Using 3D Laser Scanning Technology to Create Digital Models of Hailstones

Ian M. Giammanco, Benjamin R. Maiden, Heather E. Estes, Tanya M. Brown-Giammanco

3D LASER SCANNING AND HAIL. Hailstorms account for more than $1 billion in annual insured property losses, and their increasing trend seen over the past two decades has outpaced advances in observation, forecasting, and mitigation of hail damage (Changnon et al. 2009; Roeder 2012; Kunkel et al. 2013). In 2012, the Insurance Institute for Business and Home Safety (IBHS) began a comprehensive research program with the overarching goal to help mitigate property losses from severe hail. A component of this initiative included determining the properties of hailstones that must be accounted for in laboratory material impact tests such that the results of these standardized test methods would be reasonably predictive of real-world performance of building materials. Subsequently, this led to a field campaign to measure the physical and material properties of hail, and to explore emerging technologies to aid in this effort.

It is well known that hailstones are found in a variety of nonhomogeneous shapes and can have large protuberances, which makes characterizing their true shape difficult using conventional means (i.e., caliper or ruler). Obtaining an accurate volume through physical measurements is also difficult, even when measuring multiple dimensions. In the past, record-breaking hailstones were kept in cold storage so a cast could be made of the hailstone. The impact craters of giant hailstones have also been examined and molds made of their shapes, as well (Knight and Knight 2001). While the process is effective in capturing the hailstone shape, it is cumbersome and time-consuming. A method was needed that provided accurate 3D measurement data without substantial contamination or melting of the hailstone prior to strength testing. The finescale, nonhomogeneous nature of hailstones provided the motivation to investigate how 3D laser scanners could be applied toward hail research.

The emergence of 3D scanning technology has led to new research opportunities across a wide range of fields (e.g., medical, mechanical and civil engineering, archaeology, etc.) but with little application within physical meteorology. In the atmospheric sciences, measurement systems such as lidar, particle imagers, laser disdrometers, scintillometers, optical rain gauges, and visibility sensors come to mind when considering laser-based applications. These systems are focused on in situ measurement of atmospheric particles or rely on backscattered energy from these particles. For 3D laser scanners, most atmospheric particles are too small and their in situ collection is too difficult for a manually operated laser scanning system to be of use to map their shape. However, hailstones are large enough and their shape is complex enough for laser scans and the 3D models that are produced to be scientifically beneficial. Three-dimensional laser scanners are also efficient for collecting sizeable datasets to evaluate the complex shapes of hailstones. During field campaigns in 2015 and 2016, a handheld 3D laser scanner was used successfully by IBHS to collect full digital 3D models of hailstones. It is believed this is the first time this technology has been used in this manner.

AFFILIATIONS: Giammanco, Maiden, Estes, and Brown-Giammanco—Insurance Institute for Business and Home Safety, Richburg, South Carolina
CORRESPONDING AUTHOR: Ian M. Giammanco, igiammanco@ibhs.org

DOI:10.1175/BAMS-D-15-00314.1

EVOLUTION OF 3D SCANNER TECHNOLOGY. The development of scanning technology to obtain accurate and precise measurements of objects began in the 1960s with advances in computer technology. Optical methods proved to be much faster, did not require direct physical contact with specimens, and were well-suited for complex shapes. The foundational research that integrated both passive photogrammetric and active laser techniques was pioneered by the National Research Council of Canada (Mayer 1999). Modern systems apply an active laser and passive photogrammetric components to capture point-cloud data to produce the digitized 3D model. At each data point, the distance and angle from the object to the system is recorded in a scanner-relative coordinate system. For large objects, several footprints of data are needed to stitch together the full 3D shape. Processing algorithms assimilate these footprints and remove duplicate data. Most current systems connect the point-cloud data by applying a nonuniform rational basis (NURB) spline fit. The result is faceted polygons (typically triangles), which produces the 3D surface. With advancements in reducing the size and cost of electronic components, small, single-operator, handheld units have become less cost-prohibitive for a wide range of research projects, including field studies and commercial applications.

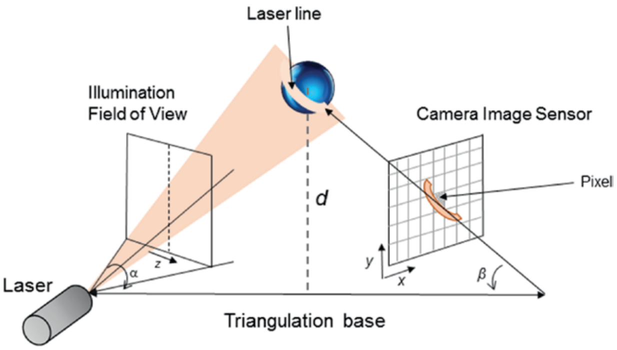

Fig. 1. Conceptual diagram of the laser, single-camera configuration, and triangulation coordinate system for a typical 3D laser scanning system, where *d* is the distance between the object and the scanner unit. Note that multiple cameras are used in hand-held systems, and the figure describes the configuration of one camera unit relative to the laser.

CAPABILITY SCOPING. The system selected to explore 3D scanning of natural hailstones was a handheld HandySCAN EXAscan system, manufactured by Creaform Inc. The system is a noncontact active scanner that employs a class II eye-safe laser to project a beam on a target. An array of cameras tracks the projected laser location, as shown in the conceptual diagram in Fig. 1. Its relatively small size, low weight (~1.5 kg), and simple operation by a single person made it ideal for use in a field vehicle, under

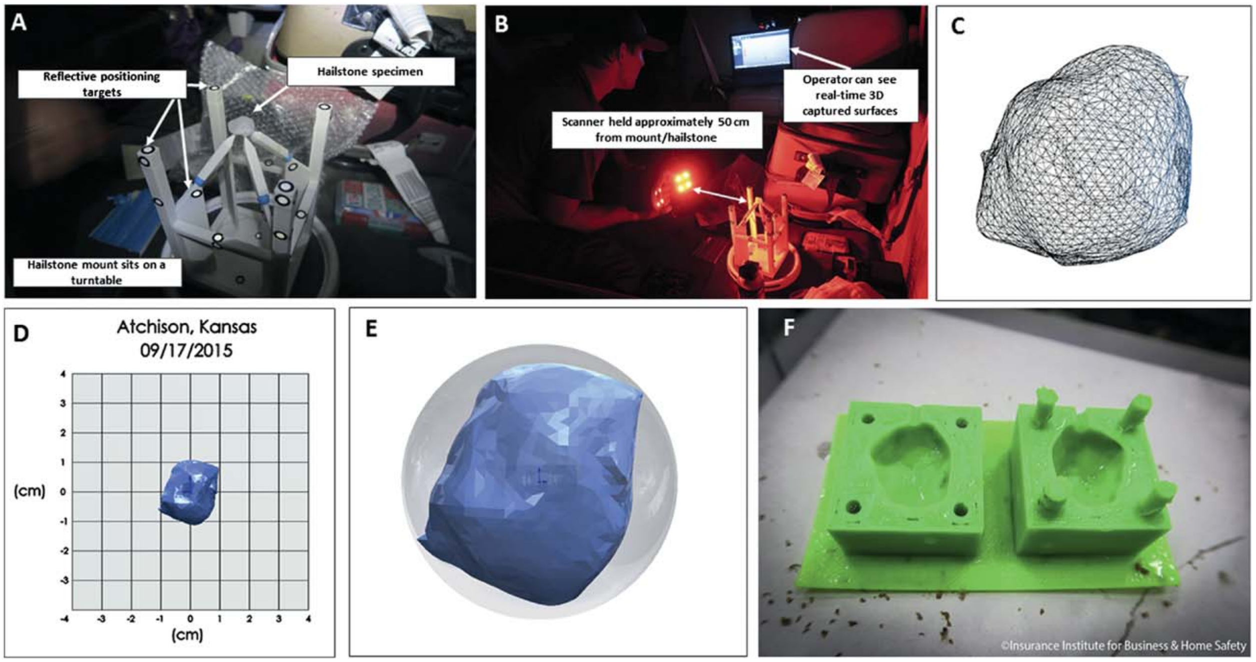

Fig. 2. (a and b) Photographs of the scanner in operation. The positioning targets, hailstone mount, and turntable are annotated; (c) the 3D faceted surface created by processing the collected point-cloud data; (d) the full 3D model of the first hailstone captured with this system; (e) comparison with a sphere of the same maximum diameter; and (f) the 3D-printed cavity mold of this hailstone.

nonoptimal conditions (Fig. 2a,b). To operate the unit, information must be simultaneously collected on the unit's position while it is scanning the specimen. Additionally, the unit must be calibrated prior to operation periods. The scanner is calibrated by using a plate with a grid of reflective targets, supplied by the manufacturer (reflective targets are identified in Fig. 2a,b). The precise dimensions and target locations of the plate are stored in the operating software, which is able to identify and adjust for any small bias errors. Small errors may result from temperature changes and the expansion and contraction of hardware components such that calibration is recommended prior to scanning sessions. The reflective positioning targets are also used to define the coordinate system with respect to the specimen being scanned. Targets are scanned separately (only one time) prior to data collection. The information is stored by the operating software and applied when scanning of the specimen is underway. The targets are adhered either to the specimen itself or to a mounting system such that the unit always has several positioning targets in its field of view (HandySCAN EXAscan requires at least three). If the minimum number of targets is not detected during data collection, the software will cease logging until they are identified to automatically avoid data gaps due to user error. The system has a trigger that toggles the laser projection, camera operation, and data collection.

The unit has a maximum configurable resolution of 0.008 cm, an accuracy of ±0.004 cm, and a maximum sampling rate of 25 kHz. It is tethered to a laptop computer running Creaform's VXelements software package to operate the scanner, view ongoing scans in real time, and store the data. The NURB spline-based polygon-mesh approach is used by VXelements to capture, process, and display the 3D data. The processed dataset can then be quality controlled to synthetically fill in missing data, remove other objects that may have been in the field of view, and filter spurious returns. Once the data have been processed, additional analyses can be performed on the digital model to extract more information on the characteristics of the hailstone. Data can also be exported in a .STL file format for use in standard CAD packages or other computational analysis tools.

LABORATORY ICE TESTING. The EXAscan system's ability to detect and map ice surfaces was tested using ice spheres made with pure distilled water (very clear ice) and water with diffused carbon dioxide gas (bubble-filled, opaque ice). The ice spheres were then chipped or deformed to introduce small shape changes to evaluate the scanner's ability to detect these deformations. It was quickly discovered during initial testing that ice surfaces are difficult mediums to effectively scan. Clear ice surfaces and ice surfaces coated with a large amount of liquid water scattered the projected laser such that it was not well defined on the object surface. Subsequently, the photogrammetric camera tracking functionality could not resolve the true location of the projected laser. This resulted in large gaps in the digitized model. Performance was improved when opaque, bubble-filled ice was tested, but this required long scanning durations and revisiting scanned areas to capture a complete model. To reduce the amount of scatter, a light dusting of a fine powder (i.e., athlete's foot spray) was used, enabling the system to adequately track the projected beam and map the ice surfaces. At times, compressed air was also used to help remove any liquid water on the surface of the hailstone. Although this introduces a foreign substance onto the hailstone similar to an immersion test, compressive strength testing yielded no detectable influence between coated and uncoated laboratory ice spheres. The method is still more practical than immersion testing in a field setting, especially when considering substances used in past research (i.e., liquid mercury). During this initial testing, it was also determined that full scans can be completed in less than 1 min at low sampling resolutions, while higher resolution scans can take 2–3 min to complete. The length of time needed for a complete scan was determined to be suitable for a pilot field application to help mitigate the melting of stones while they were being scanned.

SCANNING HAILSTONES IN THE FIELD. The scanner system was pilot tested in the field for the first time in 2015 to determine if it would be effective for use during the 2016 field measurement program. Calibration was performed after the target storm was selected but prior to data collection. This helped mitigate any measurement errors from temperature changes and possible expansion and contraction of hardware components during transit. Hailstones were collected from a target thunderstorm following its passage across an identified roadway. Liquid water present on the surface of the hailstone was quickly wiped clean or blown off using compressed air prior to the powder application.

To allow the operator to quickly scan the full volume, a custom mount was designed and 3D-printed to support the stone. The acrylonitrile butadiene styrene (ABS) plastic material helped reduce melting resulting from the direct contact between the hailstone and the supports. The mount used three points of contact to support the stone with as little interference as possible. Reflective positioning targets were permanently fixed to the mount to calibrate the scanner position relative to the mount and allow for the mount to be placed on a turntable. The reflective targets allow the unit to "know" its relative position in three-dimensional space. The turntable allowed the hailstone to be rotated so that the sides of the stones could be scanned without the operator needing to move frequently within the vehicle. The mount also allowed enough space between supports so the bottom of a hailstone could be captured by the operator simply turning the unit to allow the laser to pass across the underside of the hailstone. The support mount is detected during scanning, but is removed in data processing, leaving just the 3D model of the hailstone. An example of a hailstone being scanned in the field and the resulting 3D model can be seen at https://vimeo.com/167924554. Before a hailstone was scanned, specimens were photographed, measured with a caliper, and weighed.

2015 PILOT FIELD TESTING. The system was first deployed during a period of active severe weather in the Central Plains on 15–18 September 2015. The field team intercepted a supercell thunderstorm near Atchison, Kansas, on 17 September 2015, which produced a relatively high bulk concentration of small hail (<2 cm). Attempts to collect a full scan of small hailstones (<1 cm) were unsuccessful due to the original design of the prototype mount (corrected in a later version). The hailstones were too small to effectively support as they began to melt. Fortunately, a larger hailstone (2.5 cm in diameter) was gathered, and a successful scan was made. The data were processed to remove scanner interference, synthetically fill any small data gaps, and produce the full 3D model (Fig. 2c,d). It is believed that this was the first successful 3D laser scan of a hailstone. The scan of this particular hailstone was completed in approximately 3 min at a resolution of 0.008 cm and used a maximum sampling rate of 25 kHz. The fully scanned hailstone had a mass of 2.50 g, and a maximum diameter of 2.504 cm. The diameter was defined as the longest straight line between two points, which passed through the center of the hailstone model. The volume, determined from the model, was 3.654 cm^3, which was 54% less than a sphere of the same diameter (Fig. 2e). The volume coupled with the measured mass yielded a bulk density of 0.68 g cm^{-3}. The digitized 3D model was used to 3D-print a cavity mold based upon the highly detailed hailstone shape (Fig. 2f), and demonstrated the linkage between 3D scanning and printing technology. The success of integrating the digital hail model into a CAD design application and 3D-printing a model highlighted the ability to duplicate natural hailstone shapes and their intricate details in a laboratory setting. This, coupled with exploration of diffused gas ice mixtures, could lead to the re-creation of laboratory hailstones that match the physical and material properties of hailstones observed in the field.

2016 FIELD MEASUREMENT PROGRAM AND ANALYSIS. The 2016 field measurement program focused on obtaining 3D models of hailstones and performing corresponding compressive strength tests. The efforts produced 42 digital hailstone models collected primarily from supercell thunderstorms in the Southern Great Plains of the United States in May and June of 2016. A subset of scanned hailstones, showing the variety of shapes that were captured, is shown in Fig. 3. The high-resolution models allowed for an accurate volume estimate to be obtained for each hailstone. It is acknowledged that some melting may have occurred prior to collection, and/or liquid water contained within small cavities in the hailstone may have drained, resulting in a small bias. It is also possible that protuberances may have been rounded off because of melting or impact with the ground. When compared with hailstone densities estimated using physical measurements and shape assumptions, the errors are expected to be reduced.

Throughout historical literature, summarized by Knight and Knight (2001), hailstones are commonly referred to as "hard" or "soft" with no quantification of their strength. It is frequently assumed that hailstone strength and their damage potential scales with bulk density (Knight et al. 2008). The true relationship between density and strength is unknown at this time. The use of 3D-scanned hailstones combined with recent advances in the ability to test hailstones for their compressive strength can help clarify the relationship and determine if laboratory impact tests must replicate it in order to accurately produce a true correlation with real-world performance of building materials.

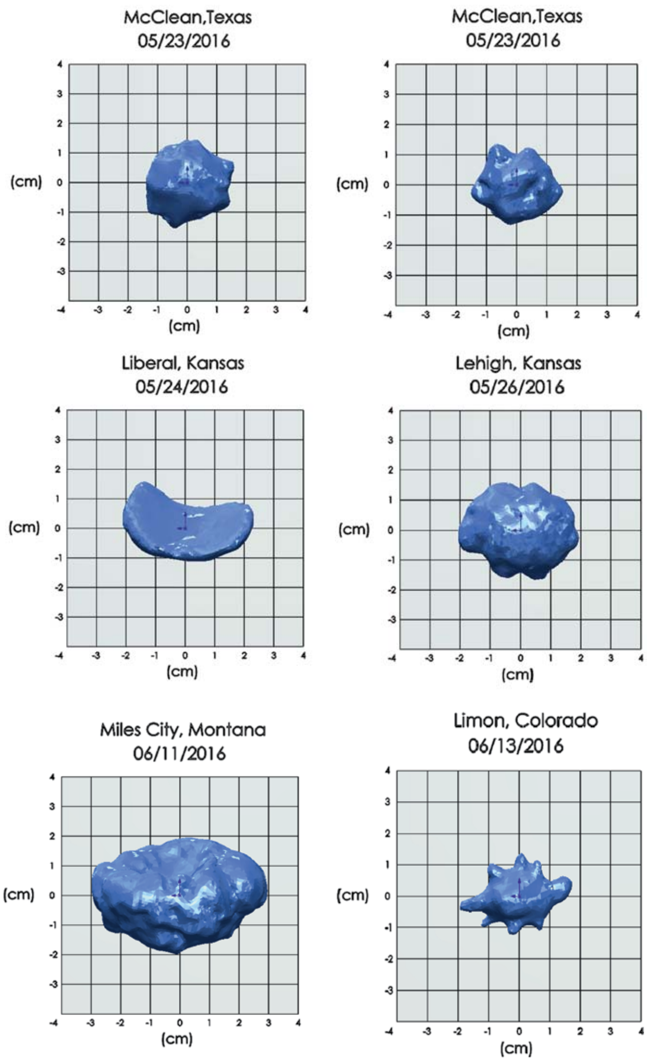

Fig. 3. Collection of several hailstone models showing the variety of shapes captured during the 2016 field program. The date and general location are provided for each hailstone.

The 3D-scanned hailstones were subjected to compressive strength testing, which applies an increasing compressive force with a strain rate on the order of 10^{-1} s^{-1} to the hailstone until it fractures. The peak force at the time of fracture is captured and then scaled by the cross-sectional area (i.e., plane) in which the force was exerted to produce an estimate of uniaxial compressive stress. The compressive stress was used as a proxy to represent the hardness property of the hailstone (Giammanco et al. 2015). These stones were also examined with respect to the diameter-to-mass relationship, bulk density, their volume normalized by that of a sphere with the same maximum diameter, and their compressive strength (Fig. 4). The observations also showed that hailstone densities trend closer to pure ice (0.9 g cm^{-3}) as they get larger. Three hailstones exhibited a density greater than 0.9 g cm^{-3} and were characterized by nearly all clear ice with no visible layering structure. The hailstones also had notable protuberances. The high density of these stones raises the question of whether "super" density ice occurs in hailstones or if this was the result of a measurement error. It is possible that some mass loss between measurement and scanning occurred such that the density estimate contained an error; however, the maximum diameter measured using a caliper was within 0.04 cm for all three hailstones when compared to the scanner-based diameter. The scale used has a precision of 0.01 g, but any shaking or movement of the scale could have introduced some source of measurement error. The use of this system in the field will help improve the understanding of hailstone bulk density distributions and determine if high-density and/or low-density hailstones are more prevalent than historical literature would suggest. It was clear that the measured hailstones departed from spherical shapes with increasing diameter, which is in agreement with recent field observations (Heymsfield et al. 2014) (Fig. 4c).

Throughout historical literature, low-density hailstones were often associated with being soft and of low strength. There has been little quantitative analysis to substantiate this expectation or to investigate a potentially different relationship. The datasets collected through 3D scanning and compressive strength testing allowed for a preliminary examination of how the two variables may be related. The relationship between the measured peak forces showed a general linear trend, with a larger force required for higher densities (not shown). However, the peak force must be scaled by the area of the plane in which the force was applied to produce an appropriate measure of strength. As shown in Fig. 4d, the slight linear trend was toward weaker hailstones with higher bulk densities. It is noted that the sample size shown here is only 42 hailstones, and larger datasets are needed. The ability to evaluate these properties is a notable advance that will foster new research toward understanding hailstone characteristics and determining their properties that affect damage potential.

RESEARCH APPLICATIONS OF 3D HAILSTONE MODELS. The first effort to 3D-scan hailstones was successful in proving the system could be operated efficiently in the field, collect a

DOCKET
ALARM

Explore Litigation Insights

Docket Alarm provides insights to develop a more informed litigation strategy and the peace of mind of knowing you're on top of things.

Real-Time Litigation Alerts

Keep your litigation team up-to-date with **real-time alerts** and advanced team management tools built for the enterprise, all while greatly reducing PACER spend.

Our comprehensive service means we can handle Federal, State, and Administrative courts across the country.

Advanced Docket Research

With over 230 million records, Docket Alarm's cloud-native docket research platform finds what other services can't. Coverage includes Federal, State, plus PTAB, TTAB, ITC and NLRB decisions, all in one place.

Identify arguments that have been successful in the past with full text, pinpoint searching. Link to case law cited within any court document via Fastcase.

Analytics At Your Fingertips

Learn what happened the last time a particular judge, opposing counsel or company faced cases similar to yours.

Advanced out-of-the-box PTAB and TTAB analytics are always at your fingertips.

API

Docket Alarm offers a powerful API (application programming interface) to developers that want to integrate case filings into their apps.

LAW FIRMS

Build custom dashboards for your attorneys and clients with live data direct from the court.

Automate many repetitive legal tasks like conflict checks, document management, and marketing.

FINANCIAL INSTITUTIONS

Litigation and bankruptcy checks for companies and debtors.

E-DISCOVERY AND LEGAL VENDORS

Sync your system to PACER to automate legal marketing.

WHAT WILL YOU BUILD? | **sales@docketalarm.com** | **1-866-77-FASTCASE**

fastcase®
Smarter legal research.