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Forensic Investigation to Retrieve 3D Shoe Impression: A Review

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ABSTRACT

In crime scenes such as burglary and murder, the search for physical trace evidence left behind by the suspect is a priority for forensic investigators. A shoe impression is a type of trace evidence that can link the crime scene and the suspect. However, 3D shoe impressions are often neglected at crime scenes due to the complexities of retrieving and preserving the evidence. Shoe impressions are typically retrieved using the standard method of casting. Various techniques have been introduced to retrieve 3D shoe impressions which are reviewed in this paper, including recently introduced techniques that focus on casting using different materials, Structured from Motion (SfM), and 3D light scanning. Additionally, this review discusses alternative techniques to uncover shoe impressions, including each technique's benefits, drawbacks, and gaps.

1. Introduction

Crime scene investigation requires a thorough inspection of the surroundings to search for traces of potential evidence such as DNA, fingerprints, ink, hair, nails, gunshot residue, fibre, etc [1-7]. According to an Interpol review of shoe and tool marks by Baiker-Sørensen *et al.,* [8] trace evidence of shoe impression is more prevalent at crime scenes compared to other forms of trace evidence. The evidence of shoe impressions is crucial, particularly in the crimes of trespassing, burglary, or murder but it is frequently overlooked. The recovery of shoe impressions can corroborate information from other physical evidence and narrow down the number of suspects [9]. Shoe impressions are categorised as class evidence that presents class characteristics such as physical size, design, and mould characteristics (from the manufacturing process). The presence of random, unintentional, and unique damages on the outsole of footwear can serve as individual evidence from the crime scene.

The direct physical contact between the outsole of footwear and a surface forms a shoe impression. Shoe impressions are regularly found in the vicinity of entry or exit locations, suspected

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travel pathways, and any surface or object that may have been walked on (e.g., tabletops, counters, and papers on the floor) [10]. Shoe impressions can come in the form of 2D prints and 3D impressions. 3D impressions are formed when the footprint is visible on malleable surfaces such as soil, mud, and snow. 2D prints materialise when there is a transfer of trace residue, such as soil and dirt from the shoe's outsoles onto a flat surface.

The most common technique to retrieve 2D prints is lifting. This technique transfers residual material to another imprinted surface to acquire higher fidelity impressions [10]. Gel lifters and electrostatic dust lifters are examples of well-known lifting techniques. As for 3D impressions, casting has been the gold standard in forensic investigation for centuries. The most common materials in casting are dental stone and Plaster of Paris.

However, these materials can pose challenges for crime scene technicians. Thus, forensic researchers are continuously exploring other ways to obtain 3D shoe impressions. Their studies offer various techniques that can assist forensic investigators in more efficiently collecting 3D shoe impressions. This paper evaluates these alternative techniques and materials and it incorporates valuable insights from a senior superintendent at the Forensic Laboratory of the Royal Malaysia Police via a formal interview. Furthermore, the drawbacks, advantages, and gaps of each technique are discussed in this paper.

2. Body

Shoe impressions can be located on various indoor and outdoor surfaces at a crime scene. Specific techniques are necessary for recovery and retaining shoe impressions from substrates with varying characteristics. Recent studies in this niche propose alternative techniques to retrieve 3D shoe impressions. Nevertheless, casting is still the preferred technique in forensic investigations. Table 1 lists a summary of the casting techniques explored in previous studies, including their advantages and disadvantages. The details on each technique are discussed in the following sections.

Table 1
Summary of techniques based on the level of training, time taken, output, advantages, and disadvantages

Technique	Level of training	Time taken	Output	Advantages	Disadvantages
Casting with Plaster of Paris and Dental stone (these materials are standard techniques)	• Scene: Low • Lab: Medium	• On the scene: 30 to 40 minutes, depending on the substrate's condition. • In the lab: 48 hours to dry and clean the cast before analysis	Bulky and fragile artifact	Plaster of Paris and dental stone are rigid compared to other materials	The drying process is time consuming, and the efficiency of the cast depends on the environmental condition of the crime scene. Plaster of Paris casts are often fragile. Occasionally, the cast breaks while being lifted or transported to laboratories, resulting in the waste of Plaster of Paris, time, and effort
Casting with Soap [11]	• Scene: Medium. Soap can be handled easily. • Lab: Medium	• On the scene: 5-10 minutes to melt the soap, 20-25 minutes for the cast to dry. In total, a	The study did not explain the physical features of the artifact produced	Soap is easy to handle, with shorter time of drying process. The cast is also easily removed	This technique involves the heating and melting of soap with heating appliances which may not be convenient in crime scenes

		maximum of 35 minutes.		from the impression	
Casting with Hot Melt Adhesive (HMA) [12]	• Scene: Medium • Lab: Medium	• On the scene: The melting of glue stick takes about 5 minutes and 10 minutes for the cast to dry.	More durable and less bulky artifact	The cast can be dried quickly. Plus, the cast is more durable, less fragile, and easily stored	The melting of glue sticks or HMA with heating appliances may not be convenient in crime scenes
Bio-foam [13]	• Scene: Medium. Appropriate amount of pressure is needed to avoid any damages to the impression. • Lab: Medium.	The study did not clearly state the amount of time required at the crime scene. However, it takes a shorter time than other casting materials as drying process is not necessary.	Indented Bio-foam blocks	It does not require any post-cleaning	Inappropriate pressure can destroy the impression
Structure from Motion (SfM) photogramme try [14]	• Scene: Medium. Training is needed to capture various angles of the impression. • Lab: Intensive training is required and specialists are required in the 3D model making and analytical comparison.	• On the scene: Approximately 70 seconds per target. • In the lab: Around an hour to build and analyse the 3D model.	Printable 3D model	SfM is a non-invasive method and the procedure is simple when applied in a crime scene. The output is easily stored and transferable	The accuracy of the models produced after leaving the scene may be low, mainly due to the surface's textural homogeneity or reflections from wet surfaces
3D structured light scanning [15,16]	• Scene: Intensive training is required to operate the 3D scanner. • Lab: High level of training is invested, and specialists are required in the 3D model making and analytical comparison.	• On the scene: Preparation time before scanning varies among scanner models. However, impressions can be captured in less than a minute.	Printable 3D model	This is a non-invasive method with simple procedures. The output can be easily stored and transferred	This method may not be efficient to examine impressions on reflective substrates

2.1 Conventional Technique – Casting with Plaster of Paris and Dental Stones

According to the interview snippets with the senior police officer, the evidence of shoe impressions recovered by casting technique are acceptable in Malaysian courts. However, the casting process can be tedious for crime scene technicians. The plaster powder needs to be mixed with a specific water-to-powder ratio before pouring the mixture into the impression. On top of that, different brands of plaster powder require a unique water-to-powder ratio to ensure the consistency of the casting [17,18]. The stirring of the casting materials may be affected by several parameters, including stirring speed and period as well as blade angle of the stirrer [19].

The most common materials in casting are by-products of gypsum crystal, a soft sulphate mineral of calcium dehydrate. It has two variants which are alpha hemihydrates and beta hemihydrates. Alpha hemihydrates are commonly known as gypsum cement. This variant has higher compression strength and is more substantial than beta hemihydrates. In contrast, beta hemihydrates are weaker and softer. Dental stone is alpha hemihydrate, whereas Plaster of Paris is beta hemihydrate.

Due to the differences in the materials' compression strength, Plaster of Paris typically falls behind in preference for application. Previous articles show that dental stone is more preferred by forensic experts as casting material as compared to Plaster of Paris [17,18,20]. Dental stone is easily accessible from dental supply companies. Moreover, this casting material produces casts with superior quality without the need to apply fixatives (i.e., hairspray) before casting.

The senior superintendent of Royal Malaysia Police noted that Plaster of Paris is the standard material for casting in forensic investigation. However, the cast output can be bulky, making it difficult to store the evidence. In addition, the application of Plaster of Paris is time-consuming which is not preferable for forensic investigators. The setting of the cast requires 30 minutes prior to its collection and transportation to the lab. An additional 48 hours is needed to dry the cast. A dry cast allows forensic professionals to collect trace residues from the cast and analyse the shoe impression. This drawback drives forensic professionals to seek alternative techniques for acquiring 3D shoe impressions.

In 2011 research by Cohen *et al.,* [19] different techniques of mixing dental stones powder with water were explored to improve the casting technique. The mixing of dental stone with water is performed using zip lock bags, bottles, and a bucket. The use of zip lock bags is convenient for forensic investigators with lesser time for cleaning after the mixing process. Mixing in a zip lock bag is the preferred route due to its convenience and the lack of need to clean up afterwards.

Cohen *et al.,* [19] tested different techniques to mix the dental stone powder with water to improve the casting method. The authors simulated experimental shoe impression using three methods that integrated the dental stone powder with water, using a bottle, a bucket, and a zip lock bag. The most common method used is mixing the powder using zip lock bags due to its convenience. However, vigorous mixing of the powder and water in a bottle gave the fastest result for a uniform mix in 40 seconds.

In addition, no post-cleaning was required, unlike mixing the powder in a bucket. Despite the presence of minute air bubbles on the cast, the method of mixing the powder and water in a bottle produced better results compared to the other techniques. The convenience and reliability of mixing in a bottle are on par with mixing in a zip lock bag.

2.2 Casting with Other Materials

Retrieving 3D shoe impressions with Plaster of Paris and dental stones can be time-consuming and tedious. Hence, alternative casting materials have been explored by several researchers. Malviya *et al.,* [11] studied the application of soap as casting material to retrieve 3D shoe impressions on wet mud. Besides its simplicity, it was discovered that soap powder could conform to any shoe shape or design which provides greater details than other material. Although the statistics of the findings demonstrate good casting outcomes, it is difficult to assert that using the term 'better' to highlight its fantastic results compared to other materials because the only casting material used in the study was soap.

Standard materials, such as plaster of Paris and dental stone, should be included in the study to support the claim that soap provides better shoe impressions than other materials. Casting with soap powder requires around 20 to 25 minutes to solidify and evaluate the details of the impression, which is significantly faster than Plaster of Paris or dental stone. However, the disadvantage of utilising soap as a casting material is that the soap powder needs to be melted with a Bunsen burner before pouring it over the shoe impression.

A 2021 study by Shrivastava *et al.,* [12] describes a technique to cast experimental shoe impressions with hot melt adhesive (HMA) on wet mud, slightly dry mud, sand, and soil on construction sites. It was revealed that the material is durable, fast setting time (within 10 minutes) and it takes up lesser space than Plaster of Paris. The shoe impressions produced using HMA showed outstanding results on various surfaces. In addition, HMA cast is easier to store and transport as compared to Plaster of Paris and dental stone.

Like soap, this material requires melting by exposure to heat, which can be a limiting factor for its application. The melting procedure would be challenging given the complexities of crime scenes, locations, and circumstances in forensic investigations. As a result, traditional materials that do not require melting are more favourable in certain situations compared to alternative materials (i.e., soap and HMA). Nonetheless, such alternative materials should be considered for future cases when required.

A study by Petraco *et al.,* [13] explored shoe impressions casting on snow with commercially available bio-foam blocks. The authors recommended connecting the cardboard to one side of the league and placing the other side on the impression. Manual pressure should then be applied as usual. A suitable pressure is necessary to avoid disruptions of the impression.

Too little pressure can cause difficulty for the bio-foam to cast the impression, meanwhile excessive pressure can destroy the impression. The testing was performed by casting multiple shoe impressions and grading the casts qualitatively. The article presented the results visually in a summary format. The cast helps to identify class and random characteristics. Furthermore, this technique can cast shoe impressions on other surfaces, such as sand, dry dirt, or mud. It is recommended that additional research on different surfaces to be performed using this casting technique.

2.3 Structure from Motion (SfM) Photogrammetry

The forensics community is leaning towards non-invasive methods to prevent damage to shoe impressions. Various alternatives to retrieve shoe impressions have been proposed, including the Structure from Motion (SfM) photogrammetry technique [21]. The technique of photogrammetry is viable using metric or non-metric cameras [22]. Metric camera is typically used for mapping purposes, whereas non-metric camera may be video and digital cameras [22].

SfM method involves the photography of the impressions in top view, from various oblique angles as well as several divided segment from top view. The key to photographing the impressions using the SfM technique is to ensure that the captured images overlap with one another. An essential criterion with this technique is the need to capture at least 20 images that can be digitally repurposed into a 3D format. Acquiring 3D shoe impressions with SfM requires less time than physical casting. While a digital SLR camera is desirable, a smartphone camera is sufficient for technical development [14].

Nonetheless, according to the senior superintendent, utilising a personal smartphone camera in a crime scene investigation can lead to a legal dispute. The attorneys may question the chain of custody on the shoe impression photographs, as obligated by the Evidence Act of 1950. The act stipulates that the camera in question must not be tampered with for other reasons; hence no personal camera or smartphone can be used in a formal investigation. The application of smartphones is only allowed when the device is listed as a property of the police force.

Although a short period of time is needed by investigators to capture the images of the shoe impressions at the crime scene for SfM, they require more time to render the 3D impressions in the lab using the 'DigTrace' software [23]. The software imports all the overlapping photos from various oblique angles to create 3D point cloud models with x, y, and z coordinates for each point cloud. Furthermore, the software records precise RGB values in each separate point cloud, allowing 3D models to reveal colour depth points which facilitate analysis of the impressions. The SfM technique has proven to provide consistent and reproducible outcomes [21].

In indoor crime scenes, shoe impressions can be found on discarded or spilt food items, paper towels, body parts, or any surface (e.g., carpets, floors, tables, etc.). In a 2021 study by Larsen *et al.,* [24] experimental shoe impressions on a carpet were recovered with SfM. The shoe imprints in the study were created from a pressure equivalent to the weight of two adults and the carpet's ability to keep 3D information in an impression rather than transmitting any trace evidence.

It was proved that SfM photogrammetry can recover latent 3D traces in a standard polypropylene-based carpet, providing an alternative or supplementary technique to more common recovery techniques such as 2D photography. This finding proved that SfM could retrieve shoe impressions at indoor and outdoor crime scenes.

However, SfM requires intensive training for IT skills of rendering and comparing 3D models. The 3D models enable easy storing, dissemination, and quantitative analysis of impressions [8]. Therefore, further studies are required before SfM can be accepted as a common practice to retrieve shoe impressions.

2.4 Structured Light Scanning

Nowadays, the forensics community prefer straightforward and modernised techniques to recover evidence. Driven by Industry Revolution 4.0, the path forward is to adopt digitalised systems to retrieve and store forensic evidence. Another contemporary technique for capturing 3D shoe impressions involves the use of 3D structured light scanning, which is commonly adopted in other research areas, such as architecture and anthropology [25-27]. This method produces 3D models which can be printed using 3D printers [28]. This scanning technique. 3D scanning gives greater impression details to capture minute trace evidence while minimising perspective distortion effects that are common with standard photographic techniques [29].

The 3D scanner emits a laser beam onto the 3D impression. Light deformation occurs due to ridges and depth differences in the impression. The camera of the 3D scanner then extracts the 3D surface form based on the distortion of the structured-light pattern induced by the scanned object's non-planar surface [30]. As the 3D scanners beam a laser light onto the impression, it captures coordinate data to determine the distances to the mark according to the differences between the emitted and return signal as well as the time of the round-trip of light [31].

Numerous researchers have applied 3D structured light scanning to retrieve shoe impressions. Montgomerie *et al.,* [15] used Artec Spider Structured-Light Scanning (SLS) device, an operational scanner that an Australian forensic agency favours. The study aimed to validate the adoption of 3D structured light scanning to retrieve shoe impressions. The pictures of the scanned shoe impression were imported into the Artec Studio 12 Professional (v. 12.1.5.1) program, which in turn generated a 3D model from a large number of frames from the 3D scans. The study established the precision and reproducibility of scanning as a suitable acquisition technique for class characteristics.

Moreover, Thompson and Norris [16] used 3D light structured scanning with PicoScan as the 3D scanner as shown in Figure 1. The study focused on the capacity of structured light scanning to recover footwear impressions from various substrates. The authors evaluated whether the 3D scans of the shoe impressions and outsoles can be compared with commonly accessible computer software. It was discovered that the process of scanning the impressions and post-processing tasks require 90 minutes, which is faster than casting technique.

However, the technique is not reliable for comparison. Therefore, future research is recommended to develop a higher precision technique for comparing scanned footwear to footwear impressions. Additionally, the study indicated that alternative light, such as blue light, may be employed as a laser instead of white light. Blue light has a smaller bandwidth and is more resistant to environmental variables.

Fig. 1. Scanned photos of shoe impressions on sand and soil with PicoScan

3. Conclusions

The techniques in this review are not intended to replace current practices to recover shoe impressions. However, these techniques can be considered as alternative techniques. Modern techniques, such as SfM and 3D structured light scanning, demand intensive training of the investigators. Continuous research and simulations of retrieving shoe impressions should be prioritised to improve the practicality of the reviewed alternative techniques. Furthermore, optimising the techniques to retrieve shoe impressions is essential to duplicate the success rate of experimental shoe impressions in actual crime scene cases.

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