Using LADAR to characterize the 3-D shape of aggregates: Preliminary results

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Using LADAR to characterize the 3-D shape of aggregates: Preliminary results

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Abstract

Previous publications have shown how a combination of X-ray computed tomography and spherical harmonic series could be used to characterize the 3-D shape of rocks used for aggregates in concrete. The X-ray computed tomography was used to obtain the raw 3-D numerical data for the coordinates of the aggregate surface. In this paper, we demonstrate how laser detection and ranging (LADAR) numerical data can replace X-ray computed tomography data and be used in conjunction with spherical harmonic series analysis to analyze the 3-D shape of aggregates.
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1. Introduction

Many properties of concrete depend more or less sensitively on the 3-D shape of aggregate particles [1–4]. The shape of aggregates is treated in the ASTM standards [e.g., ASTM Standard Test Method for Flat Particles, Elongated Particles, or Flat and Elongated Particles in Coarse Aggregate (D 4971)]. However, most test methods do not give a complete 3-D shape characterization and analysis. Shape quantities that are defined from 2-D measurements are only semi-quantitative at best. Previously, we have shown that for aggregate particles [5,6] and for cement particles [7] a combination of X-ray computed tomography (CT) and spherical harmonic analysis can, within resolution limits, determine the complete 3-D shape of an aggregate. The X-ray CT gives the numerical shape of the aggregate, in terms of a 3-D digital collection of voxels of a certain size. Shape features that are smaller than this voxel size will not be properly represented. A numerical surface function is constructed from this 3-D volume, which is then represented with a spherical harmonic expansion that results in an analytical expression for the surface of the real particle. This surface function is defined as $r(\theta,\phi)$, where r is the distance from the center of mass of the particle, as determined from the 3-D digital image, along the direction (θ,ϕ), and θ and ϕ are the usual spherical polar coordinates. The spherical harmonic expansion is:

$$r(\theta,\phi) \cong \sum_{n=0}^{N} \sum_{m=-n}^{n} a_{nm} Y_{nm}(\theta,\phi) \qquad (1)$$

where the Y_{nm} are the complex spherical harmonic functions [8] and the a_{nm} are complex coefficients. When $N \to \infty$, the expansion is exact [8].

In this present work, we show how laser detection and ranging (LADAR) can be used to determine the surface function, from which the spherical harmonic coefficients can be extracted. Direct comparison to experiment is made for two rocks (shown in Fig. 1), denoted in this paper as Rock 1 (larger and naturally rounded) and Rock 2 (smaller and crushed), of unknown mineralogy. Rock 1 was previously analyzed by X-ray CT in Ref. [6], where it was also denoted as Rock 1.

2. LADAR

A LADAR instrument is an instrument that allows for the rapid capture of 3-D information of a scene — typically measuring, in minutes, the 3-D coordinates of several million points. A laser beam is sent out by the instrument and its reflection from the object is measured, giving the coordinates of the surface points of the object measured [9].

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Fig. 1. Digital camera images of (a) Rock 1 (long dimension of rock is about 70 mm) and (b) Rock 2 (long dimension of rock is about 13 mm).

The three basic methods used for range measurement are time-of-flight, phase based, and triangulation. The maximum ranges of ground based LADARs vary from less than 10 m to over 1 km. The range uncertainties vary from the micrometer level to the tens of millimeter level with the lower uncertainties normally associated with shorter-range instruments.

The instrument used to obtain the 3-D data of the aggregates in this paper has a range of 24 m and measurement uncertainties varying from 50 μm to 300 mm. The lower uncertainties are obtained by slowing the scan speed. The field-of-view of the LADAR is ±200°, horizontally, and ±45° vertically. The data were obtained with the point spacing set at 0.5 mm for Rock 1 and 0.25 mm for Rock 2.

LADARs are line-of-sight instruments and as a result, no data is obtained for the back of an object or for objects obscured by another object. Generally, several scans have to be obtained from different viewpoints or by rotating the object to obtain complete coverage. These scans have to be registered so that they have a common reference frame. Four scans of each of the rocks were sufficient to acquire complete coverage of the rock surfaces and these scans were registered using tooling balls (targets) that were placed in the scene and served as stationary reference points.

LADAR has been used to compute the shape of a very large rock — a 30 km long asteroid [10], but to our knowledge, has never been used to evaluate the 3-D shape of aggregates that are used in concrete. Laser scanning has been used previously to give partial shapes of such aggregates [11], but the scans were not truly 3-D since not all sides of the aggregates were imaged.

3. Numerical analysis

The measured cloud of points on the surface of the rocks do not lie on any kind of grid, as they are typically composed of several different overlapping scans. These points are converted to spherical polar coordinates, with the origin at the centroid of the coordinates, so as to give a numerical representation of the surface function $r(\theta,\phi)$. To compute the spherical harmonic coefficients, a_{nm}, the following integral must be numerically performed using the measured surface points:

$$a_{nm} = \int_0^{2\pi} \mathrm{d}\phi \int_0^{\pi} \mathrm{d}\theta \sin(\theta) r(\theta,\phi) Y^*_{nm}(\theta,\phi) \quad (2)$$

where the asterisk indicates the complex conjugate. In previous work, this integral was performed using Gaussian quadratures [5]. Since the LADAR grid of points is not set up for Gaussian quadratures, a Monte Carlo integration technique was chosen [12].

4. Results

There were about 40000 surface points for Rock 1 and 7000 surface points for Rock 2. Because this was a preliminary study, the method by which the rocks were held for analysis was not optimized, and so surface points on the sample holder also formed part of the cloud of surface points generated. These points were approximately "clipped" away using software, but a small part of the rock surface points that was covered by the holder surface was also removed. Fig. 2a and b shows the rocks after points were clipped away to approximately remove the sample holders. A small amount of rock volume was lost in this "clipping" process. Fig. 3a and b shows Virtual Reality Modeling Language (VRML) images of the same rocks, produced with the techniques previously described [6]. Fig. 3c shows a VRML image of Rock 1, in approximately the same orientation as in Fig. 3a, but produced from the X-ray computed tomography data [6]. It is hard to visually tell the difference between Fig. 3a and c.

The volume and dimensions of each rock were measured experimentally; the volume by weighing in air vs. water, and the dimensions using a digital caliper. The dimensions were defined as the length (L), the longest surface point-to-surface point distance on a rock, the width (W), which is the longest surface point-to-surface point distance on a rock that is also perpendicular to the length, and the thickness (T), which is the longest surface point-to-surface point distance on a rock that is also perpendicular to the length and the width (ASTM D4791). These values give a rough idea of the shape in terms of an equivalent box shape [13]. The volume and these dimensions can be readily computed from the spherical harmonic representation [5,6]. The L, W, and T measurements were made using a digital caliper that had an uncertainty of 0.01 mm. However, the overall uncertainty was dominated by the error in actually determining the correct orientation of L, W, and T on

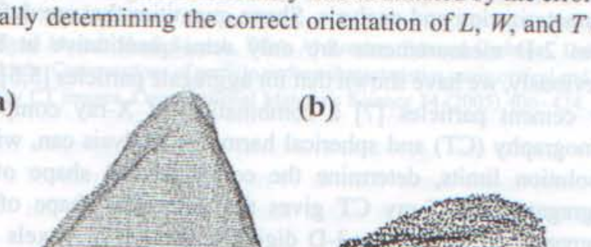

Fig. 2. LADAR images after removing the points associated with the holder. (a) Rock 1, (b) Rock 2. Images are not to scale.

Fig. 3. (a) VRML visualization of Rock 1, (b) VRML visualization of Rock 2. The figure is not to scale, as Rock 2 is actually much smaller than Rock 1. (c) VRML visualization of Rock 1 based on numerical surface coordinates from X-ray CT.

the surface of the irregular rocks, so that the actual uncertainties were much higher.

Table 1, first and third rows, shows the comparison between 3-D imaging using LADAR and experimental measurements for Rock 1 and Rock 2. The comparison is quite close. The fact that the computed volume of both rocks is a little less than the measurements (−4% for Rock 1, −5% for Rock 2) is because the clipping process removed some rock volume when the sample holding material was removed. Comparisons made with full images show very close agreement in volume, about 1% or less [6,13]. The agreement between the measured and numerical results for L, W, and T is about the same, though again, the loss of some rock material in the final LADAR images has caused some small changes in the values of L, W, and T. The second row of Table 1 shows equivalent computed L, W, and T data for the spherical harmonic expansion that was based on X-ray CT.

5. Discussion

It is clear from our results that LADAR imaging can be used in the same way as X-ray CT to produce the raw surface data needed for spherical harmonic analysis. Since both methods can be so used, how do they compare?

First, X-ray CT requires that the aggregates be embedded in a cylindrical matrix that has a reasonable X-ray contrast with the aggregates, while LADAR can and indeed must operate directly on the aggregate. However, many aggregates can be measured simultaneously with X-ray CT, at the price of proper preparation of the samples [6], which can be time-consuming. LADAR can only handle one aggregate at a time, but each aggregate can be scanned much faster than in X-ray CT, in a matter of a few minutes per aggregate rather than a few hours for an X-ray

Table 1
Measured (Meas) and numerical (Num) values of volume, length, width, and thickness for rocks 1 and 2

Rock	Meas (mm^3)	Num (mm^3)	Meas (mm)± 2.0 mm			Num (mm)		
	Volume	Volume	L	W	T	L	W	T
1	47800±400	45842	80	58	31	77	55	30
1*	–	–	80	58	31	78	56	31
2	680±4	643.6	15.2	12.9	7.0	15.0	12.8	7.6

The row marked 1* gives the results for Rock 1 using X-ray computed tomography instead of LADAR [6]. The numerical results were found using the spherical harmonic series generated from the LADAR surface data. The uncertainties in the experimentally measured quantities are given in the table.

computed tomography sample. One of the goals of future research will be to further reduce the LADAR scanning time that is necessary to characterize a given aggregate in 3-D.

Second, X-ray CT produces a digital 3-D image of the aggregates, so that the numerical surface function as a function of angle is produced by linear interpolation between these voxel faces. It is possible, however, to envision a more mathematically sophisticated way of interpolating the surface of an X-ray CT scan by using some sort of iso-surface algorithm like marching cubes [14]. LADAR is not limited to the faces of a digital image, but directly gives the (x,y,z) position of all points that it samples on the aggregate surface, which is an advantage for characterizing irregular objects.

"Texture" is often mentioned along with shape as affecting the properties of concrete made with a certain aggregate type [15]. What is meant by texture is the small scale surface irregularities that can be easily felt but not easily seen by the naked eye. In reality, texture and shape are equivalent entities but are at different length scales. Texture is the same as shape, just at smaller length scales. The voxel roughness of the typical X-ray CT image limits the length scale of texture measurement to be at least 5 voxel lengths; i.e., a surface feature needs to be represented by about 5 voxels in order for any reasonably accurate measure of its true shape to be made. If an X-ray CT image is made at a voxel size of, e.g., 10 μm per voxel edge, the only texture information it produces that is trustworthy would be on the length scale of 50 μm or larger. Since LADAR is not limited to voxel edges, it should be able to do a better job imaging texture even at an equal or larger resolution. For example, the LADAR unit used in this work has a minimum resolution of 50 μm, which means it measures distances to that resolution. Texture information at that size or smaller may be accurate, depending on how many surface point positions are measured.

There are many, basically empirical, characterizations of particle shape such as "flakiness," "flat and elongated," "roundness/sphericity," and others. These are typically estimated from 2-D measurements, whose accuracy cannot be estimated, since there are no 3-D references against which to compare them. However, once a complete 3-D characterization of an aggregate has been made, so that the surface is known analytically in terms of an expansion in spherical harmonic functions like in Eq. (1), then any shape characteristic can be computed [5,13]. So a use of this 3-D technique could be to look at a small but statistically reasonable subset of aggregates, and use the essentially exact 3-D data to understand the results of and quantitatively estimate the accuracy of a faster but less accurate 2-D method.

6. Conclusions and future research

It is clear from our results that LADAR imaging can be used in the same way as X-ray CT to produce the raw surface data needed for spherical harmonic analysis. Sample preparation is much easier, but at present only one aggregate at a time can be characterized. The essentially exact 3-D data that comes from a combination of LADAR or X-ray CT along with spherical harmonic analysis can serve to check and understand what faster, 2-D methods give. Two-dimensional methods of shape measurement can never be completely accurate, since they always must miss some aspect of the true 3-D shape.

Future work on LADAR will include developing better sample holding methods that do not require losing some of the aggregate image, increasing the speed of imaging to the maximum extent possible, and automatic aggregate handling to replace the manual handling required at present. It will not be difficult to improve the sample holders — some kind of sharp point holders on top and bottom of the rocks will take care of most of the difficulties. Optimizing the scanning procedures should increase the speed of effective scanning. Automatic aggregate handling will be more difficult to achieve, but is certainly capable of being accomplished. With these improvements and because of the promise of LADAR, we intend to further pursue its use in getting shape and texture information on aggregates used in concrete and other construction. However, since there are areas in which X-ray CT is superior to LADAR, at least at present, we do not intend to abandon X-ray CT as a measurement method. With the two methods acting in parallel, we should be able to more accurately and easily capture the shape of aggregates used in concrete, whose shape can play an important role in determining the properties of the concrete in which they are present.

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