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# Summary Report

**Project title:** Development of a portable 3D scanning system for capturing shoe and tire impressions

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## 1. Summary of the work

This project was designed to test the hypothesis that a novel noninvasive optical 3D imaging sensor can capture the critical, detailed characteristics of shoe or tire impressions in snow or soil, and on uneven surfaces, required for forensic examinations. Our research validated the hypothesis by developing portable and fully automated 3D systems to automatically measure high contrast, or low reflectivity surfaces. The hardware was designed to be portable and easy to setup; and the software graphical user interface (GUI) was designed to be intuitive and thus users do not need training for operation. Compared to the high-end commercially available 3D scanner (GOM ATOS CORE), our technology achieves a similar level of accuracy and resolution, our system has the merits of 1) being more affordable (a fraction of the cost of the commercial system), 2) being much easier to operate, and 3) being more robust. Compared to the current practice of casting, our technology demonstrates its superiority because 1) it is non-destructive, 2) it collects more evidence detail than casts especially when an impression is fragile (e.g. in dry fine sand), and 3) it saves time and costs less to collect each impression. The digital impression captured at the crime scene allows analysts in the lab to view a digital impression like they were studying the actual impression in situ. The scan also provides a 3D "digital cast" that represents the actual shoe or tire that produced the impression. Overall, the 3D digital cast provides detail equal to or better than that of a physical cast and is invaluable not only for comparison purposes but also as an investigative aid. Therefore, this technology promises to be a game changer as it allows the fast collection of 3D detail of impressions with minimal training.

## 2. Purpose of the project

The purpose of this project was to develop a novel noninvasive 3D optical imaging technology for the forensic science community that can measure challenging impression marks such as shoe or tire impressions in snow or soil. The ultimate goal of this research was to transform the current practice for shoe or tire impression capture: from invasive casting to noninvasive optical imaging. To achieve this goal, this research developed a novel and portable high-resolution optical 3D scanning system to measure shoe or tire impressions. This project addressed the "development goal" and was intended to produce a novel system and method for collecting 3D images of tire tread and footwear impressions in difficult materials – snow and soil. Compared to previous developments in this area, this system produced higher resolution images than any existing technology, removed the need for on-site calibration, was significantly more portable and affordable than alternative 3D imaging systems, was eye safe, and was faster than either casting or alternative 3D imaging technologies. This technology met the stated objective of improving "front end" evidence collection at crime scenes with a non-contact, rapid, high-resolution method for impression collection.

## 3. Project design and methods

We developed a fully automated 3D imaging system that allows the user to easily and quickly capture high-resolution shoe and tire impressions. The 3D imaging system employs the digital fringe projection (DFP) technique where a projector shines defocused binary fringe stripes onto the object. The object surface distorts the fringe images that are captured by the camera from another angle. Fringe analysis techniques are used to obtain the phase that is further used to reconstruct 3D surfaces, pixel by pixel.

The fully automated 3D imaging technique was enabled by our efficient optimal exposure time determination method that was extended to high dynamic range (HDR) capability. These algorithms were based on our findings: 1) the intensity of the image acquired by a camera is approximately linearly related to the camera exposure time when the camera is responding properly (i.e., no saturation); and 2) the offset of the response curve is a fixed value for a given camera setting (e.g., gain, lens, aperture). After pre-calibrating the camera's linear response function, these findings allow us to determine a global optimal exposure time by capturing one single image with proper exposure (e.g., no saturation). Since only a single exposure is used, our auto-exposure control algorithm is very fast. Furthermore, we can also automatically determine the optimal exposure times required to achieve HDR by analyzing the image captured with the global optical exposure time (preferably for better prediction) or the same image used for global exposure time determination.

The hardware was designed for easy setup and operation. The prototype system we have developed is portable and can be packed into a Pelican 1450 Case (interior dimension 14.62" × 10.18" × 6.00"). The system can be set up quickly with four steps for data capture: 1) plug in the power cord; 2) connect the USB cable between the device and a laptop computer; 3) toggle the power switch on; and 4) start the software for data capture.

The software graphical user interface (GUI) was designed to be easy to use. The software was designed to be intuitive such that no training is necessary to operate our prototype system. We sent the prototype system without user instructions to Mr. William Henningsen at the Omaha

Police Department and his team had no problem properly operating the system for high-quality data capture. We brought our system to IAI, IPTES, and IAFSM conferences, those attendants also found that our software is easy to use.

Two prototype systems were developed for evaluations: high resolution and low resolution. The low-resolution system achieves approximately 137 dpi with a field of view (FOV) of 14" × 8.75". The high-resolution system achieves approximately 400 dpi with an FOV of 5.12" × 3.84".

## 4. Data analysis

**System accuracy evaluation:** Our high- and low-resolution systems were compared against a commercially available high-end 3D optical measurement device (GOM ATOS CORE). The accuracy was evaluated by measuring a planar surface (the backside of a mirror) at 8 different poses. An error map for each measurement was created by taking the difference between the measured data and the ideal fitted plane. An area of 100 × 80 $mm^2$ for GOM and our high-resolution system, and 200 × 160 $mm^2$ of the low-resolution system from the central portion of the imaged area was chosen to calculate the root-mean-square (rms) error. A 5 × 5 Gaussian filter was applied to reduce the most significant random noise. These experimental data show that: 1) for the same sized area, our high-resolution system captures more data points than the GOM system despite these two systems having a similar resolution; 2) our high-resolution system achieved slightly higher measurement accuracy than the GOM system (rms error: 0.027 mm vs 0.031 mm); 3) our lower resolution system accuracy is slightly lower than the GOM system (rms error: 0.050 mm vs 0.31 mm); and 4) the GOM system discarded numerous data points, creating holes on the surface. We further evaluated the accuracy of the systems by measuring a sphere of diameter of 80 mm. Once again, our high-resolution system achieves higher measurement accuracy (rms error: 0.070 mm vs 0.117 mm) with more data points that the GOM system does, and our low-resolution system is slightly less accurate than the GOM system (rms error: 0.125 mm vs 0.117 mm).

**System resolution evaluation:** These two systems were evaluated by measuring objects with detailed features. Fig. 1 shows the results. Our observations from this test are: 1) our high-resolution system resolves all the fine details, and the GOM system can resolve most of the fine details but the 3D features are less sharp probably due to inherent filtering; 2) even though our low-resolution system does not show sharp details, it captured most of the important features; 3) GOM system discarded numerous data points, creating holes on the surface.

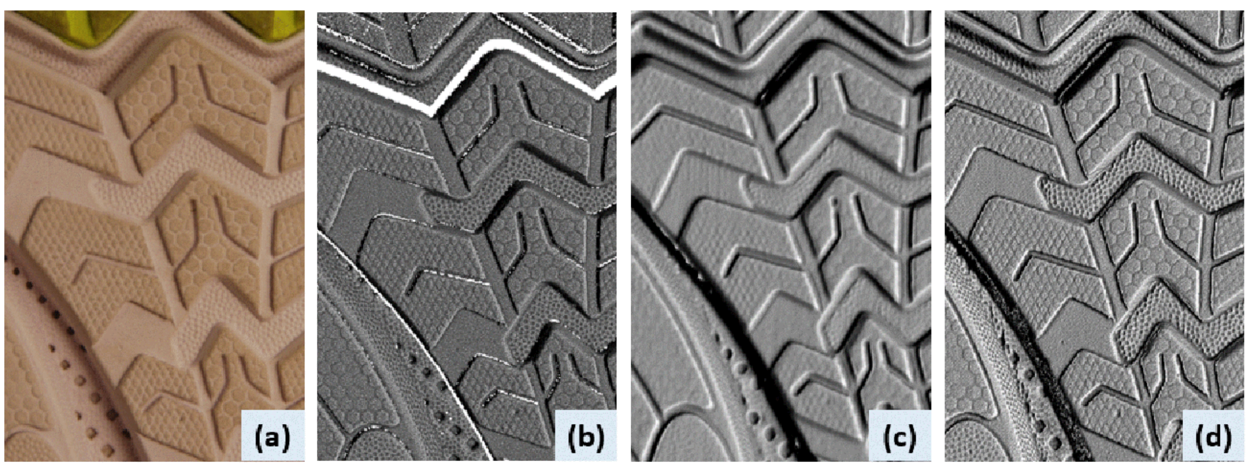


Fig. 1: *Measurement results of a region of shoe bottom. (a) 2D photograph; (b) 3D data captured by GOM; (c) 3D data captured by our low-resolution system (d) 3D data captured by our high-resolution system. (b)-(d) rendering results with MeshLab (http://www.meshlab.net).*

**Lab tests and findings:** The experiments captured shoe or tire impressions in clay (grain size < 0.01 mm), damp sand (grain size < 1 mm), dry fine sand (grain size 0.2-0.6 mm), damp fine silt (grain size < 0.1 mm), wet snow (air temperature 34 F), and dry snow (air temperature 17 F). The impression in each experiment was documented by digital 2D photography, scanned with the 3D scanners and then cast. Dental stone was used to cast the sand/silt impressions and snowprint plaster was used to cast the snow impressions. To produce a 3D "digital cast" the captured 3D image was rotated to view the back side of the scan. This digital cast was then compared to the physical cast, photograph and source shoe or tire. The 2D photograph was flipped horizontally to correspond to the casts and source shoe or tire. The clay experiment is detailed here to demonstrate the evaluation process. Our observations for other tests will be documented in the next section.

Fig. 2(a) shows the USPA shoe outsole used to create impressions in clay, damp sand and damp fine silt. Fig. 2(b) shows the region that was closely examined.

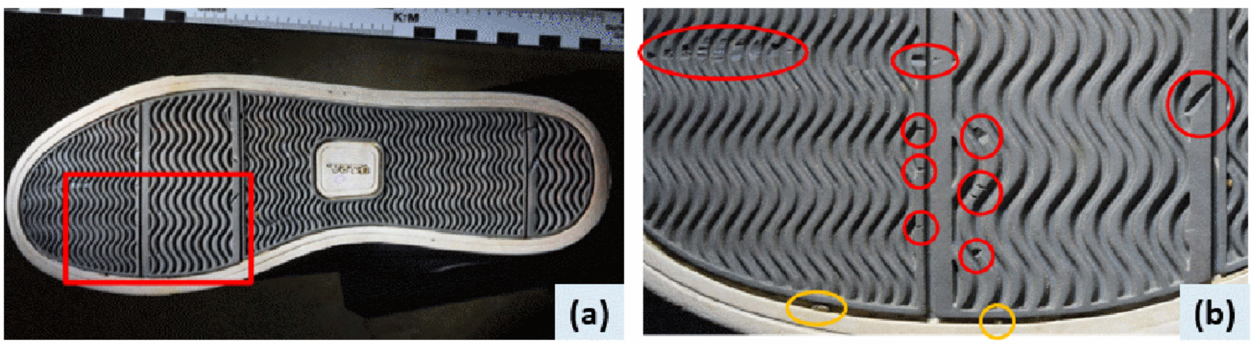


Fig. 2: *The USPA shoe used to create impressions for examination. The red box outlines area subjected to closer exam. The red circles outline the cut marks and the orange circle outlines two small rockholds. (a) 2D photograph; (b) region that was closely examined.*

The USPA shoe was used to make an impression in clay (grain size < 0.01 mm) that was further evaluated. Fig. 3(a) shows the evidence quality photograph. The impression was then captured by our high-resolution and low-resolution systems, as well as the physical cast. From the captured 3D data, we created a 3D "digital cast". Fig. 3(b) shows the image of physical casts, and Figs. 3(c)-(d) shows the digital casts. Our observations from this test are: 1) the evidence quality photograph with oblique lighting resolved all 10 test cuts and the two small rockholds, but the lack of 3D information would make it difficult to characterize the small rockholds; 2) the cast resolved all 10 test cuts and both small rockholds, yet small bubbles in the casts (casting artifacts) interfered with characterizing several of the test cuts and also had the potential to obscure other impression detail; 3) our low-resolution 3D scan clearly resolved 9 of 10 test cuts and also the two small rockholds. The smallest test cut (#10) could be barely visualized using oblique lighting in Meshlab; and 4) our high-resolution 3D scan clearly resolved all 10 test cuts and the two small rockholds. The high-resolution scan also provided sharper detail of the outsole design and test cuts, compared to the low-resolution scan.

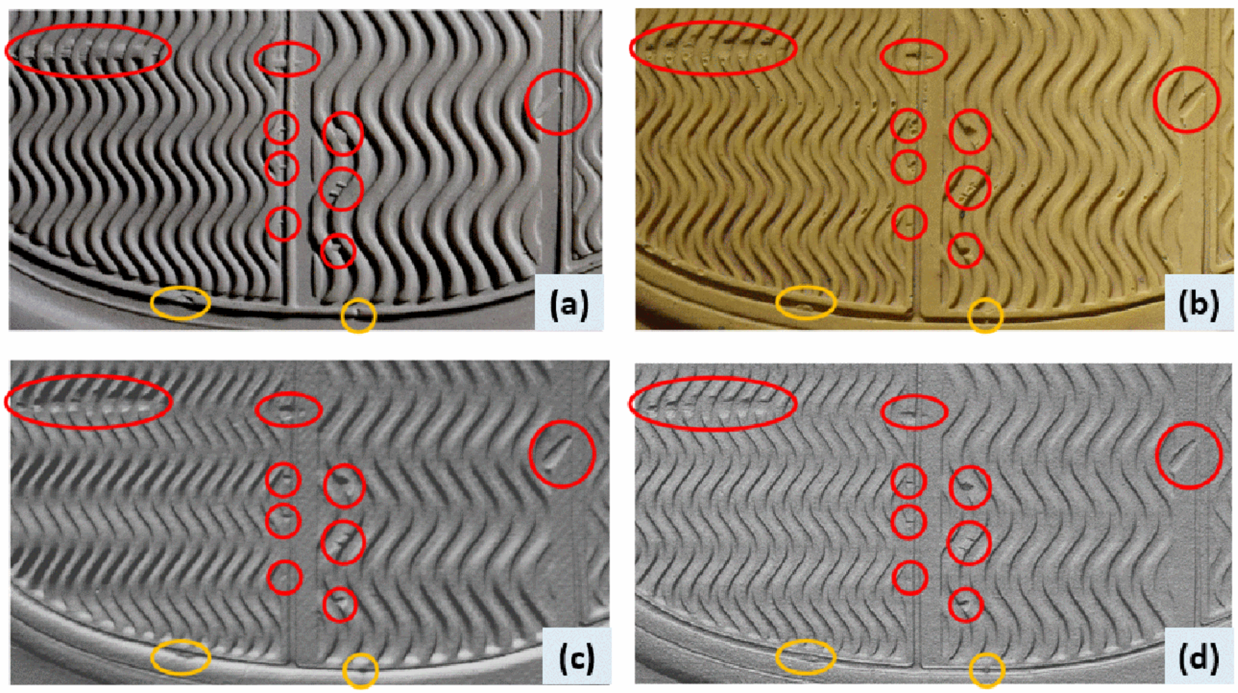


Fig. 3: *Test of shoe impression in clay. The red circles outline locations that correspond to test cuts in the shoe outsole and the orange circles outline locations that correspond to small rockholds in the shoe outsole. (a) Evidence quality 2D photograph; (b) conventional physical cast; (c) low-resolution 3D digital cast; (d) high-resolution 3D digital cast.*

## 5. Project findings

Besides clay tests, different impressions were also made and examined following similar procedures. Our observations will be detailed next. Overall, we found that 3D digital cast provides detail equal to or better than that of a physical cast and is invaluable not only for comparison purposes but also as an investigative aid. Compared with the current practice of casting, our technology demonstrates its superiority because 1) it is non-destructive, 2) it collects more evidence detail than casts especially when an impression is fragile (e.g. in dry fine sand), and 3) it saves time and costs less to collect each impression. In summary, our technology promises to be a game changer as it allows the fast collection of 3D detail of impressions with minimal training.

**USPA test impression in damp sand (grain size < 1 mm):** Our observations from this test are: 1) both low and high-resolution 3D digital casts resolve the test cuts almost as well as the photograph; 2) the rockhold was difficult to characterize in the 2D photograph; 3) compared to the physical cast, 3D digital casts captured more details; 4) there are pouring artifacts present on the physical cast, destroying some areas of details.

**USPA test impression in fine silt (grain size < 0.1mm):** Our observations are: 1) all methods resolved 10 test cuts; 2) because the damp fine silt used has a much smaller grain size than the sand, the 3D digital casts have better results than the previous test; and 3) like the previous test, the conventional cast has the worst performance, with some features eroded or more rounded because the impression was degraded by the casting process.

**Tire Impression in dry snow (17F):** Our observations from this test are: 1) the limited quality of the impression seems to make the high and low-resolution scans equal in visualizing detail; 2) the low-resolution scan rendering provides a little more contrast making it easier to discern the studs and rockholds; and 3) 3D scans resolved comparable detail to the physical cast. It is important to note that from our experience, spray painting of the impression in dry snow did not make a noticeable difference on our scanned data quality.

**XtraTuf test impression in wet snow (air temperature 34F):** Our observations from this test are: 1) the wet snow causes a strong reflection problem and coating the impression with gray spray paint (KRYLON Colormaster Primer gray) was necessary before 3D capture; 2) under sunlight, the light-blocking skirt is needed to block the bright ambient light for a good quality scan; 3) 2D photograph resolved the worn areas, barely allowed the visualization of the patent label, and had difficulty resolving the rockhold; 4) since the impression is quite deep, it was difficult to capture high-quality 2D photographs; 5) the physical cast resolved the rockhold and the worn areas, but portions of the outsole design in the heel were melted by the casting process; 6) with the help of the gray primer spray paint and the light-blocking skirt, 3D digital casts clearly resolved the worn areas and the rockhold. The ability to view the digital cast from different angles gives 3D scanning the advantage of interpreting the worn areas; 7) the patent label is much more obvious in 3D digital casts.

**Tire test impression in fine dry sand (grain size 0.2-0.6 mm):** Our observations from this test are: 1) the evidence quality photograph clearly resolved all 4 wear bars but was only able to discern 2 of 4 rockholds. It did not have 3D information to easily characterize the rockholds; 2) the physical cast destroyed much of the fine impression detail either due to fragile soil or by casting artifacts, only one wear bar was clearly visualized and no rockholds were clearly visible, and only small portions of the mold flash were apparent; and 3) our low resolution 3D digital cast was able to resolve all 4 wear bars and 3 out of 4 rockholds, clearly resolved the mold flash, and 3D information helped to characterize the rockholds.

## 6. Implications for criminal justice policy and practice

The 3D imaging system is unique in that it can be used to automatically and easily capture shoe or tire impressions in snow or soils. The portable and easy-to-operate system allows examiners to quickly and efficiently collect impression evidence. The easy 3D capture of images will improve the recovery of useful footwear and tire prints by reducing the impact of poor photographic practices and unlevel surfaces. The research could transform the current forensic practice for capturing shoe or tire impressions in snow or soils: instead of using the invasive casting process, the noninvasive optical 3D imaging method could be extensively adopted. Given its noncontact and nondestructive nature it could be used in conjunction with conventional methods. Additionally, it could significantly improve the ability to collect and record impressions in materials that are difficult for obtaining physical casts (fine or dusty soils) or in situations where there is not enough time to collect a cast (dangerous environments or degenerating weather conditions). It could make the collection of standard images of prints significantly easier and more reliable as well by relaxing the need for flat surfaces, distortion free optics, and perpendicular camera placement.

Since practitioners have found that this 3D imaging technology would substantially benefit the forensic science community, PI Zhang has co-founded a company Vision Express Optics Inc. (Auburn Hills, MI) and secured $2M in private funds to develop an affordable 3D imaging device for the community that could be on the market this year.

# Products

### Journal publications

S. Zhang, "Rapid and automatic optimal exposure control for digital fringe projection technique," Optics and Lasers in Engineering 128, 106029 (2020)

Y. Liao, J.-S. Hyun, Y.-H. Liao, J. Wolfe, I. Bortins, D. Baldwin, and S. Zhang, "Portable high-resolution automated 3D imaging for footwear and tire impression capture," Journal of Forensic Science (under preparation)

### Other publications, conference papers, and presentations.

S. Zhang, D. Baldwin, J. Wolfe, "3D footwear and tire tread impression capture," the National Institute of Justice's Impression, Pattern, and Trace Evidence Symposium (IPTES 2018), Alexandria, VA, January 23, 2018

S. Zhang, I. Bortins, D. Baldwin, "3D footwear and tire tread impression capture," IAI meeting, San Antonio, TX, July 31, 2018

S. Zhang, J.-S. Hyun, Z. Liu, C. Jiang, T. Bell, I. Bortins, D. Baldwin, J. Wolfe, "Portable high-resolution automated 3D scanning system," $5^{th}$ Annual International Educational Conference, International Associate of Forensic & Security Metrology (IAFSM), Fort Worth, TX, December 13, 2018

S. Zhang, "Portable advanced 3D imaging for footwear and tire impression capture," Webinar facilitated by Forensic Technology Center of Excellence, a program of the National Institute of Justice, October 23, 2019

S. Zhang, T. Bell, M. Feller, J.-S. Hyun, Y.-H. Liao, I. Bortins, D. Baldwin, and J. Wolfe, "Capture snow and soil impression tests with a portable high-resolution automated 3D imaging system," $7^{th}$ Annual International Educational Conference, International Associate of Forensic & Security Metrology (IAFSM) conference, Nashville, TN, Feb. 26, 2020