXPERIMENTAL DESIGN

The apparatus setup to acquire fingerprint images is composed of a mobile device for capturing the image and an apparatus for adjusting illumination. The distance from the macro lens to the surface is 12 cm, and also the light ring is placed at the same distance with an angle = 90. The setup configuration is shown in Fig. 2 and Fig. 6. The size of the captured samples is 3264 × 1836 pixels, and the specification of devices used in image acquisition is shown in Table 3. The position of the mobile device was manually adjusted to focus, and lenses with different magnification ratios were used to consider the structural features of the fingerprints.

B. DATABASE DESCRIPTION

The performance of the proposed approach was evaluated using datasets collected in our biometry laboratory.

TABLE 3. Specification of the devices used in data acquisition.

	Mobile Device	Touch-based Sensor
Input window's size	28 mm x 28 mm	20 mm x 20 mm
Resolution	560 dpi	500 ppi
Captured Image Size	3264 x 1836 pixels	300 x 450 pixels

Fingerprints were collected from 30 volunteers, including men and women (students and staff) ranging in age from 18 to 50. These plain and latent fingerprints were collected from individuals using both the sensor and the developed apparatus, respectively. The latent fingerprints were collected from two different non-porous surfaces: glass and metal. Each individual's left and right forefingers were imaged separately four times with the developed apparatus (contactless samples) and an optical sensor (contact-based samples). Three different datasets were created to evaluate the proposed data acquisition and enhancement approach. A detailed explanation of the datasets is given in Table 4.

C. EVALUATION METRICS

In order to verify the effectiveness, the accuracy of the proposed latent fingerprint development and enhancement approach was evaluated by measuring two widely used matching systems, Source-AFIS [51] and VeriFinger-SDK [52]. Using these matching systems in verification mode, collected touchless and touch-based database of 720 subjects was evaluated. The fingerprint database consists of 4 samples from two different fingers (right and left forefinger) of each individual. Q = 30 × 2 = 60 classes and p = 8 (4 samples from contact-based and 4 samples from contactless acquisition) samples per class, so the total number of genuine and imposter scores are calculated for each dataset according to Eq. 10 and Eq. 11 below:

$$Genuine\ score = Q\,x\,\frac{P!}{(P-2)!\ 2!} \tag{10}$$

$$Imposter\ score = p^2\,x\,\frac{Q!}{(Q-2)!\ 2!} \tag{11}$$

In order to ascertain the verification performance of contactless fingerprints, common performance metrics including genuine acceptance rate (GAR), false acceptance rate (FAR), equal error rate (EER), and receiver operator characteristics (ROC) were employed to assess fingerprint verification performance in contact-based versus contactless examples.

D. VERIFICATION PERFORMANCE

Within the scope of the study, scenarios were needed that could separately analyze the performance of both the development method responsible for detecting and collecting latent fingerprints, and the enhancement approach responsible for making the collected latent fingerprint usable in the biometric verification system. These test scenarios are summarized below:

- Fingerprints collected by both contactless and contact-based techniques were used together for cross-validation

TABLE 4. Specification of the devices used in data acquisition.

	Dataset A	Dataset B	Dataset C
Used Devices	Sensor + Apparatus	Sensor + Apparatus	Apparatus
Dataset description	240 samples (with sensor) + 240 samples collected from a glass surface	240 samples (with sensor) + 240 samples collected from a metal surface	240 samples collected from glass surface + 240 samples collected from a metal surface
Total number of samples of a finger	4 samples captured from sensor + 4 samples imaged from a glass surface with apparatus	4 samples captured from sensor + 4 samples imaged from a metal surface with apparatus	4 samples imaged from glass surface with apparatus + 4 samples imaged from a metal surface with apparatus
Total number of whole samples	480	480	480

to evaluate the performance of the enhancement method. In this manner, the characteristic data they include were compared between the plain traces recorded by the sensor and the latent traces collected using the proposed development method. These datasets created for cross-validation are named Dataset A and Dataset B.

- In order to evaluate how the suggested development method performed on various surfaces, Dataset A and Dataset B were generated. Among non-porous and reflecting surfaces, glass and metal surfaces were picked. Latent fingerprints from the glass surface and plain fingerprints obtained using the sensor made up Dataset A, whereas latent fingerprints from the metal surface and plain fingerprints obtained using the sensor made up Dataset B.
- Dataset C was designed to compare fingerprints obtained from two different reflecting, non-porous surfaces across their distinguishing characteristics. Dataset C offered the opportunity to observe the latent-latent comparison result.

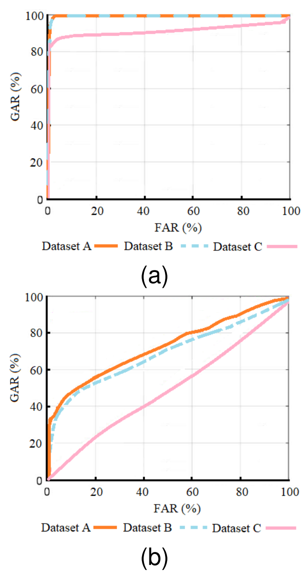

FIGURE 10. Verification performance of (a)VeriFinger and (b) SourceAFIS.

The following outcomes are obtained when this study was assessed using these scenarios:

- The matching performance of latent fingerprints gathered from glass surfaces is higher than that of metal surfaces, as can be observed from the EER scores. The fact that glass surfaces interact with light more differently than metal surfaces is among the most significant causes of this. It is evident that the proposed development method performs better when the surface is more reflecting and non-porous.
- The reason for higher accuracy in dataset A and dataset B compared to dataset C is that print-trace comparisons are more successful than trace-to-trace comparisons. Most of the latent fingerprint characteristics could be matched with the plain fingerprint characteristics since there are enough distinguishing features in the plain fingerprint.
- For the two distinct matchers utilized, a significant difference in equal error rate was seen. This difference has been seen to be related to the matcher designs, and studies in the literature that combine the usage of these two matchers have also observed similar differences.
- There are no comparable studies in the literature that evaluate the performance value offered by the proposed system. Since all studies on latent fingerprints in the literature involve physical and/or chemical interventions to enhance visibility, there are no studies or datasets available for comparison under the same data acquisition conditions.

TABLE 5. Performance analysis of the acquired fingerprints using matching algorithms in terms of EER.

Matching Algorithm	Dataset A	Dataset B	Dataset C
Source-AFIS	8.17	34.12	49.15
VeriFinger-SDK	0.9	1.23	12.39

V. DISCUSSION

In this study, starting with the development and collection of a fingerprint detected at a crime scene, all enhancement steps and the approaches employed in these steps were evaluated to ensure the trace could be used in an identification/ verification system. As a result of this evaluation, a novel system was proposed. In the first stage, the fingerprint detected at the crime scene and classified as evidence was analyzed from a forensic perspective. This examination revealed that detecting a fingerprint at a crime scene involves highly challenging, complex, and time-consuming steps that require expertise, as well as the use of high-cost and professional equipment. From this perspective, the methods employed for detecting and developing fingerprints at crime scenes were thoroughly investigated. This research highlighted a critical need for a low-cost fingerprint development method that does not require specialized expertise, preserves the fingerprint's structure during application, and facilitates crime scene investigations. To address this need, a system was developed, incorporating a novel data development method and enhancement approach.

The proposed system facilitates the detection, development, and collection of latent fingerprints using visible light and a straightforward data collection mechanism. To evaluate the effectiveness of the proposed development method, the collected fingerprints were processed into a format compatible with biometric identification/ verification systems via the presented enhancement approach. Subsequently, the system underwent a performance evaluation using fingerprint samples gathered from non-porous surfaces. Results indicate that the proposed system, utilizing an alternative data development method, effectively detects, collects, and enhances fingerprints acquired from crime scenes.

The motivation for presenting this new fingerprint development and collection method stemmed from recognizing existing deficiencies in this domain. The proposed system provides a robust solution for developing and collecting latent fingerprints on specific surfaces, addressing the disadvantages of latent trace acquisition and collection also pointed out in this study. Furthermore, the presented system can be seamlessly integrated into the identification/ verification systems currently employed by law enforcement.

VI. CONCLUSION AND FUTURE WORK

The field of fingerprint forensics is evolving and gaining new dimensions in light of technological developments. To consider the availability of automatic mechanisms that will replace the manual interventions, which form the backbone of forensic fingerprint investigation, is a crossroads in forensic fingerprint examinations. In this paper, a new system is proposed using the possibilities offered by today's technology to reduce the workforce of the field expert involved in the detection, development, acquisition, and enhancement of the latent fingerprint. A detailed analysis of the contactless fingerprint image acquisition methods and enhancement approaches were made to achieve the maximum matching performance at first. The development steps of the apparatus that can collect latent fingerprints using non-invasive and non-destructive optical treatments and the enhancement process of these fingerprints are proposed within this analysis. The main purpose of the development of this system is to minimize the manual intervention of the latent fingerprints in crime scene investigation, collect the fingerprint without destroying the trace residue, and convert it into a suitable format for matching in fingerprint databases. Both latent and plain impressions of 30 individuals were collected via the apparatus developed and sensor to evaluate the performance of the proposed system. The suitability of the collected and improved latent fingerprints for verification was tested using two different fingerprint matchers, and the results obtained were given in the previous section. The study detailed in this paper indicates that latent fingerprint acquisition from reflective and non-porous surfaces is possible without using any physical and chemical treatments. For future works, we want to evaluate the performance of the proposed system on real crime scene investigations and test the collected latent fingerprints on massive fingerprint databases to determine matching success.

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