Recovery via SfM photogrammetry of latent footprint impressions in carpet

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ABSTRACT

Impression evidence retained in carpet is usually recovered, if at all, in two dimensions via a vertical photograph. Here we show that recovery is also possible via SfM photogrammetry and this gives good quality results that allow digital measurements both in the x-y plane and by depth (z axis). This study focuses on recovery from polypropylene carpets which are widespread due to their resistance to wear and low cost. We show how traces can be recovered using both SfM photogrammetry and conventional photography with illumination provided via a crime scene light source. Experiments show that traces are retained for considerable time periods if left undisturbed, in excess of four weeks, but are quickly lost in under 8 hours by subsequent footfall. A simple simulation shows how the movement of an individual can be determined from carpet traces and the value of 3D recovery is illustrated via a set of experiments conducted with barefoot traces. We draw attention to the fact that 3D models allow a more statistical-based approach to be taken to match bare footprints at crime scenes. SfM photogrammetry is shown to provide a useful compliment to existing techniques and therefore worthy of further experimentation and potentially operational use.

KEYWORDS: Photogrammetry; Carpet; Three-Dimensional; Footwear Impression; Barefoot Impression; Structure from Motion

HIGHLIGHTS

- **SfM photogrammetry is a complimentary recovery method for 3D impressions in carpet**
- **Significant details can be recovered from footwear outsole impressions left in polypropylene carpets**
- **Undisturbed polypropylene carpet impressions can remain for over a month**
- **Statistical approaches to analysis of barefoot impressions can compliment expert opinion**

Footwear outsole impressions are some of the most common types of trace evidence across a range of crime scenes types in Europe and in the USA (1,2,3). The type of evidence falls into two broad categories, either two-dimensional or three-dimensional impressions and the latter are sometimes referred to as plastic traces (3). At indoor crime scenes 2D traces form the bulk of the evidence and may be either visible or latent (4). Hong et al. (5) states that most impressions found at crime scenes are latent. Three-dimensional impressions can be found at indoor crime scenes in discarded/spilt food items, on paper towels, body parts, and as latent traces in carpet. It is the potential for 3D latent carpet traces which form the focus of this technical note.

Footwear outsole impressions, and bare footprints, are common at crime scenes especially those where bodily fluids have been tracked around a location by either a victim or assailant (6,7,8,9). Discussion of 3D versions of these traces, in materials such as carpets, is currently limited to that by the footwear expert William Bodziak in his seminal book (6). He categorises all outsole impressions by their level of permanency and goes on to state that depressed carpet may remain visible, but is “usually of little value beyond indicating some general size, shape and design features of the suspects footwear and the areas where the suspect(s) walked.” He states that photography is the only way to recover this type of impression but does also discuss the use of electrostatic lifting for a 2D context. The use of ultraviolet crime lights or oblique lighting may help reveal such traces and aid photography. With increasing availability of Structure from Motion (SfM) photogrammetry (10,11) 3D recovery of these latent carpet traces is now possible and our aim here is to illustrate this potential. The work was stimulated by the serendipitous observation of 3D marks in a carpet and their effective recovery via SfM photogrammetry. Limited comparisons between recovery methods have been undertaken within this study, but it should be noted that this is initial research into the potential of SfM photogrammetry and not a complete comparative study with traditional 2D photography. Our aim is not therefore to compare methods of recovery but simply to show what is possible via an approach based on SfM photogrammetry as a compliment to existing methods.

Method

The prints analysed in this study involve no transfer of materials to the surface and are simply formed by the weight of the subject and the ability of the carpet to hold 3D data in an impression. The main carpet used in this study was purchased in 2017 from Carpet Right, product code A32603950501. The material is 100% polypropylene with a pile height of 15 mm, a total height of 17.5 mm and a tog rating of 1.80. In addition, carpet samples (Tapi Carpets Ref: 192895 %100 Polypropylene Twist Fibre) were used in repeat experiments. A range of ad hoc experiments were conducted using a range of footwear (Fig. 1A).

The first of these investigated the longevity of footwear outsole impressions in areas of low traffic and without vacuuming. A print was made with a UK male size 11 Adidas^{TM} walking shoe by a male volunteer weighing 76 kg. The print was made in an area that receives heavy footfall but once made the print was protected from further traffic via an upturned plastic crate. Using photogrammetry, a standard protocol (11) and the OpenMVG SfM engine embedded within freeware DigTrace (www.digtrace.co.uk; 10) a 3D model was built every hour for the first 12 hours after the impression was made. The impression was recovered every 12 hours for the next 72 hours, moving to every 24 hours until the print was 14 days old. The print was then recovered twice more at three and four weeks before the study was concluded. This study was repeated without protecting the impression after it was formed thereby allowing subsequent footfall from two adults and two cats to modify the impression. This part of the floor was not however vacuumed.

In order to examine how easy, it was to track an individual around an area a set of footprints were made as above following a random route around a living room (UK male size 11 Adidas^{TM} walking shoe, volunteer weighing 76 kg). The volunteer walked into a room, staged an altercation in one particular area of the room and left via the same entry point. A crime light (Foster and Freeman Crime-Lite® 82L) was used to identify the location of each print, photographed from above using a tripod and Sony A7 camera and also recovered via SfM photogrammetry. High-level photographs were also taken from above to provide a method of mapping. Where prints were overlapping, SfM models were built of larger areas containing multiple tracks.

To examine the ability of impressions to preserve randomly acquired characteristics (RACs) a Nike^{TM} UK size 6 Female Running shoe, a brandless UK size 6 female trainer and a brandless UK size 9 men's trainer were used to create a series of impressions. The Nike^{TM} shoe had general wear visible on the outsole and in addition multiple cuts, grooves and tears made artificially in the surface to simulate RACs. The brandless female shoe was purchased for this experiment and had features cut into the outsole to represent individualising features. The brandless men's shoe was heavily worn and the individualising features were all natural and as a result of heavy wear. The impressions were made in a medium worn area of carpet under normal weight bearing and made dynamically (i.e., walking traces). The traces were recovered using SfM photogrammetry and also photographed from above while illuminated with a crime light.

Because of the potential for barefoot (or sock-covered feet) to leave impressions a female volunteer (60.3 kg) made a series of dynamic traces in three areas of the carpet all corresponding to different levels of footfall/traffic, namely: [1] an area receiving little or no footfall labelled low wear; [2] an area which historically received a modest amount of wear (medium wear); and [3] in an area of maximum and persistent traffic (high wear). The volunteer also left a dynamic trace in a sheet of modelling compound to create a test impression (Bubber^{TM}, 12). A further nine dynamic traces were made in an area of low wear. All traces were recovered using both SfM photogrammetry and 2D photography illuminated via a crime light. Using the Reel method, basic dimensions of all the barefoot impressions including the test impression were taken digitally within DigTrace (13,14,15,16,17).

All overhead images were taken with a Sony A7 camera mounted on a tripod to provide as close to crime scene quality as possible. All SfM models were based on between 25 and 30 individual photographs which were taken with a Sony A7 or an iPhone XS Max and found previously to give undistinguishable results (11). The process of photographing an impression for SfM involves each of the 25-30 photos, all of which need to be appropriately focussed and sharp, being taken at different heights and oblique angles. They need to have an element of overlap and fully encompass the impression and surrounding area. This process takes in the region of 70 seconds and does not require the use of a tripod. An advantage of which is that no equipment needs to come into contact with the carpet which may disrupt other impressions. These photos are then uploaded to the freeware/software of choice and 3D models are subsequently built.

In this study, freeware DigTrace was used and once the 3D models had been built within DigTrace, they were scaled and auto-rectified so that the principal plane was parallel to the original surface and orthogonal to the viewer. Comparison of SfM models was made in CloudCompare (www.danielgm.net/cc) using Hausdorff Distances and the point clouds (i.e., the models were not surfaced).

Results and Discussion

The first point to make is that SfM photogrammetry recovers the traces from the carpet well and in full 3D (Fig. 1B). In terms of the survival of an impression in a protected (i.e., no subsequent footfall) area the impression was largely unchanged after four weeks. The mean cloud to cloud distance between Model-0 made minutes after the impression was first created and the last model four weeks later is just 0.821 mm with a standard deviation of 0.67 mm. The spatial variation of this variance can be visualised via a heat map (Fig. 2) in which the uniform blue tone signifies little change and the lighter red/white tones maximum divergence. The key point is that the variance is highly localised. You can just pick out the outline of the trace and some relaxation has occurred within selected treads and around the margin. The high area of divergence outside the trace is caused by movement of uncompressed carpet fibres. In summary the likelihood of this trace surviving considerable periods of time in a protected or zero traffic area of a floor is high, and therefore recovery does not need to be made as a first priority at a crime scene if it can be left undisturbed. There is sufficient detail for make, model and size of the shoe to be determined but as with all trace evidence it is dependent on the particular circumstances at a crime scene. One could argue that it is slightly unrealistic to have a trace protected by a crate however. When repeating the experiment without the protective crate the last fragment of the trace was lost after only 8 hours 45 minutes (Fig. 1C). Without the crate the track was subjected to footfall in a high traffic area of a living room. There was no strong draught or airflow that contributed to the degradation of the trace and it can therefore be assumed that it was the act of being overtrodden that led to the loss of the track. Tracks are lost instantly if the trace is vacuumed.

In terms of comparing recovery methods both the crime light and the SfM models provide good visualising of surface impressions whether shod or unshod (Fig. 3). In all cases the class characteristics of the outsole can be determined easily allowing make, model and perhaps size to be determined. Visualisation of the tread is arguably sharper in the SfM models, but we are sure that more experienced crime scene photographers could improve the 2D image capture. The advantage of SfM lies in the ability to capture the complete trace in one model, whereas multiple photographs each with adjusted illumination are needed to capture all areas of the trace using the crime light and vertical photographs. Moreover, the SfM method allows depth to be quantified and different colour renders applied, but despite this there is little to choose between the methods and some would no doubt argue that it is simply a matter of preference and experience. Perhaps where the SfM models have a slight advantage is in the visualisation of RACs as illustrated in Fig. 4. The female sports shoe with the artificial damage (Fig. 4C) illustrates that a range of different types of RACs can be recovered from carpet impressions both by SfM and traditional photography. For example, a triangle cut from a side portion is clear in multiple images, while a small hole can also be seen in most of the recovered images. The first point here is that it is clearly possible to recover individualising features from carpet impressions by whatever method, but we would suggest that the colour-depth renders in the SfM 3D models provide slightly superior visualisation although that is no doubt a matter of opinion.

In terms of the ability to track movement around a crime scene using carpet traces this is illustrated in various ways in Fig. 5. The crime scene light allows the latent tracks to be picked up, identified, and located for recovery via SfM photogrammetry. The 3D models pick out the cross-cutting relationships between tracks allowing the order of events to be easily established and mapped. The later impression obliterates the older impression clearly. Of the impressions recovered, eight were complete enough for measurements to be taken of full length. The average maximum length measurement of the recovered traces was 319.3 ±0.491 mm. Without a series of sample shoes from a manufacturer matching the tread pattern it is not possible to produce a precise estimate of shoe size. This is further complicated by the fact that dynamic traces are known to be larger than static impressions (e.g., 14,18).

The final observation here is that barefoot impressions are easily recovered from this type of carpet as illustrated by the SfM models in Fig. 6. The barefoot prints can be recovered via photography in conjunction with oblique lighting (Fig. 3C), but the uniformity of the lighting in the SfM models aids precise definition of the foot outline and therefore measurement. We can test the reliability of these measurements by comparing dimensions from individual tracks with a test impression (Fig. 6D) and those taken using an inkless printing pad for the same volunteer (Table 1). The average standard error for the test impression is ±0.32 mm, one model measured ten times by five measured dimensions (E1). The inkless print gives a value of ±0.62 mm which is based on ten prints five measurements per print (E2). SfM recovery and measurement of footprints made by the same individual is associated with much larger errors ±3.23 (E3). If you remove the SfM measurement error (i.e., E1-E3) you get an estimated error of ±2.9 mm associated with the carpet variance alone. Inter-print variability in length is commonplace due to subtle variations in biomechanics as well as the behaviour of the substrate (19), in this case the carpet. You can see the morphological diversity of the prints in Fig. 6A. The variance in linear length measurements is shown in in Fig. 7 first via cluster of landmarks subject to a Generalised Procrustes Transformation and with 95% confidence ellipses around the point and as simple violin plots.

Within vertebrate ichnology, especially human fossil footprints (e.g., 20,21,22), biometric and biomechanical inferences are increasingly made from computed mean footprints allowing a more statistical approach to hypothesis testing. This move to a more objective and statistical basis interpretation of footprints reflects the fact that experts have previously tended to identify specific traits in individual tracks without any knowledge of how frequent those traits occur within a population of tracks (i.e. in a trackway) made by an individual and without a true understanding of just how naturally variable human footprints are (20,23). We can apply this type of approach to the ten recovered carpet traces in Fig. 6A using the software DigTrace which has a function to co-register (i.e., overlay) a series of 3D footprints on the basis of matching paired landmarks (10). Once co-registered the depth or z values associated with each x-y point are used to compute a mean and associated measures of central tendency for that point. Fig. 6B shows a mean footprint for the ten recovered carpet tracks. Also shown is the standard deviation (Fig. 6C) showing that most variation between the tracks is focused on the depth of the heel impression. We can use this approach to compare the mean carpet track (Fig. 8A) with one or more test impression (Fig. 8B, C). The overlay of depth contour lines of the volunteer's test impression with the carpet mean track show good anatomical fit (Fig. 8B), however when a test impression from a second individual is compared (Fig. 8C) the anatomical fit is less clear. We can compare the second test impression with the mean carpet trace statistically by co-registering the tracks and looking at the standard deviation between them (Fig. 8D). If we threshold this at 95% then we can see those areas which are statistically different at this confident level. In this case the key differences picked out are around the length of the first and second toes and their separation. This analysis is one of the standard tools within DigTrace (10). If we repeat this for mean carpet trace with the test impression of the volunteer, we get no areas of significant difference at 95% confidence. In no way are we suggesting that the statistical approach is necessary in this case the footprints clearly match or not, but we are suggesting that this would reinforce statistically the opinion of an expert forensic podiatrist.

We have shown here that latent 3D traces in a relatively common polypropylene based carpet can be recovered by SfM photogrammetry thereby providing an alternative, or complimentary, method to more conventional recovery via 2D photography. The results suggest that given no subsequent footfall a trace may be retained over an extended period of time. In the survival test executed here class characteristics were still visible four weeks after the impression was made. Comparison of impression and tread depth between the initial and final SfM 3D models shows only minor decompression of selected tread areas. This holds for both shod and unshod impressions. However, if the impression was not protected and therefore subject to subsequent footfall the impression was quickly obliterated in a matter of a few hours, although class characteristics could still be recognised on part of the impression after eight hours. Any form of vacuuming causes the impression to be lost immediately.

While artificial, the simulated crime scene demonstrates how latent 3D carpet traces can be used to track the movement of individuals around a scene. In this context the advantage of an SfM model is that cross-cutting track patterns can be viewed in 3D from different angles and perspectives thereby giving confidence to their relative order. Digital measurements can also be taken allowing footwear size to be profiled, something which is also possible from conventional photographs.

In terms of recovery methods, conventional photography coupled with a good quality oblique light source produces good results as does the more innovative application of SfM photogrammetry. In either case the crime light is essential to identify the traces for recovery. The light is not needed to build the SfM model however, but without a good knowledge of the extent of each target SfM photogrammetry cannot be applied successfully. The minor disadvantage with conventional photography (+crime light) is the need for multiple images with different directions of illumination to capture all the detail. Clearly at the start of an investigation the areas of interest are unknown and therefore not available to guide this. The SfM models provides a single image, with a more uniform illumination that can be colour-rendered by depth and re-orientated multiple times to pick out different aspects. It is akin to being able to re-visit the trace and the scene throughout a subsequent investigation.

One of the more striking aspects of the experiments reported here is the potential to recognise RACs from the carpet impressions. Bodziak (6) suggests that only class characteristics are typically recovered but we suggest that by both 2D photography and SfM photogrammetry RACs can be identified increasing the evidential value of such traces. There are many identifying features on a bare footprint that can assist in the comparative process between a crime scene print and a test impression (e.g., 7,8,9,24). One of the emerging themes from the study of human fossil footprints is that one needs a relatively large sample of tracks to adequately characterise an individual in terms of basic linear foot dimensions, biomechanical depth inferences, and anatomical properties (22). This reflects subtle variation in gait, and therefore applied plantar pressure, and variations in substrate. While carpet may appear to have uniform properties, variations in dirt, grime and crucially electrostatic properties will occur all of which may impact on the morphology of an individual track and its immediate taphonomy. The ten tracks recovered from a low-wear area of the carpet demonstrate this variability as do simple linear measurements of these tracks. Intra-trackway variability is a real issue in the fossil record. No single track truly represents an individual, but a population of tracks may begin to. This is one reason why there has been a progressive move to the study of mean tracks, something which is only possible thanks to the depth dimension captured by SfM photogrammetry or optical laser scanners. We have illustrated this approach by computing a mean track from the ten recovered carpet traces. In addition, we have shown how this can allow a statistical assessment and comparison of a known print with a questioned print using the terminology of Reel et al. (13). While we are in no way suggesting that this can in any way replace the opinion of the expert podiatrist, we do suggest that it might help support their opinion. As a radiologist stated at a recent conference in conversation with one of the authors: “digital methods will not replace radiologists, but radiologists who use these methods will replace the ones who don't". We suggest that you could replace the digital with the word SfM and radiologist with forensic podiatrist.

In conducting a set of experiments like this, one must always question whether they have wider applicability. In this context, is there something special about the carpets used? Carpet materials are generally divided into two brackets, natural fibres such as wool and man-made or synthetic fibres. Synthetic fibre makes up 90% of carpets currently made (25) of which polypropylene is widespread due to its stain resistance, good colour fastness and value for money. The carpets used in these experiments all contain polypropylene and are in no way unusual. Synthetic carpets are prone to the build-up of static electricity and once compressed this may help account for the lack of rapid relaxation of the pile compared to natural fibres. For example, wool carpets reputedly recover faster from furniture compression than synthetic fibres and may hold footwear outsole impressions less well. Trade information suggests that cut pile carpets show footprints, vacuum marks, and traffic patterns, while loop pile carpets do not. Certain carpet styles may accentuate this further. For example, Saxony style carpets feature cut fibres that are all twisted in the same direction and present a similar finish to velvet, so when you brush your hand in one direction across the carpet surface, the fibres appear either lighter or darker than their neighbouring fibres. In summary we suggest that carpet outsole impressions are quite common given the widespread nature of polypropylene carpets at least in the UK, but clearly further research is required to test this and to explore retention on different makes of carpet.

Conclusion

The results of this investigation highlight the potential for polypropylene carpet at least to retain footprint impressions both those of shod and unshod individuals. Traces of this type have a potential permanency that has perhaps been under-estimated previously (Cf. 6), although it is highly dependent on the amount of subsequent footfall. We have also shown that not only class characteristics but individualising RACs can also be recovered from carpet traces. All of which suggests that carpet traces may be of greater value than is sometimes suggested.

While conventional recovery via 2D photography coupled with an oblique light source captures traces well, we argue here that the recovery of such traces in 3D using SfM photogrammetry offers an exciting and complimentary alternative. In particular, it allows a single model of a trace to be re-visited multiple times from different angles, while colour renders by depth pick out detail which may otherwise be lost. We also show how in the case of barefoot prints 3D models allow a more statistical approach to be taken to forensic podiatry complimenting expert opinion.

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	D1	D2	D3	D4	D5
Carpet SfM					
Mean	266.63	254.18	239.87	225.83	210.32
Std. Error	3.2	3.18	3.57	3.48	2.67
Stand. Dev	9.61	9.56	10.71	10.45	8.03
Bubber^{TM}					
Mean	251.11	239.86	229.89	218.94	202.97
Std. Error	0.31	0.43	0.26	0.31	0.29
Stand. Dev	0.99	1.37	0.84	1.00	0.92
Inkless Print					
Mean	248.11	233.67	224.08	213.25	198.85
Std. Error	0.65	0.40	0.54	0.68	0.80
Stand. Dev	2.05	1.28	1.73	2.16	2.55

Table 1: Foot length measurements between the heel and the five digits.

FIG. 1 - Footwear outsole traces in carpets. **A.** The outsoles used in these experiments from left to right: UK male size 11 Adidas^{TM} hiking shoe; Nike^{TM} UK size 6 Female Running shoe; un-branded UK size 6 female trainer; and un-branded UK size 9 men's trainer. **B.** Adidas^{TM} hiking shoe impression made in carpet and recovered via SfM over a period of 4 weeks, shown here with a depth-colour render. Note that the class characteristics are still visible after four weeks. The trace was protected from traffic. Also note that a linear line over the impression can be seen in weeks 3 and 4 which cannot be traced back to a particular source, the protective crate may have been inadvertently placed upon the trace at an unknown time. **C.** As above but the trace was not protected from subsequent footfall. Note the trace was lost rapidly, with the heel areas still visible after 8 hours although the main class characteristics had disappeared after just 3 hours.

FIG. 2 - Cloud to cloud comparison of SfM point clouds for the same outsole impression made in carpet. The image compares the surface at time zero with that after 4 weeks, bright white/red colours indicated maximum divergence. The analysis was completed in CloudCompare. The units are mm, and the trace is orientated so that the forefoot is at the top of the image.

FIG. 3 - Recovery of carpet traces using 2D vertical photography plus crime light (A and C) and via SfM photogrammetry with a grey depth-colour render (B and D) and blue-red colour-render (E).

FIG. 4 - Recognition of RACs within carpet traces. **A.** Nike^{TM} sport shoe with various gouges made on the outsole. The main 'crater' which is circled is visible in the SfM colour-rendered model but not in the 2D photograph. **B.** There are number of RACs on this worn unbranded male shoe the horizontal gash is visible in both the SfM model and the 2D photograph illuminated with a crime light. **C.** Various artificial RACs were made in this unbranded female sports shoe and circled for reference. The adjacent two images to the left show SfM models with different depth-colour renders. Some of the RACs are visible as circled. Some RACs are not visible in the conventional photograph but are just visible in the photograph illuminated via the crime light.

FIG. 5 - Simulated crime scene to show how carpet outsole traces can be used to track movements. **A.** Crime scene diagram of the living room and shoe prints. **B.** SfM photogrammetry output of prints 2 and

4. **C.** Wide photograph of area with markers on each identifiable print. **D.** Area of scene photographed with oblique lighting. **E.** SfM photogrammetry output of prints 7 and 8. **F.** Area of scene photographed with oblique light. **G.** SfM photogrammetry output of print 9.

FIG. 6 - SfM photogrammetry derived 3D models of barefoot prints in carpet. **A.** Ten barefoot impressions recovered from areas of low carpet wear, depth-rendered with a grey colour scheme. All these traces were made under normal walking. Note the natural variability between footprints, this would be true of any medium, not just carpet. **B.** This is a mean footprint created by co-registering all ten individual footprints to create a new model. **C.** Standard deviation around the mean footprint in part B, note the high variance in the heel area. **D.** SfM photogrammetry model of a dynamic footprint made in the modelling compound Bubber^{TM}. This effectively is the test impression. **E and F.** Barefoot print in area of medium carpet wear (E) and in heavy wear (F).

FIG. 7 - Measured landmarks placed on the SfM recovered carpet traces (N=10). **A.** Landmark positions with 95% confidence ellipse. As is normal with landmark analyses x-y point coordinates have been transformed via a Generalised Procrustes Analysis undertaken in the statistical package PAST. **B.** Violin plots and mean for the five main length measurements. Length measures are based on Reel et al., (14).

FIG. 8 - Co-registration of barefoot tracks. A. Selected contour lines (0.5 mm interval) taken from the mean carpet track (N=10, Fig. 6C). B. Co-registration of the mean carpet track with the test impression (in red, Fig. 6D). C. Co-registration of the mean carpet track with a second test impression (in red) made by a second volunteer. D. Standard deviation across the surface of the co-registered tracks, in this case mean carpet track and that of the second volunteer. Adjacent to this is a version of this plot with 95% confidence level threshold applied. Those areas picked out in blue are therefore statistically significantly different at this level.