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Abstract

In forensic science the finger marks left unintentionally by people at a crime scene are referred to as "latent fingerprints". Most existing techniques to detect and lift latent fingerprints require application of certain material directly onto the exhibit. The chemical and physical processing applied onto the fingerprint potentially degrades or prevents further forensic testing on the same evidence sample. Many existing methods also come with deleterious side effects. We introduce a method to detect and extract latent fingerprint images without applying any powder or chemicals on the object. Our method is based on the optical phenomena of polarization and specular reflection together with the physiology of fingerprint formation. The recovered image quality is comparable to existing methods. In some cases like the sticky side of a tape our method shows unique advantages.

Disciplines

Operations Research, Systems Engineering and Industrial Engineering

Comments

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Polarization- and Specular-Reflection-Based, Non-contact Latent Fingerprint Imaging and Lifting

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In forensic science the finger marks left unintentionally by people at a crime scene is referred to as "latent fingerprints". Most existing techniques to detect and lift latent fingerprints require application of certain material directly onto the exhibit. The chemical and physical processing applied onto the fingerprint potentially degrades or prevents further forensic testing on the same evidence sample. Many existing methods also come with deleterious side effects. We introduce a method to detect and extract latent fingerprint images without applying any powder or chemicals on the object. Our method is based on the optical phenomena of polarization and specular reflection together with the physiology of fingerprint formation. The recovered image quality is comparable to existing methods. In some cases like the sticky side of a tape our method shows unique advantages.

OCIS codes: 150.0150 Machine vision, 110.0110 Imaging systems, 100.0100 Image processing, 260.5430 Polarization.

Introduction

Fingerprinting is one of the most widely used biometric methods for identifying and authenticating individual persons. The modern science of fingerprinting started in the second half of the 19th century. For an interesting historical review see references[1-3]. There are two types of fingerprint data, distinguished by their formation processes. In forensic science finger marks left unintentionally at a crime scene are referred to as "latent fingerprints". Fingerprints acquired directly from human fingers using ink or scanners in controlled environments are referred to as "exemplar fingerprints"[1-4]. Although both types of fingerprints are related to some extent, the recovery of "latent" and "exemplar" fingerprints poses very different technical challenges. There have been considerably more successful optical methods for exemplar fingerprints than for latent fingerprints and sometimes the classification can be confusing. For example, there exist methods using *laser* and *polarization* for extracting fingerprint images directly from live human fingers[5]; such methods are for acquiring "exemplar fingerprints". The purpose and the detailed physical background of that system are both different from those involved in the application of *laser* or *polarization* to *latent fingerprints*. Another example is a device that claims to "optically reads a latent fingerprint"[6]. However, the main function of the particular device is to read directly from a human finger (and simultaneously comparing with a known fingerprint pattern) and such device should be classified as an "exemplar fingerprint" reader. Recovery of latent fingerprints are much more difficult than the recovery of exemplar fingerprints because the physical and chemical composition of latent fingerprints and the surfaces on which they are found vary greatly and can often undergone unknown degradation before being examined. In this paper we present a new method for the detection and recovery of "latent fingerprints".

Latent fingerprints differ from exemplar fingerprints in that they are very difficult to detect with unaided human vision under most ordinary viewing conditions (hence their name); they are usually also of lower quality than the exemplar fingerprints, although high quality fingerprint marks can at times also be found at a crime scene. To be precise, non-exemplar fingerprints that can be easily seen by a human observer should be called "patent fingerprints" [1-4]. In practice, however, the term "latent fingerprints" is often used to refer to all fingerprints that are not "exemplar". It is the really "latent" fingerprints that are more common at a crime scene and require greater efforts to render visible. Most techniques employed for this purpose utilize a chemical or physical process that applies some kind of material directly to the surface suspected to bear fingerprints[1-4, 7-9]. Once the contrast of the fingerprint mark is sufficiently enhanced by such treatments, the mark is either photographed or "lifted" in order to be permanently archived as evidence. The term "lifting the fingerprint" originates from the oldest, but still widely used fingerprint detection method -- powdering -- in which the powders applied adhere to the fingerprint material, and then are physically lifted out of the original crime scene object by a sticky tape.

Since applying chemicals or powders onto a surface on which fingerprints reside changes the chemical and/or physical composition of the surface, the use of such "invasive" methods can potentially interfere with subsequent forensic testing of different type, and can sometimes inflict deleterious side effects on the surface or the operator. Therefore, in the past 30 years several techniques that can recover latent fingerprints without the need to apply foreign material directly onto the fingerprints have been developed. Many of these methods use specialized light sources (e.g. Laser, UV), filters, and detectors[1-4, 7-12]. They are very successful in some cases. However, like all other existing techniques, they do not work in all possible cases and are known to fail completely with certain types of latent fingerprints or object surfaces. As a result chemical enhancers are often reintroduced to aid in the detection of latent fingerprints[1-3, 9, 12-19]. Further studies show that techniques using special light sources and filters work much better and in more cases when combined with the application of certain chemicals on the fingerprint sample first[1, 9, 12-19]. However the application of chemicals directly onto the fingerprints effectively negates the advantages of non-contact methods, and the composite methods revert back into invasive.

It has been known by experienced law-enforcement officers that by varying the angle of a flashlight shining onto a surface suspected to bear latent fingerprint, one can potentially locate latent fingerprints that are otherwise difficult to see[7]. However, in order to "lift" the latent fingerprints in a form that can be documented and presented as evidence in a court trial, some "invasive" enhancement treatments are usually considered necessary. Pfister[9, 20] devised an optical method that uses a semi-transparent mirror that can project light onto a surface at a right angle, while at the same time allowing a camera or observer to view the surface at a right angle. A smooth surface is expected to appear bright due to strong specular reflection, while a fingerprint mark would appear darker due to much less specular reflection. Lennard and Margot[9, 21] reported that such method works better when the sample is pretreated with cyanoacrylate. The use of only a right angle in Pfister's method sacrificed quite a bit of flexibility, and polarization based techniques cannot be applied to further improve the contrast because the specular reflection observed at a right angle from the surface is not preferentially polarized. It is widely known that specularly reflected light from dielectrics would be partially polarized at certain range of viewing angles. However, to the best of our knowledge, no known application of polarization has been reported for latent fingerprints, with the exception of using a polarizing filter to remove glare when taking pictures, which is considered a standard photographic technique. Menzel[22] briefly mentioned the possibility of using optical polarization to enhance visibility of latent fingerprints left on glass but it appears that no further development took place.

We propose here a new method which allows the detection and "lifting" of latent fingerprints into clearly identifiable digital images without the application of chemical treatments or indeed, without any physical contact with the surface and fingerprint material. Rather than employing extraneous material, our method takes advantage of the optical properties. In particular we exploit those properties related to specular reflection and polarization of the latent fingerprint, which usually consists of tiny ridges of skin residue material including sweat (salty water), grease, and lipid[2, 3, 23], all of which are rather transparent dielectric materials, making them difficult to detect under most viewing conditions. Our method is also applicable to latent fingerprints left on a smooth but pliable dielectric surface. The recovered fingerprint images have comparable or better quality to those obtained by conventional methods.

Non-contact optical latent fingerprint enhancement and lifting: Core technique outline and experimental setup.

We start with the principal physical and physiological basis of our non-contact optical latent fingerprint enhancement and lifting in this section. The actual formulae used in our computation will follow later. The physics underlying the method is illustrated in Fig. 1. When a finger touches the object surface, a dielectric residue mark bearing the fingerprint pattern is imprinted on it. The residue on the surface induces differences in optical polarization or reflection or both between the clean part of the surface and that bearing the print. The optical information is captured and enhanced by our unique optical setup and stored as digital images. Further digital processing of the captured images enables us to "develop" or "lift" the latent fingerprint pattern without applying any powder or other chemicals to the object. Our optical setup is based on the well known Fresnel reflection theory for orthogonal polarizations and the theories for macroscopic surface reflectance developed for computer vision and graphics. As an aside, it is interesting to note that biologists and zoologists have found that certain animal species have visual systems that sense and utilize (in or near) visible light's polarization in the natural environment. e.g. backswimmer *Notonecta glauca* can detect the polarization of light reflected from smooth water surfaces and use it to land and plunge safely on the water surface[24, 25]. Indeed, our original step to design our optical setup for latent fingerprint detection was inspired from this ability of *Notonecta glauca* in detecting the surface of the water.

In Fig. 1(c), we illustrate a cross section view of the fingerprint on a surface. The ridge area corresponds to a small amount of residue on the surface, while the furrow area does not. All existing enhancement methods take advantage of this situation by applying materials that selectively attach to or interact with only the residue area and produce a colored or fluorescent pattern of the residue area. Our non-contact method exploits this situation in a different way (Fig. 1(d)), with a common household light source (incandescent or fluorescent, does not really matter here), a camera and the surface being inspected arranged in such a way that the geometry conforms approximately to the law of (specular) reflection. Thus, the incident angle of light from the source approximately equals the viewing (reflection) angle of the camera, so that the camera will capture the light reflected specularly from the non-residue area, and also only the light reflected diffusely from the residue laden area. The reason for this arrangement is that the residue stain area is likely to have different surface normal directions and indices of refraction as compared with the uniform or smoothly varying surface normal direction of the unstained surface area. The localized nature of specular reflection energy distribution makes it sensitive to changes in the direction of the surface normal caused by the presence of fingerprint residue on the surface. Since the specular reflection component is, in general, much stronger than the diffuse reflection component[26] (see Fig. 1(a)), one potentially finds an enhanced contrast between the residue laden ridge mark and the clean surface furrow ‘negative-mark’. Another often encountered case is a plastic fingerprint left on a pliable dielectric surface. There may or may not be biological residue left on the surface but the ridge and furrow patterns formed by the pliable dielectric material itself create differences in surface normal compared to the undisturbed surface area and will serve the same purpose.

Note that Fig. 1(d) is NOT drawn to scale. The micro structure of the fingerprint ridges have been magnified hundreds of times for illustration purposes and the sizes of the light source and the camera and the distances from each of them to the sample surface have been greatly scaled down in order to fit in the limited figure space. In this Figure, if one tries to draw straight lines linking a point on the light source to a ridge and another straight line from the same point on the light source to a valley point in Fig. 1(d), it would appears that the two lines are far from parallel. The fact is that it does not make any sense to draw these two lines in Fig. 1(d) where sizes and distances were not drawn to scale. A typical fingerprint is quite small, about 1 inch (25.4 mm) by 0.3~0.5 inch (7.6mm~12.7mm) while a typical light bulb is about 3 inch (76mm) in diameter and need to be placed at least 7 inch (177.8mm) from the sample surface to avoid blocking the FOV of the observing camera or overheating the surface. In Fig. 2 we show a more scale drawing. The area occupied by the print mark of one finger extends only the small area around the point p in Fig. 2. There are typically more than 50 ridges and valley periodic patterns within this small area. The distance from a ridge point to its immediately adjacent valley point is typically only about 0.5 mm. Note that we only need to make sure that the contrast between one valley and its immediately adjacent ridge area is high enough for detection. So the only thing we need to check is that whether light coming from the same point source would have practically the same incident direction for a point on a fingerprint ridge area compared to a point on the valley area immediately adjacent to the ridge. This is indeed the case. See Fig. 2, if we put a typical setup dimensions of OP=177.8mm and OL=177.8mm, with incident angle 45 degree, then the incident angles of light from the same source point L to the immediately adjacent valley points (suppose that P is a ridge point) are arctan((177.8+0.5)/177.8)=45.08 degree and arctan((177.8-0.5)/177.8)=44.92 degree respectively. They are indeed practically parallel. All realistic light sources are extended light sources which can be modeled as a group of countless number of point sources. The illumination effects can be found by integrating the contribution from every light emitting point source comprising the whole light source. Since we are using an ordinary incoherent light source the contributions to the irradiance from each point source simply add up and we do not need to consider interference here. Fig. 2 (a) and (b) also describes how the directional reflecting nature of specular reflection and the directional light acceptance of the observing camera work together to create the desired contrast between adjacent fingerprint ridge and valley areas using simple non-collimated extended light source like a light bulb with a diffuser plate. Because a camera placed at the point C only records light energy reflected from P along the direction PC, only light incident along the direction LP would have almost all its specular reflection component being recorded by the camera at point C for the specular irradiance (I_S) of point P. The diffuse reflection components has energy almost even spread in all directions and only those small fractions of energy directed toward the direction LP would be recorded by the camera at C for the diffuse reflection irradiance (I_D) for the point P. In Fig. 2 (a), if we setup collimated light beams then every incident light beam contribute about the same ratio of specular irradiance and diffuse reflection irradiance. In Fig. 2 (b) we show what happens when a non-collimated extended light source is used. First, while there can be many incident light rays parallel to the direction LP, they do not contribute to the specular reflection irradiance of point P in the observed image because the camera at point C does not see them reflecting from the point P, except only the ray LP. Any light ray incident from direction different from the direction LP will have its specular reflection component reflected to directions other than the direction pc but the camera only collect irradiance energy emitted along the direction PC for the point P so has no effects on our images. The light rays coming from different angles does contribute to the diffuse reflection component because diffuse reflection energy is almost evenly distributed along all directions regardless of incident direction. Since the recorded irradiance is the algebraic sum of all collected irradiance the observed specular reflection irradiance would come from only the incident light along the direction of LP. Thus the specular reflection signal I_S remains the same for both Fig. 2 (a) and (b). The diffuse reflection signal I_D would be stronger in Fig. 2 (b) than in (a). Thus the effect of using non-collimated extended light source is just some decrease in contrast between I_S and I_D. Note that although I_D gets contribution from more light source points but each contribution is rather small compared to the strength of the specular reflection so in many cases we can still observe the fingerprint pattern easily. Note also that when the distance S is large compared to the dimension of the light source then the incident angle differences α will be negligible. In other words an ordinary household light source like a lamp can nicely approximate an ideal point light source as long as the distance S is several times that of the dimension of the light source.

Another point we want to mention here is the use of diffuser in front of the light bulb in our experiment. Specular reflection is the same type of reflection we see from a mirror, which means that by observing the specular reflection we will be seeing the mirror image of our light source. A bare light bulb without diffuser will project its own image, e.g. the filament and its shade,...etc, on top of the fingerprint sample. This would add clutter to the fingerprint image we want to recover. Adding a diffuser in front of a light bulb would diffuse the “mirror image” pattern of the light source so that we get a cleaner fingerprint image. The image of a lighted diffuser plate is almost featureless so its image projected on the surface would not add its own patterns over potential fingerprint patterns on the surface being illuminated. One should not confuse this “diffuser” with the term “diffuse reflection” we mentioned elsewhere in this paper. The “diffuse reflection” and “specular reflection” are two different types of reflection from a surface (although in reality they coexist in virtually every surface reflection). A surface reflects any incident light partially in the form of diffuse reflection and partially in the form of specular reflection, regardless of how and where the incident light comes from. In other words, any incident light, whether it is directly from a light bulb or has undergone scattering by a diffuser, will be reflected by the surface we are examining partially via specular reflection and partially via diffuse reflection. The “diffuser” we put in front of the light bulb has nothing to do with the surface we look for fingerprints. The “diffuser” does not even have anything to do with “reflection” on the fingerprint bearing surface that is the main topic of our detection method. The function it performs in our setup is scattering and transmitting the light before they even reach the surface bearing fingerprint.

The tradeoff of using a diffuser is a stronger observed diffuse reflection for every point, and thus reduced fingerprint contrast in the specular reflection only based method. In some cases the contrast between the diffuse reflection component and the specular reflection effect becomes too low to be useful. It is also possible that the object itself may have a complicated high contrast pattern under the top coating of the surface (see Fig. 1 (c) and (d)) that interferes with fingerprint pattern even after the enhancement. This problem has been recognized by many practitioners[27, 28]. Discrete Fourier transform analysis has been shown to be able to remove regular patterns that vary periodically, but cannot deal with a general background that is not periodic. In cases where the intensity difference caused by specular reflection alone is not enough to detect fingerprints, we use polarization imaging to accomplish the fingerprint detection. An additional characteristic of the specular reflection is that it tends to be partially polarized in a plane perpendicular to the plane of reflection, see Fig. 1(b). One or more polarization analyzers collecting polarization components at different angles can provide complete information about the polarization state of the reflected light. Based on the polarization information we can further extract only the specular component of this reflection and get a much cleaner fingerprint image because for the most part the light coming from the pattern beneath the top coating of the object surface is due mostly to unpolarized, diffuse reflection. We have also found that in some cases some of the polarization images simply show higher contrast between the fingerprint and its background than the fingerprint images recovered using specular reflection alone.

The general expression for the observed intensity of partially polarized light I as a function of the angle φ of orientation of a polarization analyzer can be written as follows[29, 30]:

$$I(\varphi) = I_U + I_A \cos\left[2(\theta - \varphi)\right] = I_U \left\{1 + p\cos\left[2(\theta - \varphi)\right]\right\} \qquad (1)$$

where θ is the orientation angle of the major axis of the polarization ellipse, I_U is a half of the total pixel intensity, and $p \equiv I_A / I_U$ is the degree of linear polarization at a given pixel in a digitized image. The reference axis for φ and θ can be arbitrarily chosen. Since there are more than one unknown parameters, putting one polarizer at a given orientation angle in front of the camera and taking a picture cannot provide complete information about the polarization state of the received light. By taking three pictures with the polarizer oriented at three different angles, for example φ=0, 45 and 90 degrees, we can recover I_U, I_A, and θ for each pixel of the image using the following expressions:

$$\begin{aligned} I_U &= \left(I_0 + I_{90}\right)/2 \\ I_A &= \sqrt{\left(I_{45} - I_U\right)^2 + \left(I_U - I_{90}\right)^2} \\ \theta &= \arctan\left[\left(I_{45} - I_U\right)/\left(I_U - I_{90}\right)\right]/2 \end{aligned} \tag{2}$$

Here indices 0, 45, and 90 indicate the orientation of the polarizer in degrees when the image was taken. Because θ and $\theta + \pi$ are indistinguishable for phase-blind visual sensors in most conventional cameras, the meaningful range of θ is restricted to ($0 \sim \pi$). We usually use θ in the range from 0 to π. Polarization camera systems able to rapidly take the required pictures have been developed by Wolff and his colleagues[31-33]. The formulation and symbols used here follows from our previous work[29, 30] and are slightly different from those used by Wolff. Since the background object pattern is most likely caused by pigments beneath the transparent substrate that is used to hold them, the object pattern intensity signals are mostly due to diffuse reflection, which is nearly unpolarized and thus I_A and sometimes p are close to zero. Thus, with our polarization technique we can extract the purely specular reflection component from the top surface by computing images of I_A or p for every image point. Such images often carry a substantial contrast between the fingerprint residue pattern and the clean area in between. Note that if only 0 and 90 orientation images are taken, the fingerprint may still be enhanced in the polarization-difference image[34-38], but the 0 or 90 direction must be nearly parallel to either the object surface or the fingerprint ridge surface, which can be challenging to arrange when the surface is not flat. Fig. 3 is an overview picture of our experiment setup that is arranged according to the geometry shown in Fig. 1(d). Fig. 4 shows some of our test items that are often found to bear fingerprint.

Experiments

A step-by-step application of the new optical method is presented in Fig. 5. Fig. 3 gives an overview of the experimental setup when the specially arranged light is on and the ordinary room light is turned off. We have performed the experiments with both the room light on and off and found that the results are very similar. This means that our method can be easily applied to a crime scene without strict ambient lighting control. The surface being inspected is the metal casing of an electric air pump (with brand name sticker “Linicon”) which is painted orange. Fig. 5 (a) and (b) show how the surface looks like with the specially arranged lighting turned off, and the ordinary diffuse fluorescent room light on. The image in Fig. 5(a) is shown with a common digital enhancement available in most image-processing software, setting the brightest pixels in the image to the maximum possible value allowed by the display, and the darkest pixels to the lowest display value and linearly rescaling the rest pixel intensity values. Fig. 5 (b) presents the same image data as in Fig. 5(a), but enhanced instead by histogram equalization. This enhancement method remaps the pixel values according to the histogram distribution of their magnitudes, distributing them more evenly over the dynamic range of the display (see[39]). These two images illustrate the ‘latent’ nature of the fingerprint: the natural contrast is so low that not only the unaided human eye cannot detect it, but even widely used digital image enhancements do not reveal its presence. Fig. 5 (c) and (d) present images taken with only the specular illumination turned on, and digitally enhanced with the same methods as used to produce Fig. 5 (a) and (b), respectively. Imaging the light specularly reflected from the surface yields a major enhancement not achievable with the digital enhancements alone, an enhancement traditionally achieved with powders and chemicals, but completely without destructive side effects. Fig. 5 (e) and (f) are zoomed in view showing the detailed quality of the recovered fingerprint images. As an example comparison with the fingerprint quality lifted by conventional method, Fig. 5(g) shows the same fingerprint being lifted after being dusted with forensic black magnetic powder. Fig. 5(h) shows the fingerprint lifted by a forensic sticky tape after dusting. The fingerprint image quality recovered by the proposed non-contact method is more consistent compared to the results obtained by powdering. It is difficult to spread the powder evenly across the whole fingerprint and area with too much or too little powder will be lifted with lower quality. Furthermore, the process of lifting by a sticky tape can itself introduce missing parts in the fingerprint.

The results of another experiment employing our non-invasive optical method are illustrated in Fig. 6. In this case, the surface with the latent fingerprint was the paper cover of an ordinary desk calendar (Fig. 6(a)), and presented a greater challenge than the solid colored metallic surface. The paper surface contained a printed pattern whose light absorption interferes with the optical detection of the fingerprint. We used both specular reflection and polarization analysis to extract the latent fingerprint. For the polarization analysis, images were taken with a linear polarization analyzer mounted in front of the camera, and oriented at three different angles. The picture displayed in Fig. 6 (b) is the value image of the derived quantity I_A (see Eq. (2)). We emphasize here that Fig. 6 (b) is not an image of the ordinary intensity distribution, but rather a mapping of a certain physical quantity derived from the polarization distribution of the light comprising the image. The specular component of the surface reflection is now evident, and the background pattern is gone. Fig. 6 (c) shows a cropped, close-up of the fingerprint area of the image seen in Fig. 6(b). These results lead to two additional conclusions: first, the non-invasive optical method can extract latent prints from some paper surfaces as well as from smoother surfaces; and second, the processing of the polarization information in the image can further enhance the quality of the recovered latent fingerprint under certain conditions.

Sometimes the specular reflection component can be obscured by more intense diffuse reflection. We applied our methods to such a case, deliberately picking one of the strongest diffuse reflectors, a white cotton lining underneath a soft clear plastic CD sleeve (Fig. 7). Fig. 7 (a) shows an image taken without a polarizing filter in front of the camera. The diffuse white light is so strong that the specular reflection output can barely enhance the latent fingerprint on the plastic surface. However, the polarization-based analysis followed by the histogram equalization readily enhances the latent fingerprint (Fig. 7 (b) and (c)).

Fig. 8~Fig. 10 illustrate the fingerprint detection and lifting capabilities of our new methods applied to several common items and surfaces. Note that our method is not restricted to viewing the surface at a right angle, and our use of polarization is not restricted to glass, and is not used for removing glare.

The sticky side of a tape has traditionally caused trouble with invasive methods, especially methods that apply powder to the surface. Most powders and reagents can stick easily anywhere on the sticky surface, not just the fingerprint area. In contrast, sticky side of the tape is ideally suited to our method. The “sticky” material is a thin coat of pliable semi-transparent dielectric that fits our surface model perfectly. Whether the latent fingerprint mark is formed by skin residue or by a plastic mark formed on the “sticky” surface, our surface model predicts that high contrast intensity or polarization images can be formed with proper lighting. We tested our method on a piece of transparent packing tape and the results are very good (Fig. 11). An example of plastic fingerprint mark detection using our method is shown in Fig. 12.

Fig. 13 shows a series of experiments using both the specular reflection only based and the polarization based method detecting a fingerprint on the metal case of a pump (the same pump surface as appeared in Fig. 5). Here the observing view angle of the camera is varied (with corresponding change in the incident light direction to maintain the specular reflection relationship). Three angles, 30, 45, and 75 degree are chosen to represent near frontal, near Brewster's angle, and near grazing view angles. It is clear that near grazing angle is unsuitable because it is difficult to see the fingerprint pattern. On the other hand, the light from the light source used here is definitely unpolarized. As predicted by the Fresnel equation, near the Brewster incidence angle of the sample surface the reflected light from the clean sample surface has a large degree of polarization while the light reflected from the fingerprint tainted area is still relatively unpolarized. This creates a good contrast in several kinds of polarization images when the incident light angle is near the Brewster incidence angle of the sample surface and relatively poor contrast at other angles. However, at exactly normal incidence to the sample surface the reflected polarization from the clean sample surface is the same as the incident one, unpolarized, and not much different from those light reflected from the fingerprint deposited area. Therefore we see poor results in all polarization images when light from our light source is incident at exactly normal incidence angle to the sample surface. In summary it is best to pick viewing angle close to Brewster's angle, typically from 45 to 60 degrees from the surface normal.

Fig. 14 is exactly the same experiment set up as Fig. 13, except that these images are taken under almost dark room environment (room lights all turned off, doors and windows shut) while Fig. 13 is taken under no special control of ambient room light. In fact we would like to point out that ALL experiment pictures except Fig. 14 in this paper were taken without special control of ambient room light (i.e. room light from ceiling left on, doors/windows left as is). We note that our method works well without the need of a highly controlled laboratory dark room. Please compare corresponding images in Fig. 14 and Fig. 13. One can hardly see any significant improvement in Fig. 14 where experiments were taken in a controlled dark room environment. In fact they are almost identical. The reason behind this result can be described as follows: Irradiance is related to both the power of the light source and the distance between the light source and the surface. In a typical office or residence room the lighting is not much stronger than a flash light or desk lamp that would be used in our setup. Furthermore the light used to detect fingerprint can easily has the advantage of being much closer to the surface under examination. In our experiment we put a Lux meter on the surface and we got about 2000 Lux reading when both the room light and the dedicated light source was on and 1900 Lux reading when we turned off the room light and shut the doors/windows to create a dark room environment leaving only the dedicated light source illuminating the surface. These numbers indicate that the ambient light accounted for only about 5% total irradiance of the surface and the dedicated light source clearly dominated. This means that our method can be applied directly at many crime scenes without the need to bring samples back to a special laboratory class dark room. This statement should not be misinterpreted to mean that we claim that our method works in all possible ambient light conditions without some control. It is well known that the irradiance of direct sun light in a sunny day is several orders of magnitude stronger than any man-made light source so one should not try to perform this method under direct sun light. For indoor environments it may generally not be a problem to control stray light by either turning off some lights or avoiding direct illumination of a room light or temporarily blocking certain ambient light. If a particularly strong light is coming from a particular direction one may simply use that light as the main light source. The main point we are raising here is that our method does not require a dark room so much as developing a traditional camera film, where any stray light would expose and ruin the film. Our method only needs to have one dominating light source with known and controllable direction of illumination.

Theory of the application of specular reflection to latent fingerprints

Modeling surface reflection on a microscopic scale is complicated and depends heavily on the detailed knowledge of the molecular material composition of the surface material. However, macroscopically, a more general model can be used that applies to a wider range of surfaces without the need for details about the surface with acceptable reduction in accuracy. This is desirable in many practical applications, notably in computer vision and graphics, where the details of the chemical and physical composition of surfaces are not known or are not of vital importance. Beginning with Refs[40, 41], many surface reflection models based not on the exact chemical composition but rather on a plausible statistical model of the surfaces were proposed, see e.g. Refs[42, 43]. A review of various models can be found in Refs[44, 45]. Because in our applications we intend to extract the fingerprint without using any chemical analysis, the possibility of knowing the properties of surface material beforehand is excluded. However, a simple model that describes a general trend is good enough, because the ultimate form required for a fingerprint image is that of binarized black and white regions separating the ridge and furrow areas. There is no need to recover or to predict the exact brightness differences in the gray-level images taken for the purpose of recovering fingerprint marks. The simple Phong model[43] and Lambertian model[40], both widely used in many computer vision and graphics algorithms, satisfy these purposes.

Macroscopically, two well known general types of reflection can be named. The Lambertian model describes a surface producing perfectly diffuse reflection as

$$I = I_p k_d \cos\theta = I_p k_d \left(\hat{n}\cdot\hat{l}\right) \tag{3}$$

where I is the intensity of the image point sensed by the camera, I_p is the point light source's intensity, k_d is the reflection coefficient (either for a particular wavelength or for a particular camera's spectral response), θ is the angle between the surface normal $\hat{n}$ and the unit vector $\hat{l}$ in the direction of the light source as viewed from the point of reflection (see[44]). Note that the diffusely reflected light has the same intensity for all viewing directions.

Another type of reflection is that of highlights, or mirror like reflection observed on many smooth surfaces. A more subdued version is usually called "sheen". The Phong model is given by

$$I_\lambda = I_{a\lambda} k_a O_{d\lambda} + f_{att} I_{p\lambda} [k_d O_{d\lambda} \cos\theta + W(\theta)\cos^n \alpha] \tag{4}$$

where λ is the wavelength of the light, subscript 'a' denotes ambient light source, subscript 'p' denotes point light source, subscript 'd' denotes a diffuse reflection component, the new symbol O denotes color components in human and digital color vision components, f_{att} is the inverse square of decay distance of a point light source intensity, $W(\theta)$ is the diffuse reflection coefficient of the surface with a point light source angle of incidence θ, α is the angle between the exact view direction predicted by the law of reflection and the actual view direction, as shown in Fig. 1(d). For the current study, the most important information derived from (4) is that the intensity is proportional to $\cos^n \alpha$. This gives a simple way to model a rapid decay in intensity if the view angle is different from that predicted by the law of reflection. This term suggests that if the camera, the light source, and the surface being inspected are arranged in a way predicted by the reflection law (see Fig. 1(d)), the image point for the original smooth surface without skin residue will show intensity typical for specular reflection, while the area with skin residue will have much less specular reflection due to the slight change in the direction of surface normal caused by the skin residue. The more mirror-like a surface can be modeled, the larger power of cosine decay it exhibits, which means better contrast in our specular-reflection --based latent fingerprint detection and lifting technique.

Providing all other factors being equal, the intensity of the specular reflection component is in general much stronger than the diffuse reflection component. Although, this statement is not always true, it has been widely accepted as a good rule of thumb in the majority of practical situations[26]. Since specular reflection has a tendency of concentrating reflected energy in a small solid angle, as opposed to the diffuse reflection which spreads all the reflected energy into a full hemisphere, the same amount of reflected energy will result in a much greater flux density in specular reflection and thus in image brightness. The specular reflection tends to be reflected only once from the smooth surface, while the diffuse reflection gives light that experienced a multiple scattering inside the surface before re-emerging. Each scattering only weakens the intensity but seldom enhances it. Wolff[26] experimentally measured the ratio between specular and diffuse reflection intensities for several different surfaces and reported ratios varying from about 150:1 to 250:1. For many digital sensors with 8-bit brightness resolution, this is close to the maximum intensity ratio of 255:1. This gives a strong support to our main assumption, that the specular reflection component is in general stronger than the diffuse one. Our experiment results so far also support the validity of such assumption.

In Ref[26] another important theoretical result relating to fingerprint detection issue was reported, i.e.: if the reflection coefficient of the diffuse component is more than about 1/33 the reflection coefficient of the specular component, the diffuse component can be stronger or at least comparable to the specular component. If the underlying surface consists of complicated patterns similar in strength and spatial frequency to the latent fingerprint pattern on top of it, the method based on a purely specular reflection is not satisfactory. This is the point where the polarizer should be used.

The behavior of specular component is governed by the well-known Fresnel reflection coefficients formula[46]:

$$\begin{aligned} r_{\perp} &\equiv \left(\frac{E_{0r}}{E_{0i}}\right)_{\perp} = \frac{n_i \cos\theta_i - n_t \cos\theta_t}{n_i \cos\theta_i + n_t \cos\theta_t} = \frac{\sin(\theta_i - \theta_t)}{\sin(\theta_i + \theta_t)} \\ r_{\parallel} &\equiv \left(\frac{E_{0r}}{E_{0i}}\right)_{\parallel} = \frac{n_t \cos\theta_i - n_i \cos\theta_t}{n_i \cos\theta_t + n_t \cos\theta_i} = \frac{\tan(\theta_i - \theta_t)}{\tan(\theta_i + \theta_t)} \end{aligned} \tag{5}$$

where subscripts ‘i’, ‘t’, and ‘r’ stand for incident, transmitted, and reflected component. The subscripts ‘$\perp$’ and ‘$\|$’ are related to the plane of incidence. In Fig. 1(b) the plane of this paper is the plane of incidence. In case of the specular reflection it contains both the incident and reflected light wave vectors. It is well known (see e.g.[46]) that $r_{\|}$ can be exactly zero at Brewster’s angle θ_B, which is given as

$$\tan\theta_B = \frac{n_t}{n_i}. \tag{6}$$

If light is incident from the air, $n_i \approx 1$, while n_t varies from 1.4 to 2.0 for most of dielectrics in the visible band (wavelength of about 400~700 nm)[46]. Eq. (6) shows that the corresponding Brewster’s angles vary from 55 to 74 degrees, respectively. Although, there are certain materials with higher refractive index[46], we confine our discussion to the above-mentioned range of n_t. Therefore, when we consider the angle of incidence between 55 and 74 degrees, the reflected light is highly partially polarized with the plane of polarization perpendicular to the plane of incidence. This case is referred to as “horizontal polarization” with respect to the surface being inspected. So far we have only discussed dielectric surfaces which are adequate in most cases since “pure” metallic surfaces are rather rare in everyday life. Pure metal surfaces are oxidized quickly and the actual layer “responsible” for specular reflection is often either the oxides on the surface or the protective painting layer which is also a dielectric material. In fact, a lot of metallic-looking merchandise today is actually coated with highly reflective dielectric paints. In cases when the underlying pure metal reflects more light than the upper dielectric coating, the proposed method may not work.

Discussion

The currently popular latent fingerprint detection and extraction methods used by law enforcement agencies include, but are not limited to, powdering, Sudan black staining, iodine fuming, ninhydrin (sometimes followed by further enhancement with zinc chloride) and DFO application, silver nitrate development, cyanoacrylate (glue) fuming, gentian violet staining, vacuum metal deposition, laser excited luminescence, and RUVIS (Reflected Ultra Violet Imaging System)[1-4]. While this list may seem long, there is still need for new methods, because every existing method tends to be unsuitable for some surfaces, due either to its inadequacy in lifting the print from, or to its damaging side effects to the surfaces. In particular, the chemical and physical processing directly applied to the fingerprint bearing surface in order to extract latent fingerprints can potentially inflict deleterious effects upon the fingerprint, the operator, and/or the object surface being examined [1-3, 10, 18]. For example, the iodine vapor in the iodine fuming method is highly corrosive and toxic[2]. Thus, in practice, often valuable and/or irreplaceable objects are not searched for fingerprint at all[2, 3, 7], except in a few major cases involving extremely serious crimes. Furthermore, the chemicals used to enhance fingerprint contrast or to induce luminescence may need long processing time, are sometimes toxic, environmentally unfriendly, or radioactive. The process to speed up the chemical reaction can be dangerous, e.g. sodium hydroxide used to speed up cyanoacrylate fuming can generate extreme heat if the two come into contact[4]. Samples are often baked to high temperature after many fuming procedure to speed up the print development. Chemicals used for fingerprint enhancement can often be harmful to the operator if not handled correctly using proper procedure and protective equipments because they are designed to react with or adhere to the fingerprint residues, which are the same material found on human skin[3]. Some chemicals require specific solvents that have undesirable side effects; e.g. the phenol in the solution for Gentian violet is highly caustic and poisonous[2].

Lasers induced fluorescence is one of the first optical methods for lifting latent prints, utilizing induced luminescence of the fingerprint material[1-3, 10]. However, there are several factors limiting its use. The natural fluorescence signal (without the prior application of strongly fluorescent chemical or powder) is in general very weak. Thus the laser used must operate in a specific frequency, and must have a high enough power rating. Such a laser device is fairly expensive and bulky (due to power and cooling requirements), and thus it can be deployed only to a few large and well funded crime labs and not easily made portable outside a dedicated crime lab[18]. Less powerful laser or arc lamp with filter can be used as substitute but will produce much reduced effectiveness. As a result these alternative systems need chemical enhancements. The fact that many commonly encountered fingerprint laden objects found at a crime scene contain organic substances that also fluoresce when excited by a laser often causes significant background noise[1, 2, 10, 13, 17-19]. Thus, laser-excited luminescence, like other existing methods, cannot be applied to certain types of surfaces. It has also been found that the signal strength of the natural fluorescence of fingerprints varies greatly from person to person and even from time to time of the same person[10]. As a result, in real applications laser-excited luminescence techniques are more often used with the aid of applying fluorescence enhancing chemicals to get better and more consistent results[1, 2, 13, 17-19]. However the use of chemical fluorescence enhancers negates the non-contact advantage and the combined method reverts back to an invasive method.

RUVIS is pioneered by the research at the National Police Agency of Japan and was originally targeted for enhancing cyanoacrylate-developed latent prints. It is found that the cyanoacrylate-developed latent prints that are translucent under visible light become opaque under UV. Latent prints deposited in sebaceous matter or oily residue can sometimes be detected by RUVIS before the application of enhancing materials. The oil strongly absorbs UV and show up as dark patterns under UV light and detector. RUVIS can sometimes detect fingerprints up to a year old in purely non-contact style[1]. The drawback is the need of relatively expensive specialized UV light source and sensors. UV light can be harmful to both human eyes and skin so proper precaution and protective gear is necessary. Bramble *et al.*[47] proposed using laser in UV band to induce luminescence that is also in UV band. Although UV laser is not considered invasive, they find that the luminescence property of the fingerprint material decrease significantly after being exposed to UV laser for extended period of time[47].

The "Episcopic Coaxial Illumination" method proposed by Pfister[20] use the intensity difference between specular and diffuse reflection to enhance the visibility of latent fingerprints. The design always looks at the surface from the right angle. The advantage is that the picture will always appear in frontal view suitable for archiving. However with the advent of digital image processing, an oblique view can be easily reprojected back to frontal view so it is not that crucial. We have shown that by varying observation angles we can get better contrast in some cases (compare e.g. Fig. 12 (a) and (b)). We have also shown that the partially polarized nature of oblique specular reflection can significantly enhance the contrast of latent fingerprint and at the same time suppress the interfering background pattern. Viewing the surfaces only at the right angle precludes the use of polarization because the specular reflection at the right angle is not partially polarized by the surface.

There is a commercial product called “fingerprint camera” that has existed for a long time[4]. Some may confuse it as yet another non-contact optical method for the detection of latent fingerprints. However, this device is in fact an ordinary camera customized to record non-exemplar fingerprints that have been enhanced by other methods (e.g. by an application of chemicals) or for “patent fingerprints” that is already visible. The customization include dedicated lighting to reduce uneven lighting, shadow, and glare; a fixed object distance and fixed focus, aperture, exposure time, …etc. These preset camera settings enable law enforcement officers who may not be photographic experts to be able to take good fingerprint pictures consistently for court use. Such a “fingerprint camera” does not have any “contrast enhancement” or “detection” capability for hidden latent fingerprints.

The novel optical method we propose here is capable of recovering high quality digital images of hidden latent fingerprints without the application of any chemicals or physical contacts with the examined object. Like any other existing latent fingerprint enhancement technologies, our method has its limitations. Our method is designed to take advantage of the intensity and polarization differences between specular and diffuse reflections so it will work best on a relatively smooth and non-porous surface. The chance of detecting fingerprints on a highly porous and absorbing surface like certain kinds of paper using our method is fairly low. However our method possesses unique advantages over existing methods on smooth surfaces in that complex patterns on the surface can be easily suppressed optically using our polarization method. Note that while the most common use of a photographic polarization filter is to remove glare, our use of the polarizer is quite the opposite. Our polarization method, in a sense, extracts only the specular “glare” that was usually treated as a mere nuisance. Specifically we discovered that inside the specular “glare” under certain conditions a high contrast clean latent fingerprint image is present.

Menzel[22] briefly mentioned the possibility of using polarization to detect fingerprint on glass. We have shown that polarization can be used to enhance fingerprint visibility on a wide variety of surfaces, not just on glass. We also show that polarization can be used to remove interfering background pattern that has not been mentioned before. Another advantage of our method is that our method is less affected by the degradation of latent fingerprint over time compared to methods that relies on chemical reactions with the organic residues or water in the latent fingerprint marks. Over time an exposed latent fingerprint mark will lose its water contents via evaporation, and the amino acid components will degrade and its chemical properties change[1-4]. Since our method does not rely on water or detailed chemical composition of the fingerprint mark, our method is less likely to be affected by chemical decomposition. As long as the geometric difference in the surface remains, our method can be used effectively. The example pictures shown were taken up to several weeks after the fingerprint is made (and kept in our lab/office environment undisturbed) and they show little degradation of quality.

We have shown that our method can work under regular room light without the need of a highly controlled laboratory class dark room. This may enable law enforcement officers to use our method right at the crime scene without the delay of sending samples back to a special crime laboratory. This effectively means that our method can usually examine the most fresh fingerprint samples. The only requirement is a strong dominating light source illuminating the surface examined from a known direction. This can be easily achieved by either using a strong portable light source close to the target surface or simply use the strongest directional ambient light source found at the crime scene. For most indoor crime scene, the standard fingerprint search procedure calls for restricting the access to the crime scene and only the fingerprint specialists will be working at the scene during the fingerprint search. The specialists have total control over the scene during the search so it is generally not a problem to turn on and off any room light. It is also quite easy to use something like a shade to temporarily block some ambient light, e.g. a piece of cloth, an umbrella, or even the body of the specialist him/her self because the size of a fingerprint is very small. In other words, our method can be performed directly in most crime scenes and even more cases with a little simple common sense light control. There is essentially no need for a special dark room similar to a film developing dark room.

Because of a great variety of the latent fingerprints that can potentially be found in very different crime scenes, no single latent fingerprint enhancement method can handle all possible cases. Since every method targets different physical and chemical properties of different kinds of fingerprints, it is often found that applying more than one method on the same surface will unveil different fingerprints for different method, e.g. [18]. Thus the introduction of a new latent fingerprint detection method that uses different physical principles than those used by existing methods and one that will not interfere with other methods should be beneficial to law enforcement efforts.

Conclusion

We have introduced a novel optical method to detect, enhance and lift latent fingerprints that are otherwise difficult to see. The method is non-invasive and so will not interfere with other forensic examinations and will not inflict deleterious side effects on the surface. The equipment required is much less expensive than most other non-contact methods proposed so far. The new method is not applicable to highly porous and absorbing surfaces, but works well on most other surfaces. The new method also works on the sticky side of the tape, which is a particularly problematic surface for many invasive methods. The new method can be easily performed right at the crime scene without the need to bring samples to a specialized lab. The recovered latent fingerprint image has very good quality compared to other existing method. Since it does not interfere with other methods it is advisable to try this method before other invasive or destructive methods.

Acknowledgments

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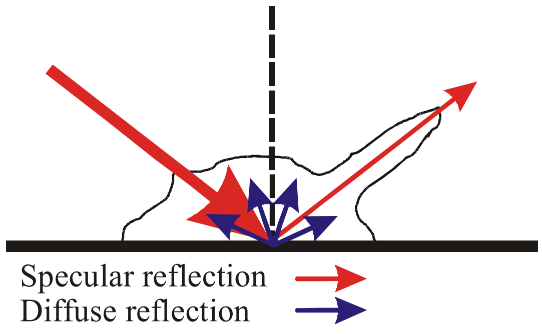
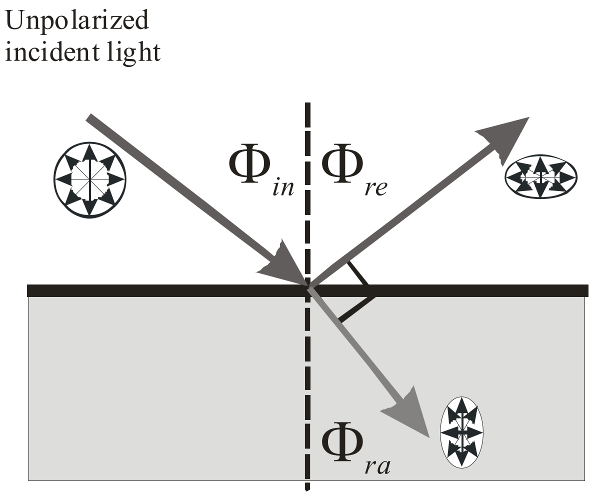
Figure Captions


Specular reflection
Diffuse reflection


Unpolarized
incident light
Φ_in
Φ_re
Φ_ra

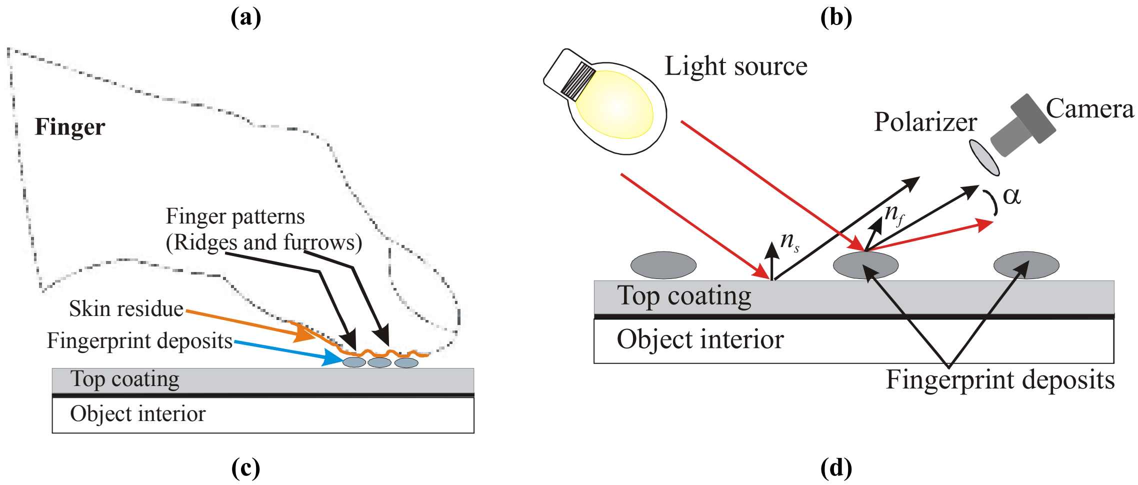


Fig. 1 (Color online) Schematic of physical principles concerning non-contact latent fingerprint enhancement and lifting. (a) Macroscopic reflection from a surface consists of two distinct kinds, i.e. specular and diffuse. For specular reflection the angles of incidence and reflection are equal, while for the diffuse case the reflected intensity may approximately have an effectively uniform distribution over all directions in a hemisphere. Most surfaces exhibit both types of reflections, but one type may be stronger than the other. (b) Partial polarization of specularly reflected light from a semi-transparent dielectric surface. It is known that the light reflected from the smooth surface is partially polarized with the polarization being perpendicular to the plane of reflection. (c) Live human skin is kept soft and pliable by the constant oily secretion of hypodermic glands. The ridge area of the skin pattern tends to leave a dielectric residue on a surface touched by a finger. (d) The residue left in (c) forms the latent fingerprint. Using a method that generates a sufficient contrast difference between the latent fingerprint and the rest of the surface in the camera image, a successful detection and extraction can be achieved without applying physical or chemical treatments to the surface. Note that the camera position in (d) is oriented in such a way that it captures the specular component of reflected light from the clean surface only while the specular reflection component of the residue is not captured. Additionally, when a finger touches a pliable dielectric surface it could cause a plastic print on the surface. In this case the difference in the surface normal caused by the plastic print ridges will serve the same purpose of creating contrast in intensity and polarization under proper lighting.

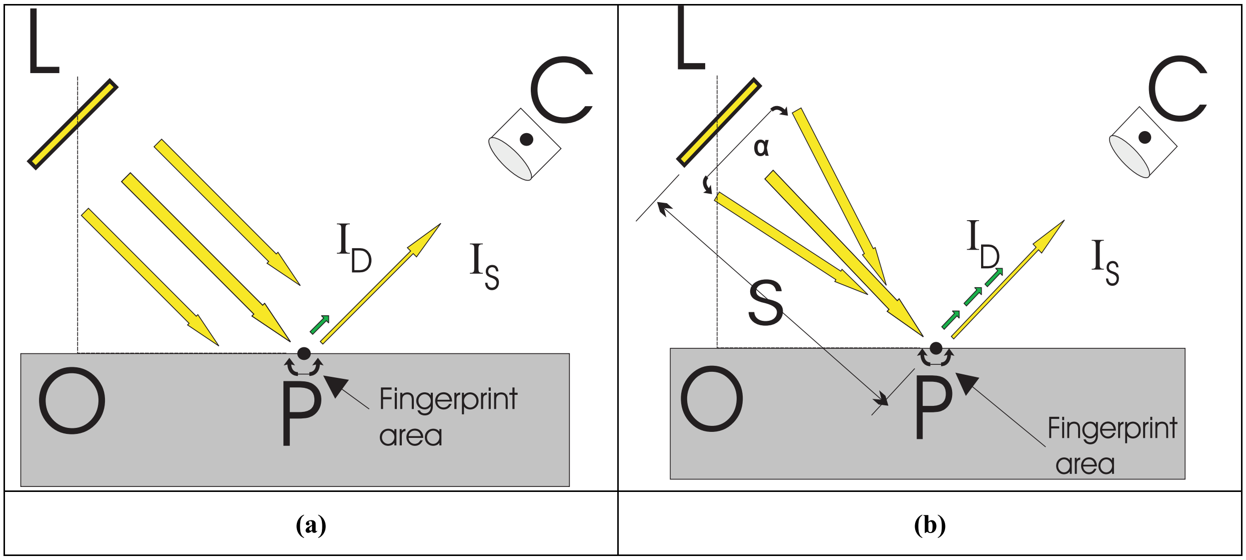


Fig. 2 (Color online) Drawings depicting the same setup as in Fig. 1(d) but with relative distances and object sizes drawn to scale to explain the effects of real light source compared to idealized collimated light source. In both (a) and (b), L is the position of light source; O is the orthogonal projection on the surface for L; P is a

ridge or valley point around the center of the fingerprint pattern, C is the camera view point. I_D is the irradiance of the point P from diffuse reflection and recorded by the camera at C. It is typically weak and is also represented here as the small arrow(s) along the direction PC. I_S is the irradiance of the point p from specular reflection and recorded by the camera at C. It is typically much stronger compared to irradiance from diffuse reflection, and is depicted here by the large arrow along the direction PC. (a) shows the simple condition when the light source is effectively collimated along the direction of LP. (b) shows the situation when non-collimated extended light source is used. The I_S remains the same as in (a) but I_D is stronger due to contribution from more point sources. The end result is decreased contrast between I_S and I_D. However since only I_S contains polarized component, polarization based method is equally effective in both conditions.

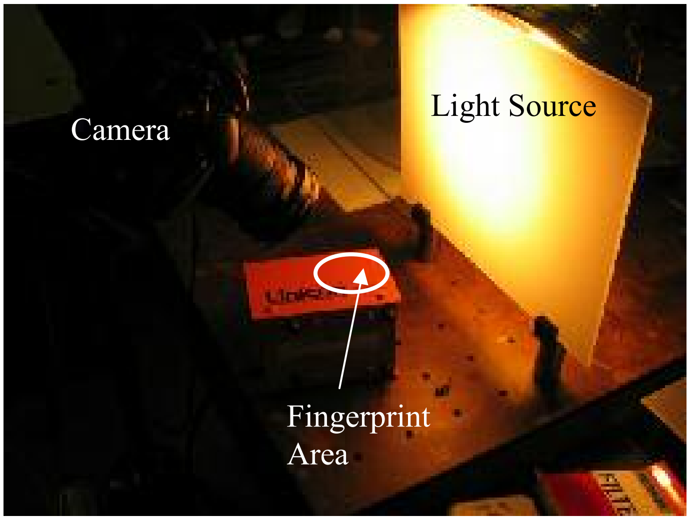


Fig. 3 (Color online) Example experiment setup overview for Fig. 5.

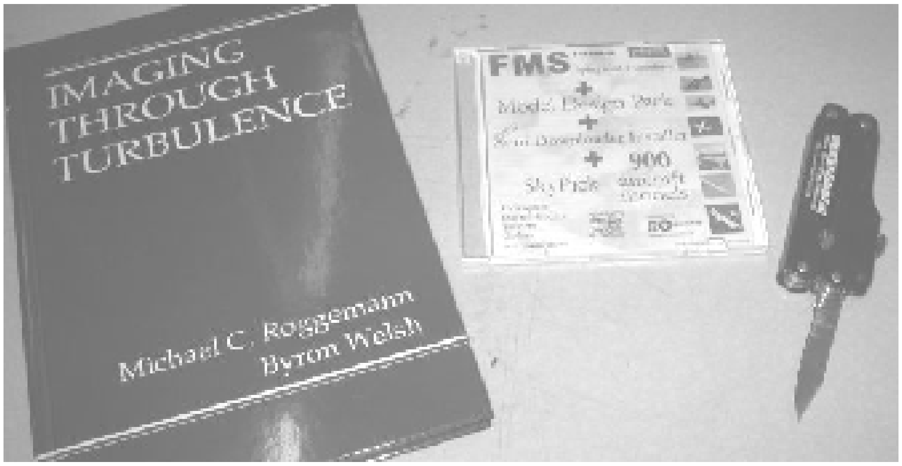
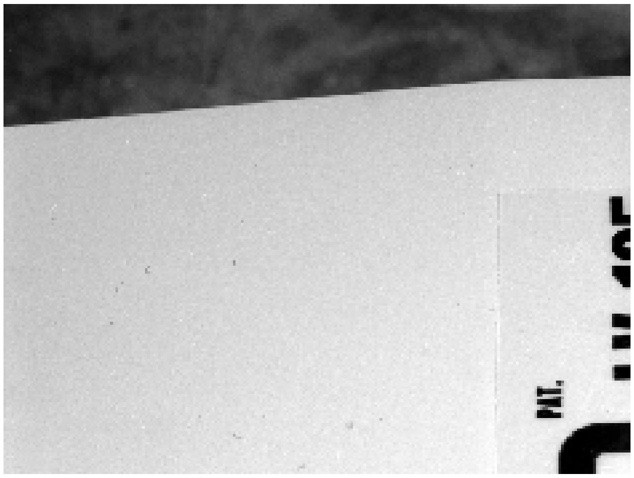
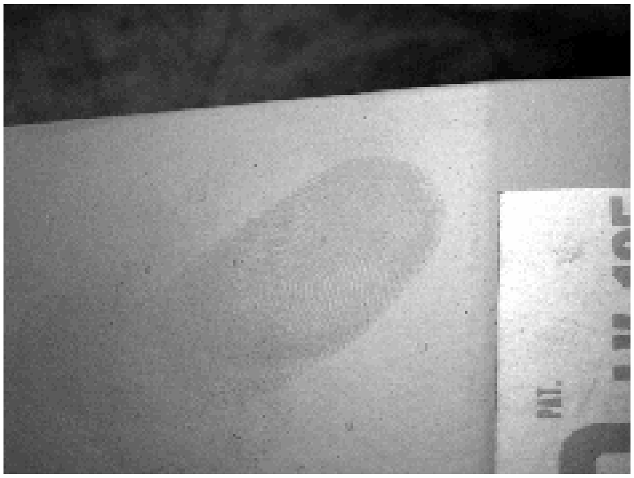


Fig. 4 Picture of the three sample items bearing latent fingerprints: a hard cover book, a plastic CD case with underlying insert patterns, and a stainless steel blade of a Swiss army knife. Experiment results on these items are presented in Fig. 8, Fig. 9, and Fig. 10.

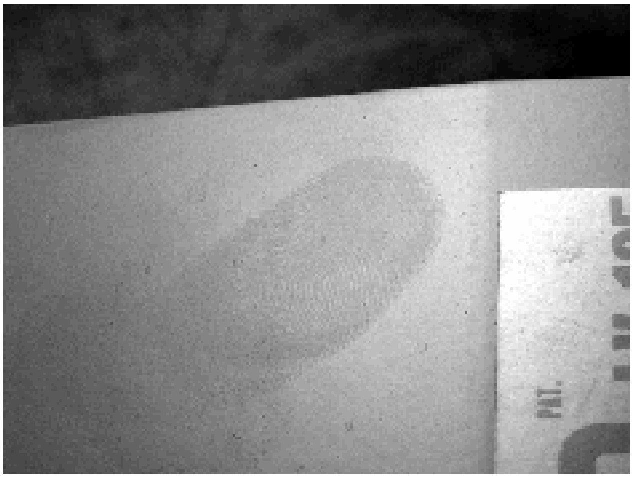


(a)

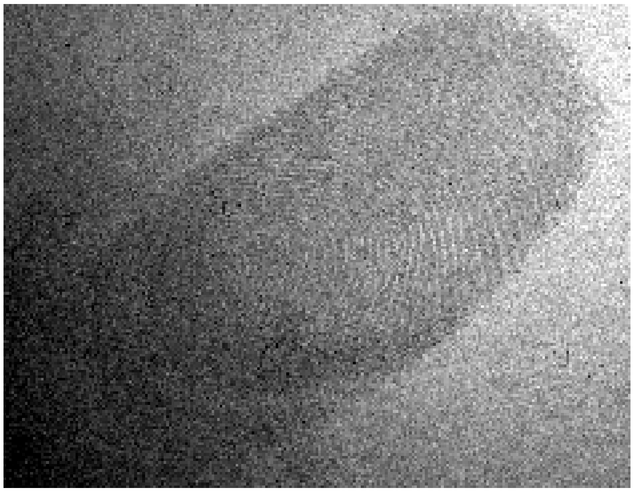
(b)



(c)

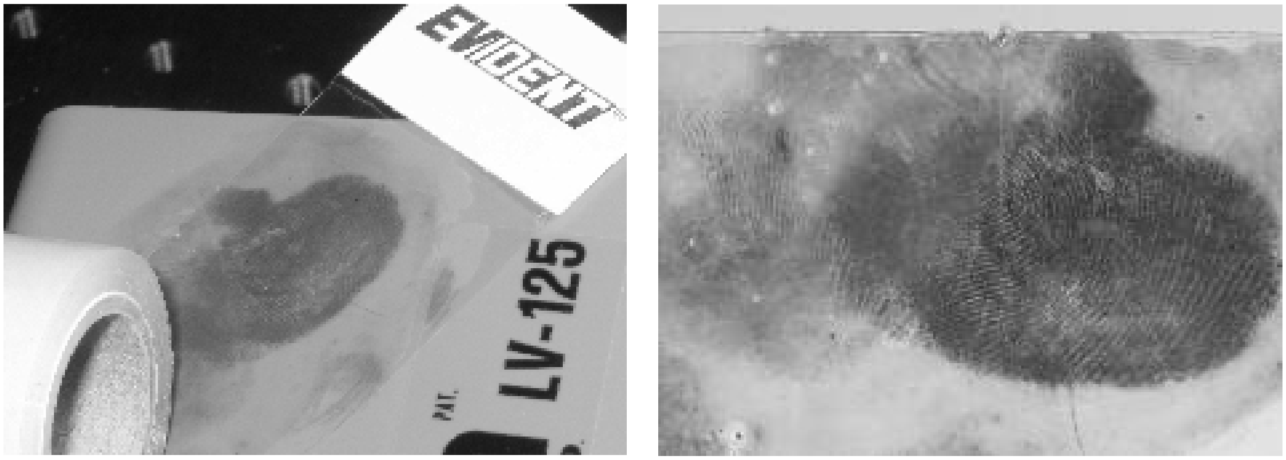


(d)



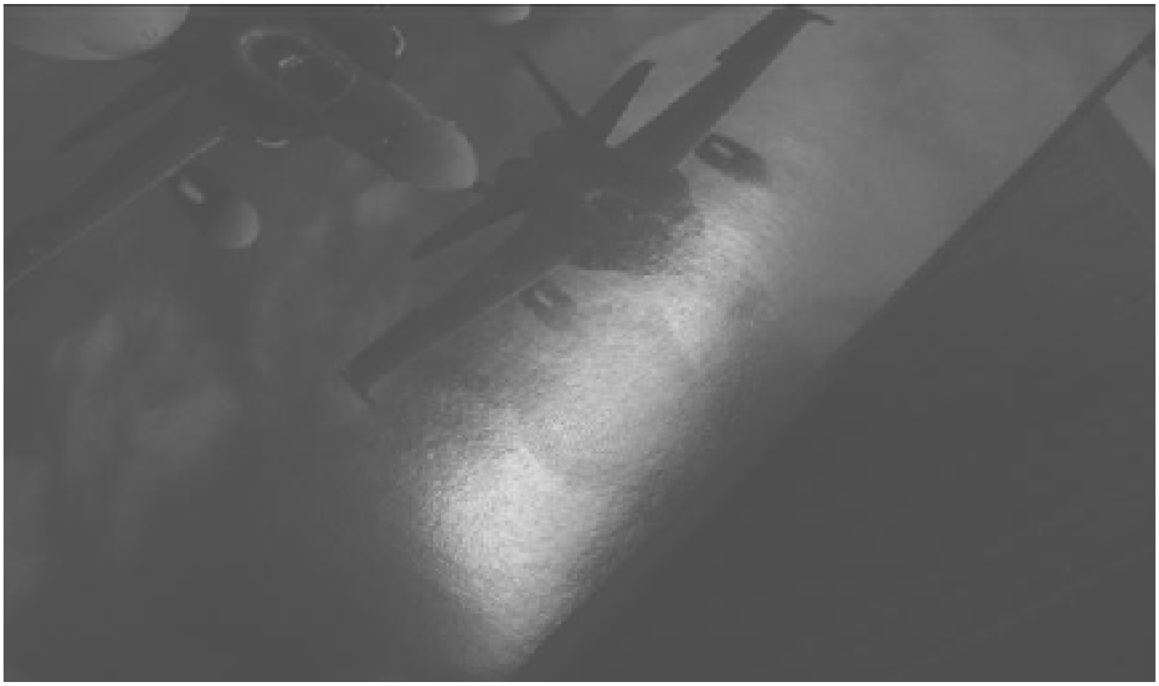
(e)

(f)

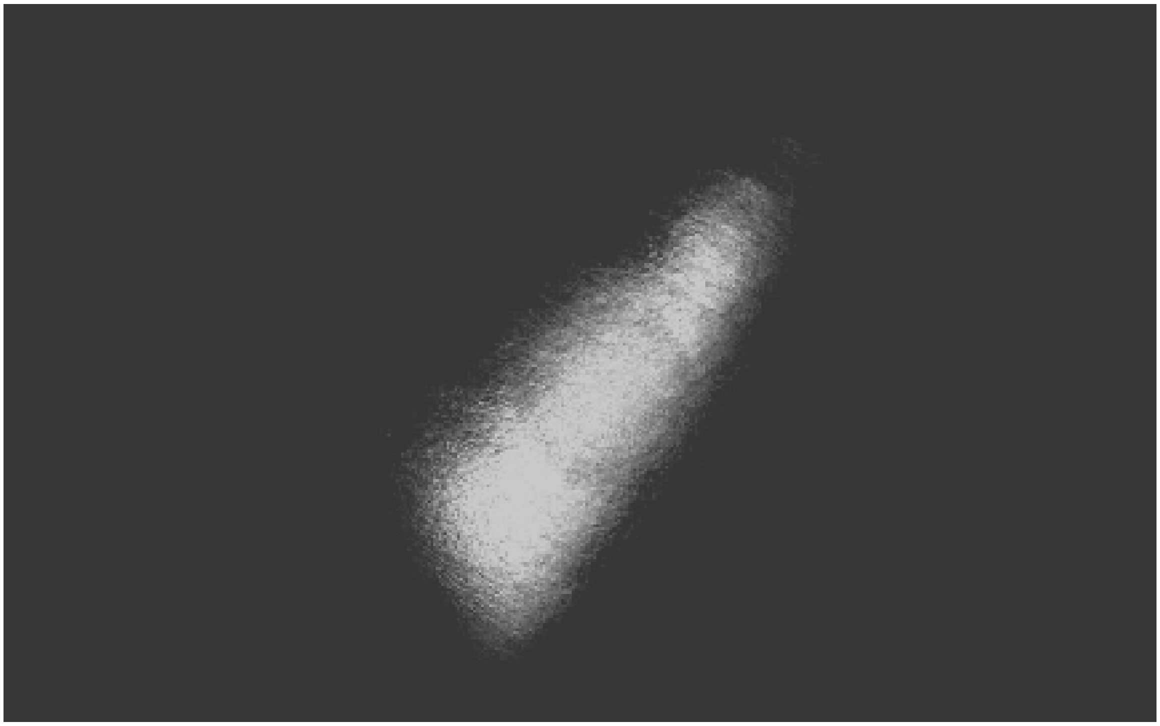


(g) **(h)**

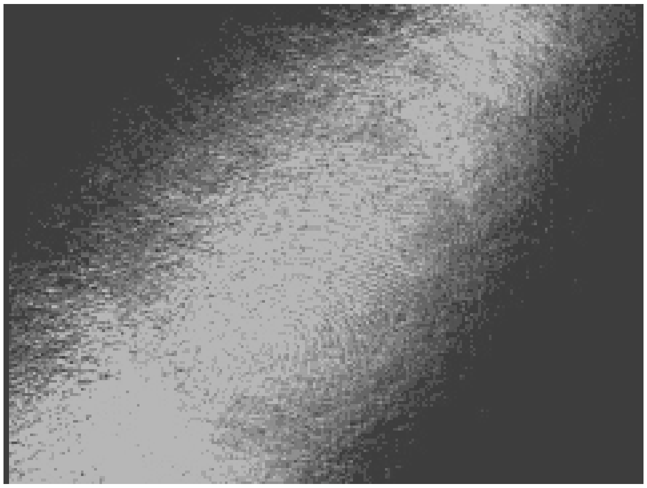
Fig. 5 Fingerprint detection experiment on a sample surface, a metal case of a pump painted orange. (a) Sample surface picture taken under ordinary lighting, linearly scaled. (b) Same as (a), but used histogram equalization for contrast enhancement. (c) The same surface as (a) and (b) taken under our special lighting setup in which the clean surface without fingerprint residue is showing strong specular reflection. The fingerprint residue disrupts the specular reflection geometry so its pattern is revealed as dark diffuse reflection pattern. This image is linearly rescaled. (d) Same as (c), only the contrast enhancement is done using histogram equalization. (e) Zoom in view of the fingerprint revealed in (c) and (d). (f) Further zoom in view of (e), showing the very fine details of the recovered fingerprint pattern. (g) The same fingerprint being lifted with tape after being dusted with forensic black magnetic powder. (h) The fingerprint lifted using the traditional powdering and tape lifting. The fingerprint lifted by the proposed new method as shown in (e) and (f) is cleaner.



(a)



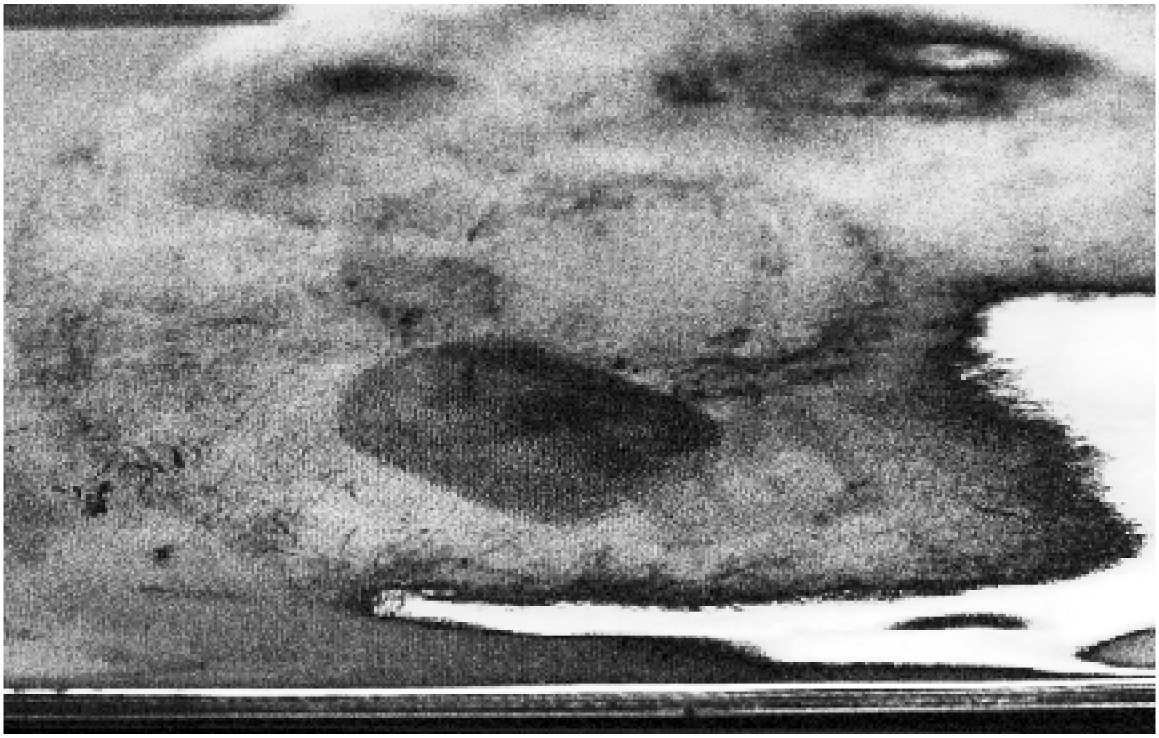
(b)



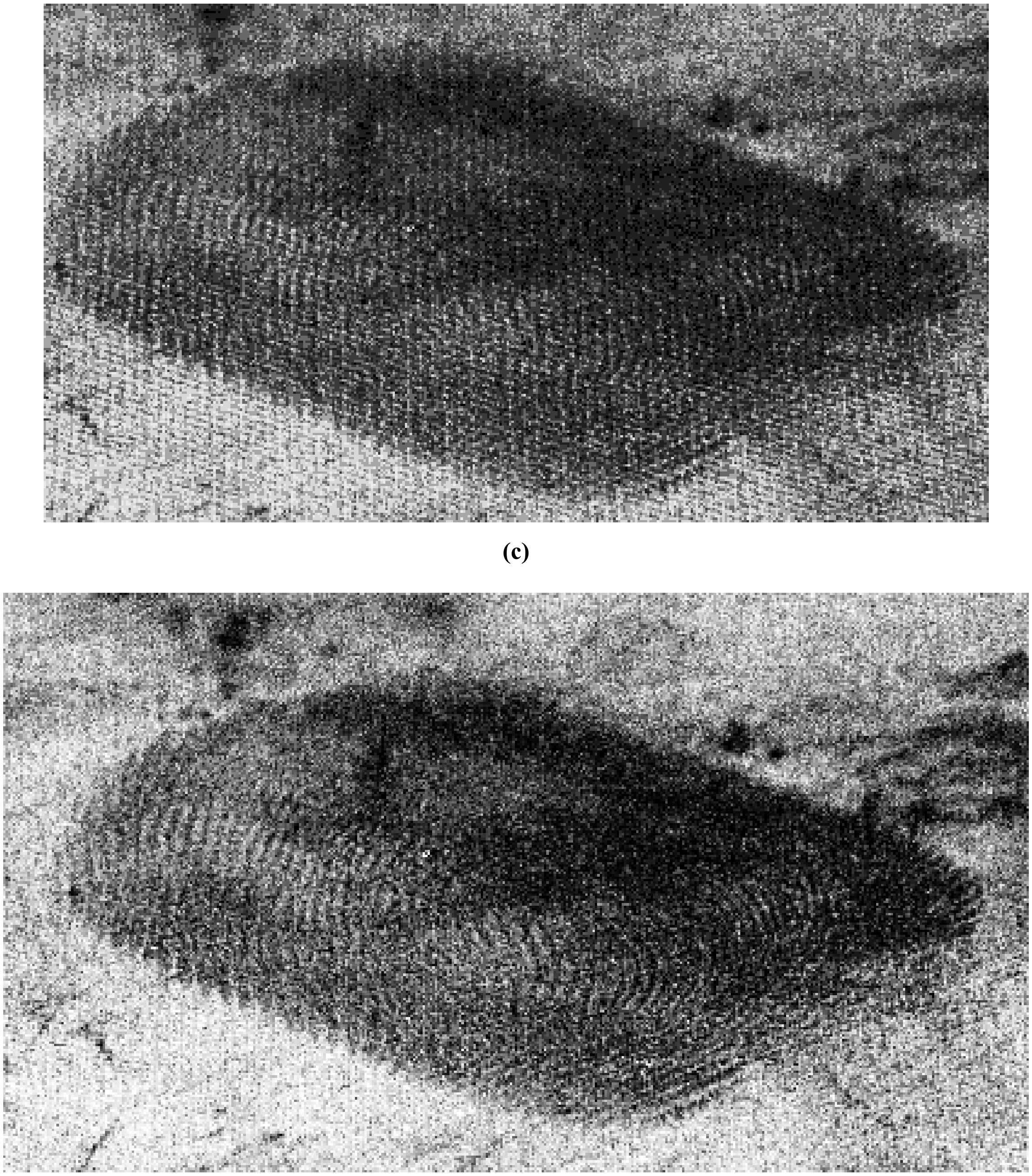
(c)

Fig. 6 Paper calendar cover with underlying picture. (a) A fingerprint is revealed by specular lighting. (b) Same item as in (a) but with polarization processing. This is the I_A image. Background completely removed. (c) Zoom in view of the fingerprint in (b).

(a)



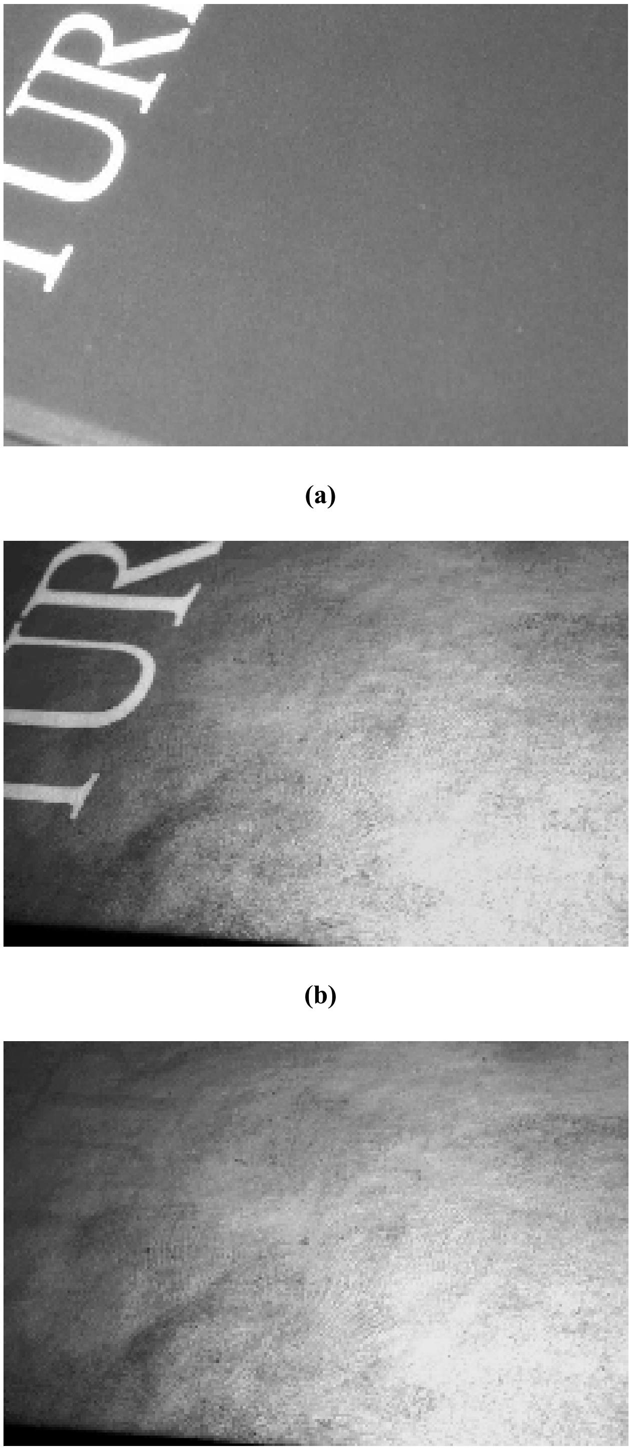
(b)



(c)

(d)

Fig. 7 A soft plastic CD sleeve with white cotton lining underneath. (a) Under ordinary lighting. (b) Polarization I_A image. The latent fingerprint on the CD sleeve is exposed in high contrast. (c) Zoom in view of the fingerprint in (b). (d) The periodic pattern caused by the cotton lining as seen in (c) can be removed by Fourier transform processing.



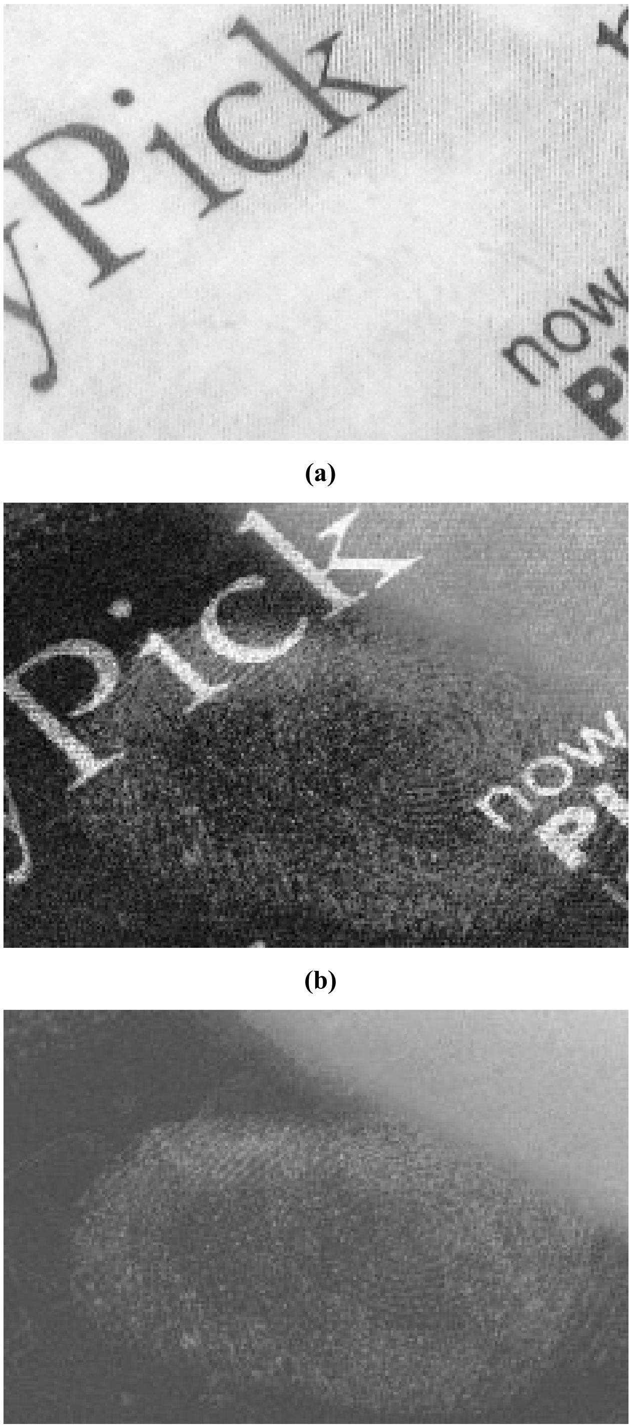
(a)

(b)

(c)

Fig. 8 (a) Close up view of the hard cover book bearing latent fingerprint under normal (no polarizer, no special lighting arrangements) viewing condition. Note that this image has undergone digital linear contrast enhancement but still the fingerprint mark is not visible. (b) The same area as in (a) but taken with our specially arranged specular lighting condition. The latent fingerprints are revealed. (c) The same area as in (a) but taken with our specially arranged specular lighting condition plus polarization image processing. This

is the I_A image linearly rescaled to fit 8 bit display. The latent fingerprints are revealed and at the same time the background pattern from the book title is greatly suppressed.



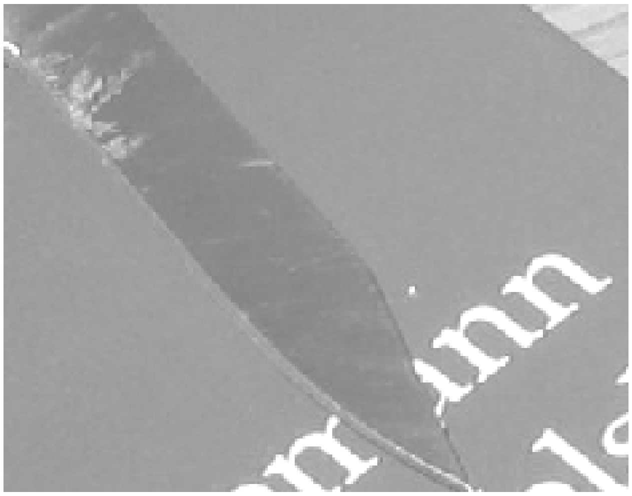
(a)

(b)

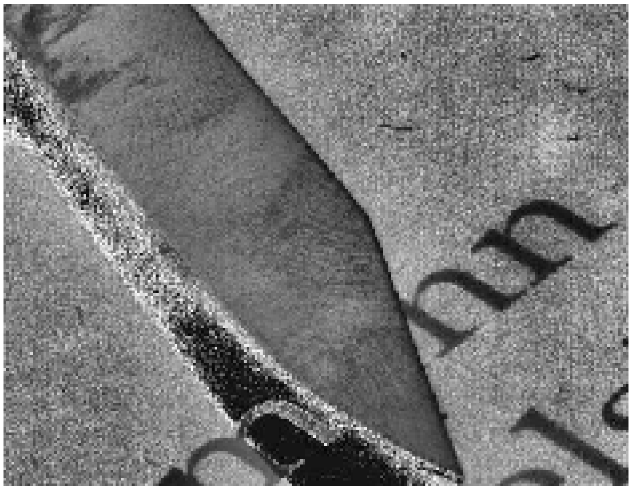
(c)

Fig. 9 (a) Close up view of the plastic CD case with insert pattern under normal viewing condition. No fingerprint is visible although the image has undergone digital linear contrast enhancement. (b) The same area of the plastic CD cover with insert pattern as in (a), but taken with our specially arranged specular lighting condition with three different polarizer orientation and then the degree of polarization image

computed. The latent fingerprints are revealed. (c) The same area of the plastic CD cover with insert pattern as in (a), but taken with our specially arranged specular lighting condition plus polarization image processing. This is the I_A image linearly stretched to fit 8 bit display. The latent fingerprints are revealed and at the same time the background pattern from the CD insert is greatly suppressed. The upper right corner of image (b) and (c) appears brighter because those areas are showing the specular reflection image of the light source. This is an example where the fingerprint stained area shows specular reflection instead of the adjacent 'clean' surface.



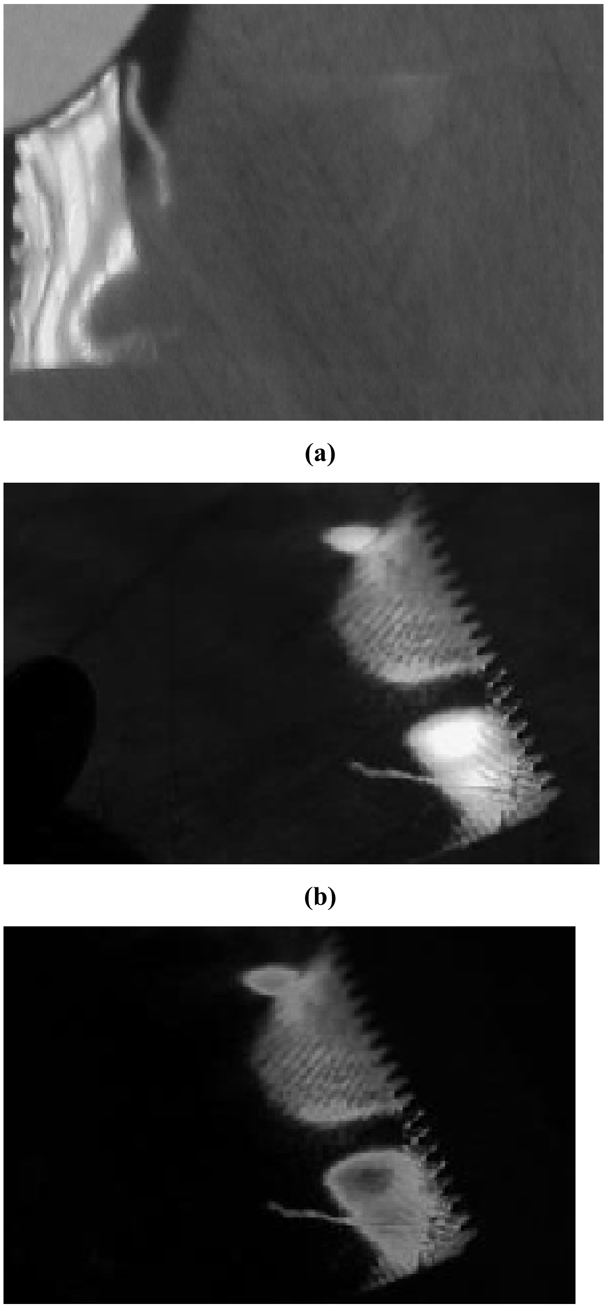
(a)



(b)

(c)

Fig. 10 Close up view of the stainless steel Swiss army knife under normal viewing condition. No fingerprint is visible although the image has undergone digital linear contrast enhancement. The same area of the stainless steel Swiss army knife as in (a) but taken with our specially arranged specular lighting condition plus polarization processing. The latent fingerprints are revealed in the degree of polarization image. The same area of the stainless steel Swiss army knife as in (a), but taken with our specially arranged specular lighting condition plus polarization image processing. This is the I_A image. The latent fingerprints are revealed and at the same time the background pattern from the book cover is greatly suppressed.



(a)

(b)

(c)

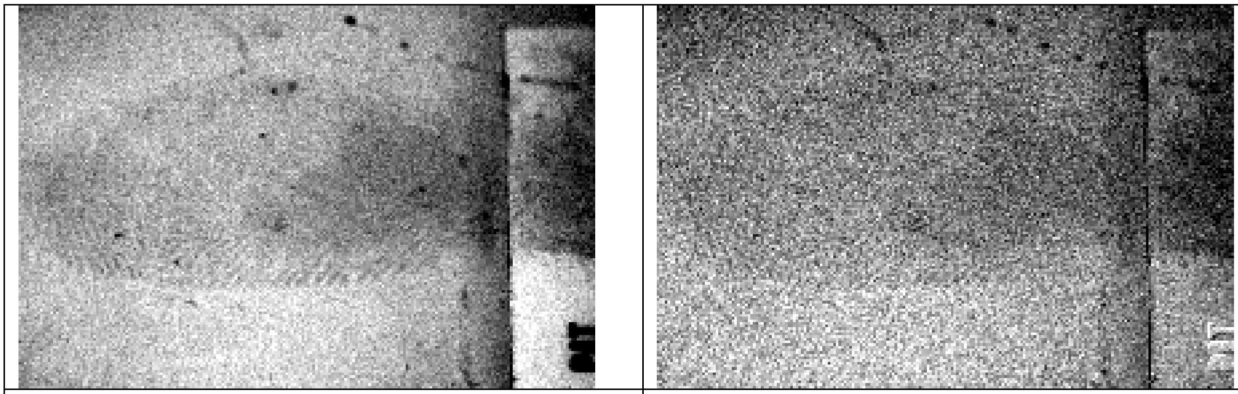
Fig. 11 (a) A transparent tape under normal viewing condition. No fingerprint is visible. The tape itself is barely recognizable since it is transparent. (b) fingerprint found on the sticky side of the tape using specular

reflection. (c) fingerprint found on the sticky side of the tape using polarization. The image is the I_A image. Note that no ordinary digital contrast enhancement is used on any of the images in this figure.

(a)

(b)

Fig. 12 (a) A piece of hardened epoxy resin under ordinary lighting condition and view. No fingerprint is visible even after linear rescale to fit 8 bit display. (b) Plastic fingerprint mark revealed on the same piece of hardened epoxy resin as in (a) in the degree of polarization image. No ordinary digital contrast enhancement is used on this image.



(a) (b)

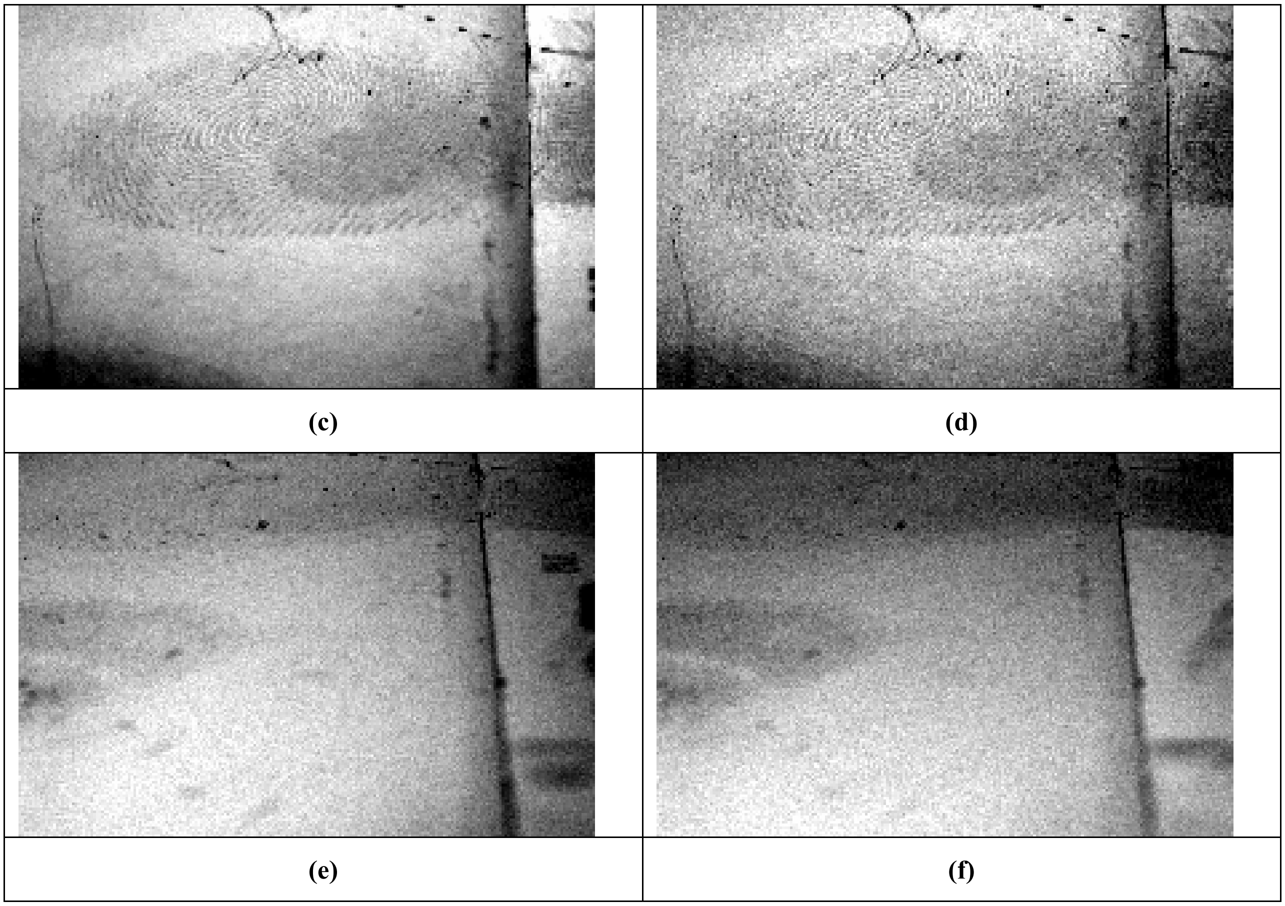
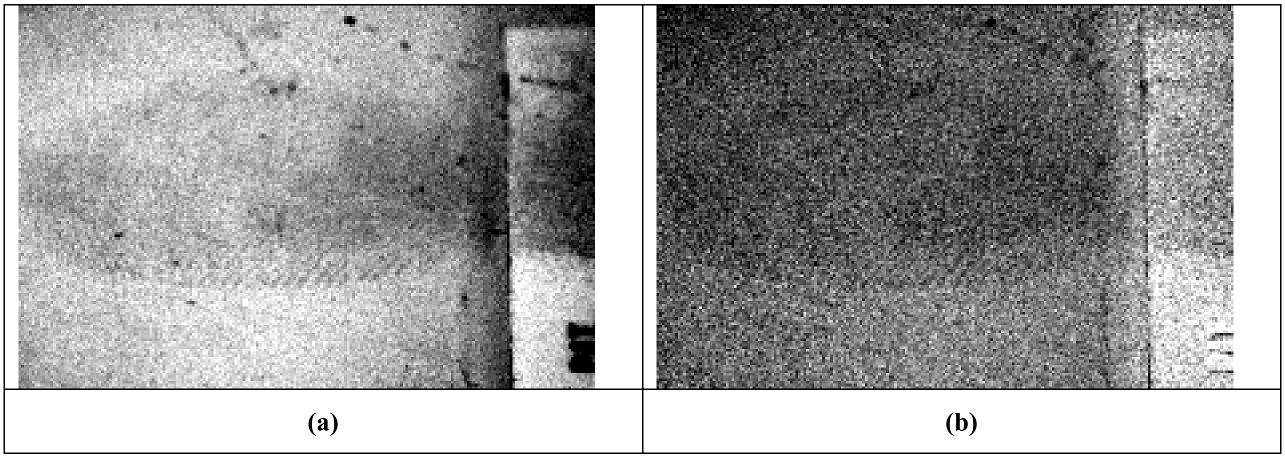


Fig. 13 Comparison of fingerprint lifting at different view angles (varying both the incident angle of the light source and the view angle of the camera simultaneously to maintain the specular reflection condition described in our theory). All images are for the same fingerprint taken within about one hour of experiment session. View angles (the angle between the surface normal of the sample to the view direction of the camera) are about 30 degree for (a)(b), 45 degree for (c)(d) and 75 degree for (e)(f). Images (a)(c)(e) are contrast enhanced (linear gray level stretch) U, representing the specular reflection based method. Images (b)(d)(f) are contrast enhanced (linear gray level stretch) A, representing the polarization based method. It is clear that at near grazing angle (75 degree) it is difficult to see the fingerprint pattern. At near frontal view (30 degree) the polarization signal is very weak so after contrast enhancement the result is very noisy. Around 45 degree we get the best results.



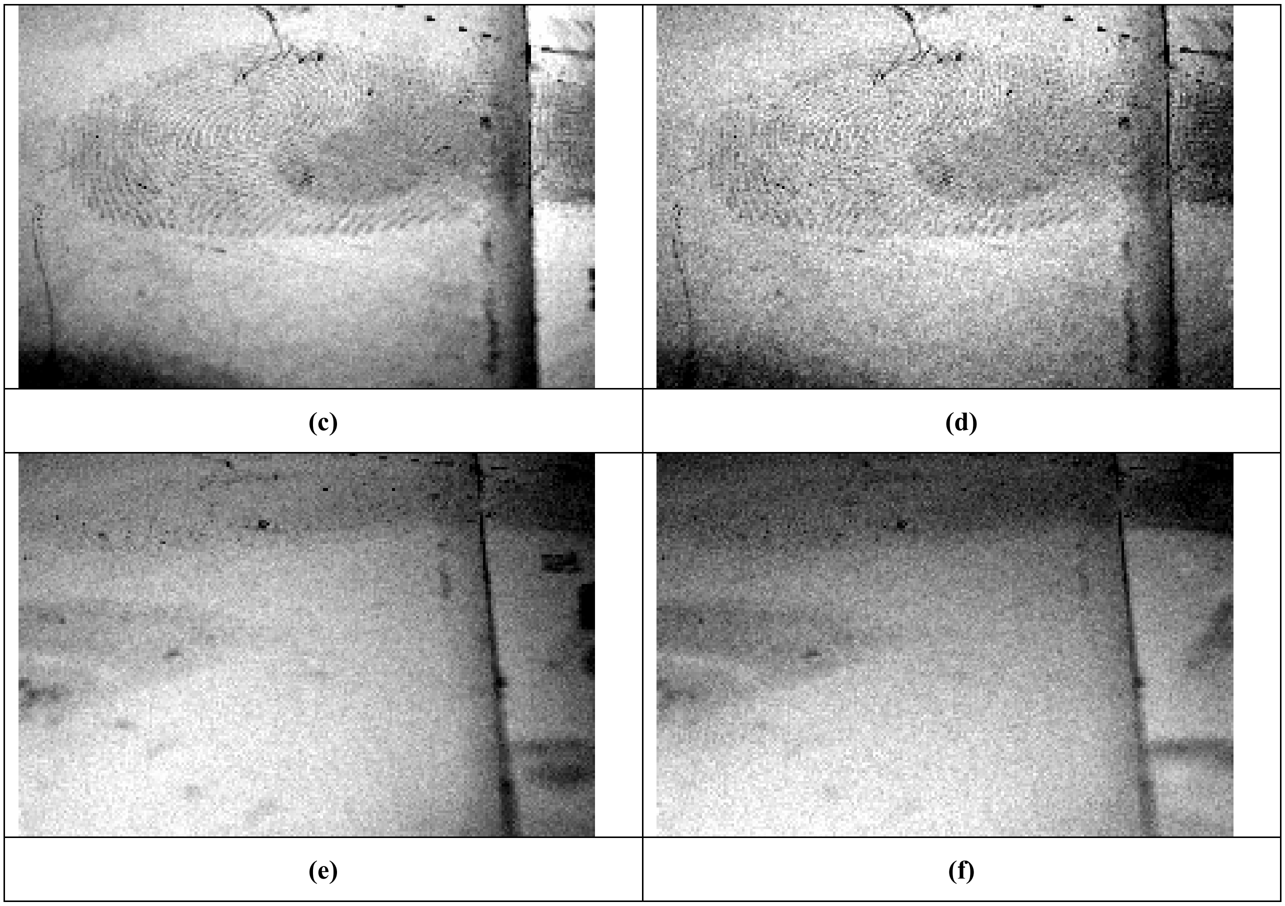

(c) (d)
(e) (f)

Fig. 14 These are the exact same fingerprint target and the same experiment as shown in Fig. 13, with only one important difference: the pictures shown here are taken with all ordinary room light shut off in the room and room door shut to create a near dark room environment. We would like to point out that all experiment pictures shown in this paper except pictures in this figure (Fig. 14) are all taken without any particular ambient light control, i.e. the room lights from the ceiling were not shut off, and room doors are not closed. It is clear that our method performs equally well with reasonable amount of ambient light and does not need a special photo lab level dark room. The corresponding images in Fig. 13 and Fig. 14 look practically identical. We have used Lux meter to measure the irradiance difference at the surface of the fingerprint sample for both “ambient light on” and “ambient light off” condition and the readings are around 2000 Lux and 1900 Lux respectively. It is clear that as long as our controlled light source dominates the irradiance at the surface of interests the ambient light has little effects on the effectiveness of our method and thus we can safely apply our method directly at many crime scenes without the need to bring the sample to a dedicated laboratory dark room.