Validation study of three-dimensional scanning of footwear impressions

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Abstract

Three-dimensional impressions are typically photographed and cast for further comparison when reference items become available to investigators. Three-dimensional scanning has been proposed as a more time-efficient and objective, less destructive method for footwear impression analysis. This project sought to acquire repeat scans of outsole footwear impressions and corresponding shoes at high resolutions to investigate the precision and accuracy of 3D scanning on both footwear and impressions.

Impressions were created using three footwear types representative of footwear encountered in casework. Scans of each impression were created using the Artec Spider structured-light scanner. Calculations of the statistical variability between scans were carried out using the CloudCompare software package.

The distance between corresponding points within the impression tested for precision (n=6) averaged 0.45mm, with σ 0.29mm. When comparing the impression to the reference shoe, the distance between corresponding points averaged 2.41mm, with σ 1.98mm. The maximal differences within the scans were at the toe of the shoe and may be due to flexion, as well as damage to the soil around the edges of the impression. This research has validated the hardware and software used to acquire data from a 3D impression and from the reference item that produced the trace.

Introduction

Three-dimensional (3D) impressions are typically photographed and/or cast for further comparison when reference items become available to investigators[1]. When a reference item becomes available, investigators create inked impressions of the reference item, allowing for a two-dimensional (2D) representation of the 3D item[2]. An inked impression is created of the reference item and photographed by investigators to allow for a 2D comparison between trace and reference impression photographs[2].

Casting of 3D impressions often requires a significant amount of time and effort and has been shown to result in diminished evidential value of the impression or other traces due to the destructive nature of the process and presence of other artefacts within the impressions[3]. The evidential value may also be lost due to a number of environmental conditions, such as the moisture content of the impression, weather conditions, incorrect collection techniques, non-validated casting products, and the substrate in which the impression was formed.[4] Due to the destructive nature of casting, if the process is not performed correctly, the evidence may be rendered unusable.[5]

Photogrammetry, a method to measure and interpret the shapes and locations of an object from numerous 2D photographs or 3D scans, is also used in the analysis of footwear.[6] 2D photogrammetry can be performed using a single image, two images (known as stereo-photogrammetry) or multiple images where the object is photographed from various angles and 3D models can be generated from the images using specialised software.[6]

Beyond the lack of standardisation within interpretation, impression analysis is also subject to misinformation caused by varying distortions present in the imaging process itself, such as perspective and noise effects[7]. 3D scanning has been proposed as a more informative and accurate technique to capture trace evidence and other information while eliminating perspective distortion effects caused by traditional photography techniques[8]. 3D scanners capture information from a scene in the form of spatial points with Cartesian (x, y and z) coordinates, as well as images of the scene or object[9]. Laser 3D scanners acquire coordinate information as the 3D scanner emits a laser beam to calculate the physical distance to the scanned object based on either the difference between the emitted and return signal or based on the time of the round-trip of light[9]. Structured-light scanners, as used in the current research, emit a structured-light pattern onto the scanned object. The 3D scanner's camera then extracts the 3D surface shape based on the distortion of the structured-light pattern caused by non-planar surface of the scanned object.[10]

3D scanning has been proposed as a more time-efficient, objective, and non-destructive method for outsole footwear impression analysis.[3] Scanning allows for the production of a 3D replica of the outsole impression without physically affecting or contaminating the trace,[5] and creates a highly detailed model of the impression which can be stored and shared across databases and operational units for investigative and intelligence purposes with ease.[3]

The use of 3D scanners in the examination and documentation of outsole footwear impressions has been shown to produce higher accuracy results than conventional methods in snow substrates[11]. Although Buck et al.[11] were able to demonstrate that 3D scanning produced accurate results, the authors failed to report levels of intra-variability within the repeated scans. The authors also outline an experiment conducted on outsole impressions created in soil, and state that the method is suitable for impressions in soil, sand or other materials, however, do not report or discuss any results relating to the soil experiment, suggesting that this experiment may not have validated 3D scanning of these substrates. It is of note that the impressions in snow were treated with Snow Print Wax® to coat and preserve the impression prior to scanning[11] which may have affected both the impression and subsequent scan accuracy. It is also important to highlight that conflicting results were observed by Gamage et al. [12] who were unable to achieve accurate scans in a snow substrate due to scanner difficulties in detecting the laser beam because of the reflective nature of the substrate.

Thompson and Norris[13] determined that 3D scans of outsole footwear impressions in soil and sand offered a more time-effective evidence collection method and greater flexibility than traditional casting methods. However, Thompson and Norris[13] provided comparisons of scans of impressions and the outer soles of shoes by segmenting the scans which does not allow for a one-to-one comparison of the items. It is also unclear from the article as to whether the authors conducted repeated scans of the impression or assessed the level of variability within the scans. The current research sought to acquire repeated 3D scans of outsole footwear impressions and corresponding shoes at high resolutions to demonstrate the precision and accuracy of 3D scanning on footwear and impressions. Comparisons between outsole impressions and known footwear items were also examined. The current research additionally assessed the reliability of, and amount of detail acquired using each method, through quantifying the level of intra-variability within the scans as well as conducting one-to-one comparisons of scans of impressions with known reference footwear to quantify the absolute differences.

The object of the current research was to test the performance of a portable and high-resolution scanner on a typical casework impression and substrate, as well as the reference footwear. The research also aimed to test the performance of the specified 3D scanner as compared with traditional casting, and the ability of the nominated software to handle the data, calculate the precision and repeatability of the 3D scans of impressions and footwear, and to calculate the accuracy of comparisons between impressions and footwear.

Materials and Method

Outsole impressions in a soil substrate were created using three different footwear types; Nike Air Zoom Structure 21 running shoes, Converse Chuck Taylor All Star shoes, and Magnum Stealth Force 8 police boots, as they are representative of footwear typically encountered in casework. The shoes were new and clean, to ensure no additional uncontrolled variables were included in the analysis. Outsole impressions were created using the right shoe of each footwear impression within 390 mm x 290 mm trays containing 4kg of clay/loam soil. The impressions were created by wearing the shoe and walking on the soil. Images of each outsole impression were captured using a Canon EOS 700D digital SLR camera using a 50mm lens, f18 aperture and shutter speed of 1/200s. Images were captured using an external flash held at varying angles to enhance shadowing and contrast of the impression.

Following photography, 3D scans of each impression were created using the Artec Spider Structured-Light Scanning (SLS) device (see *Figure 1*). The Artec Spider was selected because it was the operational scanner used by the local forensic agency. The scanner was calibrated prior to conducting experiments using the Artec Spider calibration board and the calibration tool within the Artec Studio software. Scans were conducted at eight frames per second and at low sensitivity to minimise background noise interference within the scans. Three scans were created for each of the Converse and Magnum impressions, and six scans of the Nike impression. Repeat scans were conducted on all outsole footwear impressions to assess the reliability of the comparison, whilst additional scans were performed on the Nike impression to allow for the calculation of any variability present within the scanner itself. Three scans were also acquired of each shoe. Impressions were then cast using Pink Diestone dental stone using 24 – 26 mL of water per 100g of powder. An example of the 3D representation and a photograph of the associated footwear can be found in *Figure 2*.

The 3D scans acquired using the Artec Spider were processed using Artec Studio 12 Professional (v. 12.1.5.1) software to create a 3D model from a high number of frames within the 3D scans. The scans were edited to remove unnecessary data (outside the shoe/impression) using the eraser tool and any misalignment was corrected using the global registration tool. Outliers within the data were also removed to exclude artefacts that were present within the scans. Outliers were defined as data points where the corresponding point on the comparison scan was distant by more than four standard deviations greater than the absolute average distance between scans. Finally, scans were processed using the sharp fusion tool to merge all scans together into a single model. The rendered resolution of the scans was 0.15 mm, compared to the scanner's maximum possible resolution of 0.1 mm.

The level of intra-variability present in repeated scans was calculated on the six repeated scans of the Nike footwear impression using the program CloudCompare (v. 2.10.2). CloudCompare currently only allows accurate alignment and comparisons between two meshes or cloud points at a time. As there were six scans of the Nike footwear impressions, 15 pairwise alignments and comparisons were performed. The meshes previously exported from the Artec Studio were imported into the CloudCompare software. The intra-variability present within 3D scans was assessed primarily using six repeated scans of the Nike footwear impressions to determine the error rate of 3D scanning and this was repeated on the Converse and Magnum footwear to confirm results.

Unedited scans of the impression and footwear were approximately aligned using the "Match Bounding-Box Centres" tool; this selects a point cloud as the reference entity and translates the centre of the other entity to register the two point clouds along the same x, y and z planes and approximately align the centres of the point clouds[14]. Ahmad Fuad et al.'s[15] evaluation of the performance of variance point cloud registration methods on mobile laser scanning data provides a validation of the "Match Bounding-Box Centres" algorithm within the CloudCompare software.

Following the use of the "Match Bounding-Box Centres" tool, scans were more accurately aligned in pairs using the "Iterative Closest Point" (ICP) tool, an algorithm which aligns the closest point in a source cloud point or mesh with a reference point and produces a root mean square (RMS) error value. As ICP is an iterative process, the ICP RMS error limit was set to the default of 1.0 e^{-5}, stopping the process when the resultant error fell below this threshold. Meshes were aligned individually without compiling the alignment process.

The ICP algorithm is used to align two point clouds and to minimise the squared errors between the clouds in the form of Euclidean distances; these are the distances between two corresponding points on point clouds or meshes[16]. The tool first identifies points within the first cloud and its nearest counterpart within the corresponding cloud. The algorithm then performs a number of iterations using this algorithm until the root mean squared (RMS) distance between the point clouds is below the predetermined threshold[17].

The random sampling limit was set to the default of 50,000 points for RMS distances, which is calculated by taking the square root of the average value of the squared distances[18]:

$$RMSError = \sqrt{\sum} \frac{(Distance)^2}{n}$$

The underlying mathematical computations have been validated within a paper by Ezra, Sharir and Efrat[17] which provides mathematical equations and proofs of the ICP algorithm. The algorithms within ICP have also been utilised successfully within a number of studies, including 3D reconstruction of scenes using real-time cameras[19], and georeferencing and spatial analysis using unmanned aerial systems.[20]

After alignment, the meshes were compared using the “Cloud/Mesh Distance” tool which produces an output in the form of signed or absolute distances between the meshes, and standard deviations. The output of signed distances is presented as an average, however CloudCompare also has the ability to produce a scalar field which shows a colour map of the signed distances.

Cloud-to-Mesh distances provide absolute numerical and colour scalar fields to demonstrate the distances between two meshes, or a mesh and a point cloud[21]. Distance units are displayed corresponding to the true scale of the scanned object. The cloud-to-mesh distance algorithm has also been validated by numerous users and research papers, including Nespeca and De

Luca[22] in a survey of heritage buildings. The underlying mathematical formulation for the algorithm is based on the Hausdorff distance, a distance between 3D meshes, a measurement validated by Aspert, Santa-Cruz and Ebrahimi.[23] The mathematical proof for the algorithm has also been outlined in Eberly[24].

Comparisons of the scanned outsole impressions and the scanned exterior of the shoes were also conducted using CloudCompare software to assess the level of variability present within the 3D scanning process and subsequent analysis of footwear items and impressions.

The meshes of the impression and shoe were loaded into CloudCompare and initially rotated manually using the “Translate/Rotate” tool to ensure that the scans were roughly aligned.

Scans of the footwear impressions also contained data points from the soil surrounding the impression, potentially incorrectly increasing the distances between point clouds due to invalid data points. The “Segment” tool was used to trim extraneous data points from outside the impression by manually creating a polygon shape around the impression and retaining points within the polygon[25].

Similar to intra-variability, the comparison of impressions to reference shoes was carried out using the “Match Bounding-Box Centres” tool. Meshes were then aligned using the “Iterative Closest Point” (ICP) tool with the root mean square (RMS) error limit set to the default of 1.0^{e-5}. After alignment, the meshes were compared using the “Cloud/Mesh Distance” tool displaying results as a mean difference, a standard deviation, and a scalar field across the impression. The alignment and comparison processes were conducted pairwise with every reference and impression scan pair within the data set for each footwear type.

Output values for alignments and comparisons were then entered into a Microsoft Excel spreadsheet to calculate average distances and standard deviations across footwear types.

Results and Discussion

Results from acquisition identified that the Artec Spider SLS scanner produced data that yielded an average standard deviation of 0.171 mm across all intra-variability Cloud/Mesh Distances, i.e. comparisons between repeat scans of each footwear and impression type. The standard deviation observed demonstrated that the variability across the entire scanned dataset was higher than the specified resolution and accuracy of the Artec Spider SLS which has a stated 3D point accuracy of up to 0.051 mm and 3D resolution of up to 0.102 mm[26], but was comparable to the acquisition resolution for these experiments (0.15mm). Higher average rates of variability were observed within the repeat scans of the footwear impressions than of the footwear themselves (see *Table 1*), however, this may be due to variability from over-scanning the edges of the impression, with larger variability present in the height of surrounding soil rather than the impression itself (see *Figure 3*).

The intra-variability present within 3D scans was assessed primarily using six repeated scans of the Nike footwear impressions to determine the error rate of 3D scanning and repeated on the Converse and Magnum footwear to confirm results.

Root mean square error (RMS) outputs from CloudCompare (see *Table 2*) for the Nike footwear impressions ranged between 0.285 mm and 1.815 mm, with an average RMS of 0.994 mm. To confirm results, comparisons were also run on the Converse and Magnum footwear impressions. The Converse footwear impressions returned an RMS range of 1.056 mm to 2.085 mm, with an average RMS of 1.488 mm. For Magnum footwear impressions, the RMS range was 0.460 mm to 1.381 mm with an average RMS of 0.989 mm.

Intra-variability statistics were also calculated between the scans of each reference shoe in three pair-wise comparisons per footwear type. Root mean square error rates for comparison of the footwear scans themselves were comparable to but lower than that of the impressions.

Absolute distances between meshes were also calculated and presented as an average, a standard deviation and a coloured scalar field for each comparison.

The absolute distances between the meshes of the Nike footwear impressions ranged from 0.098 mm to 1.076 mm, with an average standard deviation across all fifteen comparisons of 0.285 mm (see *Table 4*). The average distance across all fifteen comparisons was 0.453 mm. To further confirm results, absolute distance comparisons were also run on the Converse and Magnum footwear impressions (see *Table 5*). For the three Converse footwear impression comparisons, the minimum absolute distance was 0.543 mm, and the maximum distance was 1.117 mm, with an average standard deviation of 0.290 mm. The average distance across comparisons was 0.806 mm. For the three Magnum footwear impression comparisons, the minimum absolute distance was 0.140 mm, and the maximum distance was 0.662 mm, with an average standard deviation of 0.276 mm. The average distance across comparisons was 0.453 mm.

Root mean square error rates (RMS) were calculated for pairwise comparisons within each footwear type using the "Iterative Closest Point" tool in CloudCompare.

RMS outputs from CloudCompare for the Nike footwear and impression scans ranged between 3.745 mm and 4.764 mm, with an average RMS of 4.262 mm. The Converse footwear impressions returned an RMS range of 3.679 mm to 4.739 mm, with an average RMS of 4.432 mm. For Magnum footwear impressions, the RMS range was 3.824 mm to 4.172 mm with an average RMS of 4.013 mm. A comparison of minimum, maximum and average RMS rates is provided in *Table 6.*

Absolute distances between meshes were also calculated and presented as an average, a standard deviation and a coloured scalar field, however scans of footwear impressions contained a large number of data points from the soil surrounding the impression. To prevent irrelevant data points impacting results, scans of the impressions in soil were segmented to remove external data points and allow for direct comparisons of the footwear impression to the footwear.

The absolute distances between the meshes of the scans of the Nike footwear and impressions ranged from 2.295 mm to 2.528 mm, with an average standard deviation across all fourteen comparisons of 1.984 mm. The average distance across all fourteen comparisons was 2.416 mm. For the nine Converse footwear comparisons, the minimum absolute distance was 3.153 mm, and the maximum distance was 4.031 mm, with an average standard deviation of 2.575 mm. The average distance across comparisons was 3.787 mm. For the nine Magnum footwear comparisons, the minimum absolute distance was 3.118 mm, and the maximum distance was 3.372 mm, with an average standard deviation of 2.441 mm. The average distance across comparisons was 3.278 mm. A comparison of minimum, maximum and average distances are provided in *Table 7.*

For practical application, it is recommended that the user scan beyond the edge of the tread pattern for both the impression and reference footwear item to allow for total capture and accurate removal of extraneous data points using appropriate software. A minimum of three repeated scans of both the impression and reference shoe are also recommended within casework to allow for accurate analysis.

By performing pairwise comparisons, systematic variations within the comparisons were also noted (see *Figure 4*). Consistent areas of high concordance, where observed distances between the footwear impression and the footwear item were close to or approximately zero (< 0.5 mm), were noted across all footwear types within the tread pattern present between the ball of the feet and the heel, where an individual creating an impression applies more pressure to a surface.[27, 28].

Larger distances (approximately 4.0 to 5.0 mm) between the footwear and impression were observed towards the centre of the shoe and towards the outer ends of the soles, where less pressure is applied during the creation of an impression.[27, 28]

The range of distances across the footwear is also consistent with the flexibility of footwear, as can be observed within Figure 4. Areas of smaller distances were present in regions of the footwear that typically do not allow for a large amount of flexion[29;30] and are concentrated within the soles of the shoe. The areas containing larger distances were consistent with the regions of the footwear that typically flex more, such as the midsole, the toe flexion area and the heel.[29;30]

Consistently, the area of maximum distance in the comparison was present at the toe of the shoe, indicating that this method of comparison may not be valid on the front of the sole of the shoe. The large differences within the scans at the toe of the shoe may be due to flexion, as well as damage to the soil around the edges of the impression. While these results were obtained in medium clay-content loam, it might be expected that a sandy soil would produce inferior results for the comparison process, as with other footwear comparison techniques.

When conducting a comparison between a scene trace and a reference item using a 3D scanner, agencies should take note of these results and anticipate that flexion or movement of the soil may increase the absolute distance between the scans, while still representing an explainable difference between items and without excluding common-source.

Conclusions

Three-dimensional scanning offers a non-destructive method to acquire class-level 3D features and make comparisons between an impression and the reference item using the software. Multiple scans of an impression may be acquired to produce statistically-valid results in the comparison of class features. This research demonstrated the successful acquisition of 3D scans within a realistic substrate on a known footwear item and known impression with no pre-processing of the scene.

3D scanning offers a non-destructive method to acquire a permanent representation of the footwear impression, which can later be cast after scanning as part of a sequence of techniques. The precision and repeatability of scanning as a valid acquisition technique for class characteristics has been demonstrated by the current research. The software utilised within the research was successful in providing quantitative measures of precision and accuracy, despite the limitations of allowing only one-to-one comparisons.

3D scanning offers a technique which is able to be extended to other substrates and impression evidence types such as toolmarks, however, does have some practical limitations such as the minimum resolution which may not be appropriate for capturing small class features or individualising features. SLS scanners are not appropriate for use in direct sunlight, however this limitation is easily overcome by shading with the use of umbrellas or marquees.

Recommendations for 3D scanning of footwear impressions include using scanning of traces as part of a sequence within crime scene operations. Due to its non-destructive nature, trace-level scanning is able to be carried out immediately after photography or scanning of a crime scene, if applicable.

This technique has been validated for acquisition and comparison of class characteristics, however, is not yet validated for use in comparison of individual characteristics. Future work may focus on the extension of current research to assess scanner performance for use on a wide range of substrates, to assess the practical limitations of its use at the scene, and to vailidate for individual characteristics. Whilst this study examined the performance of the Artec Spider, a popular high-resolution scanner that is commonly deployed for this purpose, other hardware solutions exist that operate differently and can attain different levels of detail under various conditions. The deployment of alternative scanners for the capture of greater resolutions, potentially capturing identifying characteristics, should be investigated.

Practical limitations for use should not exist within the scanning of reference items due to the controlled environment within a laboratory. Future work may also provide further validation and optimisation of the software for processing to allow for one-to-one comparisons of complete datasets to minimise over-processing of data.

The highest resolution at which features can be acquired and compared has not yet been validated and future work may focus on this area, as well as the validation of individual features within the defined resolution to provide quantitative errors for this technique when applied to individual features, and to determine whether the technique meets the requirements outlined in recent reports critical of impression evidence.[31, 32]

A potential method to counteract any distortion in comparison results would be to apply an adjusted, weighted approach using Thompson and Norris'[13] segmentation method, placing more emphasis on areas of minimal flexion within the shoe and reducing emphasis on areas of increased flexion to counter any systematic variation due to flexion of the shoe during creation of the outsole impression.

Another line of study would be a blind study assessing the rate of genuine positive comparisons, and other near matches, including between known footwear and impressions of the same brand and model of footwear but of different sizes or containing different damage patterns to ascertain the complete validity of 3D scanning as an alternative to existing footwear analysis techniques.

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