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Using multiple models to uncover blood vessel patterns in color images for forensic analysis

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ABSTRACT

With the proliferation of digital cameras, images of crimes, such as child sexual abuse images, are increasing dramatically. Both verification and identification of criminals and victims in these images are highly difficult and often impossible for the current biometric technology because their faces, tattoos, and distinctive skin mark patterns are not always observable. Superficial blood vessels under skin are a potential solution to compensate the weaknesses of the traditional biometric traits. However, blood vessels were neglected by law enforcement agencies because they are generally invisible in color images. To use blood vessel patterns in forensic analysis, this paper proposes three computational models to uncover hidden patterns, two optimization schemes to handle illumination variations and prevent over-relying on biophysical parameters measured in ideal medical conditions, a matching algorithm to automatically extract and compare noisy patterns, and two fusion rules to combine patterns from the three models for performance enhancement. The experimental results on 1900 color images and 1900 infrared images from 490 forearms and 460 thighs show that the matching performance of the blood vessel patterns from the color images is comparable with that from the infrared images. The proposed models are also applied to hands, arms, thighs, chests, breasts, and abdomens of men, women, and children in indoor and outdoor images collected from the Internet. Though these images were taken in uncontrolled environments and the subjects had different poses, the proposed models can uncover blood vessels. These results indicate that the potential of using blood vessel patterns in forensic analysis was underestimated.

1. Introduction

Both verification and identification of criminals and victims are always critical tasks for law enforcement agencies. These tasks are becoming more important, because images of crimes are increasing exponentially. Let us take child sexual offenses as an example. In Canada alone, Cybertip.ca received over 21,000 tips about online child exploitation between 2002 and 2008 [1] and found 12,696 websites offering child sexual abuse images (also known as child pornography) in 2009 [2]. Australia is also facing an explosion in online child sexual abuse images [3]. Anyone who possesses, makes, prints, publishes, distributes, sells, or imports child sexual abuse images commits a criminal offense. Criminals always hide their faces and tattoos, which are regularly used by law enforcement agencies for criminal verification and identification. Thus, prosecuting them is highly challenging. U.S. attorneys declined to prosecute over 30% of child sexual abuse suspects because of weak or inadmissible evidence, which was the major reason for declination of prosecution [4]. In a child sexual exploitation case *United States v. Michael Joseph Pepe*, the author A.K., who was recruited by the U.S. Department of Justice as an expert witness, faced the same challenge [5]. He was requested to verify an arrested suspect and a criminal in a set of images, which showed the lower part of his body, but his face was not observable. In addition to this case, the author A.K. saw a large number of child sexual abuse materials in the Toronto Police Service and the U.S. Immigration and Customs Enforcement with the same characteristics. Though neither faces nor tattoos of the pedophiles were available for identification, the images were high resolution and close-up of their non-facial body sites.

In addition to child sexual abuse images, many cities such as London and Athens experienced riots. Many rioters, who threaten the law and order in many societies and damage others' property, always wear face masks to avoid verification and identification. Identifying masked terrorists and masked gunmen is also important in many counties.

To address these tough verification and identification problems, new biometric traits have to be developed. Though skin marks and

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androgenic hair have been considered, not all body sites, e.g., hands, have distinctive skin mark patterns and androgenic hair patterns [6,7]. The patterns formed by the blood vessels that lie between the skin and muscle are a potential solution because of their universality, permanence, and distinctiveness. Currently, vein recognition systems depend on infrared and laser imaging techniques to capture high-quality blood vessel patterns from palms, wrists, and fingers (where the skin is thin) for commercial applications, e.g., access control [8–10,32,33]. Very limited works attempted to uncover blood vessel patterns hidden in color images for forensic analysis. The optical-based vein uncovering (OBVU) method, which was the first attempt, is very sensitive to illumination changes and heavily depends on the biophysical parameters measured in ideal medical conditions [11]. Skin is a complex structure. Different persons and different body sites have diverse skin properties. The OBVU method fails to handle skin diversity because it is a single-model approach. Only 32 color images were examined through manual comparison. To perform forensic identification, i.e., searching suspects in a given database and systematically evaluating blood vessel patterns from color images, automatic blood vessel extraction, representation, and matching algorithms are essential. Hand, wrist, and finger vein verification methods have been developed, but they were designed for high-quality near infrared (NIR) images captured in controlled environments from cooperative users. It is nearly impossible to guarantee the quality of blood vessel patterns extracted from color images because of subcutaneous fat and other uncontrollable physical parameters weakening the penetration of visible light. It is worth mentioning that the penetration capability of visible light in skin is much weaker than that of NIR in skin. Noisy blood vessel patterns are almost unavoidable. Without user cooperation, non-linear distortion is also inevitable. To address these problems and make verification and identification of criminal and victim based on blood vessel patterns hidden in color images possible, this paper proposes three optical skin models to uncover hidden patterns, two optimization schemes to handle illumination variation and avoid over-relying on biophysical parameters measured in ideal medical conditions, an identification algorithm to automatically extract and match noisy patterns, and two fusion rules to combine patterns from the three models to enhance the matching performance.

The preliminary version of this work presented in [12] was a single model approach. In this paper, two new skin optical models are presented to uncover more blood vessels in different imaging conditions. A new dissimilarity measure which takes orientation, distance, and magnitude of corresponding blood vessels into consideration and two fusion schemes which combine information from different models are also proposed. The preliminary method was evaluated on a database with 300 images from 150 right forearms. The proposed models, schemes, and algorithms are examined on a database with 3800 images from 490 forearms and 460 thighs. Furthermore, the proposed models are applied to hands, arms, thighs, chests, breasts, and abdomens of men, women, and children in indoor and outdoor images collected from the Internet.

The rest of this paper is organized as follows. Section 2 presents a physical model to compute skin reflectance. This model is used to develop the three optical models. Section 3 provides the three optical models with the two optimization schemes. Section 4 describes the proposed blood vessel extraction, representation, and matching algorithms. Section 5 reports the experimental results. Section 6 discusses the impacts of our findings.

2. A physical approach for skin reflectance computation

Skin is a semi-transparent multilayer object. When light hits skin, some is absorbed and scattered by compounds in the skin, while some is reflected and captured by the sensor in a camera. By analyzing the reflected light, the internal structure of the skin can be revealed. A number of optical theories have been developed for

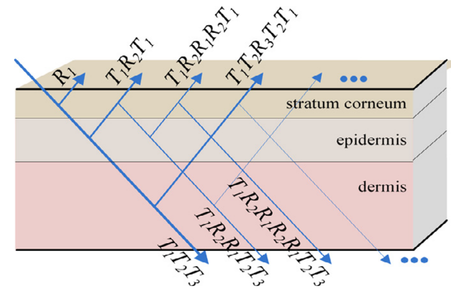

Fig. 1. Illustration of the recursive equations (Eqs. 1–2) applied to a layered skin model.

studying radiation passing through a scattering medium. The Kubelka–Munk (K–M) theory is the simplest one. In this paper, the three optical models use the K–M theory and Reichman's solution to calculate skin reflectance [13,14]. Skin can be considered as an n-layered material and its total reflectance, $R_{12\ldots n}$, and transmittance, $T_{12\ldots n}$, can be computed by the recursive equations:

$$R_{12\ldots n} = R_{12\ldots n-1} + \frac{T^2_{12\ldots n-1} R_n}{1 - R_{12\ldots n-1} R_n}, \tag{1}$$

$$T_{12\ldots n} = \frac{T_{12\ldots n-1} T_n}{1 - R_{12\ldots n-1} R_n}, \tag{2}$$

where R_i and T_i are respectively the reflectance and transmittance of the ith layer [13]. Fig. 1 shows a three-layered skin model. The total reflectance and transmittance of an n-layered skin are controlled by the absorption and scattering coefficients and the thicknesses of different layers. To simplify the notations, R_T is used to represent $R_{12\ldots n}$.

It is worth mentioning that the K–M theory has been employed by medical scientists for dermatological research [13]. Their empirical findings are extensively used in our optical models. The K–M theory is only a rough solution to the radiative transfer equation, which quantitatively describes light transport in different materials. Its exact analytical solution has not been obtained for complex and multiple scattering mediums such as human skin [15].

3. Three optical models for uncovering blood vessel patterns hidden in color images

To uncover blood vessels hidden in color images, three optical models that simulate skin color formation are developed. Each model consists of a camera model, an illuminant model, a skin structure, and a method to compute the total reflectance from the skin structure. Though our previous method has a number of problems (see the introduction) [11], we still employed it as a baseline model because with the two optimization schemes presented in this section, its performance can be significantly improved. The baseline model and the two optimization schemes together are regarded as the first model. In the second and third models, Reichman's solution to the radiative transfer equation is used to replace the K–M theory in the first model [14]. In the first and second models, a three-layered skin structure constituted by the stratum corneum, the epidermis, and the dermis is used, while in the last model, the hypodermis is also included to form a four-layered skin structure. Subsection 3.1 presents the general idea based on the optical models for uncovering blood vessels. Subsection 3.2 summarizes the baseline model for completeness. Subsection 3.3 describes the two optimization schemes to overcome the weaknesses of the baseline model. Subsection 3.4 describes the other two optical models.