

Accessible biometrics: A frustrated total internal reflection approach to imaging fingerprints

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Abstract

Fingerprints are widely used as a means of identifying persons of interest because of the highly individual nature of the spatial distribution and types of features (or minuta) found on the surface of a finger. This individuality has led to their wide application in the comparison of fingerprints found at crime scenes with those taken from known offenders and suspects in custody. However, despite recent advances in machine vision technology and image processing techniques, fingerprint evidence is still widely being collected using outdated practices involving ink and paper – a process that can be both time consuming and expensive. Reduction of forensic service budgets increasingly requires that evidence be gathered and processed more rapidly and efficiently. However, many of the existing digital fingerprint acquisition devices have proven too expensive to roll out on a large scale. As a result new, low-cost imaging technologies are required to increase the quality and throughput of the processing of fingerprint evidence. Here we describe an inexpensive approach to digital fingerprint acquisition that is based upon frustrated total internal reflection imaging. The quality and resolution of the images produced are shown to be as good as those currently acquired using ink and paper based methods. The same imaging technique is also shown to be capable of imaging powdered fingerprints that have been lifted from a crime scene using adhesive tape or gel lifters.

Keywords: fingerprint, waveguide, imaging, frustrated total internal reflection

Introduction

Digital acquisition of fingerprints is becoming increasingly important for biometric identification and evidence gathering purposes. The proliferation of both capacitive [1-4] and optical based scanners [5-9] as fingerprint acquisition tools has meant that these types of device are being routinely used to provide access to smart phones and laptops as well as more security intensive applications that involve controlling human access to safes and restricted areas. Other important areas where digital fingerprint devices are useful include domestic and international policing applications, immigration and border control and in the identification of terror suspects.

Given the relative abundance of fingerprint acquisition technologies it may at first seem surprising that many domestic police forces in the UK choose to use paper based methods to acquire fingerprint evidence. However, recent and ongoing cuts in the forensic science budget have meant that even the cheapest of these technologies can prove to be prohibitively expensive when rolled out on a large scale to all scene of crime officers. Moreover, the software interface that comes with these devices is often not fit for purpose and has expensive software licences associated with it. Considerable expenditure and work therefore has to be done to integrate these new technologies with existing fingerprint database tools.

There are a number of disadvantages to using paper based techniques that make the move towards digital fingerprint acquisition increasingly more attractive. This is particularly true in the acquisition of fingerprints from suspects in custody and at potential crime scenes, as part of border control processes and in collection of so called 'elimination prints'. These elimination prints are usually collected at the scene of e.g. a burglary, and are designed to help police to

eliminate the house holders prints from an investigation – as most of the prints found at this type of crime scene are likely to belong to the people that live there. In all of the cases mentioned above, the practical aspects of acquiring and transmitting the finger print data mean that ink and paper based methods can be unreliable and slow. Very often the person collecting the fingerprints will be an investigating police officer, an immigration official, or a member of the public (in the case of elimination prints). The fingerprints that are produced using ink and paper based techniques can sometimes become smudged, distorted or incomplete. If this occurs the fingerprints are likely to be less useful and in extreme cases unusable for identification purposes. In many cases, the resulting marks are then sent by conventional mail or courier to a fingerprint bureau where they are scanned at high resolution and imported into a fingerprint database - a process that can take many days. A more attractive approach would be to acquire these prints digitally and to transmit them to a fingerprint bureau electronically. This would increase the rate of transmission of the data (seconds vs days) while also reducing consumables costs (ink pads and paper) and ideally improving the quality of the transmitted fingerprints.

Digital images of fingerprints are routinely collected using capacitive [1-4] and optical based sensors [5-9]. In a capacitive sensor, an array of small elements is used to detect when a finger is brought into contact with the surface. The areas where the ridges of the finger touch the elements experience a change in capacitance and an image of the contact regions can be built up by electrically addressing each element in turn [1-4].

Optical sensors use light scattered by a finger which is in contact with a hard surface as a means of detecting the contact regions. A convenient and reliable approach involves the use of evanescent field techniques such as frustrated total internal reflection (FTIR) [5-9]. These devices are constructed such that light is incident on the interface between a glass (transparent

plastic) plate and air at an angle of incidence that is greater than the critical angle [10]. As a result, the light is totally internally reflected inside the glass (plastic) plate and is confined within it, creating a so called waveguide. The boundary conditions are such that the electric fields associated with the incident light do not decay sharply to zero at the interface. In fact, the amplitude of the electric field decays exponentially over distances comparable to the wavelength of the light in a direction normal to the plate surface. This exponentially decaying field is referred to as an evanescent field and any objects that come to within a wavelength or so of the glass/air interface are capable of interacting with the light confined within the waveguide.

When a finger or another object is brought into contact with the surface, the boundary conditions experienced by the light on this surface are changed and total internal reflection is frustrated. Specifically, the regions in contact have a different refractive index to that of air and one which is much closer to that of the refractive index of the glass/plastic plate. The result of this change in boundary conditions is that the condition for total internal reflection is changed and some light is transmitted in the contact regions. If the contacting object also scatters light, then the light scattered by the contact regions can be imaged using a camera or other imaging device. This technique produces images that quite clearly discriminate between regions of contact and non-contact and can therefore be used to image the ridge pattern of fingerprints. The technique has also been used successfully to image the contact regions between shoes and surfaces in forensic footwear imaging applications [11] and in other areas including multi-touch sensing applications [12], clinical imaging [13-15], measuring the gait of animals [16] and insects [17-19] as well as performing fluorescence [20] and scanning near field optical [21] microscopy measurements.

In the present study we demonstrate that the technique can also be used to image latent fingerprints that have been obtained from a crime scene. Fingerprints that have been developed using a powder and lifted using a transparent tape or gel lifter can be placed in contact with the surface of the waveguide and imaged. The regions of the fingerprint that are coated with powder scatter light at the interface in much the same way as a contacting finger would. This scattered light can then be imaged to obtain a digital image of the print.

Although the evanescent field and capacitive techniques described above are well described in the literature [1-9], the designs associated with practical devices can be quite expensive. In this manuscript we describe an inexpensive evanescent wave device for acquiring fingerprints that uses a webcam to image the contact regions between a finger and an acrylic polymer disk illuminated by a strip of LEDs. We also briefly describe open source software for acquiring images of the fingerprints that was written in the Python programming language – a copy of which is made available for use as part of the supplementary material along with a compiled executable file. Instructions describing how to build a simple are also provided in supplementary information.

Materials and Methods

Figure 1a shows a schematic diagram of the fingerprint imaging device used in this work. It consisted of a waveguide optical element on which a person can place their finger. A low-cost, high definition (HD) USB webcam with 1290 X 1080 pixel resolution was placed beneath the waveguide at a distance of ~10mm and used to acquire images of the fingerprint contact regions with a resolution of 610dpi using software written in the Python programming language (see Supplementary Information, Figures S1 and S2). The resolution was checked by placing a square grid on top of the waveguide element and measuring the number of pixels per inch in

the images acquired by the webcam. Higher resolution images could have easily been achieved by using a more expensive camera. However, this resolution is comparable to that used in UK police fingerprint bureaus when scanning fingerprint images from samples taken using ink and paper based methods.

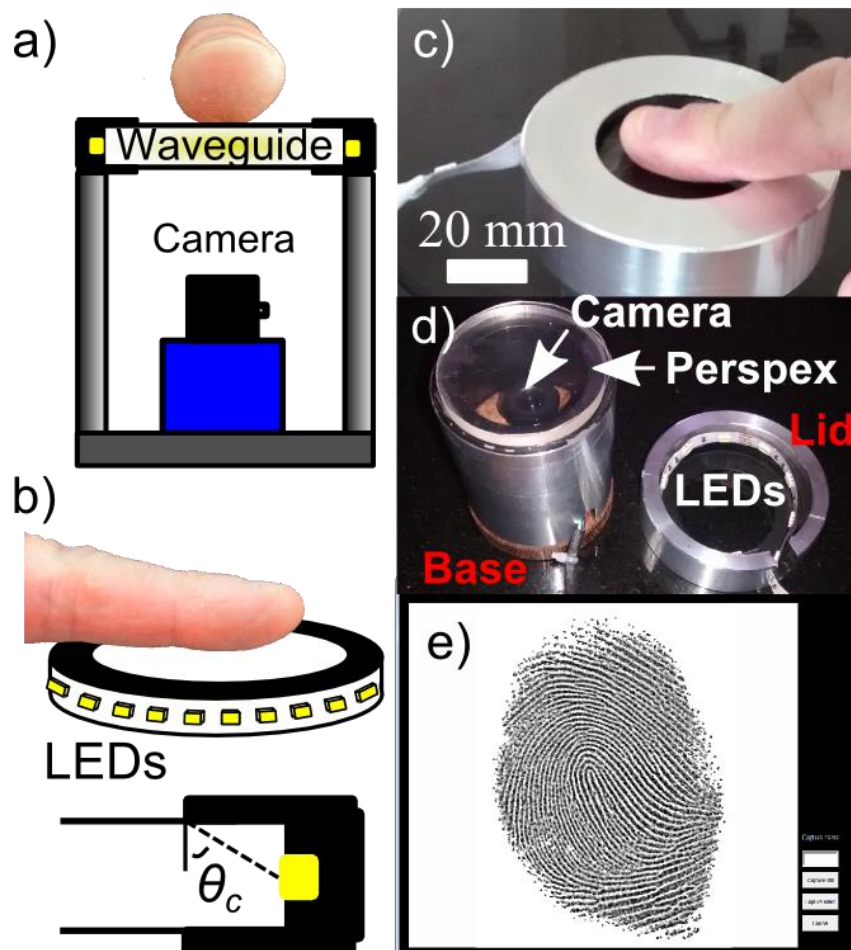


Figure 1. Waveguide imaging device for the collection of elimination fingerprints. Panel a) shows a schematic diagram of the device. Panel b) illustrates how the LEDs are wound around the outside of the acrylic polymer disk and shows how the flat surfaces of the disk are masked to ensure that light which is incident on the surface at angles less than θ_c is prevented from escaping. Panels c) and d) show photographs of the device used in this study and panel e) shows a screenshot of a fingerprint that was obtained using the Python software.

The waveguide optical element used in FTIR illumination is made from a single disk of acrylic (Perspex) polymer that is 50 mm in diameter and 6 mm thick. Illumination of the waveguide element was achieved by placing USB powered ultrabright white LED strip lights around the roughened edge of the acrylic polymer disk as shown in Figure 1b. The LED strips were mounted on the inside of a removable lid (see Figure 1c and 1d). This lid served to secure the LED strip in place and was designed to mask part of the flat surfaces of the disk to prevent ambient light from entering the waveguide at the edges. The masked regions of the two largest faces of the disk were assembled in such a way that light from the LEDs which subtended an angle of incidence less than the critical angle required for total internal reflection was prevented from escaping the waveguide (see figures 1b-d). As a result, only light with an angle of incidence greater than θ_c was incident on the surface and was confined within the waveguide as a consequence of total internal reflection. For the experimental setup shown in figure 1 the value of θ_c can be determined from the equation, $\sin \theta_c = \frac{1}{n_p}$ [10], where n_p is the refractive index of the acrylic polymer disk ($n_p=1.489$ [22], $\theta_c \sim 42^\circ$).

When a finger was brought into contact with the waveguide element (acrylic polymer disk), the condition for total internal reflection was changed and the contact regions were observed to strongly scatter the light. The contact regions were then imaged from below using the webcam. The resulting images were processed using Python software to extract the contact regions and to produce a binary image of the fingerprint similar to that shown in figure 1e. The image shown in this figure is displayed at a lower resolution than that obtained using the imaging device. Examples of full resolution images are included as supplementary information (see figures S1 and S2).

Short sequences of images containing ~5-30 frames were obtained at 30 frames per second and were used to acquire static and rolled fingerprints. In the case of static prints, a finger was placed on the waveguide surface and a sequence of 5 images was collected and averaged to produce the final image. For rolled prints, a short movie sequence containing 30 frames was collected using the webcam while a finger was rolled across the waveguide surface. The resulting movie frames were stitched together to produce a composite image of the rolled prints. This was achieved by interrogating each pixel position in the images acquired during the short movie sequence. The maximum pixel intensity measured at each position was recorded and stored at the same position in a new image. These composite images were processed and used to determine the contact regions between the finger and the waveguide during the rolling process.

Inked prints were also collected using a standardised approach where each finger was rolled from left to right on a 110mm x 75mm pre-inked plastic strip (WA Products, UK). The same finger was then rolled on to a piece of white paper (National Elimination Fingerprint Form) while applying a gentle pressure from above using a finger from the other hand. This procedure was performed in an attempt to reproduce the process currently used to collect fingerprints and was repeated for all the fingers and both thumbs. The resulting images were then scanned using an Epson V700 Photo flatbed scanner at a resolution of 600 dpi.

Latent fingerprints were also deposited on the surface of glass slides and developed by applying black fingerprint powder with a fingerprint brush (both from Scientific and Chemical Supplies Ltd., Bilston). The fingerprints were then lifted using transparent tape and the powder coated fingerprint on the surface of the tape was placed in contact with the waveguide surface. The fingerprint was then imaged using the software and the tape containing the powder coated

fingerprint was removed from the waveguide surface intact. There was no apparent transfer of powder to the waveguide surface or distortion of the fingerprint during this process.

Results and Discussion

Figure 2 shows how the images acquired from the camera were converted into binarised images similar to that shown in figure 1e. Images acquired from the webcam were flipped horizontally (Figure 2a) so that the fingerprints appeared as they would on a piece of paper or other surface. The images were then converted to greyscale (Figure 2b) before being thresholded. During the thresholding process pixels with an intensity value larger than a fixed threshold intensity were set to a value of 255 and pixels with an intensity lower than the threshold value were set to zero. This created a mask which identified the region containing the fingerprint (Figure 2c). The greyscale image in figure 2b) was then subtracted from the image in figure 2c) to produce the image in figure 2d). This image was then thresholded locally to obtain the image in figure 2e). The thresholding algorithm performed to obtain figure 2e) used a simple mean method where the local pixel intensity was averaged to obtain the threshold value. Pixels with intensities larger than the locally determined threshold value were set to a value of zero and pixels with intensity values lower than the threshold were set to a value of 255. In each case, between 5 and 30 frames similar to those in figure 2e) were averaged and the region surrounding the finger print was inverted ($255 \leftrightarrow 0$). Successive dilation and erosion morphological operations were also performed to fill in any small gaps/holes in the ridges and to produce the final fingerprint image shown in Figure 2f). In this image the black regions correspond to the positions where the fingerprint ridges contacted the waveguide surface.

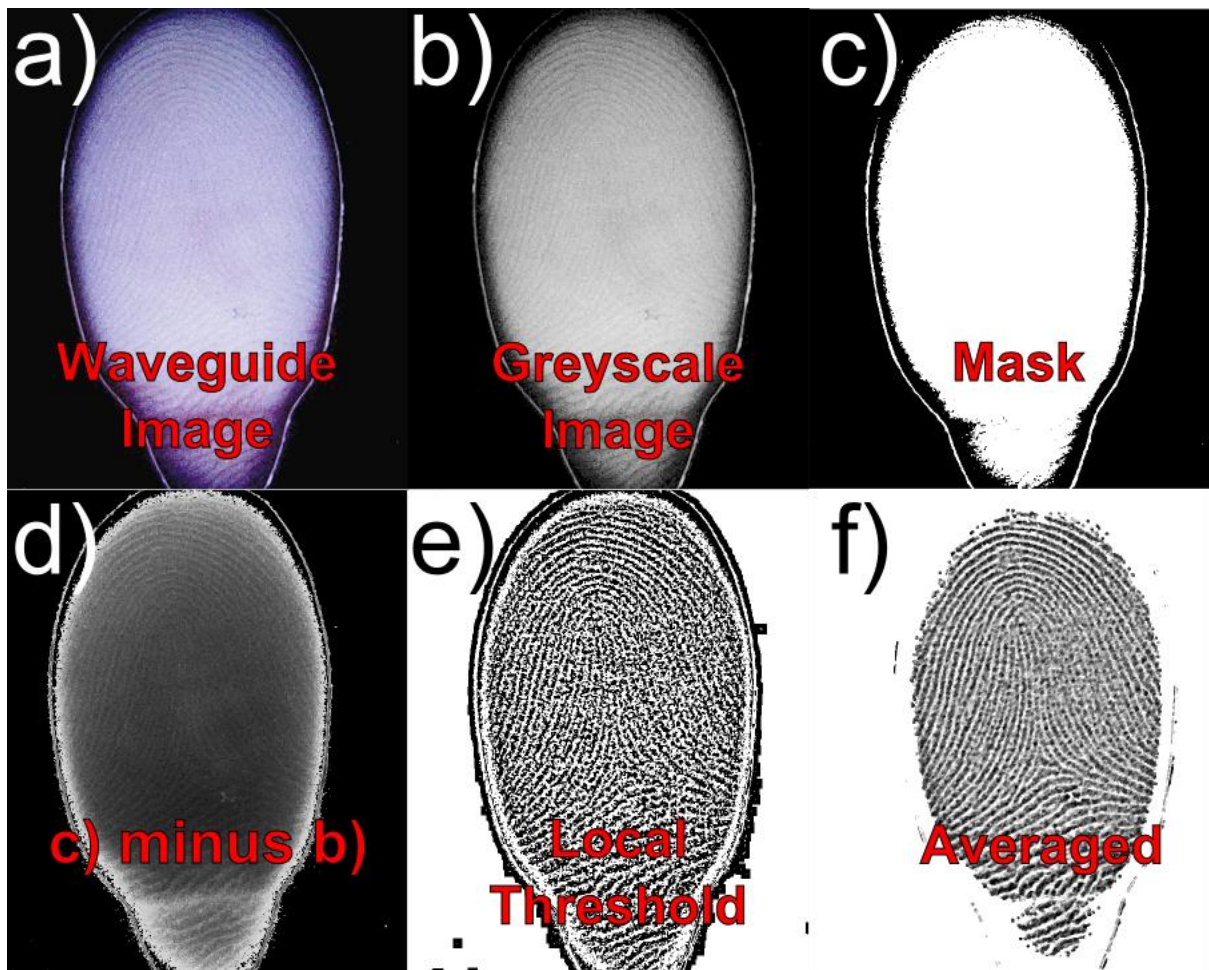


Figure 2. Waveguide images collected using the camera (panel a)) were converted to greyscale (panel b)). The greyscale images were then thresholded to create the mask in panel c). The image in panel d) was generated by subtracting the image in panel b) from the image in panel c). This image was then thresholded locally using a simple mean based approach to produce the image in panel e). Pixel intensities were averaged in the neighbourhood of each pixel in the image. The local mean intensity was used as the threshold value below which pixel values were set to 255 and above which they were set to zero. Panel f) shows the final image of the fingerprint that was created by averaging 5 frames similar to those in panel e) and performing successive dilation and erosion operations on the image to close small holes/gaps in the ridges. The background colour was also set to be white (see text). The black regions in the image correspond to the positions where the fingerprint ridges touched the waveguide.

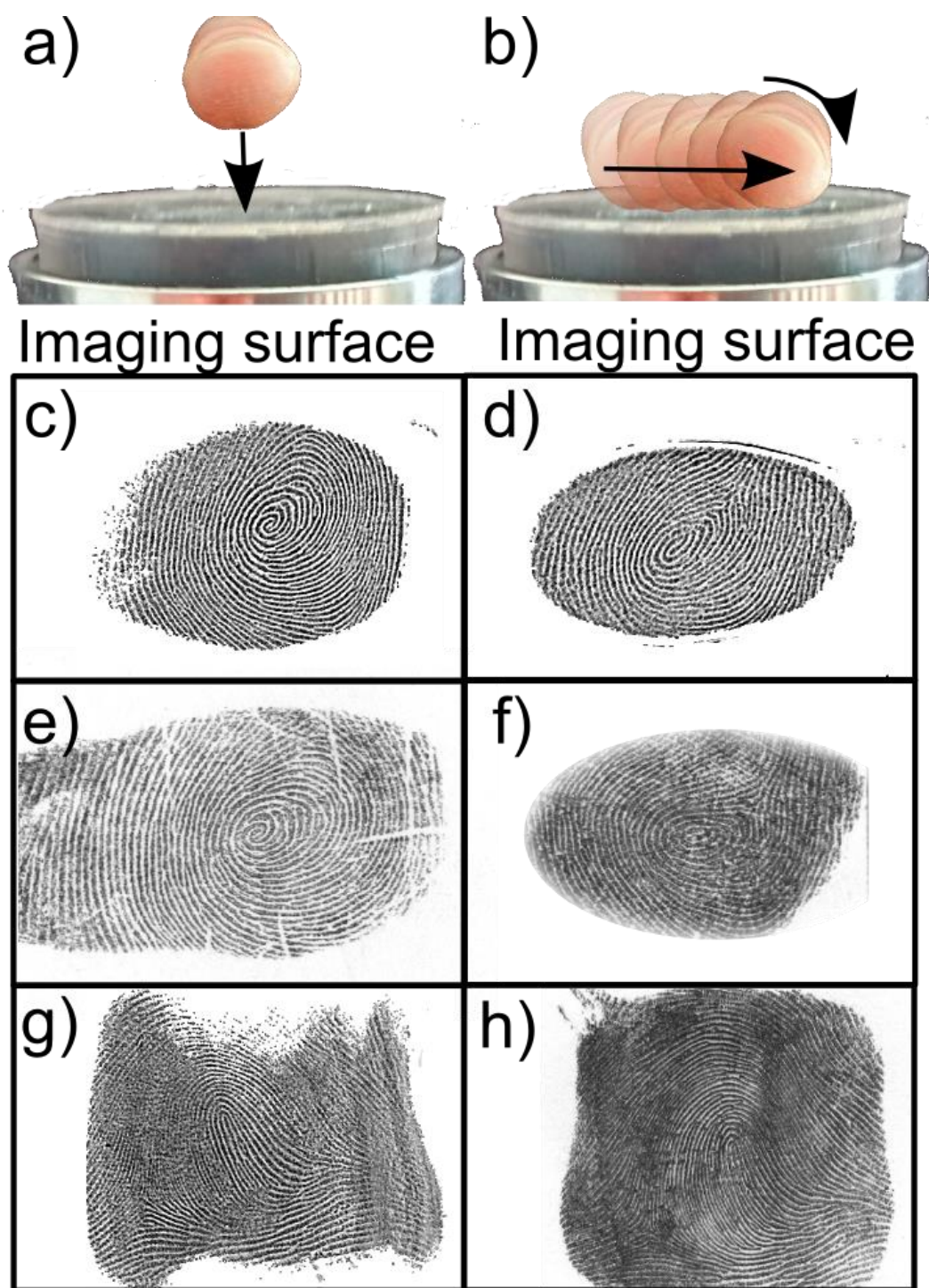


Figure 3. Comparison of waveguide images and inked fingerprints. Panels a) and b) show diagrams of how static and rolled fingerprints were collected respectively. The images shown in panels c) and d) are examples of static fingerprints collected using the waveguide imaging system. Panels e) and f) are images of the same fingerprints that were collected using ink and paper based methods. The images shown in panels g) and h) are rolled fingerprints that were collected using the waveguide imaging system and ink and paper respectively.

Figure 3 shows examples of images that were acquired using the static print (figure 3a) and rolled print (figure 3b) deposition methods. Panels c) and d) in this figure show static prints that were acquired using the device described above. The panels immediately below these (panels e) and f) respectively) show images of the same prints obtained using ink and paper. Panels g) and h) show rolled prints of a thumb that were collected using the device and ink based methods respectively.

Comparison of the images of these prints shows that the waveguide imaging device reproduces the key features and minutiae that are observed in the inked prints. There are some areas on the images obtained where the fingerprint ridge patterns are not fully developed. However, these regions are similar for both techniques which indicates that this is a property of the finger or the deposition process rather than being specific to the methods used to capture the prints.

The fingerprints obtained using the waveguide imaging technique also display some distortion/blurring around their periphery. This lack of image contrast at the edges of the print is caused by regions of the finger that are not quite in contact with the surface, but which still fall within a few hundred nanometres of the waveguide surface and hence are able to interact with the evanescent wave. Lack of contact between the ridges of the finger and the waveguide surface at the periphery of the print occur due to the natural curvature of the finger and make it difficult to resolve these features clearly. However, it is worth noting that these effects were averaged out during the collection of the sequences of images used to acquire the rolled prints (see figure 3g). This is because multiple images were collected as the finger was rolled and regions that may not have originally been in contact entered into contact during the rolling procedure. The stitching process used to combine the images that were collected during the

short movie sequences favours the brighter intensities that were obtained during contact. Hence only the frames where intimate contact was observed were used; giving rise to sharper features in the composite images.

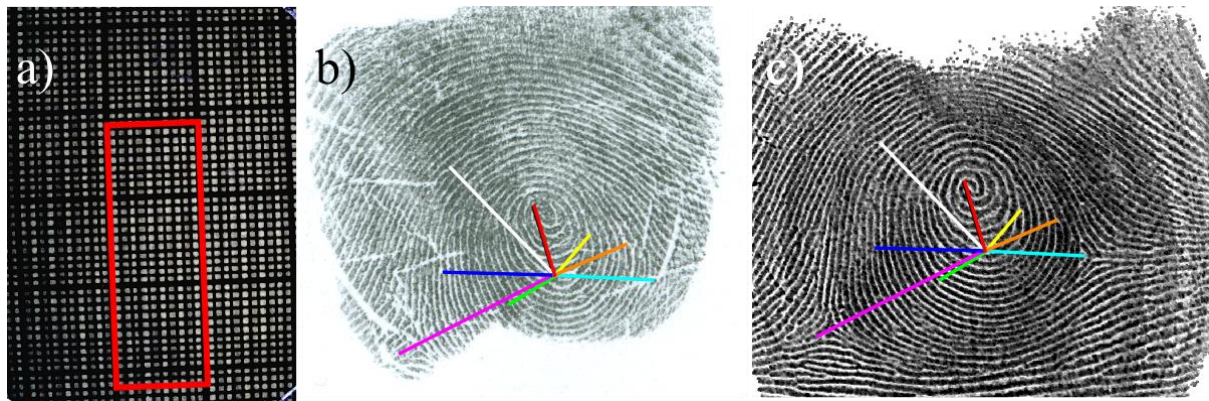


Figure 4. Reproducibility of fingerprints. Panel a) shows an example of an image of a grid containing 1mm x 1mm squares that was placed on top of the waveguide and illuminated from above. The red rectangle in this image is for comparison and demonstrates that very little distortion occurs in the grid. The images in panels b) and c) are for an inked and waveguide image of a rolled fingerprint respectively. The images have been resized slightly and rotated so that the feature sizes are the same and they have the same orientations. The coloured lines on the image show the positions of minutiae relative to a common origin and demonstrate the agreement between the two methods.

Even though the waveguide images and the inked prints show the same qualitative features, it is necessary to determine the level of quantitative agreement between the relative positions of minutia in the two types of images. This is particularly true given the quality of the lenses on the low cost webcam used and its proximity (~10 mm) to the contacting surface on the acrylic polymer disk/waveguide. We might expect that such inexpensive lenses and short working distances could result in significant image distortions. To test whether this was the case, we performed two separate sets of tests. The first (and most simple) test involved placing a piece of paper containing a square grid with 1 mm squares on it and placing it face down on the surface of the waveguide. Images of the grid were then collected using the webcam and used to determine if there were any distortions of the grid lines in the images. Figure 4a) shows an

example of an image of a grid that was taken in this way. As this image shows, there are no obvious distortion effects from the imaging system being used. However, to be certain a direct comparison of inked prints and the waveguide images was also performed.

Figure 4 shows a direct comparison of two rolled prints taken using ink and paper (panel b)) and using the waveguide imaging technique (panel c). Rolled prints were chosen for this test in preference to static prints because more of the waveguide surface is contacted during rolling and a better measure of the uniformity of the images can be obtained over the field of view of the camera. The images in panels b) and c) were rotated and scaled to take account of the small differences in resolution in the images (610 dpi for waveguide images vs 600 dpi for the inked prints).

Once the scaling had been completed a series of lines of different colours were drawn between minutiae on the inked print (see figure 4b). These lines were then placed directly onto the scaled waveguide image (See figure 4c). In this way, the coloured lines were used to check that the relative positions of minutiae were preserved in the waveguide images and that significant distortion of the images had not occurred. This method is a clear analogue of methods currently used in fingerprint identification. The lines in figure 4 clearly demonstrate the level of quantitative agreement between the waveguide images and the inked prints and confirm that significant distortion effects are not present on the waveguide imaging system.

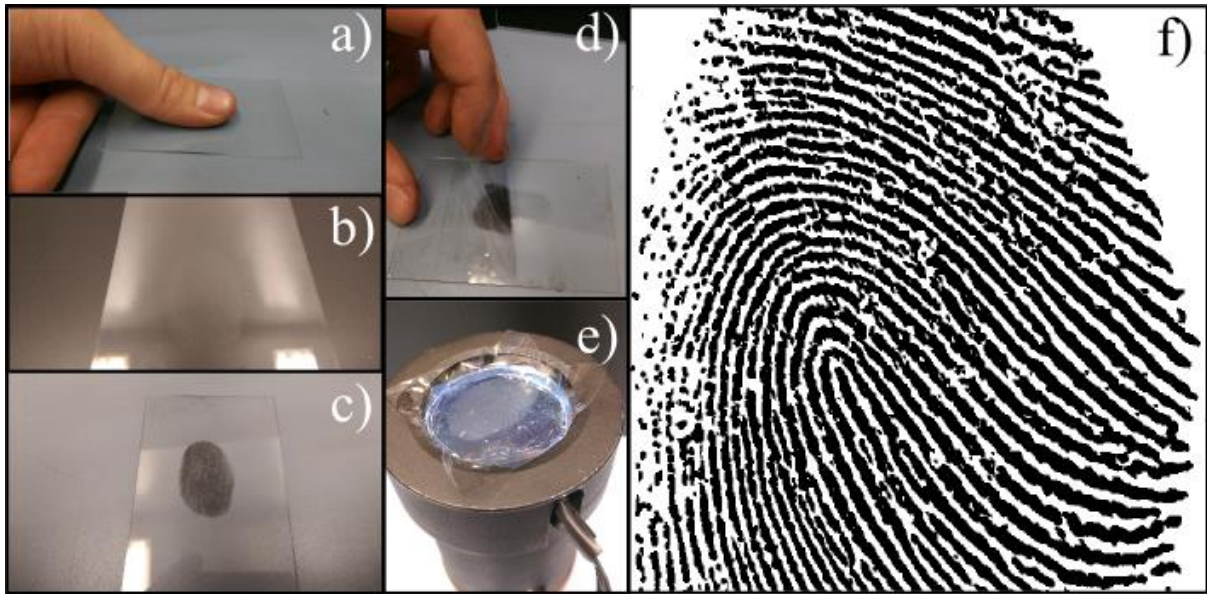


Figure 5. Waveguide imaging of powder coated fingerprints. A latent fingerprint was deposited on a clean glass slide (panels a and b) before a black fingerprint powder was applied using a fingerprint brush (panel c). The resulting powder coated fingerprint was then lifted using adhesive tape (panel d) before being placed face down on the surface of the waveguide. The image acquired from this fingerprint is shown in panel e).

The same imaging device was also used to image fingerprints that had been recovered from a surface by lifting with tape, or a gel lifter. Figure 5 shows the process involved in lifting a latent fingerprint from a glass surface using adhesive tape. In brief, the latent fingerprint was deposited on the glass (figures 5a and 5b) and dusted using a black, commercially available fingerprint powder (figure 5c). A piece of adhesive tape was used to lift the powder developed fingerprint (Figure 5d) before it was placed in contact with the waveguide surface (Figure 5e). The resulting image that was obtained from the powder developed print is shown in Figure 5f. This image shows the high level of detail that can be obtained from lifted fingerprints and highlights another potential application of the device as a means of digitally capturing and transmitting finger prints obtained at crime scenes. This further demonstrates the versatility and potential of the device as a valuable forensics tool; with the same device and software being able to be used recover latent fingerprints at a crime scene and gather prints from potential suspects and victims.

In addition to the simple test performed here, this method could also be used to image crime scene marks that have been retrieved in different ways. As outlined above, sticky tape or gel lift type approaches will work for powder coated prints. However, the only requirements for this technique to work are that the treated fingerprint is in good contact with the waveguide surface, there is sufficient optical contrast between the treated finger print and the waveguide surface and that the substrate supporting the fingerprint residue is transparent.

Achieving conformal contact does not necessarily require a sticky, adhesive surface if the treated fingerprint can be supported on a thin, flexible transparent substrate. In fact, if the substrate was thin and compliant enough, then Van der Waals forces would be strong enough to pull it into contact with the waveguide surface. The substrate could also be pressed into contact using a mechanical clamp that provides a uniform pressure, providing that sufficient care is taken not to smudge or distort the fingerprint. Alternatively, if the substrate is transparent, has a similar refractive index to the waveguide and good contact can be achieved, the fingerprint can be placed facing upwards rather than being in intimate contact with the waveguide. In this geometry, the substrate would act like part of the waveguide and the fingerprint would be undisturbed. This would allow the fingerprint to be imaged and then removed while reducing any risk of damage.

Providing conformal contact can be achieved, the waveguide imaging technique is relatively insensitive to the method used to develop the latent fingerprint. Any development process which provides optical contrast will work. This means that fingerprints that have been developed using powders (including conventional, fluorescent, magnetic etc.), super glue fuming (conventional and fluorescent), stains (amino acid and oil based) and metal vapour deposition processes would all provide sufficient light scattering for the device to work. Many of these development methods may not be appropriate for use at a crime scene and therefore

may not be relevant. However, the device could equally be used in a laboratory setting where such techniques are more prevalent.

An interesting observation that was made during these studies was that moistening the fingers with water prior to contacting the waveguide element resulted in better quality images and sharper ridge patterns. This effect is likely to be caused by improvements in the intimacy of adhesive contact caused by the formation of liquid bridges between the fingerprint ridges and the waveguide surface. The observation of an improvement in image quality is consistent with previous work by Plaipichit and Buranasiri [9] who studied the effects of changing the water content of skin on the quality of prints obtained.

The improvement in contrast that comes with moistening the fingers is a potentially important tool for improving the level of contact with the waveguide surface. This would be particularly useful for donors who had dry skin or donors whose skin had been worn as a result of hard labour. In the latter case, it may actually be desirable not to moisten the fingers and to retain the features associated with wearing of the fingerprints so that a better representation of the fingerprint detail can be obtained. However, this simple technique of moistening the fingers with water before contacting the waveguide surface can be potentially useful in extreme cases of donor variability where intimate contact between the ridges and waveguide may not be easy to achieve. In the case of donors who have particularly sweaty or greasy fingers, the material on the fingerprint ridges enhances the level of contact in the same way that moistening the fingers does. As such, the waveguide imaging device is capable of imaging fingerprints from a wide range of different donor types.

The cleanliness of the waveguide surface was not found to be critical to the operation of the device. Cleaning with soap and water was performed on a daily basis, particularly during periods of heavy use. However, it was found that successive images of fingerprint ridges could be collected from different donors without the need for cleaning between depositions - providing that heavy soiling of the waveguide surface did not occur. The reason for this is that latent fingerprint residues have similar optical properties (refractive indices) to the acrylic polymer waveguide. As such they generate little or no optical contrast with the waveguide surface and do not scatter light. However, the ridges of a fingerprint strongly scatter the light at the waveguide surface providing significant optical contrast. This makes the contact regions between the ridges and the waveguide easy to detect in the images and the large difference in optical contrast (between ridges and residues) makes the imaging technique insensitive to the presence of previously deposited fingerprint residues.

The fact that the waveguide imaging system described here was constructed from LED strips, acrylic polymer disk and a simple HD webcam, makes it an inexpensive method for collecting images of fingerprints for a range of different purposes. Both the camera and the LEDs used could be powered from a laptop or other device via USB ports making it highly portable and easy to use. Moreover, the use of an open source programming language to develop the software means that the user interface can be adapted by the end user to match their own specific requirements. As demonstrated, the device is capable of rapidly acquiring images of fingerprints while preserving the structure of ridges and the relative positions of minutiae. As such it represents a viable, distortion-free alternative to ink and paper based methods.

Conclusion

Frustrated total internal reflection is a valuable tool for the digital acquisition of fingerprints. The device described in this work was shown to produce images of fingerprints that were as good as those obtained using ink based methods and produce images of latent print lifted from a surface. The structure of ridges and relative positions of minutiae obtained from waveguide images were found to be in quantitative agreement with inked prints. The low cost, portability and ease of acquisition of fingerprints afforded by this device makes it a viable replacement for ink and paper based methods. Such a device would speed up processes involved in border control and immigration, the gathering of criminal evidence, acquisition of elimination prints and fingerprints of suspects collected in custody.

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Author Contributions

NDS wrote the python code and collected and analysed the data. JSS also performed some of the data collection/analysis and wrote the manuscript. Both authors contributed equally to the design of the fingerprint imaging device.